Quasiparticle Damping in $Bi_2Sr_2CaCu_2O_8$ and $Bi_2Sr_2CuO_6$

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The low-frequency conductivity $\sigma_1(\omega)$ of $Bi_2Sr_2CaCu_2O_8$ has a Drude-like component below T_c. Interpreting the width of this component as the quasiparticle relaxation rate (τ^{-1}), we find that τ^{-1} decreases dramatically just below T_c, in sharp contrast with the T-linear τ^{-1} above T_c and in $Bi_2Sr_2CuO_6$. This decrease causes a peak in $\sigma_1(\omega \rightarrow 0, T)$ for T just below T_c, a peak which is due to the scattering rate and not to pair coherence effects, consistent with the lack of a coherence peak in the NMR relaxation rate. This result implies that the excitations which scatter the carriers are suppressed below T_c.

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The issue of coherence effects in the high-T_c superconductors has attracted considerable attention recently. In conventional superconductors, coherence effects, a consequence of interference between Cooper-pair wave functions, provided unique signatures that led to strong support of *s*-wave pairing in BCS theory [1]. One manifestation of such coherence is a peak in the T-dependent nuclear relaxation rate (NRR) and low-frequency conductivity, $\sigma_1(\omega \ll 2\Delta)$, for T just below T_c. The NRR determined for Al by Hebel and Slichter [2], the $\sigma_1(\omega, T)$ results by Palmer and Tinkham [3] for Pb, and other experiments [1] provided convincing proof of such coherence effects. We note that $\sigma_1(\omega \ll 2\Delta)$ is determined by several factors: the quasiparticle density of states, the BCS coherence factors, and the quasiparticle relaxation rate. The coherence peak arises from a T-dependent competition between the quasiparticle density and the BCS coherence factors.

Recently, Holczer *et al.* [4] and Nuss *et al.* [5] have each reported a peak in $\sigma_1(\omega \ll 2\Delta, T)$ in $Bi_2Sr_2CaCu_2O_8$ and $YBa_2Cu_3O_7$, respectively. Holczer *et al.* [4] suggested that this peak is due to type-II BCS coherence effects [1]. However, the absence of a peak in the nuclear relaxation rate of $YBa_2Cu_3O_7$ [6], which is governed by the same coherence factors, is in disagreement with this explanation. Nuss *et al.* [5] account for the conductivity peak by the suppression of the strongly T-dependent inelastic scattering of the quasiparticles below T_c. Far-infrared measurements by several groups [7–9] used two-fluid analysis below T_c and do not report any coherence peak. With these results in mind, we have examined in detail the T-dependent low-frequency conductivity of two Bi-based copper-oxide materials, $Bi_2Sr_2CaCu_2O_8$ (2:2:1:2) with $T_c \simeq 82$ K and $Bi_2Sr_2CuO_6$ (2:2:0:1) with $T_c \ll 10$ K, to see if a coherence peak can be seen. We find that the quasiparticle relaxation rate (τ^{-1}) extracted from infrared conductivity has the expected T-linear τ^{-1} above T_c. With the onset of superconductivity, however, τ^{-1} drops abruptly. This decrease in τ^{-1} also leads to a peak in $\sigma_1(\omega \rightarrow 0, T)$ just below T_c, but in this case it is due to a T-dependent competition between the quasiparticle density and the relaxation rates.

Typical infrared conductivities of 2:2:1:2 and 2:2:0:1 at several temperatures are shown in Fig. 1. These were obtained from Kramers-Kronig analysis of the transmittance of free-standing single crystals of these materials measured over a wide frequency range [10]. The good agreement of our data with already published results [11] gives us confidence in the technique of extracting optical constants from the transmittance. In fact, transmittance measurements are potentially less prone to errors than reflectance, because no precise 100% reference is needed. The conductivities of both samples have the characteristic behavior observed in all high-T_c superconductors: a

