Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Physica C 408–410 (2004) 330–331

PHYSICA C

www.elsevier.com/locate/physc

Redistribution of the *c*-axis spectral weight and conductivity sum rules in LSCO as revealed by optical transmission

A.B. Kuzmenko [a,*], N. Tombros [a], F.P. Mena [a], A. Hadipour [a], H.J.A. Molegraaf [a], D. van der Marel [a], M. Grüninger [b], S. Uchida [c]

[a] *Material Science Center, University of Groningen, Nijenborgh 4, 9747AG Groningen, The Netherlands*
[b] *II Physical Institute, University of Cologne, 50937 Cologne, Germany*
[c] *Department of Superconductivity, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan*

Abstract

Optical transmission measurements provide a detailed picture of redistribution of the *c*-axis spectral weight of $La_{2-x}Sr_xCuO_4$ ($x = 0.12, 0.15$) and allows to examine the Ferrell–Glover–Tinkham (FGT) sum rule up to 1.8 eV. A new conductivity peak is observed below T_c at ~120 meV, which indicates a possible new collective mode and strongly increases the FGT sum rule violation. The absolute value of the violation is larger for the optimally doped sample. The sum rule starts to recover in the range of the low-lying interband transitions (~1 eV). In the normal state no clear energy scale of the pseudogap can be seen.

Keywords: Interplane conductivity; FGT sum rule

Although recent optical measurements point to a very important role of the in-plane kinetic energy lowering in the energetics of high-T_c cuprates [1,2], the large violation of the interplane Ferrell–Glover–Tinkham (FGT) sum rule [3] remains an intriguing issue. An important question is the energy scale of the sum rule recovery. However, the accuracy of the optical conductivity, obtained by the KK transformation of reflectivity is usually by far insufficient to tackle this problem. The difficulty can be circumvented by the measurement of transmission of light polarized along the *c*-axis. We performed such measurements in the range 4 meV–1.8 eV on free-standing crystals of $La_{2-x}Sr_xCuO_4$ (underdoped, $x = 0.12$ and optimally-doped $x = 0.15$) with a thickness of 10–20 μm [4]. A signal-to-noise ratio of about 10^{-4}–10^{-5} was achieved by using the reference-channel technique above 0.5 eV [5].

In the normal state the interplane conductivity decreases with cooling down, which seems at first glance to be related to the pseudogap. We found, however, that this decrease is observed in a very broad frequency range and thus no clear energy scale of the pseudogap can be derived. At the same time, one can clearly notice, that the conductivity decreases faster below the tetragonal-orthorhombic phase transition, which points to a close relation of this 'pseudogap-like' decrease to lattice effects.

The changes that occur to the *c*-axis spectral weight below T_c, have the same energy scale and very similar (apart from the absolute values) for both doping levels. These changes, which are schematically shown in Fig. 1, are as follows: (i) the delta-peak of the superconducting condensate arises at zero frequency; (ii) the gap opens (20–30 meV); (iii) the conductivity increases at intermediate frequencies with the maximal effect at about 120 meV; (iv) the conductivity slightly lowers in the range of the low-lying interband transitions (above 1 eV). In the

* Corresponding author.
E-mail address: a.kuzmenko@phys.rug.nl (A.B. Kuzmenko).

0921-4534/$ - see front matter
doi:10.1016/j.physc.2004.02.129

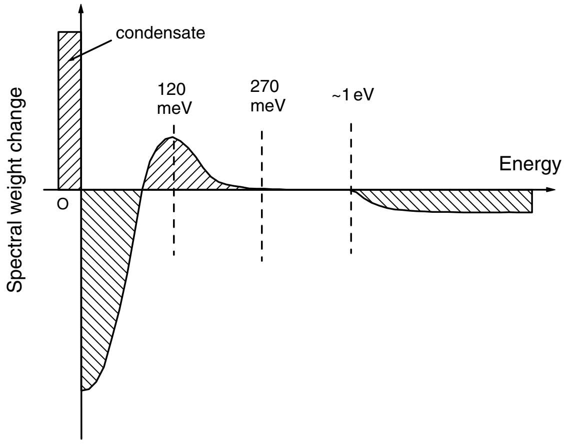

Fig. 1. A cartoon representation of the superconductivity-induced change of the interplane conductivity, derived from transmission measurements.

range 0.27–1 eV we could not detect any changes. The higher-energy region was not accessible as the sample quickly becomes non-transparent since the interband absorption sets in.

The FGT sum rule violation is usually represented by the ratio between the low-frequency conductivity 'missing area' and the condensate spectral weight D: $N_{\rm rel} = \int_{0+}^{\Omega_c}[\sigma_{1n}(\omega) - \sigma_{1s}(\omega)]\,d\omega/D$, where the cut-off frequency Ω_c is several times larger than the superconducting gap. In our case a natural choice is $\Omega_c = 270$ meV. We found that $N_{\rm rel} = 0.2$ and 0.7 for $x = 0.12$ and 0.15 respectively. It matches the previously reported value of 0.5 for a slightly underdoped $La_{2-x}Sr_xCuO_4$ sample ($\Omega_c = 100$ meV) [3] and stays in an excellent agreement with the doping dependence found in $YBa_2Cu_3O_{7-\delta}$ [6].

However, one should be careful with the interpretation of this result because the larger value of $N_{\rm rel}$ for the underdoped sample can also be attributed to a much smaller value of D, which stays in the denominator of the definition of $N_{\rm rel}$. A more relevant quantity is the *absolute* decrease of the low-frequency spectral weight $N_{\rm abs} = \int_{0+}^{\Omega_c}[\sigma_{1n}(\omega) - \sigma_{1s}(\omega)]\,d\omega - D$, which is related to the kinetic energy saving in the superconducting state. In contrast to $N_{\rm rel}$, $N_{\rm abs}$ shows the opposite doping dependence: it is about 2 times larger for $x = 0.15$. Thus we have to conclude that FGT sum rule violation in fact becomes stronger in the optimally doped sample.

The origin of the peak at 120 meV is not yet understood. It might be a signature of a new collective mode below T_c [4]. Notably, the peak significantly 'worsens' the FGT sum rule violation as it contributes to the positive change of the low-frequency spectral weight. It is important to establish its nature and the relation to the c-axis kinetic energy lowering in the superconducting state.

References

[1] H.J.A. Molegraaf et al., Science 295 (2002) 2239.
[2] A.F. Santander-Syro et al., cond-mat/0111539.
[3] D.N. Basov et al., Science 283 (1999) 49.
[4] A.B. Kuzmenko et al., cond-mat/0302394.
[5] A.B. Kuzmenko et al., in press.
[6] D.N. Basov et al., Phys. Rev. B 63 (2001) 134514.