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C-axis optical properties of high T_c cuprates

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A review is given of the experimental status of the interlayer coupling energy in the cuprates. A second c-axis plasmon is identified in the double layer compound Y123 for various dopings. The anomalous transport properties along the c-direction and in the planar directions are compared to model calculations based on strongly anisotropic scattering. An excellent description of the optical data at optimal doping is obtained if an anomalously large anisotropy of the scattering rate between cold spots and hot spots is assumed. This raises questions as to the physical meaning of these parameters.

During the past four years the issue whether the mechanism of superconductivity in the cuprates could be a lowering of *kinetic* energy (as opposed to *potential* energy in BCS theory) has received considerable attention both theoretically [1–4] and experimentally[9,16,11,10,12–14]. Although originally conceived as an *in-plane* mechanism in the hole-model of superconductivity[1], attention later was concentrated on the c-axis properties[2] first of all because the c-axis transport of quasiparticles had been found to have a very large scattering rate in the normal state[5] and, rather surprisingly, *also* in the superconducting state[6], thus providing a channel for kinetic energy lowering for paired charge carriers as soon as they become delocalized as a result of the pairing. A high value of the scattering rate for transport along the c-direction which remains high in the superconducting state appears to be a robust property of the cuprates: It has been reported for La214[6], Y123[7] Tl2201, and Tl2212 [8]. In the second place the kinetic energy lowering is just the Josephson coupling energy (or in any case not larger) in the interlayer tunneling (ILT) model, which suggested a direct experimental way to test the model by measuring both the condensation energy (E_{cond}) and E_J. The ILT hypothesis requires that $E_J \approx E_{cond}$. To avoid the complexity of having *two* possible Josephson junctions per unit cell of different strength, single layer cuprates had to be considered. Among those Tl2201 had one of the highest T_c's ($\simeq$ 80 K), and relatively large (though thin along the c-direction) crystals and thin films were available. In the spring of 1996 the first experimental results were presented[9], showing that E_J was at least two orders of magnitude too small to account for the condensation energy. Although these results seemed to rule out ILT as the main mechanism of superconductivity[3] they relied on the non-observance of a plasma-resonance where it should have been in the superconducting state (800 cm^{-1}). The issue remained dormant until first λ_c[10] of 17 μm and next the Josephson plasma resonance (JPR)[11] at 28 cm^{-1} had been observed experimentally, allowing a precise determination of $E_J \approx 0.3\mu$eV in Tl2201 with $T_c = 80$k. This is a factor 400 lower than $E_{cond} \approx 100\mu$eV per copper, based either on c_V experimental data[18], or on the formula $E_{cond} = 0.5N(0)\Delta^2$ with $N(0) = 1eV^{-1}$ per copper, and $\Delta \simeq 15meV$. A c-axis kinetic energy change even *smaller* than E_J is obtained from estimating the amount of high energy spectral weight transferred to the δ-function at zero frequency[12]: In the examples studied so far this gives a value of $\Delta E_{kin,c}$ wich is 0.5 E_J, for the underdoped materials, and less than 0.1 E_J for the optimally doped materials. In Fig. 1 the

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change in c-axis kinetic energy and the Josephson coupling energies are compared to the condensation energy for a large number of high T$_c$ cuprates. For most materials materials we see, that $E_J < E_{cond}$, sometimes differing by several orders of magnitude.

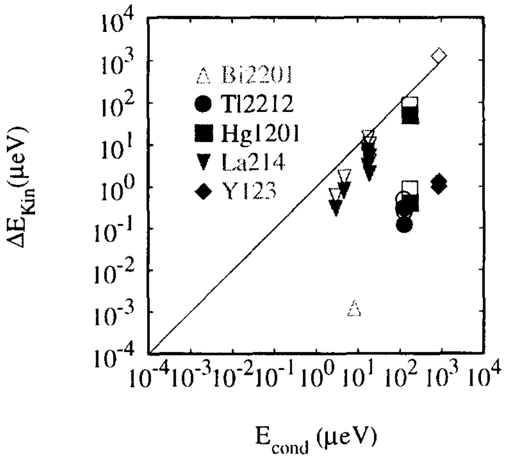

Figure 1. C-axis kinetic energy[6,10–17] versus condensation energy[18].The open symbols represent the most E$_J$ estimated from either the JPR or the c-axis penetration depth. The closed symbols represent the difference in low energy spectral weight between the superconducting and the normal state.

