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TUNNEL EFFECT IN LEAD UNDER PRESSURE

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Submitted 8 February 1968
ZhETF Pis'ma 7, No. 8, 271-277 (20 April 1968)

We investigated the tunnel characteristics of lead under pressure up to 15 kbar* at 1.3°K. We determined the change in the width Δ of the gap in the energy spectrum of the electrons of the superconductor and the shift of the characteristic frequencies of the phonon spectrum of lead under pressure. The results were used to verify the theory of superconductors with strong coupling [1].

The object of the investigation was a system of $Al-Al_2O_3-Pb$ films prepared by sputtering on glass [2]. The Pb film thickness was $\sim 10^{-5}$ cm, and the resistance of the tunnel junction was ~100 ohm/mm^2. The tunnel characteristics were used to select for the pressure tests samples having no defects in the Al_2O_3 layer. The hydrostatic pressure was produced by the method described in [3]. The pressure was calculated from the changes in the critical temperature T_c of a tin wire located in the high-pressure chamber, using the formula [4] $\Delta T_c = -4.95 \times 10^{-5}p + 3.9 \times 10^{-10}p^2$ (p is in bars). During the course of the experiment, just as in [5], we registered the characteristics $dU/dI = R(U)$ and $d^2U/dI^2 = r(U)$ of the investigated junctions.

Application of a pressure up to 10 kbar usually produced no irreversible changes in the characteristics of the junctions. A noticeable deterioration of the junctions occurred only at the maximum pressure, ~15 kbar.

The present communication is based on data that could be obtained without quantitative amplitude measurements. We discuss in this paper only the pressure-induced shift of the voltage U, at which the main singularities of the fully reversible tunnel characteristics of Pb were observed. Singularity A (Fig. 1) is due to the appearance of the gap Δ in the characteristics, and singularities B, C, and D are due to the appearance of the Van Hove singularities of the phonon spectrum of lead [6]. B corresponds to the maximum of the phonon state density, or more accurately to the function $\alpha^2(\omega)F(\omega)$ [7]; this maximum is due to transverse oscillations $\omega_\perp = U_B - \Delta \approx 4.5$ meV. The singularity C is due to the density maximum caused by the longitudinal oscillations $\omega_\parallel = U_C - \Delta = 8.5$ meV. Singularity D is due to the upper limiting energy for the phonon density state $\omega_K = U_D - \Delta \approx 10$ meV [7].

Figure 2 shows the positions of the aforementioned singularities of the tunnel characteristics at different pressures. The value of $2\Delta_0$ was calculated from the R(U) characteristics, and the value of $\omega = U - \Delta_0$ was determined from the average of the corresponding r(U) singularity and the value of Δ_0. The same figure shows the shift of the corresponding spectrum frequencies under pressure in the 3 kbar region, both in accordance with neutron-diffraction measurements [8] and in accordance with tunnel-effect data [9] with which we became acquainted during the course of the work. In the investigated pressure range, the values of $2\Delta_0$, $\omega_\perp$, $\omega_\parallel$, and ω_K shift linearly when the distance between the lattice atoms changes under pressure.

The table lists all the numerical data. To calculate the Gruneisen parameter $\gamma = d \ln \omega / d \ln V$, we used data on the compressibility κ of the lead at low temperatures [10]. For comparison, the table lists the x-ray diffraction data [11] on the frequency shift of the phonon spectrum with increasing temperature $(\partial \ln \omega/\partial T)_p$, also due to the change in the interatomic distance. From these data, knowing the coefficient of thermal expansion β [10], it is possible to estimate the shift of ω accompanying the decrease in volume. The obtained value turned out to be in satisfactory agreement with our results.

