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# Possible manifestation of spin fluctuations in the temperature behavior of resistivity of $Sm_{1.85}Ce_{0.15}CuO_4$ thin films

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A pronounced step-like (kink) behavior in the temperature dependence of resistivity $\rho(T)$ is observed in the optimally-doped $Sm_{1.85}Ce_{0.15}CuO_4$ thin films around $T_{sf} = 87\,K$ and attributed to manifestation of strong spin fluctuations induced by $Sm^{3+}$ moments with the energy $\hbar\omega_{sf} = k_B T_{sf} \simeq 7\,meV$. In addition to fluctuation induced contribution $\rho_{sf}(T)$ due to thermal broadening effects (of the width $\omega_{sf}$), the experimental data are found to be well fitted accounting for residual (zero-temperature) $\rho_{res}$, electron-phonon $\rho_{e-ph}(T) = AT$ and electron-electron $\rho_{e-e}(T) = BT^2$ contributions. The best fits produced $\omega_p = 2.1\,meV$, $\tau_0^{-1} = 9.5 \cdot 10^{-14}\,s^{-1}$, $\lambda = 1.2$, and $E_F = 0.2\,eV$ for estimates of the plasmon frequency, the impurity scattering rate, electron-phonon coupling constant, and the Fermi energy, respectively.

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**1. Introduction.** Despite numerous investigations on many different physical properties of electron-doped superconductors (EDS), these interesting materials continue to attract attention of both experimentalists and theoreticians alike, especially as far as their low-temperature anomalies are concerned (see, e.g., [1 – 7] and further references therein). Of particular interest is Sm-based EDS. Since Sm has a larger ion size than Ce, Pr and Nd, it is expected that paramagnetic scattering contribution to low-temperature behavior of $Sm_{2-x}Ce_xCuO_4$ should be much stronger than in $Pr_{2-x}Ce_xCuO_4$ and $Nd_{2-x}Ce_xCuO_4$. Recently [7], by using a high-sensitivity home-made mutual-inductance technique we managed to extract with high accuracy the temperature profiles of penetration depth $\lambda(T)$ in high-quality optimally-doped $Sm_{1.85}Ce_{0.15}CuO_4$ (SCCO) thin films grown by the pulsed laser deposition technique. We found that above and below $T = 0.22\,T_C$ our films are best-fitted by a linear [6] and quadratic [2] dependencies, respectively, with physically reasonable values of $d$-wave node gap parameter $\Delta_0/k_B T_C = 2.07$ and paramagnetic impurity scattering rate $\Gamma/T_C = 0.25(T_C/\Delta_0)^3$. We also noticed that the boundary temperature ($T = 0.22T_C$) which demarcates two scattering mechanisms (pure and impure) lies very close to the temperature where strong enhancement of diamagnetic screening in SCCO was observed [4] and attributed to spin-freezing of Cu spins. Moreover, the above crossover temperature remarkably correlates with the temperature where an unexpected change in the field dependence of the electronic specific heat in PCCO crystals was found [5] and attributed to the symmetry change from nodal to gapped.

It should be mentioned also that in addition to their unusual pairing properties, EDS exhibit some anomalous normal state behavior far above $T_C$ with a noticeable presence of both electron-phonon and electron-electron contributions [8 – 10]. Recent inelastic neutron scattering experiments [11, 12] on low-energy spin dynamics (for the energy spectrum ranging from 1 meV to 10 meV) in $Pr_{0.88}LaCe_{0.12}CuO_{4-\delta}$ (PLCCO) clearly demonstrated the evolution of PLCCO from nonsuperconducting antiferromagnet (with the Neel temperature $T_N = 210\,K$) to optimally doped superconductor (with $T_C = 24\,K$). Besides, a step-like intensity increase was observed at about $T_{sf} = 80\,K$ and linked to the manifestation of low-energy ($\hbar\omega_{sf} = k_B T_{sf} \simeq 6.5\,meV$) long-range antiferromagnetic (AFM) spin fluctuations in the excitation spectrum induced by $Pr^{3+}$ moments through $Cu^{2+}$–$Pr^{3+}$ interaction [13].

