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TEMPERATURE DEPENDENCE OF THE POSITION AND LINE WIDTH OF CYCLOTRON RESONANCE IN LEAD

I. Ya. Krasnopolin and M. S. Khaikin
Institute of Physics Problems, USSR Academy of Sciences
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Electron-phonon interaction in metals leads to an increase of the effective mass m^* of the conduction electrons on the Fermi surface [1]:

$$m^* = m_b(1 + \lambda),$$

where m_b is the effective mass due to the band structure, and λ is a coefficient characterizing the electron-phonon interaction. The function $\lambda(T)$ was calculated in [2] for Pb and Hg.

According to this calculation, a change of λ should lead to an increase of m^* by several per cent when the temperature is increased from 0 to about 4°K.

We have used cyclotron resonance (CR) to investigate experimentally the temperature dependence of the effective mass of lead, a metal with a strong electron-phonon interaction [1, 2].

The sample was single-crystal Pb in the form of a disc with the normal oriented along [011], grown by R. T. Mina from the melt in a dismountable crucible mold [3]. The sample, freely lying on a quartz substrate, was placed in a strip resonator tuned to a frequency $\sim$19.2 GHz, connected in the feedback loop of a self-oscillator using a traveling wave tube [4]. We measured either the low-frequency component (at a magnetic-field modulation frequency 12 Hz) of the generation amplitude near threshold, or the frequency deviation of the oscillator [4].

The resonator and sample were placed in a cryostat cooled with liquid He^3. The sample temperature changed less than 0.1°K during the time necessary to record each spectrum. The magnetic field H produced by the electromagnet was applied along the $[0\bar{1}1]$ axis. The field was set parallel to the sample surface with accuracy $\sim 5'$ as determined by the maximum of the CR amplitude ψ_2 (the notation is the same as in [6, 7]). The magnetic field intensity was measured with a Hall pickup, and the calibration was with a nuclear magnetometer with running water [5] during each measurement of the investigated section of the CR spectrum. The magnetic field measurement accuracy was limited by its modulation and amounted to $\sim$0.1%.

Figure 1 shows CR spectra obtained by the frequency-modulation method [4]. The figure shows three strong resonances: third-order resonances of ψ_2 on a noncentral hole orbit and of χ on a non-lanar orbit passing over the tubes in the third zone, and a first-order resonance of ζ_1 on the central section of the tube. With increasing temperature, the CR lines broaden as a result of the decrease of the relaxation time and shift to the stronger-field region, corresponding to an increase of the effective mass.

The results were reduced for the most intense ζ_1 resonance, since the ψ_2 and χ resonance lines overlap when $T \gtrsim 2$°K, owing to the decrease of the relaxation time τ. The resonant value of the field H_1 and the value of $\omega\tau$ were determined by comparing the experimental line shape with that calculated in accord with [8] for the case corresponding to the minimum effective mass. Since the Q of the strip resonator is not high ($\sim 10^3$), it is impossible to register in the experiments either $\partial X/\partial H$ or $\partial R/\partial H$ alone [9], and we chose in the reduction the combination $\partial X/\partial H + \beta\partial R/\partial H$ or $\partial R/\partial H + \beta\partial X/\partial H$, which describes the experimentally observed line. The parameter β was chosen once for the measurement run, if the tuning of the circuit did not change during the course of the measurements. The values $\beta \approx 0.2 - 0.3$ indicate that the admixture of the other component was not large.

