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c-axis optical conductivity in cuprates

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Abstract

We investigate the c-axis optical conductivity and DC resistivity of cuprate superconductors in the normal state. Assuming that the interlayer hopping is incoherent we express the conductivity with planar spectral functions obtained (i) from angle-resolved photoemission experiments (ARPES), (ii) using marginal Fermi liquid (MFL) ansatz, and (iii) with the finite-temperature Lanczos method for finite two-dimensional systems described by the t–J model. In the optimally doped regime anomalous relaxation rate $\tau_c^{-1} \propto \omega + \xi_c T$ found by Prelovšek et al. (Phys. Rev. Lett. 81 (1998) 3745) is analytically reproduced with the use of the marginal Fermi liquid ansatz for the self energy with parameters obtained from the exact diagonalization results. A semimetallic-like behavior of $\rho_c(T)$ in the low doping regime emerges due to a pseudo-gap opening in the density of states.

Keywords: Cuprates; Optical conductivity; Strongly correlated systems

The CuO_2 planes are common to all cuprate superconductors and clearly determine most of the normal-state electronic properties. The quantity which most evidently displays the anisotropy of a particular material is the optical conductivity $\sigma(\omega, T)$ and the corresponding DC resistivity $\rho(T)$ (for a review see e.g. Cooper and Gray [1]). Recently, the dynamical c-axis conductivity $\sigma_c(\omega, T)$ was investigated theoretically within the standard planar t–J model [2].

Here we present an analysis of $\sigma_c(\omega, T)$ where as in Ref. [2] we assume weak coupling between planes, so c-axis hopping t_c is much smaller than in-plane hopping t. However, here t is not necessarily hopping within the t–J model; the only assumption here is the existence of nearly *independent* electron propagation in each layer, where electrons are described with *some* spectral function $A(\boldsymbol{k},\omega)$. The linear response theory is then justified and the result is as in [2]

$$\sigma_c(\omega, T) = \frac{\sigma_c^0}{\omega}\int d\omega'[f(\omega') - f(\omega' + \omega)] \times \frac{4\pi t^2}{N}\sum_{\boldsymbol{k}} A(\boldsymbol{k}, \omega')A(\boldsymbol{k}, \omega' + \omega), \quad (1)$$

where $\sigma_c^0 = e_0^2 t_c^2 c_0/\hbar a_0^2 t^2$ is a characteristic c-axis conductivity scale. Here e_0 is unit charge, a_0 and c_0 are ab-lattice constant and c-axis interlayer distance, respectively, N is the number of sites and $f(\omega)$ is the Fermi function. Eq. (1) could be compared with a related problem of interlayer hopping [3], where the corresponding expression for $\sigma_c^n(\omega, T)$ is obtained as a convolution of the planar *density of states* $N_p(\omega) = 2/N\sum_k A(\boldsymbol{k}, \omega - \mu)$ and μ is the chemical potential. The knowledge of planar $A(\boldsymbol{k}, \omega)$ [or $N_p(\mu + \omega)$] should thus suffice for the evaluation of $\sigma_c(\omega, T)$.

We test this idea first with the Mott formula [3] for the DC resistivity $\rho_c(T) = 1/\sigma_c$ $(\omega = 0, T)$ by inserting *experimentally obtained* photoemission spectra $\propto N_p(\omega)$ for $La_{2-x}Sr_xCuO_4$ [4]. The density of states is symmetrized around the Fermi energy and the result is presented in Fig. 1(a) for various values $x = 0.074$–0.3. Note that in the underdoped regime semimetallic behavior is qualitatively consistent with measured $\rho_c(T)$ [1]. In the optimally doped regime, however, experiments for $\rho_c(T)$ give linear T-dependence, which cannot be reproduced with Mott formula and $N_p(\omega)$.

