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Pseudogap and Superconducting Gap in $YBa_2Cu_3O_{6+x}$: A Raman Study

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We present results of electronic Raman-scattering experiments in differently doped $YBa_2Cu_3O_{6+x}$. In B_{2g} symmetry, an analysis of the data in terms of a memory function approach is presented and dynamical relaxation rates $\Gamma(\omega,T)$ and mass-enhancement factors $1+\lambda(\omega,T)$ for the carriers are obtained. Starting from temperatures $T > 180$K, $\Gamma(\omega,T)$ and $1+\lambda(\omega,T)$ are extrapolated to lower temperatures and used to re-calculate Raman spectra. By comparison with our data, we find a loss of spectral weight between $T_c < T < T^*$ at all doping levels x. T^* is comparable to the pseudogap temperature found in other experiments. Below T_c, the superconducting gap is observed. It depends on x and scales with T_c whereas the energy scale of the pseudogap remains the same.

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1. INTRODUCTION AND EXPERIMENTAL

The relationship between the superconducting (SC) and the pseudogap (PG) phases and their evolution with doping is of particular interest for understanding the cuprates. In the following we will describe recent results from light scattering experiments in differently doped, high–quality $YBa_2Cu_3O_{6+x}$ (Y–123) single crystals.[1] The experiments were performed in pseudo back-scattering geometry using a standard Raman set-up. We present an analysis of the spectra in terms of a memory function approach which is well established for optical and infrared (IR) spectroscopy.[2] We

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will focus on B_{2g} symmetry only since it represents carrier properties independently of the doping level.[3]

2. MODEL AND ANALYSIS

For the study of the dynamical response we adopt the approach in terms of a memory function

$$M(\omega,T) = i\Gamma(\omega,T) + \omega\lambda(\omega,T) \tag{1}$$

with the carrier relaxation rate $\Gamma = 1/\tau$ and the mass enhancement factor $1+\lambda = m^*/m$. The formalism was introduced by Götze and Wölfle for the current-current correlation function[4] and subsequently applied to the analysis of IR data.[2] In our Raman experiment, the number of inelastically scattered photons registered per unit time is proportional to the imaginary part χ'' of the response function $\chi = RM/(\omega+M)$ which reads

$$\chi''(\omega,T) = R\frac{\omega\Gamma(\omega,T)}{\omega^2(1+\lambda(\omega,T))^2+\Gamma^2(\omega,T)} \tag{2}$$

with R a symmetry-dependent scale factor. Defining $I = \chi''/\omega$, we obtain the following expressions

$$\Gamma(\omega,T) = R\frac{I(\omega,T)}{I^2(\omega,T)+\omega^2K^2(\omega,T)} \tag{3}$$

$$1+\lambda(\omega,T) = R\frac{K(\omega,T)}{I^2(\omega,T)+\omega^2K^2(\omega,T)} \tag{4}$$

where $K(\omega,T)$ is given by

$$K(\omega,T) = -\frac{2}{\pi}\wp\int_0^\infty d\xi\frac{I(\xi,T)}{\xi^2-\omega^2}. \tag{5}$$

Applying this model to the Raman spectra from underdoped Y–123 in the normal state (Fig. 1) we find Γ to depend linearly on ω and $1+\lambda$ to be almost T–independent and close to unity for a fairly large frequency range (Fig. 2). A more detailed discussion of this formalism will be presented in a forthcoming publication.