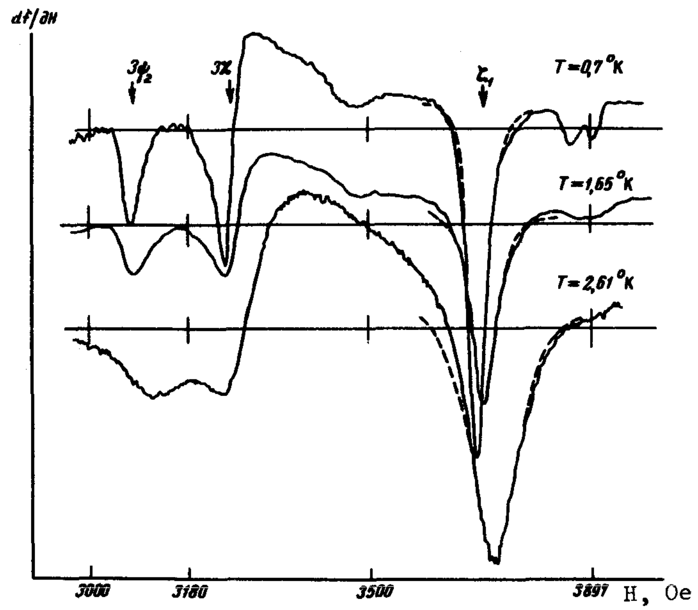

Fig. 1

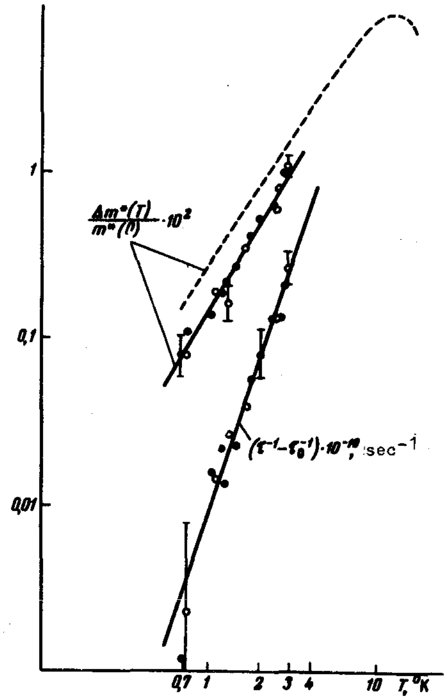

Fig. 2

Fig. 1. CR spectra obtained by the frequency-modulation method. The dashed lines show the calculated line shape for $\beta = -0.3$; the vertical strokes are NMR markers.

Fig. 2. Plots of $\Delta m^*(T)/m^*(0)$ and $\tau^{-1}(T)$ for the ζ_1 mass. o - from measurements of $\partial X/\partial H + \beta\partial R/\partial H$, o - from measurements of $\partial R/\partial H + \beta\partial X/\partial H$. The dashed line shows the theoretical plot of $\Delta m^*(T)/m^*(0)$ recalculated from [2].

The relative change of the effective mass of ζ_1 with temperature, determined from the shift of the resonant value of the field H_1 (for the case of Fig. 1, the value H_1 corresponds to a minimum on the resonant curve, as is clear already from the symmetrical line shape), is shown in Fig. 2. This mass change is not very sensitive to the choice of the parameter β, for if $\beta = 0$ is chosen, then the obtained points do not go beyond the limits of the errors indicated in Fig. 2 (but the calculated line shape will differ appreciably from the observed one). The same figure shows (dashed) a theoretical plot of $\Delta m^*(T)/m^*(0)$ obtained from the $\lambda(T)/\lambda(0)$ plot given in [2]. The relative growth of the effective mass (its absolute value is $m^*_{\zeta_1} = (0.538 \pm 0.001)m_e$ according to our measurements at $T = 0.7°K$) is smaller by a factor of about 1.5 than the value predicted in [2], but the slopes of the theoretical and experimental curves almost coincide ($(\Delta m^*(T)/m^*(0))_{\text{exp}} \sim T^{1.7 \pm 0.2}$). The discrepancy is possibly connected with the fact that in [2] the calculated value of λ was averaged over the entire Fermi surface. At the same time, comparison of the masses measured in [6] with those calculated by the 4-OPW model [10] point to anisotropy of this quantity ($\lambda \approx 1 - 1.4$).

The experimentally obtained $\tau(T)$ plot is described by the formula

$$\tau^{-1} - \tau_0^{-1} = (1 \pm 0.1) \cdot 10^8 T^{3 \pm 0.4} \text{sec}^{-1},$$

$$\tau_0 = (1.2 \pm 0.1) \cdot 10^{-9} \text{ sec},$$

indicating a phonon mechanism of relaxation of the electrons that take part in the resonance.

A temperature dependence of the cyclotron effective mass in Pb was observed also in [11], viz., $\Delta m^* \sim T^2$, and $\Delta m^*/m = 5.7 \pm 0.7\%$ when the temperature changes from 1.5 to 6.5°K.

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ERRATA

In the article by I. Ya. Krasnopolin and M. S. Khaikin, Vol. 12, No. 2, p. 55, the points of Fig. 2 should be identified as follows: o – from measurements of $\partial X/\partial H + \beta\partial R/\partial H$, ● – from measurements of $\partial R/\partial H + \beta\partial X/\partial H$.