Electron Raman scattering and superconducting gap in $Tl_2Ba_2CaCu_2O_8$ single crystals

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The temperature dependence of the electron Raman scattering has been measured in superconducting crystals of $Tl_2Ba_2CaCu_2O_8$ ($T_c \approx 110$ K) for the first time. The results indicate a pronounced anisotropy of the superconducting gap in these crystals.

One of the central problems in research on the new superconductors is identifying the mechanisms responsible for the onset of high-temperature superconductivity. Knowledge of such a parameter as the superconducting gap Δ and its temperature dependence will play an important role in solving this circle of questions. Raman

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spectroscopy is finding progressively more use as a method for experimentally determining the energy gap, in addition to tunneling spectroscopy and measurements of the far-IR absorption and reflection.

As was first pointed out by Abrikosov and Fal'kovskiĭ,[1] the electron Raman scattering in a superconductor at $T < T_c$ begins at $\omega > 2\Delta$; it should be totally absent at $\omega < 2\Delta$. This idea underlies the method for measuring the superconducting gap on the basis of Raman spectra. Experiments on the structural features in the spectra of electron Raman scattering have made it possible to trace the nature of the changes in the energy gap and in the density of the above-gap excitations as a function of the temperature in the superconductors Nb_3Sn and V_3Si (Refs. 2 and 3). The use of Raman methods to determine Δ in the new high-temperature superconductors is particularly appropriate since, on the one hand, these are contactless methods, and, on the other, Raman spectroscopy has several advantages over far-IR spectroscopy because of the limited transverse dimensions of single-crystal samples. Several published papers have reported the observation of structural features in the electron Raman spectra at $T < T_c$ for crystals of $YBa_2Cu_3O_7$ (Refs. 4 and 5) and $Bi_2Sr_2CaCu_2O_8$ (Ref. 6).

In the present letter we are reporting measurements of the electron Raman scattering in superconducting $Tl_2Ba_2CaCu_2O_8$ single crystals with a transition temperature $T_c \approx 110$ K. We studied the Raman spectra during excitation of the **ab** basal plane by the line at $\lambda = 4880$ Å from an Ar^+ laser. The dimensions of the excitation region were $\sim 0.05 \times 0.2$ mm when the power incident on the crystal was $\lesssim 15$ mW. The Raman spectra were recorded on a Dilor XY spectrometer. The test samples were held in an optical helium constant-temperature chamber in He vapor. This approach made it possible to establish the temperature within $\Delta T \approx 0.05$ K over the range $T_0 = 5$–300 K. Because of the inhomogeneity of the samples, the Raman spectra at the various temperatures were taken from the same region on the surface of the crystal within ≈ 2 μm. A microscope was used to monitor this procedure.

A distinctive feature of the Raman spectra of $Tl_2Ba_2CaCu_2O_8$ crystals from the **ab** plane in an approximately backscattering geometry is the absence of intense lines corresponding to Raman scattering by optical vibrations in the frequency range $130 < \omega < 500$ cm^{-1} (Ref. 7). The reason for this situation is that the corrugation of the cuprate planes is only slight. The more pronounced corrugation of the CuO_2 planes in $YBa_2Cu_3O_7$ crystals gives rise to an intense Raman band of symmetry B_{1g} and frequency ~ 340 cm^{-1}. This band is associated with an antiphase vibration of oxygen atoms in the cuprate planes along the **c** axis of the crystal[8] and has a distinctive temperature dependence.[9] In the $Tl_2Ba_2CaCu_2O_8$ crystals, in contrast, the shape and positions of the Raman components depend only weakly on the temperature. This circumstance is exceedingly important in measurements of the temperature-induced changes in the extended continuum near the superconducting gap.

Figure 1 shows Raman spectra at two values of the temperature (T_0) in the constant-temperature chamber.[1)] We see that a temperature increase results in an intensification of the extended background at frequencies $\omega \lesssim 400$ cm^{-1}. Figure 2 shows the temperature dependence of the intensity of the Raman scattering, I, in this frequency region as a plot of the ratio $I(T)/I(180\text{ K})$ at several values of $T \lesssim T_c \approx 10$ K. At $\omega > 400$ cm^{-1} this ratio is seen to be essentially independent of the temperature and