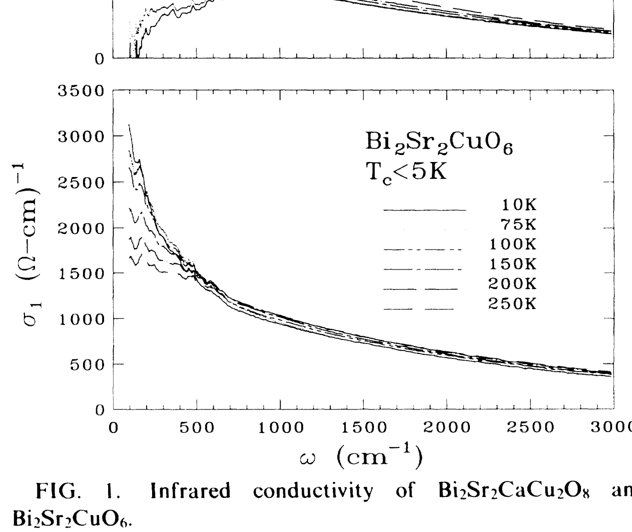

FIG. 1. Infrared conductivity of $Bi_2Sr_2CaCu_2O_8$ and $Bi_2Sr_2CuO_6$.

strongly T-dependent Drude-like conductivity in the far infrared, above which is a non-Drude midinfrared conductivity. The 2:2:1:2 sample shows a stronger normal-state T dependence than the 2:2:0:1 sample, consistent with the residual resistivity of each material [12]. 2:2:1:2, with its smaller residual resistivity, is dominated by inelastic scattering from thermal excitations or fluctuations. In contrast, impurity scattering seems to dominate in the 2:2:0:1 sample.

Below T_c, 2:2:1:2 loses a significant amount of oscillator strength, particularly at low frequencies. This lost spectral weight goes into the response of the superconducting condensate, i.e., into a δ-function contribution to $\sigma_1(\omega)$ at $\omega=0$ and gives an inductive component to the imaginary part of the complex conductivity. Near T_c, $\sigma_1(\omega)$ still shows some T dependence due to thermally excited quasiparticles. Below ~ 50 K, our spectra became T independent, implying complete condensation of the quasiparticles.

In our analysis, discussed below, we find an ω^{-2} dependence to the low-frequency infrared conductivity below T_c in $Bi_2Sr_2CaCu_2O_8$ that resembles a Drude conductivity: $\sigma_{1D}=(\omega_{pD}^2\tau/4\pi)/(1+\omega^2\tau^2)$, where ω_{pD} is the Drude plasma frequency and τ is the relaxation time. Interpreting τ^{-1} as the quasiparticle relaxation rate below T_c, we extract the T dependence of τ^{-1} by making an estimate of σ_{1D} at each T. It is $\sigma_{1D}=\sigma_1(\omega,T)-\sigma_{\mathrm{MIR}}$, where $\sigma_1(\omega,T)$ is the conductivity in Fig. 1 and σ_{MIR} represents the contribution not due to free carriers. For the 2:2:1:2 sample, we used the approximation $\sigma_{\mathrm{MIR}}\simeq\sigma_1(\omega,T=20\text{ K})$. This could not be done for the 2:2:0:1 sample since it remained normal down to $T=10$ K. To estimate σ_{MIR} in this case, we first fitted the 2:2:0:1 data at $T=10$ K as a sum of a Drude part and a Lorentzian contribution. Having determined the Drude parameters, we then subtracted the Drude contribution from $\sigma_1(\omega,T)$ to get σ_{MIR} and used this estimate at the other temperatures.

Figure 2 shows typical results for σ_{1D} for both 2:2:1:2 and 2:2:0:1. Plots of σ_{1D}^{-1} vs ω^2 yielded a straight line below 400 cm^{-1}, whose slope and intercept yielded τ^{-1} and ω_{pD} at each temperature for each sample. We note that two Drude curves with the same ω_{pD} but different τ^{-1} intersect at $\omega=(1/\tau_1\tau_2)^{1/2}$. Our results for τ^{-1} agree very well with this observation, providing a self-consistent check on our analysis.

