Low-Frequency Relaxation Rate in the Superconducting $YBa_2Cu_3O_{6.7}$

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The submillimeter-wave 3 cm^{-1} $< \nu <$ *40 cm*$^{-1}$ *complex conductivity of the reduced* $YBa_2Cu_3O_{6.7}$ *film* (T_C=*56.5 K) was investigated for temperatures 4 K* $< T <$ *300 K. The frequency dependence of the effective quasiparticle scattering rate* $1/\tau^*(\nu)$ *was extracted from the spectra.* $1/\tau^*$ *is shown to be frequency independent at low frequencies and high temperatures. On decreasing temperature the scattering rate increases with increasing frequencies. Finally, at 6 K it follows a power-law,* $1/\tau^* \propto \nu^{1.75\pm0.3}$.

It is now well established that the complex conductivity of high-T_C superconductors has a highly unconventional character.[1,2] Phenomenologically it has been proved to be useful to present the conductivity data on the basis of the extended Drude model with frequency-dependent effective mass m^* and the scattering rate $1/\tau^*$.[1,3] The analysis of the infrared conductivity has revealed a linear frequency dependence of the scattering rate with a temperature-dependent offset value.[1] Complementary, microwave techniques also allow the determination of the effective scattering rate at much lower frequencies,[4] and the corresponding values can be considered to constitute the low-frequency limit of the scattering rate. It is therefore reasonable to assume that $1/\tau^*$ becomes nearly constant below some characteristic transition frequency. Although this assumption agrees well with most experimental data, it is extremely difficult to observe the crossover frequency experimentally. This is mainly due to the fact that both components of the complex conductivity $\sigma^* = \sigma_1 + i\sigma_2$ have to be measured with high accuracy for frequencies below 50 cm^{-1}; a range which is rather difficult to explore with conventional IR techniques. As the temperature decreases below T_C, the accurate determination of the scattering rate becomes even more complicated. In that case the response of the superconducting condensate has to be subtracted from the conductivity prior to the calculation of the scattering rate. As a result, even less information exists concerning the low-frequency behavior of the scattering rate below T_C.

In view of the problems outlined above, the method of the submillimeter spectroscopy may be able to provide the necessary frequency-dependent information. Using this method we have performed transmission experiments in the frequency range $3 \leq \nu \leq 40$ cm^{-1}. The measurements were carried out in a Mach-Zehnder interferometer arrangement[5] which allows both the measurements of transmission, and phase shift of a film on a substrate. Utilizing the Fresnel optical formulas for the two-layer system, the complex conductivity can be determined directly from the observed spectra without any approximations.

The optimally doped c-axis oriented $\mathrm{YBa_2Cu_3O_{6+\delta}}$ film[6] on the (110) $\mathrm{NdGaO_3}$ substrate was oxygen depleted by heating up in a controlled oxygen atmosphere, with subsequent quenching to room temperature. The mosaic spread of the c-axis oriented grains was 0.19^o. Four-point resistivity measurement yielded an onset of the superconducting transition temperature, $T_\mathrm{C} = 56.5\pm0.5$ K. The changes of the lattice constant and critical temperature with oxygen depletion gave an estimate of the oxygen content of the sample.[7] For our sample a value of δ=0.7±0.05 has been determined.

Fig. 1 shows the frequency dependence of the complex conductivity of the $\mathrm{YBa_2Cu_3O_{6.7}}$ film at different temperatures. In addition to the submillimeter data, the results obtained on the same film in the infrared frequency range 50 $\mathrm{cm}^{-1} < \nu < 7000$ cm^{-1} are also presented for T=60 K. The infrared conductivity was obtained from the Kramers-Kronig analysis of the film reflectivity. Detailed description of these results will be given in a forthcoming paper. The imaginary part of the conductivity is presented in form of the product $\sigma_2\nu$, which allows the determination of the superconducting spectral weight $\omega_{p,s}^2$ via[8,9] $\nu\sigma_2(\nu \to 0) = \varepsilon_0\omega_{p,s}^2/2\pi$. The real part of the conductivity (right frame of Fig.1) is frequency independent at low frequencies and at high temperatures and increases with the decreasing temperature. At temperatures close to the superconducting phase transition a frequency dependence of $\sigma_1(\nu)$ is observed at submillimeter frequencies, which becomes significant as the temperature is further lowered. As the temperature decreases below T_C, the low frequency limit of $\sigma_2\nu$ becomes nonzero, which indicates the nonzero spectral weight of the superconducting condensate. The overall fre-

