Electron scattering of light in a high-T_c superconductor in the superconducting state

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A quasiparticle channel for the scattering of light in high-T_c superconductors has been analyzed at $T > T_c$. The scattering of light by the carriers which interact with phonons was found to have some characteristic features, the most important of which is the presence of a broad interval in which the retardation effects play an important role.

Experimental studies of electronic scattering of light (ESL) in various high-T_c superconducting compounds[1-4] have reported the observation of several general structural features characteristic of this class of substances. The main distinguishing feature of the Raman spectrum of cuprate metal oxides is the extended electron continuum. This continuum does not depend in any significant way on the temperature or the transmitted frequency $\omega = \omega_i - \omega_s$, where ω_i and ω_s are frequencies of the incident and scattered light, respectively. The phonon peaks are situated at frequencies $\omega < 800$ cm^{-1}. Some of these peaks demonstrate that the line has an asymmetric shape (the Fano antiresonance). This allows us to conclude that the interaction of the carriers with the phonons is not weak, and that it does not vanish in superconducting state. Furthermore, at $T < T_c$ the intensity of the electron scattering of light decreases at frequencies $\omega < 2\Delta(0)$. This decrease can naturally be attributed to the restructuring of the quasiparticle contribution. The effects resulting from a strong damping, which is comparable to that of a quasiparticle energy, and from delayed interaction must nonetheless be reexamined in light of the classical approach[5] to the description of the ESL when the high-T_c superconducting compounds are in the normal state.

The intensity of ESL is proportional to the imaginary part of the polarization operator $\mathrm{Im}\Pi(\vec{q},\omega)$. In the case under consideration ($T > T_c$) the characteristic scale of the spatial variation of q is on the order of $v_F\delta^{-1}$. At frequencies $\omega \gg v_F\delta^{-1}$ the behavior of the quasiparticle polarization operator Π_1 $(q-0,\ \omega)$ is important. The imaginary part of this operator is

$$\mathrm{Im}\Pi_1(q-0,\omega) \simeq N(0)\int_0^\infty d\epsilon \left\{\tanh\frac{\epsilon_+}{2T} - \tanh\frac{\epsilon_-}{2T}\right\}$$

$$\times \frac{2(\Sigma''(\epsilon_+)+\Sigma''(\epsilon_-))}{(\omega-\Sigma'(\epsilon_+)+\Sigma'(\epsilon_-))^2+(\Sigma''(\epsilon_+)+\Sigma''(\epsilon_-))^2}, \qquad (1)$$

where $N(O)$ is the density of states at the Fermi level, $\Sigma'(\epsilon) \simeq Re\Sigma(\epsilon,k_F)$, $\Sigma''(\epsilon) \simeq \mathrm{Im}\Sigma(\epsilon,k_F)$, and $\epsilon_\pm = \epsilon \pm \omega/2$. Let us first analyze the phonon component of the damping and restrict the discussion to two important parameters of the phonon spectrum: the electron–phonon coupling constant λ and the average phonon frequency $\overline{\omega}$. Figure 1 is a plot of the imaginary part of the polarization operator $\mathrm{Im}\Pi_1$ $(\omega)/N$ (0) versus the frequency, measured at various temperatures, for the model-based phonon spectrum $\alpha^2(\omega)F(\omega)$ distributed in the interval of phonon frequencies to ω_0. A curious feature of $\mathrm{IM}\Pi_1$ (ω) is its relatively large value over the broad range of transmitted frequencies. At energies $\epsilon > \omega_0$ the damping due to the electron–phonon interaction is nearly constant and it follows from Eq. (1) that

$$\mathrm{Im}\Pi_1(\omega) = N(0)\frac{2\Gamma\omega}{(I+\bar{\lambda})^2\omega^2+\Gamma^2}, \qquad (2)$$