In this plot we have also indicated optimally doped and overdoped Y123. Below T$_c$ we observe a transfer of spectral weight from the FIR not only to the condensate at ω=0, but also to a new peak in the MIR. This peak is naturally explained[17,19] as a transverse out-of-phase bilayer plasmon[21] by a model for $\sigma(\omega)$ which takes the layered crystal structure into account. With decreasing doping the plasmon shifts to lower frequencies and can be identified with the surprising and so far not understood FIR feature reported in *underdoped* bilayer cuprates. A second Josephson plasmon[21] has also been reported[20] for the T* phase La$_{1-x}$Sr$_x$SmCuO4. For points marked YBCO ΔE_{kin} was calculated from the total superfluid spectral weight of the two plasmons. For optimally doped and overdoped YBCO almost all (at least 95 %) superfluid spectral weight originates from the gap-region, resulting in the solid points.

As mentioned in the beginning of this paper, there is the issue of the very large scattering rate in the normal state[5] and, rather surprisingly, *also* in the superconducting state[6–8]. Usually a large scattering rate along the c-axis is interpreted as a form of tunneling with a large scattering of $k_{||}$ of the charge carriers. The term 'incoherent' is usually reserved for non- $k_{||}$ conserving tunneling. Clearly there must be some degree of $k_{||}$ conservation in the tunneling, as otherwise the c-axis critical current would be zero due to cancellation of the phases of the d-wave order parameter. However, another form of incoherent transport exists, namely where $k_{||}$ is conserved, while the memory of $k_\perp$ is lost on the timescale of a tunneling event. *If* c-axis tunneling is $k_{||}$-conserving, this has a number of interesting consequences.

In the first place the tunneling matrix elements depend strongly on $k_{||}$: As a result of some peculiarities of the crystal structure of these materials it has zero's in the zone-diagonal directions[26]. There are indications that the charge carrier scattering rate is also strongly $k_{||}$ dependend, probably due to coupling to spin-fluctuations[24]: The zone-diagonal directions remain unaffacted, while the $(\pi, 0)$ directions have a strong scattering.

This leads to a simple formula for the in-plane optical conductivity in the normal state[25,22] $\epsilon_{ab}(\omega) = \epsilon_\infty - \frac{\omega_p^2\tau}{\omega\sqrt{1-i\omega\tau}\sqrt{1+\Gamma\tau-i\omega\tau}}$. Here Γ is the hot-spot scattering rate, $1/\tau$ is the cold-spot scattering rate, and the above expression was derived assuming that the scattering rate varies smoothly between these two extrema along the Fermi-surface. In Fig. 2 we provide reflectivity curves of Bi2201 (T$_c$ $\approx 10K$) taken from Ref. [27] together with the four parameter fits. In the fit procedure the value of ω_p was kept fixed at 13700 cm^{-1} at all temperatures, while ϵ_∞, τ and Γ were adjusted to obtain the best fit. It turned out, that

$\epsilon_\infty = 4.2 \pm 0.1$ at all temperatures. The temperature dependence of Γ and $1/\tau$ are indicated in the lower panel of Fig. 2. We see, the model leads to a *very* large anisotropy between these two scattering rates: Γ is almost a constant, while $1/\tau$ has a T^2 temperature dependence on top of a small residual value. In fact the parameters obtained

