Anomalous scattering rate and microwave absorption in $Bi_2Sr_2CaCu_2O_{8+\delta}$ and $YBa_2Cu_3O_{7-\delta}$

C.Kusko[1,2], Z.Zhai[1], R.S.Markiewicz[1,2] and S.Sridhar[1]

[1] *Physics Department, Northeastern University, Boston MA02115*
[2] *Barnett Institute, Northeastern University, Boston MA02115*

February 15, 2001

Abstract

We determine the scattering rate from microwave measurements for an optimally doped Bi-2212 single crystal, using a simple two fluid model with a d-wave symmetry order parameter. In the superconducting state, the calculated scattering rate is three orders of magnitude smaller than that determined from ARPES experiments. A similar anomalously large decrease in the scattering rate is also required to explain the data within a gap-quasiparticle scenario for other HTS, such as $YBa_2Cu_3O_{7-\delta}$. The results suggest that the assumption of normal excitations vanishing at low T is invalid and an additional charge mode is responsible for the microwave absorption.

One of the outstanding problems of the high T_c cuprates is to understand the mechanism of the linear microwave properties. Whereas there were attempts to explain the microwave loss using a quasiparticle description with an order parameter satisfying a d-wave (or mixed $d+s$) symmetry, recent analyses of microwave [1] and terahertz Time-Domain Spectroscopy (THz TDS) [2] clearly indicate that an additional non-quasiparticle collective mode is responsible for the large electromagnetic absorption at low temperatures.

In this paper we analyze the temperature dependence of the complex conductivity $\tilde{\sigma} = \sigma_1 + i\sigma_2$ [3] for optimally doped high quality $Bi:2212$ and YBCO single crystals. In $Bi:2212$, while the behavior of σ_2 is consistent with a $d_{x^2-y^2}$ gap [4], the nearly linear increase of the normal conductivity σ_1 to a large value at low temperatures is in direct contradiction with the conventional picture of the competition [5] between the decrease in the number of excited quasiparticles and the dramatic increase of their scattering rate.

Above T_c, assuming a local $j - \hat{E}$ relation in the skin depth limit, the normal state surface resistance can be written as $R_n = \sqrt{\omega\mu_0\rho_n/2}$, where the microwave normal state resistivity is expected to be the same as the DC resistivity in the so-called Hagens-Rubens limit, and hence $\rho_n = 2\Gamma\mu_0\lambda(0)^2$. Here $\lambda(0)$ is the *zero* temperature penetration depth, and Γ is the normal state scattering rate. Typically the normal resistivity ρ_n obeys linear temperature dependence $\rho_n = \rho_0 + \gamma T$. Therefore the resistivity values can be translated into the inelastic scattering rates given by $\Gamma = \frac{\gamma T}{2\mu_0\lambda^2(0)}$, where γ is the coefficient of the linear term in ρ_n *vs.* T.

Below T_c, the scattering rate can be obtained from the complex conductivity $\tilde{\sigma} = \sigma_1 + i\sigma_2$. In a phenomenological "two-fluid" model the high frequency conductivity $\tilde{\sigma}(\omega, T)$ can be expressed as:

$$\tilde{\sigma}(\omega, T) = \sigma_1 + i\sigma_2 = \frac{ne^2}{m}\left[\frac{n_n(T)}{i\omega + 1/\tau(T)} + \frac{in_s(T)}{\omega}\right] \tag{1}$$

where n_n and n_s represent the fractions of normal and superconducting quasiparticles (with $n_n + n_s = 1$), and τ is the relaxation time for the normal electrons. In this model, the normal electrons have damping with the usual Drude conductivity at high frequencies, and the superconducting electrons have inertia but no damping. In the local London limit, defined by the condition $\xi \ll \ell \ll \lambda$ which is well satisfied by $YBCO$, n_n and n_s can be calculated using the Mattis-Bardeen expression [3] :

$$n_s = (1 - n_n) = 1 - 2\left\langle \int_0^\infty \left(-\frac{\partial f}{\partial E}\right) d\epsilon \right\rangle \tag{2}$$

where the quasiparticle energy is $E = \sqrt{\epsilon^2 + \Delta_k^2}$ and Δ_k is the superconducting order parameter with a d-wave symmetry. We assume a BCS temperature dependence for the $d_{x^2-y^2}$ gap parameter $\Delta(T, \phi) = \Delta_d(T)\cos(2\phi)$. The d-wave model describes well the low T behavior of $\lambda(T) \propto T$ for $Bi_2Sr_2CaCu_2O_{8+\delta}$ ($Bi : 2212$)[4].