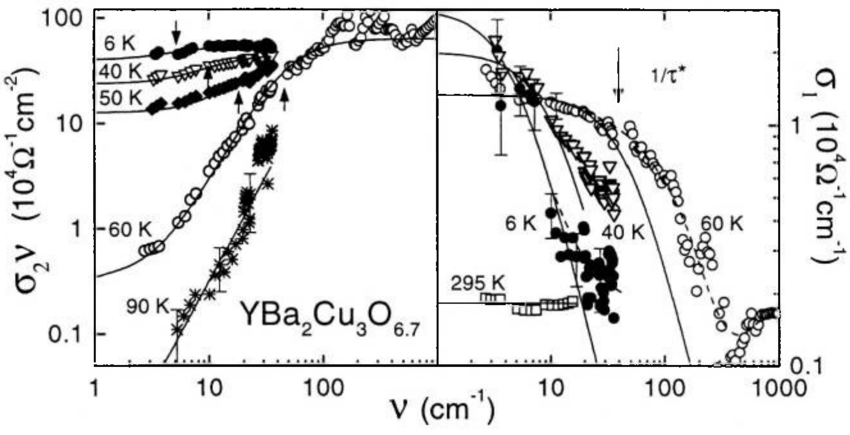

Fig. 1. Frequency dependence of the complex conductivity of the reduced $YBa_2Cu_3O_{6+\delta}$ film at different temperatures. Left panel: the product $\sigma_2\nu$; right panel: σ_1. Solid lines are fits according to Eq. (1). Dashed lines are drawn to guide the eye. Arrows indicate the approximate positions of the quasiparticle relaxation.

quency dependence of $\sigma_2\nu$ shows then a minimum at zero frequency, with a characteristic width that becomes smaller with decreasing temperature. In analogy to the complex conductivity data of the unreduced $YBa_2Cu_3O_{6+\delta}$ sample[6] and according to theoretical predictions,[9] the width of this minimum qualitatively corresponds to the effective quasiparticle scattering rate. Solid lines in Fig. 1 were calculated according to the Drude model. The effects arising from the superconducting condensate were taken into account by adding an appropriate term $\sigma_s = i\varepsilon_0\omega_{p,s}^2/\omega$ to the imaginary part of conductivity.[10] The final expression for nonzero frequencies can then be written in the form

$$\sigma^*(\omega) = \sigma_D^* + \sigma_s = \varepsilon_0\omega_{p,n}^2(1/\tau^* - i\omega)^{-1} + i\varepsilon_0\omega_{p,s}^2/\omega \qquad (1)$$

where $\omega_{p,n}^2$, $\omega_{p,s}^2$ and $1/\tau^*$ are assumed to be frequency independent, $\omega = 2\pi\nu$ is the circular frequency, $\omega_{p,n}^2$ is the spectral weight of the nonsuperconducting component, and $1/\tau^*$ is the effective scattering rate. The results of the simultaneous fitting of the real and the imaginary parts of conductivity are shown as solid lines in Fig. 1 and provide a reasonable description of the low-frequency experimental data. Prominent deviations from the fits are observed at high frequencies, which is most clearly seen for frequencies above 100 cm^{-1} and at 60 K. The experimental data reveal a significantly weaker frequency dependence compared to the fit. Therefore, a frequency dependent scattering rate has to be used in order to fit the experimental data correctly.