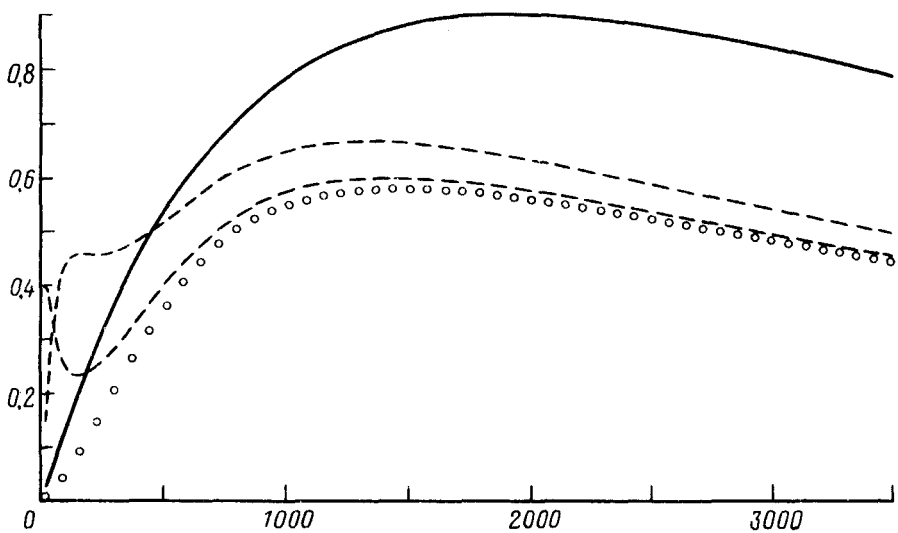

FIG. 1. $\mathrm{IM}\Pi_1$ $(\omega)/N(0)$ versus the frequency $\omega(\mathrm{cm}^{-1})$ at temperatures $T = 5$ K (×), 50 K (—), 100 K (–.), 300 K (—). The electron–phonon coupling constant is $\lambda = 0.66$ and the average phonon frequency is $\overline{\omega} = 475$ K.

where $\bar{\lambda}$ is the average value of the renormalization in the interval $\sim\omega + \pi T$, and $\Gamma = 4\pi\int d\omega\alpha^2(\omega)F(\omega)\coth(\frac{\omega}{2T})$. At high temperatures Γ increases linearly with temperature. In the case of pure metals, a contribution of this order of magnitude occurs up to frequencies $\approx v_F\delta^{-1}$ and is determined by the contribution of all electrons on the Fermi surface. In the case of a dirty metal, a relation for the polarization operator, like that in (2), with $\Gamma \sim \tau_{\text{imp}}^{-1}$, is also valid, as indicated in Ref. 6. At low frequencies, the electron–phonon damping leads to the appearance of certain singularities in the imaginary part of the polarization operator. At $T \approx 0$, the frequency dependence becomes a quadratic dependence $\text{Im}\Pi_1(\omega) \sim \alpha^2(\omega)F(\omega) \sim \omega^2$, but an increase in temperature for small coupling constants $\lambda < 1$ causes a narrow peak to appear at frequencies $\omega \sim T \ll \bar{\omega}$ (the dashed curve in Fig. 1), whose position does not depend on λ. At high temperatures, the frequency and temperature dependences are rather simple $\text{Im}\Pi_1(\omega)/N(0) = \omega/2\pi\lambda T$. An increase in the electron-phonon coupling constant reduces the dependence of the polarization operator on the frequency and temperature (bottom part of Fig. 2).