The ω–dependence of Γ and $1+\lambda$ can be fitted by monotonous functions

$$\Gamma(\omega,T) = \Gamma_0(T) + \alpha\omega \tag{6}$$

$$1+\lambda(\omega) = 1+\lambda_0+\lambda_1e^{-\omega/\omega_1}+\lambda_2e^{-\omega/\omega_2}. \tag{7}$$

with fitting parameters α, $\lambda_{0,1,2}$, and $\omega_{1,2}$. This allows us to extrapolate Raman spectra measured at T to different temperatures T'. In the following,

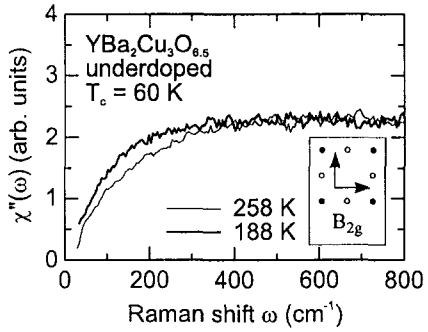

Fig. 1. Raman response $\chi''(\omega, T)$ for underdoped Y–123.

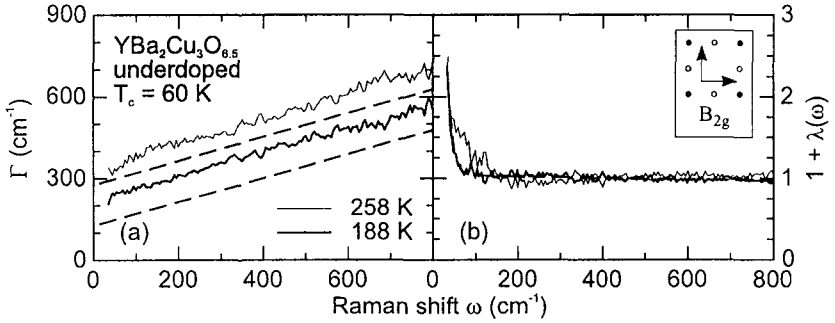

Fig. 2. (a) Dynamical relaxation rate $\Gamma(\omega, T)$ and (b) mass renormalization $1 + \lambda(\omega, T)$ for the spectra shown in Fig. 1. The dashed lines are extrapolations for 230K and 70K, respectively.

this will be done for $T' = 230$K and $T' = 70$K. We simply put $\Gamma_0(T')$ equal to the static limit of the relaxation rate $\Gamma(0, T')$ which can be determined directly from the spectra at T' while leaving α, $\lambda_{0,1,2}$, and $\omega_{1,2}$ unchanged and obtain Γ and $1 + \lambda$ via Eqs. 6 and 7 (dashed lines in Fig. 2). Using Eq. 2 we now can calculate "extrapolated" spectra $\chi''_{\rm ext}$. By comparing the 230K extrapolation to our experimental data $\chi''_{\rm exp}$ we see that this procedure is fairly reliable (Fig. 3 (a)). However, at 70K we find a deviation $\Delta\chi'' = \chi''_{\rm exp} - \chi''_{\rm ext}$ (shaded area in Fig. 3 (b)) which has been attributed to the opening of a PG.[5] Now the presented extrapolation procedure allows us to quantify $\Delta\chi''$ as a function of temperature and doping.

3. RESULTS AND DISCUSSION

Figure 4 shows $\Delta\chi''$, integrated from $\omega = 0$ to $\omega = 800\text{cm}^{-1}$ as a function of temperature. In all doping levels, spectral weight is lost be-

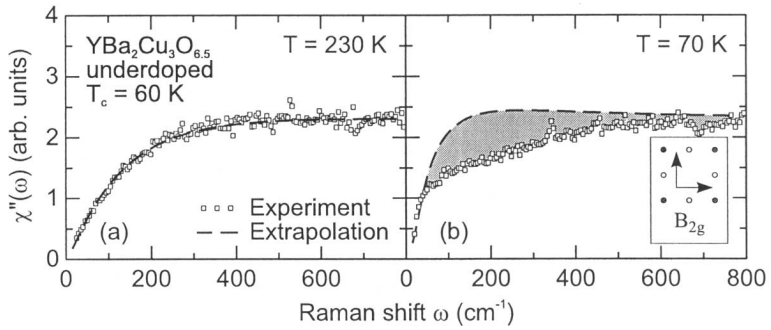

Fig. 3. Comparison between the measured χ''_{exp} (squares) and the extrapolated Raman response χ''_{ext} (dashed lines) for (a) 230K and (b) 70K.

low a characteristic temperature T^* (vertical dashed lines in Fig. 4) which compares well with the pseudogap temperature found in other experiments.[2] This effect reaches 17% in the underdoped sample and becomes much weaker towards optimal doping.