The frequency dependent scattering rate can be calculated from the complex conductivity using the modified Drude expression[1,3,11]

$$\sigma_D^* = \varepsilon_0 \omega_p^2(\omega)\,[1/\tau^*(\omega) - i\omega]^{-1} \qquad (2)$$

where the plasma frequency ω_p and the renormalized scattering rate $1/\tau^*$ are assumed to be *frequency dependent.*

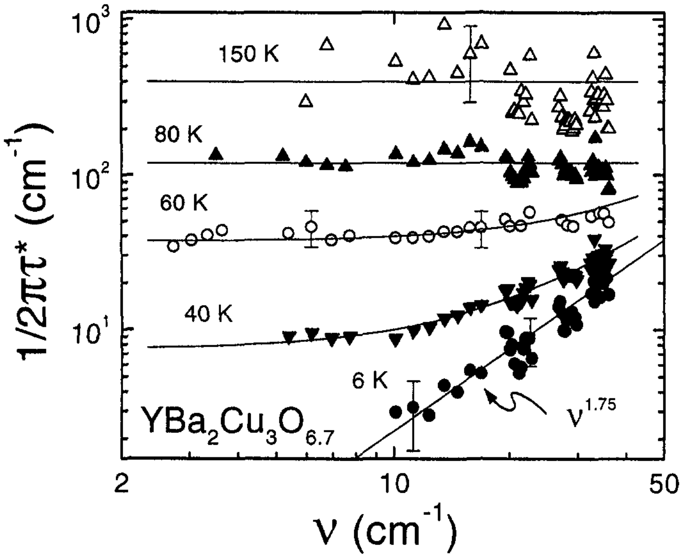

Fig. 2. Frequency dependence of the quasiparticle scattering rate of the reduced $YBa_2Cu_3O_{6+\delta}$ film at different temperatures. Solid lines are guides to the eye.

From Eq. (2) the quasiparticle scattering rate can be calculated as: $1/\tau^*(\omega) = \omega\sigma_1(\omega)/\sigma_2(\omega)$. This procedure is quite straightforward for $T > T_C$ because $\omega_{p,s}=0$. For $T \leq T_C$ the electromagnetic response of the superconducting condensate has to be subtracted from the conductivity. Because the response of the superconducting condensate at finite frequencies is purely imaginary, only the σ_2 has to be modified: $\sigma_2 \to \sigma_2 - i\varepsilon_0\omega_{p,s}^2/\omega$. The spectral weight of the superconducting condensate $\omega_{p,s}^2$ can be determined from the low-frequency limit of $\nu\sigma_2$ as mentioned above. The calculated frequency dependence of the effective scattering rate is presented in the Fig. 2. The scattering rate is almost frequency independent at high temperatures in the submillimeter frequency range, as is well documented by the 80 K data set. Therefore, in this frequency and temperature range the Drude approximation remains suitable to describe the complex conductivity data. A significant frequency dependence of $1/\tau^*$ evolves below T_C with a crossover to a constant value. The crossover frequency shifts to lower frequencies as the temperature decreases. At T=6 K the scattering rate reveals a single power-law behavior and can be approximated by $1/\tau^* \propto \nu^{1.75\pm0.3}$. This power law is close to the ν^2 behavior, which was observed in the normal state and at infrared frequencies in reduced $YBa_2Cu_3O_{6+\delta}$ sample;[12] however it is not clear, whether the same processes are determining the low frequency electrodynamics above and below T_C.

In summary, we have investigated the submillimeter-wave complex conductivity of a reduced $YBa_2Cu_3O_{6.7}$ film (T_C=56.5 K). The frequency dependence of the effective quasiparticle scattering rate has been extracted from the conductivity spectra. It was possible to show experimentally that the scattering rate is frequency independent at low frequencies and high temperatures. For decreasing temperature a transition between $1/\tau^* = const$ and $1/\tau^* \propto \nu^{1.75\pm0.3}$ is observed.

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