Temperature dependence of the Raman-scattering spectrum of a superconducting $YBa_2Cu_3O_{7-\delta}$ single crystal

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The temperature dependence of the frequency and width of a phonon line in the Raman-scattering spectrum of a superconducting $YBa_2Cu_3O_{7-\delta}$ single crystal has been measured for the first time. A temperature-independent component of the linewidth has been distinguished. This component is related to the electron-phonon interaction and an inhomogeneous broadening. It is suggested that the decrease in the linewidth at $T \ll T_c$ occurs because the phonon frequency falls in the superconducting gap, and the electron-phonon interaction mechanism is turned off. These arguments lead to a value $2\Delta/kT_c \gtrsim 5$.

Measurements of the temperature dependence of the frequencies and widths of the phonon lines in the Raman-scattering spectra of the new high-temperature superconductors are clearly pertinent to research on the superconductivity mechanism. In this letter we are reporting the first such measurements on a $YBa_2Cu_3O_{7-\delta}$ single

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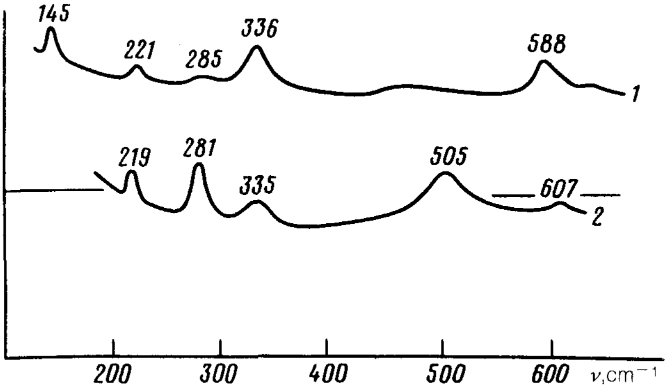

FIG. 1. 1—Raman-scattering spectrum of a $YBa_2Cu_3O_{7-\delta}$ single crystal, from the *ab* plane; 2—Raman-scattering spectrum of a single-phase ceramic $YBa_2Cu_3O_{7-\delta}$ sample ($T = 295$ K).

crystal of orthorhombic structure ($T_c = 94$ K). The single crystal was grown in the laboratory of S. M. Stishov at the Institute of Crystallography, Academy of Sciences of the USSR. The sample was a wafer with dimensions of 1×1.5 mm and with *c* axis running perpendicular to the plane. The Raman spectra were recorded by a DFS-24 spectrometer with a double monochromator, a cooled FÉU-79 photomultiplier, and a photon-counting system. The sample was excited by the line at 4880 Å of an Ar^+ laser with a power not exceeding 60 mW. The spectral width of the slit, *S*, was 4–6 cm^{-1}. The intrinsic half-width of the band was determined from the measured half-width $\Delta\nu_{exptl}$ by means of the approximation $\Delta\nu = [(\Delta\nu_{exptl})^2 - S^2]^{1/2}$, which is valid when $\Delta\nu_{exptl}$ is several times greater than *S*.

Figure 1 shows the Raman spectrum at room temperature (curve 1) and, for comparison, the spectrum of a single-phase ceramic $YBa_2Cu_3O_{7-\delta}$ sample (curve 2). Since scattering from the *ab* plane is detected in the single crystal, only vibrations with the Raman-tensor components *XX*, *YY*, and *XY* can be manifested. The band at 505 cm^{-1} is related to a vibration of A_{1g} symmetry and is manifested in the *ZZ* polarization.[1-3] This band is accordingly not observed in scattering from the *ab* plane of a single crystal. The 336-cm^{-1} band also corresponds to an A_{1g} symmetry, in our opinion, but with Raman-tensor components α_{aa}, $\alpha_{bb} \gg \alpha_{cc}$. This interpretation agrees with the data of Ref. 2.

In the spectrum of the single crystal we made a detailed study of the temperature dependence of the band at $\nu = 336$ cm^{-1}. Figure 2a shows the temperature dependence of the frequency over the range 1.6–296 K. The behavior is not monotonic. There is rounded maximum near the superconducting transition temperature. A similar temperature dependence has been observed[4] for this band in a ceramic $YBa_2Cu_3O_{7-\delta}$ sample. Figure 2b shows the temperature dependence of the half-width of this band. We see that the temperature dependence is very weak above 100 K. Shown for comparison here is the temperature dependence of the half-width of the band at $\nu = 387$ cm^{-1} (close along the frequency scale), which we observed in the spectrum

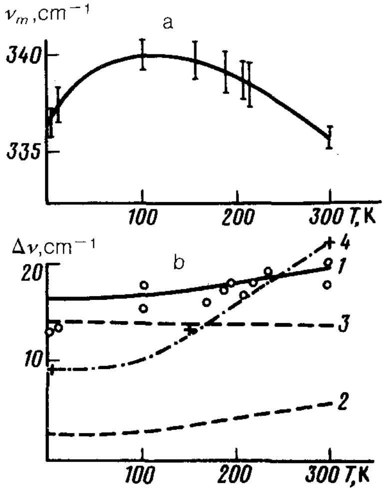

FIG. 2. a: Temperature dependence of the frequency of the 336-cm^{-1} band in the single crystal. b: Temperature dependence of the half-width of the line at $\nu = 336$ cm^{-1} in a $YBa_2Cu_3O_{7-\delta}$ single crystal. Circles—Experimental; line 1—theoretical functional dependence $\Delta\nu(T) = \Delta\nu_a(T) + \Delta\nu$; line 2—$\Delta\nu_a(T)$; dashed line 3—$\Delta\nu_c$; line 4—temperature dependence of the half-width of the line at $\nu = 387$ cm^{-1} for the nonmetallic phase (a polycrystalline polyphase sample).

of a polyphase ceramic sample.[1)] This behavior can be approximated well by an anharmonic decay into two phonons of identical frequency; i.e.,

$$\Delta\nu \sim 2\tilde{n} + 1 ,$$

where $\tilde{n} = (\exp(h\nu/2kT) - 1)^{-1}$. On the other hand, the dependence of the band at $\nu = 336$ cm^{-1} in the $YBa_2Cu_3O_{7-\delta}$ single crystal cannot be explained on the basis of an anharmonic decay process. Above 100 K, it can be represented as the sum of two terms: an anharmonic term $\Delta\nu_a \sim 2\tilde{n} + 1$ and a temperature-independent term $\Delta\nu_c$. The solid line in Fig. 2b shows the dependence $\Delta\nu(T) = \Delta\nu_a(T) + \Delta\nu_c$. We believe that both the electron-phonon interaction and an inhomogeneous broadening, probably due to an oxygen disorder (characteristic of these compounds), contribute to the term $\Delta\nu_c$.

The Raman spectra of ordinary metals (Cd and Mg) also exhibit a temperature-independent contribution to the phonon damping, which amounts to 3–5% of the vibration frequency.[5] The relative size of the temperature-independent contribution to the broadening in $YBa_2Cu_3O_{7-\delta}$ is 4% of the vibration frequency and thus comparable to the values observed in ordinary metals.

Below the temperature of the superconducting transition, the measured half-width of the 336-cm^{-1} band does not conform to the calculated dependence. Its decrease may be due to a decrease in the electron-phonon interaction, if the vibration under consideration falls in the vicinity of the superconducting gap. This result would imply $2\Delta/kT_c \gtrsim 5$.

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[1)]Our measurements showed that this spectrum belongs to a phase which does not have a superconducting transition and which was identified in Ref. 1 as a nonmetallic phase of Y_2BaCuO_5.

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