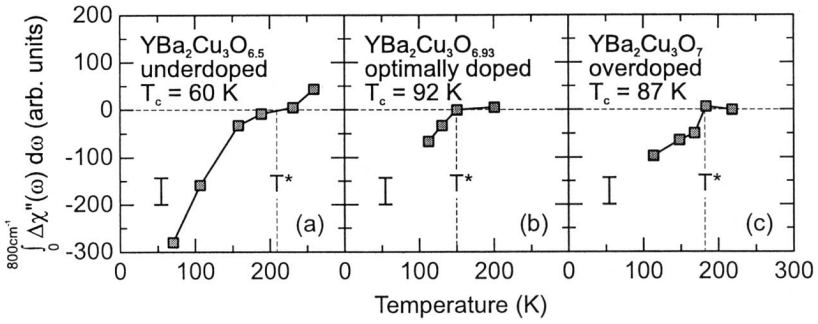

Fig. 4. Integrated change of spectral weight $\Delta\chi''$ in the normal state as a function of temperature for (a) underdoped, (b) optimally doped, and (c) overdoped Y–123. The vertical bars represent the experimental errors.

To study the influence of doping on the energy range of the PG Δ^* we choose the lowest temperatures (where the effect becomes largest) in Figs. 4 (a) and (c) and plot $\Delta\chi''(\omega, T)$ as a function of ω. Fig. 5 (a) shows that the presence of the PG leads to a suppression of spectral weight up to $800\mathrm{cm}^{-1}$ in both cases. The energy scale of Δ^* seems to be fixed and independent of the doping level. This is not the case for the ω-range of the SC correlations which clearly scales with the SC transition temperature T_c (Fig. 5 (b)). The breaking of Cooper pairs leads to an increase of spectral weight between 3 and $12kT_c$ for both doping levels. This means that the

absolute value of the SC energy gap Δ has to increase by 45% when going from the underdoped (T_c = 60K) to the overdoped (T_c = 87K) regime. A similar behavior has been found for $Bi_2Sr_2CaCu_2O_{8+\delta}$[3] and $La_{2-x}Sr_xCuO_4$.[6]

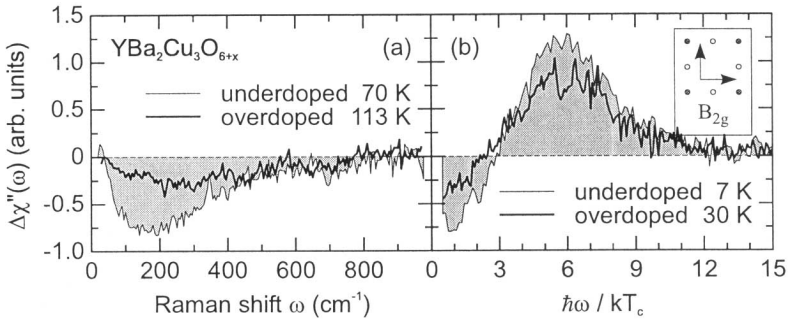

Fig. 5. Change of spectral weight $\Delta\chi''$ (a) in the PG state and (b) in the SC state for underdoped (T_c = 60K) and overdoped Y–123 (T_c = 87K).

In summary, our Raman experiment allows to compare Δ and Δ^* in the same sample. We find that whereas the range of finite Δ scales with T_c, the energy range of Δ^* is independent of doping. As a result, our experiments do not support evidence for a relation between the PG and the SC gap.

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