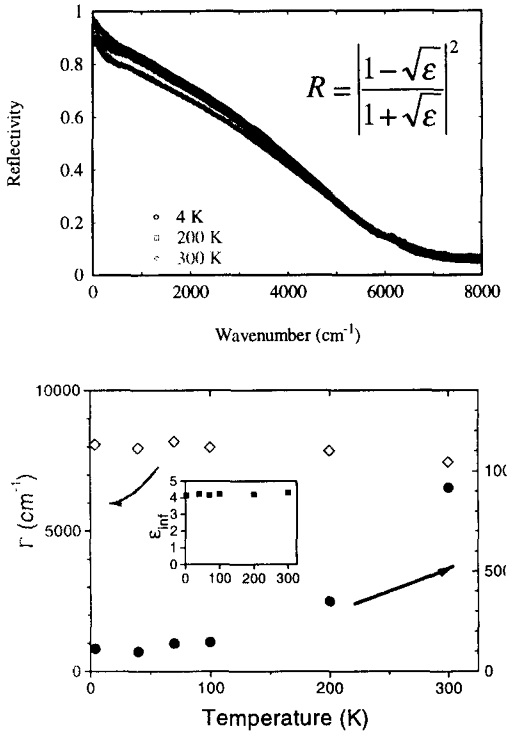

Figure 2. Top: Reflectivity curves of Bi2201 adopted from Ref.[27] (open symbols), and fits to the anisotropic scattering model (solid curves). Bottom: Fitparameters, $\omega_p/2\pi c = 13700\text{cm}^{-1}$.

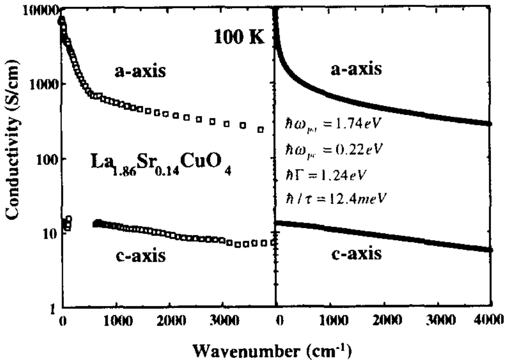

Figure 3. Left:Experimental σ_{ab} and σ_c of La214 (T_c = 32 K), adopted from Refs[28] and [29]. Right: Comparison of $\sigma_{||}$ and σ_c using the model expressions of [22], and using the parameters $\hbar\omega_{p,a} = 1.7eV$, $\hbar\omega_{p,c} = 0.2eV$, $\hbar\Gamma = 1.2eV$, and $\hbar/\tau = 12meV$.

with this fit look quite unreasonable. A scattering rate of almost 1 eV around the hot spots is an order of magnitude larger than typical linewidths observed with ARPES. On the other hand for the optical spectra a rather complete and selfconsistent description is obtained: The optical conductivity along the c-axis is largely determined by the hot-spots, as a result of the strong k-dependence of $k_{||}$. The resulting analytical expressions for the c-axis conductivity provide spectra which closely resemble the experimentally observed optical conductivity along c. In the righthand panel of Fig. 3 we display the theoretical curves for the in-plane and c-axis conductivity using the same parameters as above. In the lefthand panel of Fig. 3 the experimental curves for La214 along the two crystallographical directions are displayed[28,29]. Clearly there is a close resemblence between these datat sets. The significance of these results is really not clear at this moment. Questions that need to be answered are:

1. To what extent is $k_{||}$ conserved in the tunneling?
2. What is the minimum value of $t_\perp(k_{||})$? The 'chemical' arguments mentioned above provide no arguments why it should be exactly zero.
3. Do the minimum value of the hopping pa-

rameter, of the scattering rate and of the gap always coincide at exactly the same value of $k_{||}$? This is not dictated by the symmetry of the materials, which is more often than not orthorhombic rather than tetragonal.

4. If the answer to the above is affirmative, what is the microscopic reason?
5. Why are the scattering rate observed with ARPES and transport/optical probes completely different?

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