Before proceeding to discuss our results, we will first justify our procedure for extracting the T dependence of the relaxation rate. In general, above T_c, the complex infrared conductivity of the high-T_c superconductors is given by [13,14]

$$\sigma(\omega,T)=\frac{i\omega_p^2/4\pi}{\omega m_{\mathrm{eff}}(\omega,T)/m_b-i\Gamma_{\mathrm{eff}}(\omega,T)}+\sigma_{\mathrm{MIR}}(\omega)\,. \quad (1)$$

The first term on the right-hand side is the free carrier contribution with ω_p the total free-carrier oscillator strength, $\Gamma_{\mathrm{eff}}(\omega,T)$ the T- and ω-dependent damping of

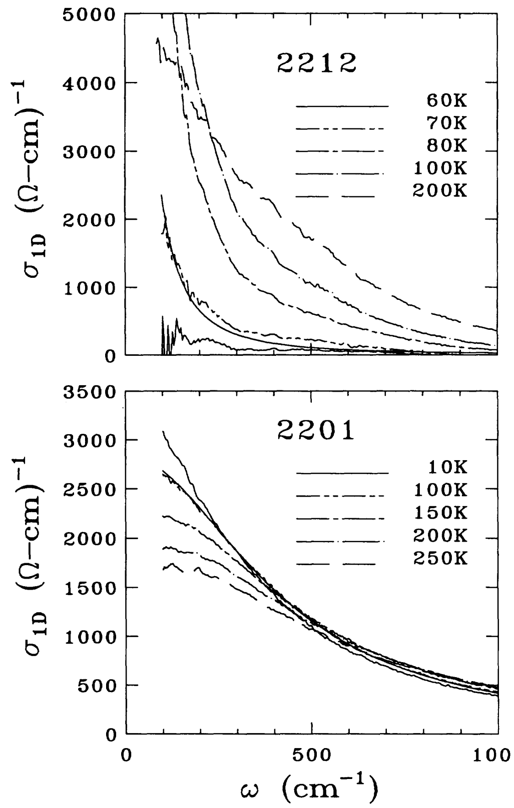

FIG. 2. Drude conductivity in $Bi_2Sr_2CaCu_2O_8$ and $Bi_2Sr_2CuO_6$.

the quasiparticles, and m_{eff}/m_b the mass-renormalization parameter. The latter two parameters are ω and T dependent because of the interaction of the free carriers with some thermal excitation or fluctuation. The second term, σ_{MIR}, accounts for a weakly T-dependent second component in the low-frequency conductivity [10,13]. A number of earlier studies [10,15,16] give evidence for a second contribution to the infrared conductivity of the high-T_c superconductors aside from free carriers. This is evident in Fig. 1, where the 20-K conductivity becomes quite large above 120 cm^{-1} (15 meV), a frequency well below the estimate from photoemission of 50 meV for the energy gap [17].

Despite the ω dependence in Γ_{eff} and m_{eff}/m_b, the free-carrier behavior is Drude-like at low ω. A widely used [10,12,18] form is $\Gamma_{\mathrm{eff}}\propto\max(\pi T,\omega)$. According to recent calculations [13,14], the corresponding mass-enhancement parameter will be given by $m_{\mathrm{eff}}/m_b=1+\lambda\ln[\omega_c/\max(\pi T,\omega)]$. Therefore, at low frequencies, Γ_{eff} and m_{eff}/m_b are independent of ω and give a Drude-like $\sigma_1(\omega)$. Furthermore, the Drude parameters are related to ω_p and $\Gamma_{\mathrm{eff}}(\omega=0,T)$ by $\omega_{pD}^2=\omega_p^2 m_b/m_{\mathrm{eff}}$ and $1/\tau(T)=\Gamma_{\mathrm{eff}}(\omega=0,T)m_b/m_{\mathrm{eff}}$ and can be interpreted respectively as a renormalized plasma frequency and relaxation rate. (There is a logarithmic dependence of m_{eff} on T, which we have neglected because the effect we observe occurs over a relatively narrow temperature range.) Evidence for Drude-like free-carrier behavior at low frequencies is the agreement between σ_{dc} calculated from the Drude parameters and the measured σ_{dc}, as illustrated in the top panel of Fig. 3.