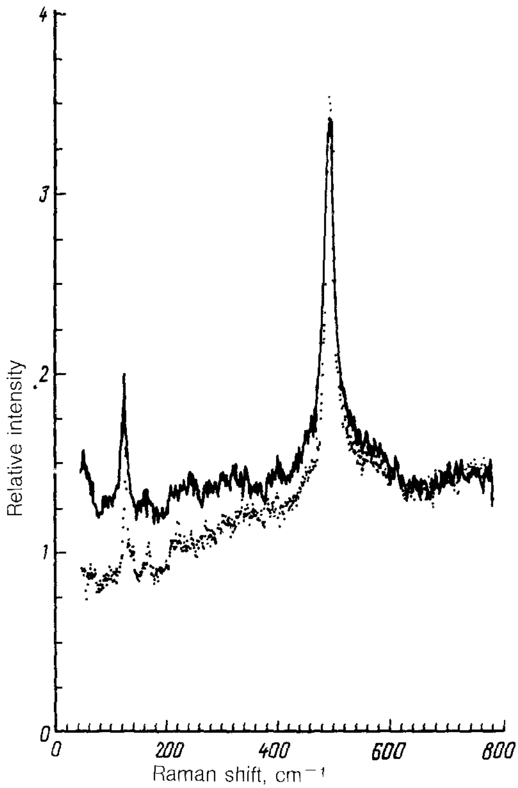

FIG. 1. Raman spectra of a $Tl_2Ba_2CaCu_2O_8$ single crystal at two temperatures T_0. Points—4.5 K; solid line—180 K.

to have a value close to 1. At frequencies $\omega < 400$ cm^{-1}, we observe a $\sim 30\%$ dip at low temperatures; as the temperature is raised, this dip decreases in magnitude, and it disappears at $T \approx T_c$. A further increase in the temperature causes no significant spectral changes. The features observed in the extended background in the Raman spectrum are characteristic of electron Raman scattering in the presence of a superconducting gap. Even at liquid-helium temperatures, however, we do not observe a complete vanishing of the Raman scattering anywhere in the frequency range studied. This result apparently means that there are normal regions in our samples which continue to contribute to the electron Raman scattering down to the lowest temperature. Our measurements of the diamagnetic susceptibility of the $Tl_2Ba_2CaCu_2O_8$ crystals agree well with that suggestion.

The shape of this dip observed in the Raman spectrum is quite different from that predicted by the theory[1,10] for the case of an isotropic superconducting gap. In the case of an anisotropic gap,[10] in contrast, there should be no electron Raman scattering beyond a frequency $\omega \approx 2\Delta_{\min}$, where $\Delta_{\min}$ is the minimum value of the superconducting gap. The spectral shape of the dip and its temperature dependence are apparently evidence of a significant anisotropy of the gap in the $Tl_2Ba_2CaCu_2O_8$ crystals (Fig. 2).

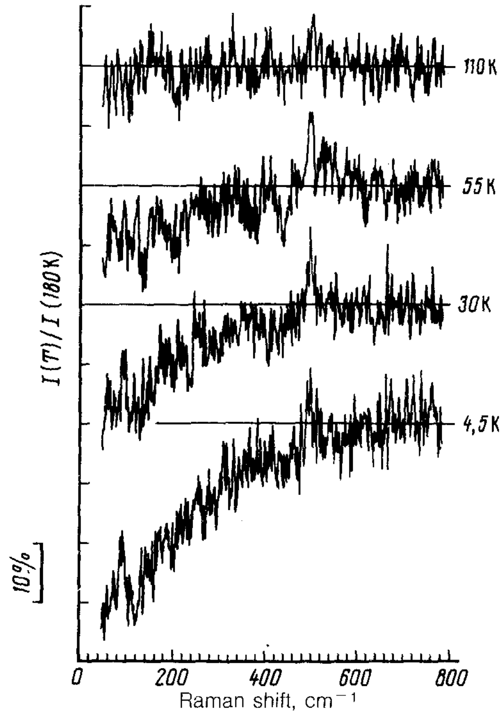

FIG. 2. Ratio of the intensity of the Raman scattering in a $Tl_2Ba_2CaCu_2O_8$ crystal at several temperatures T_0 to the intensity of the Raman scattering at $T_0 = 180$ K. The straight lines correspond to the value $I(T)/I(180\ \mathrm{K}) = 1$.

Since the decrease in the electron Raman scattering begins at frequencies $\omega \lesssim 400$ cm^{-1}, it becomes possible to estimate a maximum value of the superconducting gap: $2\Delta_{\max} \approx 5k_B T_c$. A correct determination of $\Delta_{\min}$ will require further research.

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[1)]We estimate the heating to be $\Delta T \lesssim 15$ K at $T_0 = 5$ K.

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