Relation of frequencies and damping of transverse phonons in lead at $T=4.2\,°K$

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(Submitted May 27, 1975)
Pis'ma Zh. Eksp. Teor. Fiz. 22, No. 1, 39–42 (July 5, 1975)

We investigated the frequencies and widths of transverse phonons in lead in the [ξξξ] direction at temperatures 4.2, 20.4, 78, and 300°K. At $T=4.2\,°K$ we observed softening of the phonons with wave vectors in the interval $aq/2\pi=0.35$–5, and a strong broadening of the single-phonon resonances for $aq/2\pi=0.5$–0.867.

PACS numbers: 63.20.K

The method of inelastic coherent neutron scattering makes it possible to observe directly the influence of electron-phonon interaction on the phonon frequencies and lifetimes. Thus, in[1,2] they investigated the damping, due to the transition in the superconducting state of the phonons in Nb_3Sn and in pure Nb.

In the present study, for transverse phonons in the [ξξξ] direction in lead, we investigated the phonon frequencies ω and the widths $2\Gamma_0$ (full width at half height) of single-phonon neutron resonances at the temperatures 4.2, 20.4, 78, and 300 °K.

The sample was a single crystal of pure (99.9999%) Pb with a resistivity ratio $\rho_{300K}/\rho_{7.3K}\sim 2000$. The measurements were performed with a three-axis neutron spectrometer by the method of constant momentum transfer ($\mathbf{Q}=$const) for phonons with $aq/2\pi=0.26$, 0.35, 0.40, 0.45, 0.50, 0.60, 0.70, 0.80, and 0.867, where a is the lattice constant and $\mathbf{q}$ is the phonon wave vector. The experimental data were reduced and the measurement errors estimated by the procedures proposed in[3].

In the interval 300–20.4 °K we observed for all the phonons the usual increase of the frequency and decrease width of the resonances with rising temperature. At $T=4.2\,°K$ we observed an anomalous decrease of the frequency of the phonons with $aq/2\pi=0.35$, 0.40, 0.45, and 0.50, whereas for the remaining investigated phonons we found $\omega(4.2\,°K)>\omega(20.4\,°K)$. Figure 1 shows plots of $\omega(T\,°K)/\omega(300\,°K)=f(T)$ for phonons with $aq/2\pi=0.80$ and 0.45, which are typical representatives of the indicated two groups.

The widths of the one-phonon resonances also behave differently for the different phonon groups when the temperature is lowered from 20.4 to 4.2 °K. For phonons with $aq/2\pi=0.50$, 0.60, 0.70, 0.80, and 0.867 we observed a broadening at $T=4.2\,°K$, and the values of $2\Gamma_0(4.2\,°K)$ were not only larger than $2\Gamma_0(20.4\,°K)$, but even larger, by one order of magnitude and more, than the widths at $T=78\,°K$. (The Debye temperature for lead is $\Theta_D\approx 80\,°K$). On the average we have for this phonon group the ratio $2\Gamma_0(4.2\,°K)/2\Gamma_0(20.4\,°K)\sim 1.25$.

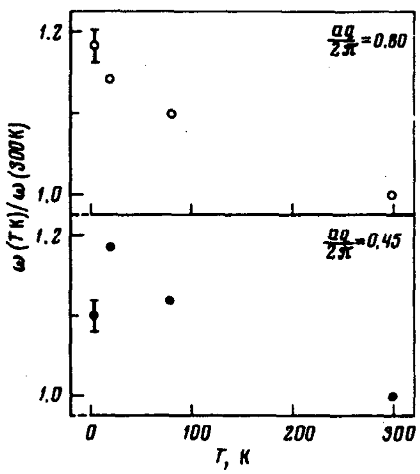

FIG. 1. Dependence of the relative frequency $\omega(T\,°K)/\omega(300\,°K)$ of the transverse phonons on the temperature in lead in the [ξξξ] direction.