Both samples have an essentially constant normal-state Drude oscillator strength: $\omega_{pD} \simeq 9800 \pm 200$ cm^{-1} for 2:2:1:2 and $\omega_{pD} \simeq 8300 \pm 150$ cm^{-1} for 2:2:0:1. At $T \lesssim 50$ K, the oscillator strength of the superfluid in 2:2:1:2 [estimated either from the differences in the sum rule $\int \sigma_1(\omega) d\omega$ above and below T_c or from a fit of $\epsilon_1(\omega)$ by $1/\omega^2$] is nearly the same as the Drude oscillator strength above T_c, $\omega_{ps} \simeq 9200$ cm^{-1}.

Shown in the bottom panel of Fig. 3, the quasiparticle relaxation rate that we obtain has the expected linear-T dependence above T_c. The slope is related to the strength of the coupling to the fluctuations that give rise to this behavior. Using, for the moment, the relation $\tau_{dc}^{-1} = \pi^2 \lambda T$, we obtain nearly identical values of λ for both 2:2:1:2 and 2:2:0:1 ($\lambda \simeq 0.2$), as can be seen from the nearly identical slopes in Fig. 3. The solid straight lines show a least-squares linear fit to the normal state for each sample. They differ only in their intercept, which is due to the large difference in the residual resistivity of each sample. This result is further evidence that the linear-T behavior in τ^{-1} is an intrinsic in-plane property of the copper-oxide systems.

Below T_c, τ^{-1} for the 2:2:1:2 sample shows a dramatic drop from T-linear behavior and approaches zero as T is lowered. Gao *et al.* [7] noted a similar behavior of τ^{-1} from their two-fluid analysis of $\sigma_1(\omega, T)$ of $YBa_2Cu_3O_7$ films. However, they found that τ^{-1} did not go to zero at low T, possibly an indication of less than ideal sample quality. Our results differ sharply from those of Collins *et al.* [9], who find the quasiparticle conductivity goes like $(1-f_s)\sigma_1(\omega, T=100\text{ K})$, where f_s is the superfluid fraction, which implies $1/\tau =$const below T_c. We point out that an important part of the present work is the result on the 2:2:0:1 sample, which shows linear-T behavior of τ^{-1} even at low T. This clearly implies that the sharp drop in τ^{-1} below T_c for the 2:2:1:2 sample is unique to the superconducting state.

Based on a two-fluid approach, we calculate the superfluid condensate fraction, $f_s = (\omega_{pn}^2 - \omega_{pq}^2)/\omega_{pn}^2$, where ω_{pn} is the average of the nearly constant Drude oscillator strength above T_c and ω_{pq} is the quasiparticle Drude oscillator strength below T_c. The results are shown as solid circles in the top panel of Fig. 4. We must note that the scatter of the data about zero for $T > T_c$ indicates not a small superconducting fraction above T_c but rather errors in the estimated Drude oscillator strength above T_c. This scatter is also a measure of the uncertainty in the superconducting fraction below T_c. The solid line shows the phenomenological Gorter-Casimir [19] two-fluid result,