In this Letter we present our latest results on the temperature behavior of resistivity $\rho(T)$ for the same optimally-doped $Sm_{1.85}Ce_{0.15}CuO_4$ films [7], paying special attention to their normal state properties. In addition to the expected contributions from the electron-phonon and electron-electron scattering processes, we also observed an unusual kink like behavior of $\rho(T)$ around $T = 87\,K$ very similar to the one seen in inelastic neutron scattering data [11, 12]. Given that Sm has a larger ion size than Pr and assuming that the long-range AFM correlations should be even stronger in thin films (than in single crystals), we attribute the appearance of this kink in our SCCO films to the manifestation of thermal excitations due to spin fluctuations induced by $Sm^{3+}$ moments through $Cu^{2+}-Sm^{3+}$ interaction.

**2. Results and discussion.** A few SCCO thin films ($d = 200\,\mathrm{nm}$ thick) grown by pulsed laser deposition on standard $LaAlO_3$ substrates were used in our measurements (for more details on our samples including their other physical properties, see Ref. [7]). All samples showed similar and reproducible results. The structural quality of the samples was verified through X-ray diffraction (Fig.1) and scanning electron microscopy together with energy dispersive spectroscopy technique.

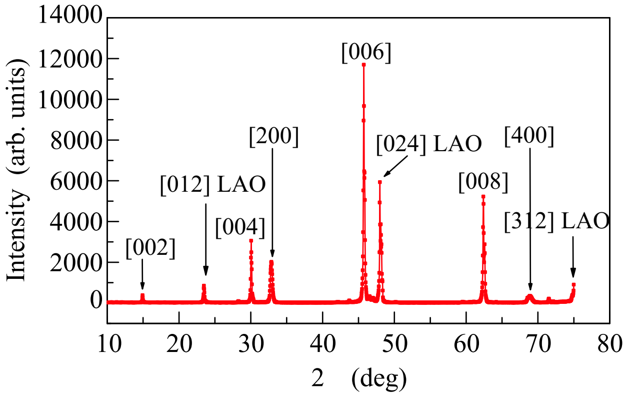

Fig.1. X-ray diffraction spectrum of SCCO films

To account for a possible magnetic response from substrate, we measured several stand alone pieces of the substrate. No tangible contribution due to magnetic impurities was found. The electrical resistivity $\rho(T)$ was measured using the conventional four-probe method. To avoid Joule and Peltier effects, a dc current $I = 1\,\mathrm{mA}$ was injected (as a one second pulse) successively on both sides of the sample. The voltage drop $V$ across the sample was measured with high accuracy by a $KT256$ nanovoltmeter.

Fig.2 shows the typical results for the temperature dependence of the resistivity $\rho(T)$ in our SCCO thin films. Quite a pronounced step (kink) is clearly seen around $T = 87\,\mathrm{K}$. Since, according to the X-ray diffraction spectrum (Fig.1), our films do not show any low-energy structural anomalies, it is quite reasonable to assume that the observed kink can be attributed to the manifestation of long-range AFM spin fluctuations induced by $Sm^{3+}$ moment with the characteristic energy $\hbar\omega_{sf} = 7\,\mathrm{meV}$ (corresponding to an effective temperature $T_{sf} = \hbar\omega_{sf}/k_B = 87\,\mathrm{K}$). More specifically, to account for fluctuation induced thermal broadening effects (of the width $\omega_{sf}$) we suggest a Drude-Lorentz type expression for this contribution (cf. Ref. [14]):

