SUM RULES and ENERGY SCALES in BiSrCaCuO

A.F. Santander-Syro, R.P.S.M. Lobo, N. Bontemps
Laboratoire de Physique du Solide (UPR5 CNRS) ESPCI
10 rue Vauquelin, 75231 Paris cedex 05, France
nicole.bontemps@espci.fr

Abstract From very high accuracy reflectivity spectra, we have derived the optical conductivity and estimated the spectral weight up to various cut-off frequencies in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212). We show that, when evaluating the optical spectral weight over the full conduction band (1 eV), the kinetic energy decreases in the superconducting state, unlike in conventional BCS superconductors. As a consequence, the Ferrell-Glover-Tinkham sum rule is not satisfied up to this energy scale. This stands as a very unconventional behavior, contrasted with the overdoped Bi-2212 sample.

Keywords: High Tc superconductors, infrared conductivity, spectral weight

Introduction

A long lasting debate about the cuprate superconductors, stems from the differences and similarities with BCS behavior. The actual pairing mechanism, which eventually results in lowering the free energy of the system, is not yet known. In BCS superconductors, the free energy gain results from a competition of electronic kinetic energy increase and an eventually larger potential energy decrease. If the free energy in cuprates can be (somewhat arbitrarily) separated between potential and kinetic energy [1, 2], then the latter is measured by optics [3, 4]. The kinetic energy can be inferred from the partial sum rule or spectral weight W, defined as:

$$W(\Omega) = \int_0^{\Omega} \sigma_1(\omega, T) d\omega \qquad (1)$$

where $\sigma_1(\omega, T)$ is the frequency (ω) and temperature (T) dependent conductivity, and Ω is a cut-off frequency. Setting $\Omega = \Omega_B$, where Ω_B is the conduction band widht, one can get the kinetic energy E_k per copper site [4], through:

$$W(\Omega_B) = \frac{\pi}{2} \frac{e^2}{\hbar^2} \frac{a^2}{V_u} [-E_k] \qquad (2)$$

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where a is the lattice parameter, and V_u the volume per Cu site.

In the superconducting state, the integral in eq.1 or 2 includes the contribution of the superfluid, i.e. the weight of the $\delta(\omega)$ function centered at zero frequency. The Ferrell-Glover-Tinkham (FGT) sum rule [5, 6] requires that the spectral weight lost at finite frequency in the superconducting state must be retrieved in the spectral weight W_s of the δ function. In conventional superconductors, it was found to be fulfilled if integrating up to $\hbar\Omega_0 \sim 4\Delta$ (Δ is the superconducting gap). $\hbar\Omega_0$ is a characteristic energy of the boson spectrum responsible for the pairing mechanism. The FGT sum rule would then be exhausted for cuprates, if conventional, for $\hbar\Omega_0 \sim 0.1$ eV (assuming $\Delta \sim$ 25 meV) [7, 8].

The studies of the FGT sum rule, first performed from c-axis (interlayer) optical conductivity data, showed a strong violation, interpreted as a change of interlayer kinetic energy [3, 9]. However, the amount of kinetic energy saving which was found is too small to account for the condensation energy. Although *in-plane* data appeared firstly to yield a conventional behavior [9], these early results were subsequently contradicted by ellipsometric and infrared data [10]. Our own infrared-visible reflectivity experiments, in Bi-2212, showed that in-plane spectral weight lost from the visible range is transferred into the δ function [11]. These two independent sets of data yielded a *decrease* of kinetic energy below T_c of the order of 1 meV.

The present paper implements our previous report [11] by using the *partial sum rule* in Eq.2. Although this is in principle equivalent to the FGT sum rule, we found this method to be more robust, because we can trace the entire temperature evolution of the spectral weight. We focus here on the underdoped thin film from the Bi-2212 family. We pin down the raw reflectivity data which allows to establish small changes at high energy (up to 10000 cm^{-1}) in the conductivity, hence in the spectral weight, thus illustrating why our unprecedented resolution is a necessary condition to trace this phenomenon. Our present, more elaborate analysis confirms that within error bars, the in-plane kinetic energy, calculated from Eq.2, decreases in the superconducting state. Using the partial sum rule in Eq.2 (and not only the FGT sum rule, as in [11]) shows qualitatively the opposite, conventional behavior in the case of the overdoped sample [12].

1. Experimental results

Reflectivity spectra, recorded in the range 30-25000 cm^{-1} for 15 temperatures between 300 K and 10 K, are reported elsewhere [13]. An example is recalled in Fig.1, for selected temperatures, up to 3000 cm^{-1}, for the underdoped sample (T_c=70 K). Most of the change with temperature occurs below 1000 cm^{-1}. However, the difference between the spectra at 10 K and 100 K