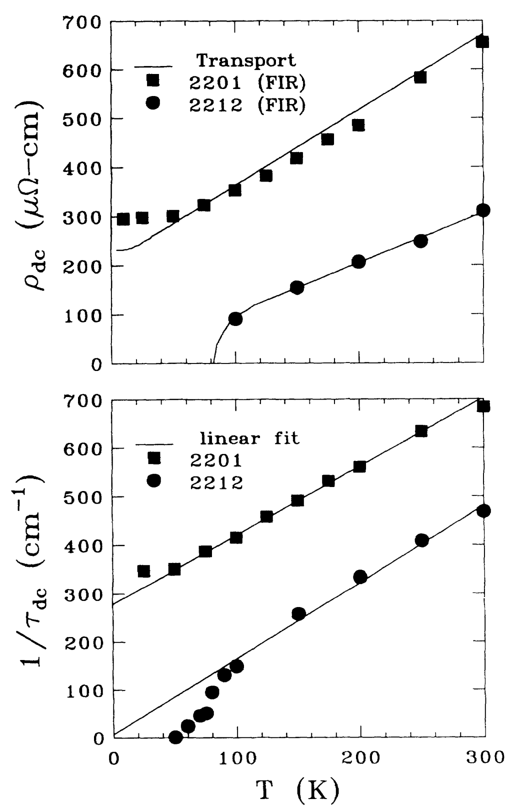

FIG. 3. Top: Comparison of the dc resistivity from Drude parameters with transport measurement. Bottom: Temperature dependence of the quasiparticle relaxation rate in $Bi_2Sr_2CaCu_2O_8$ and $Bi_2Sr_2CuO_6$.

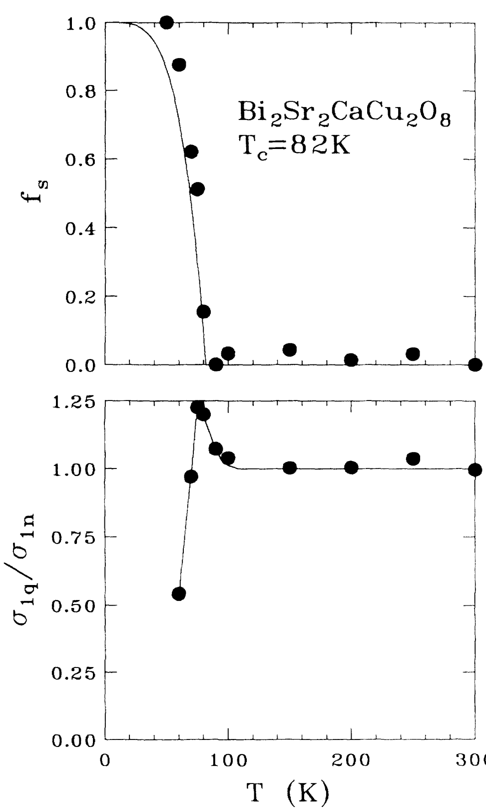

FIG. 4. Top: Temperature dependence of the superconducting condensate fraction. Bottom: Low-frequency quasiparticle conductivity divided by the measured normal-state transport conductivity for $T > T_c$ and a linear extrapolation for $T < T_c$.

$f_s = 1-(T/T_c)^4$, with $T_c \simeq 82$ K.

The low-frequency limit of the quasiparticle conductivity (ignoring coherence and density-of-states effects) can be determined from

$$\sigma_{1q} = \omega_{pq}^2 \tau / 4\pi . \quad (2)$$

This quantity has a maximum just below T_c, as shown in the lower part of Fig. 4. To remove the $1/T$ temperature dependence of the normal-state conductivity, we plot the ratio σ_{1q}/σ_{1n}, where σ_{1n} is the measured normal-state transport conductivity for $T > T_c$ and a linear extrapolation for $T < T_c$. This ratio shows a peak close to T_c. According to the results for τ^{-1} and f_s, shown in Figs. 3 and 4, this peak arises from the combination of an appreciable number of thermally excited quasiparticles right below T_c and the sharp drop in τ^{-1}. The peak occurs over a narrow temperature range, consistent with the data of Holczer *et al.* [4] but narrower than the peak reported by Nuss *et al.* [5]. The difference may be due to the materials ($Bi_2Sr_2CaCu_2O_8$ versus $YBa_2Cu_3O_7$) or to the different frequencies of measurement. (The present work is essentially a zero-frequency analysis, whereas Holczer *et al.* [4] reported the $\omega = 60$ GHz conductivity and the conductivities of Nuss *et al.* [5] are for $\omega \gtrsim 500$ GHz.)