From Eq. 1 we can calculate the inverse lifetime in the superconducting state using the approximation that the frequency ω is negligible in comparison with the scattering rate.

In Fig. 1 we show the scattering rate $\Gamma(T)$ for $Bi : 2212$ calculated using a d-wave symmetry model . $\Gamma(T < T_c)$ drops rapidly at T_c but does not reach a limiting value, and instead continues to decrease rapidly at lower temperatures. This very large variation of Γ is necessary to quantitatively describe the large values of the microwave absorption within the quasiparticle framework.

Recently the scattering rate in $Bi : 2212$ has been measured by angle resolved photo-emission techniques (ARPES) [6, 7]. The resulting experimentally measured values of the scattering rate Γ by ARPES are also shown in Fig.1. It is more appropriate to compare the microwave data with the ARPES results of Valla, et al.[7]. The ARPES results of [6] are measured at the points $(\pi, 0)$

in the Brillouin zone where the d-wave superconducting gap has the largest value, while the results of [7] are measured at the nodal $(\pi/2, \pi/2)$ points of the superconducting gap which gives the dominant contribution in the transport measurements. The microwave measurements, which are integrated over the entire FS are dominated, particularly in the superconducting state, by the nodal quasiparticles.

Valla et al. [7] find that in the normal state the energy and temperature dependence of the scattering rate are consistent with a Marginal Fermi Liquid phenomenology $1/\tau = \max(\omega, T)$ and this is not affected by the superconducting transition. The normal state values measured by both the microwave and ARPES techniques are in good agreement. However, below T_c the ARPES scattering rate continues to drop but only linearly with T. The strong temperature dependence of Γ ensures that these measurements are not resolution limited, even at the lowest temperatures. Clearly the calculated microwave Γ and the measured ARPES Γ are significantly different at $T < T_c$, although they agree well in the normal state.

The ARPES results of [6], at $(\pi, 0)$, are considerably broadened, and apparently resolution limited at the lowest temperatures. (The Gaussian lineshape reported by Ding, et al.[8] suggests inhomogeneous broadening, with the intrinsic linewidth considerably smaller.) Nevertheless ARPES is unlikely to achieve the resolution $(< 0.1 meV)$ required to measure the extremely low scattering rates implied by the microwave measurements.

It is worth pointing out that using the measured ARPES Γ would lead to a microwave absorption (represented by the surface resistance R_s) orders of magnitude less than measured. This is shown in Fig.1 where we have calculated the R_s using the scattering rates obtained from both sets of ARPES measurements from [6] and [7] and $\lambda(0) = 2600 \mathring{A}$. The resulting calculated R_s is clearly several orders of magnitude lower than the measured data.

Lee, et. al., [9] have also measured R_s and λ of $Bi : 2212$ crystals at 14.4, 24.6 and 34.7 GHz. At 14.4 GHz their R_s values are lower than ours, although the $\lambda(T)$ data are essentially the same. Their data are also included in Fig.1 and show that the conclusions arrived at are still unchanged, i.e. the calculated values using the above scattering rates are several orders of magnitude lower than the measured ones.

While we have specifically discussed the case of $Bi : 2212$, similar conclusions also hold for other superconductors. Fig. 2 shows the d-wave calculated $\Gamma(T)$ for $Y : 123$. Here again the data require that the scattering rate drop by 10^2 from the normal state value. However, there are no ARPES determinations of the scattering rate to compare with. One does not expect that the scattering rate would differ by orders of magnitude between YBCO and BSCCO. We note that the situation is substantially more complicated in YBCO than in BSCCO, due to the presence of multiple conductivity peaks [11] leading to a picture not consistent with a single d-wave superconducting order parameter. A model based on a nested Fermi surface with a d-wave superconducting order parameter has been developed in order to explain the anomalous behavior of the microwave conductivity and surface resistance in YBCO [12]