For the optimally doped regime we rather use Eq. (1) with planar spectral functions consistent with the marginal Fermi liquid concept [5] and with parameters for the self-energy taken from exact diagonalization (for a review see Ref. [6]). From Fig. 1(b), where we present

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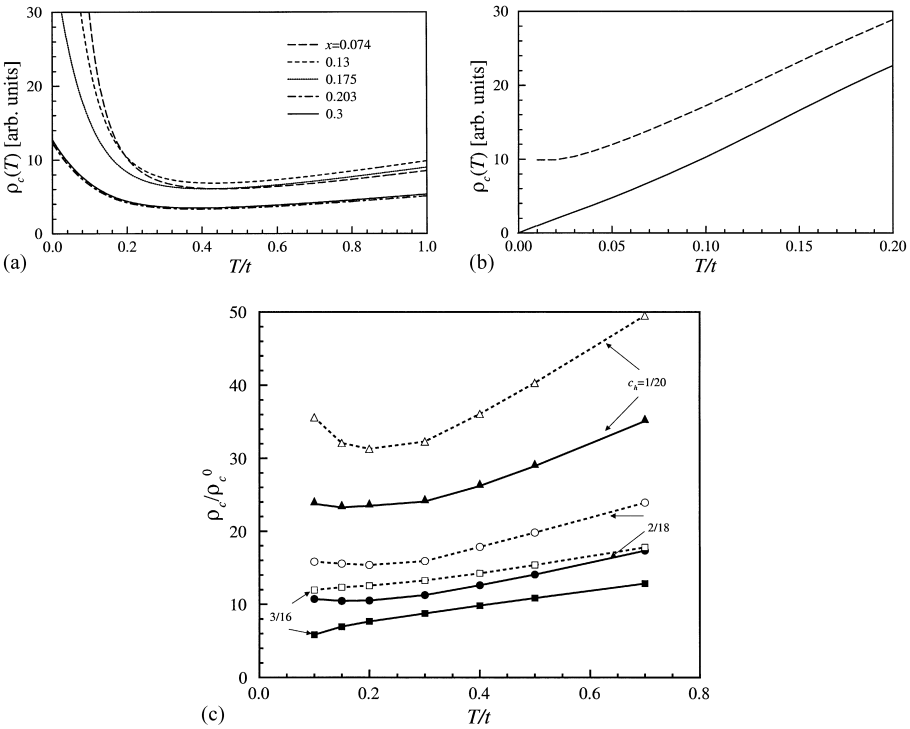

Fig. 1. $\rho_c(T)$: (a) from ARPES N_p for various doping x; (b) from MFL: Eq. (1) (full line) and Mott formula [3] (dashed line); (c) from Eq. (1) (full lines) and Mott formula (dashed lines) obtained with the t–J model for various doping c_h.

results for $\rho_c(T)$ from Eq. (1) with full line and $\rho_c(T)$ from the Mott formula with dashed line, it is clear that only Eq. (1) gives correct $\rho_c(T) \propto T$.

Finally, we present in Fig. 1(c) the DC resistivity $\rho_c(T)$ where we use numerical results both for $A(\boldsymbol{k}, \omega)$ and $N_p(\omega)$, for systems with $N = 16, 18, 20$ sites [6] and for temperature regime not reached in [2]. For the underdoped limit due to the opening of the quasi-gap in the density of states $\rho_c(T)$ exhibits a semimetallic-like behavior, and in the regime of intermediate doping $c_h \geqslant \frac{3}{16}$ $\rho_c(T)$ is metallic-like for all T [2]. From Fig. 1(c) it is also clear that in the optimum doping regime the result of Eq. (1) (full line) gives a better agreement with experiments [1] than the Mott formula (dashed line), all in agreement also with Fig. 1(b).

To conclude, we point out that our approach is in a qualitative agreement with experiments in LSCO, what gives a support to the minimum coupling, Eq. (1). Our results obtained with spectral functions taken from ARPES experiment and exact diagonalization confirm the general experimental observation that $\rho_c(T)$ becomes semimetallic at low temperatures, while using MFL and exact diagonalization spectral functions linear c-axis resistivity in optimum doping regime is reproduced.

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