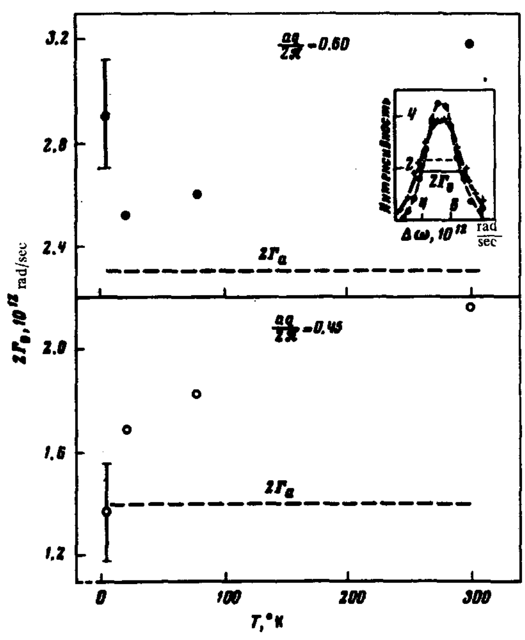

FIG. 2. Dependence of the experimentally observed width of one-phonon resonances on the temperature in lead in the [ξξξ] direction. Dashed line—apparatus width $2\Gamma_a$. The insert shows one-phonon resonance with $aq/2\pi=0.60$, measured in a magnetic field $H\sim 1300$ Oe (dash-dot line) and without a field (line with crosses).

The widths of the resonances for the phonons with $aq/2\pi = 0.26$, 0.35, 0.40, and 0.45 decrease with decreasing temperature. Figure 2 shows by way of illustration plots of $2\Gamma_0$ for phonons with $aq/2\pi = 0.45$ and 0.60.

The energy of the phonons for which broadening was observed exceeds the energy gap $2\Delta(0)$ in lead. Therefore, just as in[2], it can be assumed that the broadening is due to an increase of the density of the states of the electrons near the Fermisurface as a result of the appearance of an energy gap when the sample becomes superconducting. Favoring this assumption are also measurements performed at 4.2 °K, with the sample placed in a magnetic field $H > H_{cr}$ ($H \sim 1300$ Oe). The insert of Fig. 2 shows the neutron resonance for a phonon with $aq/2\pi = 0.60$, obtained in measurements with and without a magnetic field. We see that application of a field $H > H_{cr}$ leads to a noticeable narrowing of the resonance, accompanied by an increase of the peak intensity. In the case of a phonon width $aq/2\pi = 0.26$ (phonon energy smaller than $2\Delta(4.2\,°\text{K})$) in a magnetic field, we have observed broadening of the resonance with a decrease of its peak intensity.

An analysis of the apparatus contribution to the width of the resonances, performed by the method of[4,5] with allowance for the change of $d\omega(q)/dq$ with temperature, gives grounds for stating that the observed effect is not connected with a change in the apparatus width. The procedure for extracting the proper widths of the phonons is not reliable enough at our resolution. We therefore present the experimentally observed width, although the effects on the proper widths would have been more appreciable.

Attention is called to the fact that phonons with $aq/2\pi = 0.40$ and 0.45, whose energy $\hbar\omega$ is larger than the gap energy cited in the literature, remain narrow at $T = 4.2$ °K, and the first broadened phonon with $aq/2\pi = 0.50$ has an energy[1)] $\hbar\omega \approx 1.14 \times 2\Delta(4.2\,°\text{K})$. In addition, the broadening effect itself is quite appreciable.

More detailed results of the study will be reported later.

The author is grateful to Professor S.K. Sidorov for constant interest in the work.

[1)]Data obtained by different workers differ significantly. Our estimate, based on the maximum gap known to us $2\Delta(0)/k_B T_c = 5$,[6] with allowance for the temperature dependence of the gap,[7] yields $2\Delta(4.2\,°\text{K})/k_B T_c = 4.5$.

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