Clearly then a quasiparticle mechanism, with its attendant assumption that n_n decrease with decreasing T, is violated in $Bi:2212$ and other high temperature superconductors. This strongly indicates that the microwave absorption mechanism is distinctly different from a gap-quasiparticle scenario. A number of alternative mechanisms are suggested. A possible alternative is a collective mode occuring in the superconducting state. Indeed collective modes such as density waves are extremely likely in low dimensional materials. The contribution of a collective excitation due to an overdamped charge density wave (CDW)-like mode turning on at the superconducting transition has been already employed to describe this anomalous temperature dependence of σ_1[1] in $Bi:2212$. This is described in terms of an additional CDW-like contribution with a phenomenological temperature dependent dielectric constant $\epsilon(T) = \epsilon(0)(1-t^2)$, where $t = T/T_c$ and $\epsilon(0) \approx 10^8$ which accounts for the linear increase of the σ_1 in the superconductive state. Such a large value of dielectric constant is not uncommon in low-dimensional CDW systems[14].

It should be noted that dielectric modes have been recently observed by us at microwave frequencies in non-superconducting $YBa_2Cu_3O_{6.0}$ [15], and at THz frequencies in superconducting $YBa_2Cu_3O_{6.95}$ films by Wilke, et. al., [13]. Possible origins for dielectric modes in high-T_c cuprates have been earlier proposed in the literature [16].

At terahertz frequencies Corson et al.[2] have found a significant excess non-quasiparticle contribution to σ_1 which represents 30% of the condensate spectral weight. They calculated the difference σ_{cm} between the measured σ_1 and the conductivity due to quasiparticles calculated assuming a linear temperature dependence of the inverse lifetime. They have ascribed this difference to a collective mode which could be due to either classical phase fluctuations of the superconducting condensate [17] or to Josephson coupling associated with spatial variation of the superfluid density [18]. Altough at terahertz frequencies the quasiparticle contribution is important, whereas in the microwave regime this is negligible, it is worth pointing out the similarity between the THz σ_{cm} and the microwave σ_1. This strongly suggests that the charge mode which is the dominant mechanism for electromagnetic absorption at microwaves frequencies as proposed in ref.[19] is also present at much higher THz frequencies.

The presence of the nanoscale phase separation (stripes) in the high-T_c superconductors naturally leads to an inhomogeneous ground state, and could lead to a mechanism explaining the anomalous non-quasiparticle absorption and finite normal conductivity at low T.

The huge discrepancy between the calculated normal microwave conductivity using a conventional quasiparticle scenario and ARPES scattering rates and the experimental one clearly indicates the breakdown of the quasiparticle description of the high-T_c superconductors at microwave frequencies. A plausible candidate for the observed microwave absorption is a charge mode, which may also be responsible for the electromagnetic response over a much wider frequency range.

This work was supported by ONR N00014-00-1-0002 and NSF-9711910.

References

[1] S. Sridhar and Z. Zhai, preprint, cond-mat/0004119

[2] J. Corson et al., preprint, cond-mat/0003243.

[3] D. C. Mattis and J. Bardeen, Phys. Rev. **111**, 412 (1958).

[4] T. Jacobs, et al., Phys. Rev. Lett. **75**, 4516 (1995).

[5] D. A. Bonn, et. al., Phys. Rev. Lett. **68**, 2390 (1992).

[6] M. R. Norman, et al., Phys. Rev. B **57**, R11093 (1998).

[7] T. Valla et al., Science **285**, 2110 (1999).

[8] H. Ding, et al., cond-mat/0006143.

[9] Shih-Fu Lee, et. al., Phys. Rev. Lett. ***77**,* 735 (1996).

[10] M. A. Trunin et al., (private communication).

[11] H. Srikanth, et. al., Phys. Rev. B **57**, 7986 (1998).

[12] C. T. Rieck, k. Scharnberg and J. Ruvalds, Phys. Rev. B **60**, 12432 (1999).

[13] I. Wilke, et. al., Proc. M2S-HTSC-VI, Houston (Physica C, 2000) (to be published).

[14] G. Gruner and P. Monceau, in L. P. Gorkov and G. Gruner, eds., Charge Density Waves in Solids, North Holland (1989).

[15] Z. Zhai, P. V. Parimi, J. B. Sokoloff, A. Erb, S. Sridhar, preprint, cond-mat/0005535.