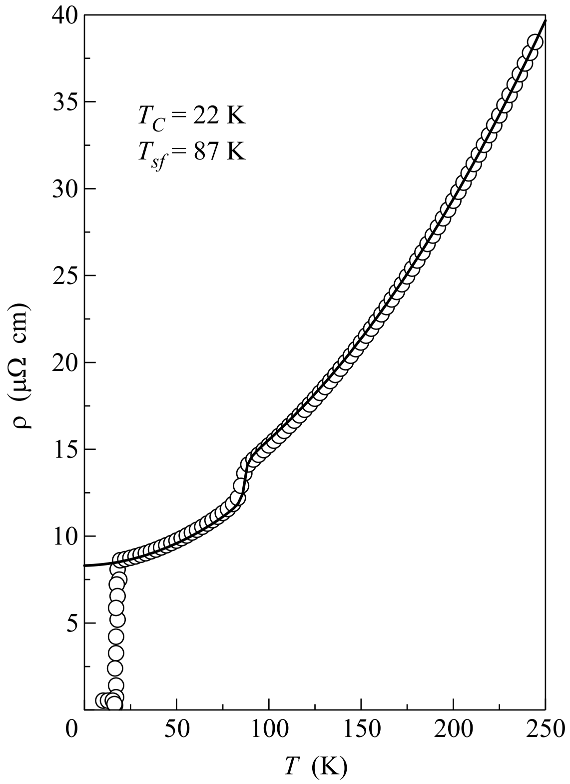

Fig.2. Temperature dependence of the resistivity $\rho(T)$ measured for a typical SCCO thin film ($T_C = 22\,\mathrm{K}$). The solid line is the best fit according to Eq.(3)

$$\rho_{sf}(T) = \rho_{\mathrm{res}} \int_{-\omega_{sf}}^{\Omega(T)-\omega_{sf}} \frac{\omega_{sf} d\omega}{\pi(\omega^2 + \omega_{sf}^2)} = \\ = \rho_{\mathrm{res}} \left[ \frac{1}{4} + \frac{1}{\pi} \tan^{-1} \left( \frac{T - T_{sf}}{T_{sf}} \right) \right], \quad (1)$$

where $\rho_{\mathrm{res}}$ is the residual contribution given by

$$\rho_{res} = 1/\omega_p^2 \epsilon_0 \tau_0, \quad (2)$$

with $\omega_p$ being the plasmon frequency, $1/\tau_0$ the corresponding scattering rate, and $\epsilon_0 = 8.85 \cdot 10^{-12} F/m$ the vacuum permittivity. Notice that $\rho_{sf}(0) = 0$.

The temperature dependence in Eq.(1) comes from the cutoff frequency $\Omega(T) = U(T)/\hbar$ which accounts for spin fluctuations with an average thermal energy $U(T) = \frac{1}{2}C\langle u^2\rangle \simeq k_B T$ where [15] $C$ is the force constant of a two-dimensional harmonic oscillator, and $\langle u^2\rangle$ is the mean square displacement of the magnetic Sm atoms from their equilibrium positions.

After trying many different temperature dependencies, we found that our SCCO films are rather well fitted (solid line in Fig.2) using the following expression for the observed resistivity:

$$\rho(T) = \rho_{\text{res}} + \rho_{sf}(T) + \rho_{e-ph}(T) + \rho_{e-e}(T), \qquad (3)$$

where the other two terms in the rhs of Eq.(3) are related to the electron-phonon contribution [8] $\rho_{e-ph}(T) = AT$ with

$$A = \lambda k_B / \hbar\omega_p^2 \epsilon_0 \qquad (4)$$

and to the electron-electron contribution [9, 10] $\rho_{e-e}(T) = BT^2$ with

$$B = k_B^2 / \hbar\omega_p^2 \epsilon_0 E_F \qquad (5)$$

Here, $\lambda$ is the electron-phonon coupling constant, and $E_F$ the Fermi energy.

Using the experimentally found values of $\rho_{\text{res}} = 8.8\mu\Omega\,\text{cm}$, $A = 0.14\mu\Omega\,\text{cm/K}$, $B = 0.0012\mu\Omega\,\text{cm/K}^2$, and $T_{sf} = 87\,\text{K}$, the best fits through the data points produced $\omega_p = 2.1\,\text{meV}$, $\tau_0^{-1} = 9.5 \cdot 10^{-14}\,\text{s}^{-1}$, $\lambda = 1.2$, and $E_F = 0.2\,\text{eV}$ for very reasonable [8 − 10] estimates of the plasmon frequency, the impurity scattering rate, electron-phonon coupling constant, and the Fermi energy, respectively.

In summary, a pronounced step-like (kink) behavior in the temperature dependence of resistivity $\rho(T)$ was observed in the optimally-doped $\text{Sm}_{1.85}\text{Ce}_{0.15}\text{CuO}_4$ thin films around $T = 87\,\text{K}$ and attributed to manifestation of strong spin fluctuations resulting in thermally activated displacement of Sm atoms. The normal state experimental data were successfully fitted by accounting for the residual, fluctuation, electron-phonon and electron-electron contributions.

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