Because of the complex and diversified structure of the electronic spectrum of high-T_c superconducting compounds, a direct scattering of light may occur even on collective modes. It is conceivable, moreover, that collective modes have a strong effect on the intensity of single-particle scattering of light through the interaction with the carriers. Consequently, the contribution of the carriers that interact with the phonons is not the only factor that affects the behavior of the Raman spectrum. A system of localized spins, whose dynamic spin fluctuations may be active in the Raman spec-

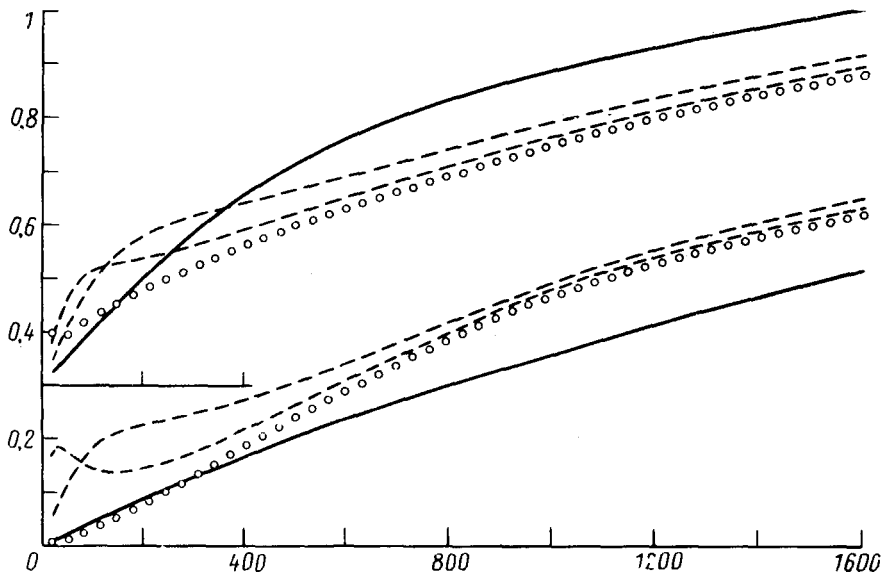

FIG. 2. The plot of $\text{Im}\Pi_1(\omega)/N(0)$ versus the frequency for the interaction of the carriers with the phonons ($\lambda = 1.98$, $\bar{\omega} = 475$ K) and with the collective modes in the model of two-level centers [shifted up the scale by $0.3N(0)$] with $\bar{\lambda} = 2.0$ and $E_0 = 800$ K at the same temperatures.

trum, might be the source of collective modes. As a model for the interaction of electrons with such a system, we will choose a model of two-level centers with a disintegration energy E, which are distributed within an interval E_0 with a density $\tilde{\omega}(E)$.[7] It is easy to see that at $T \approx 0$ and low energies the self-energy has the form

$$\Sigma(\epsilon) \simeq -\tilde{\lambda}\epsilon\left(\ln\frac{E_0}{|\epsilon|}+1\right)-i\frac{\pi}{2}\tilde{\lambda}\epsilon. \tag{3}$$

The self-energy, expressed in this form, was suggested in Ref. 8. In contrast with the electron–phonon reciprocal relaxation time, for which the linear temperature dependence begins at T higher than approximately $\overline{\omega}/4$, the behavior of $\tau^{-1}(T)$ with the interactions such as (3) is linear, beginning at very low temperatures. If both types of interaction are present, $\tau^{-1}(T)$ will contain these two terms and the relationship between them will depend on the relationship between λ and $\bar{\lambda}$ and between $\overline{\omega}$ and E_0. The frequency dependence of the imaginary part of the polarization operator for the case in which the electrons interact with the two-level centers at frequencies (or temperatures) on the order of E_0 is described by (2) with $\Gamma = \pi\bar{\lambda}E_0$. At very low temperatures the curve does not approach zero rapidly, as it does in the case of electron-phonon interaction (Fig. 2, upper part). The intensity of direct scattering of light by two-level centers is proportional to their distribution density, $\tilde{\omega}(E)$. A complete identification of the components of the Raman spectrum—identification of the carriers that interact with the phonons and with the collective modes and also determination of the collective modes themselves—requires more comprehensive information on the temperature dependence of the scattering intensity at frequencies $\omega < 400$ cm^{-1}.

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