[16] S. Shenoy, Phys. Rev. Lett. **79**, 4657 (1997).

[17] S. Barabash, D. Stroud and I.-J. Hwang, preprint, cond-mat/0002346.

[18] D. van der Marel and A. Tsvetkov, Czech. J. Phys. **46** 3165 (1996).

[19] Z. Zhai et al. Rev. Sci. Inst. (in press)

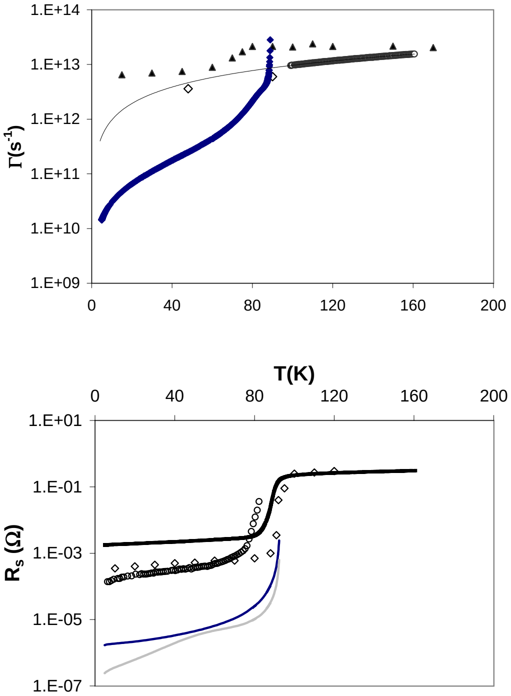

Figure 1: Upper panel: The calculated scattering rate for BSCCO using a two fluid model and a d-wave order parameter (filled diamonds), the experimental scattering rate obtained from ARPES at $(\pi, 0)$ points in the Brillouin zone (filled triangles) and the one measured at the nodal points $(\pi/2, \pi/2)$ (open diamonds). The thin line represents the extrapolation of the normal state scattering rate (grey thick line) below T_c according to the marginal Fermi liquid phenomenology. Lower panel: The experimental surface resistance determined from our microwave measurements (black thick line). The open diamonds are the R_s from [9] and the open circles are the R_s from [10]. The black thin line represents the calculated surface resistance using the scattering rate obtained from the nodal points $(\pi/2, \pi/2)$ ARPES measurements, and the grey thin line is the one using the scattering rate from the $(\pi, 0)$ ARPES measurements.

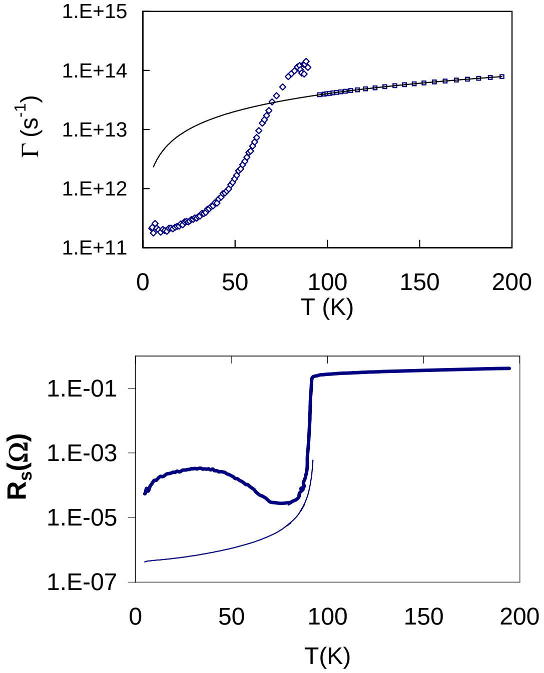

Figure 2: Upper panel: The calculated scattering rate for YBCO determined from microwave measurements using a two fluid model and d-wave order parameter. The open diamonds represent the scattering rate in the superconducting state, the filled squares are the scattering rates in the normal state. The thin solid line is the linear extrapolation of the normal state scattering rate below T_c. Lower panel: The experimental surface resistance determined from our microwave measurements (black thick line). The thin solid line is the calculated surface resistance using the linear extrapolation of the normal state scattering data.