Recently, a calculation by Nicol, Carbotte, and Timusk [20] of the T dependence of τ^{-1} in lead showed an enhancement below T_c due to coherence effects. Since we find the opposite behavior, we conclude, contrary to the suggestion of Holczer *et al.* [4], that coherence factors are not the origin of the observed peak. This conclusion is consistent with the absence of the coherence peak in the nuclear relaxation rate [6] of $YBa_2Cu_3O_7$. To emphasize this point, we note the similarity of the sharp drop in both the quasiparticle and nuclear relaxation rates, which suggests an interesting connection between the nuclear relaxation rate and the quasiparticle damping. However, contrary to the analysis of Collins *et al.* [9], one cannot arrive at this conclusion by simply comparing the infrared conductivity directly with the nuclear relaxation rate. In fact a strong case against such comparison is the observation of a conductivity peak at low frequencies [4,5]. A more appropriate comparison is the nuclear relaxation and quasiparticle relaxation rates as done in the present work.

The sharp drop in τ^{-1} is clearly a signature of the suppression of quasiparticle scattering below T_c. It suggests that, as the free carriers condense into the superfluid, whatever mechanism is responsible for the T-linear resistivity is also suppressed. This result strongly hints at an electric mechanism for the scattering of the carriers, perhaps interaction of the free carriers with a parallel channel of optically inactive excitations (e.g., spinons) or perhaps interaction of the carriers with themselves.

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[1] See the article by D. M. Ginsberg and L. C. Hebel, in *Superconductivity*, edited by R. D. Parks (Dekker, New York, 1969).
[2] L. C. Hebel and C. P. Slichter, Phys. Rev. **107**, 901 (1957).
[3] L. H. Palmer and M. Tinkham, Phys. Rev. **165**, 588 (1968).
[4] K. Holczer *et al.*, Phys. Rev. Lett. **67**, 152 (1991).
[5] M. C. Nuss *et al.*, Phys. Rev. Lett. **66**, 3305 (1991).
[6] P. C. Hammel *et al.*, Phys. Rev. Lett. **63**, 1992 (1989).
[7] F. Gao *et al.*, Phys. Rev. B **43**, 10383 (1991).
[8] D. van der Marel *et al.*, Physica (Amsterdam) **176C**, 1 (1991).
[9] R. T. Collins *et al.*, Phys. Rev. B **43**, 8701 (1991).
[10] D. B. Romero *et al.*, Solid State Commun. (to be published).
[11] M. Reedyk *et al.*, Phys. Rev. B **38**, 11981 (1988); L. Forro *et al.*, Phys. Rev. Lett. **65**, 1941 (1990).
[12] L. Forro *et al.*, Phys. Rev. B **42**, 8704 (1990).
[13] C. M. Varma *et al.*, Phys. Rev. Lett. **63**, 1996 (1989); P. B. Littlewood and C. Varma, J. Appl. Phys. **69**, 4979 (1991).
[14] A. Virosztek and J. Ruvalds, Phys. Rev. B **42**, 4064 (1990); J. Ruvalds and A. Virosztek, Phys. Rev. B **43**, 5498 (1991).
[15] J. Orenstein *et al.*, Phys. Rev. B **42**, 6342 (1990).
[16] K. Kamaras *et al.*, Phys. Rev. Lett. **64**, 84 (1990).
[17] C. G. Olson *et al.*, Science **245**, 731 (1989); B. O. Wells *et al.*, Phys. Rev. Lett. **65**, 3056 (1990); Y. Hwu *et al.*, Phys. Rev. Lett. **67**, 2573 (1991).
[18] Z. Schlesinger *et al.*, Phys. Rev. Lett. **65**, 801 (1990).
[19] M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1975).
[20] E. J. Nicol, J. P. Carbotte, and T. Timusk (to be published).