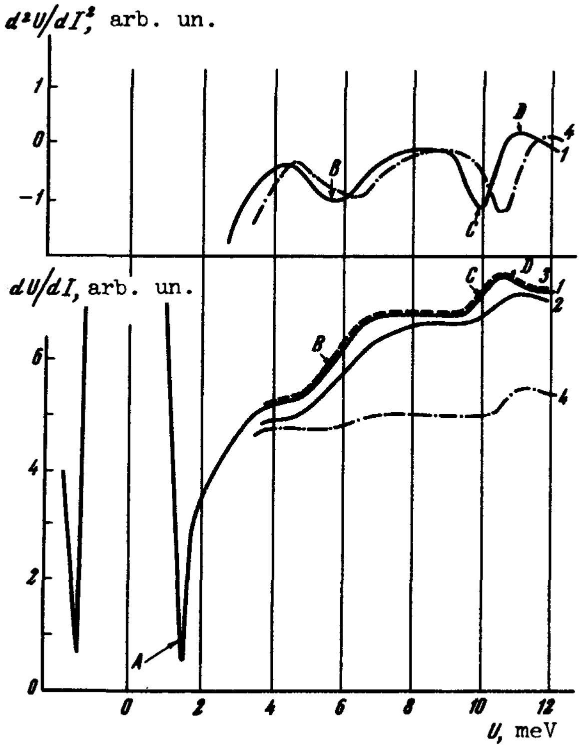

Fig. 1. Plots of R(U) and r(U) for one junction at different pressures. The numbers on the curves correspond to the sequence of the experiments: 1) p = 0, 2) p = 10.3 ± 0.3 kbar, 4) p = 15.5 ± 0.3 kbar. The letters denote the singularities on the curves.

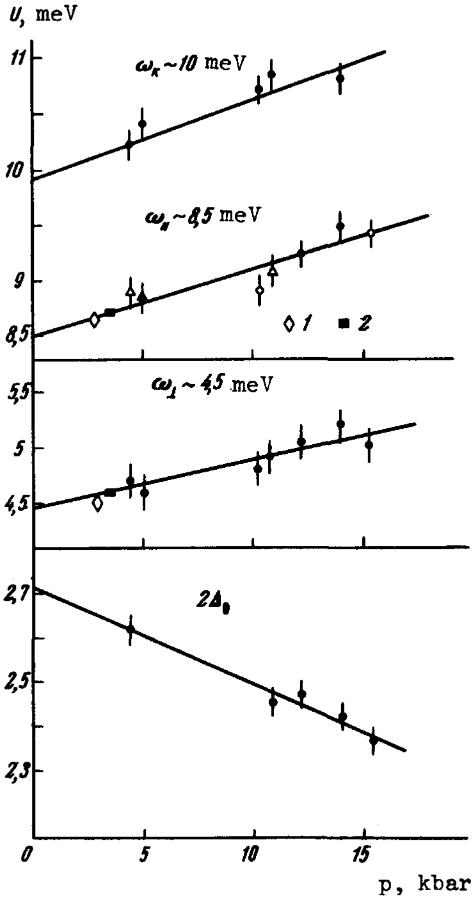

Fig. 2. Pressure dependence of the position of the main singularities of the tunnel characteristics of lead. Different points on the $\omega_\parallel = 8.5$ meV curve correspond to different samples: 1 - calculation according to the data of [8], 2 - according to the data of [9].

	Investigated quantity X			
	$2\Delta_0$	$\omega_\perp$	$\omega_\parallel$	ω_K
Energy X, meV	2.71	4.45	8.5	9.9
$(\frac{dX}{dp}) \times 10^{-5}$, meV/bar	2.16 ± 0.6	4.5 ± 0.6	6 ± 0.6	7 ± 1
$(\frac{d \ln X}{dp}) \times 10^{-6}$, bar^{-1}	8	10.1	7.05	7.1
$\gamma = \frac{d \ln \omega}{d \ln V}$	-	4.95	3.45	3.45
$(\frac{d \ln \omega}{dT}) \times 10^{-5}$ deg^{-1} [11]	-	-32 ± 6	-13 ± 8	-8 ± 9

The exact calculation, as follows from thermodynamics, should be based on the formula

$$\left(\frac{\partial \ln \omega}{\partial T}\right)_p = \left(\frac{\partial \ln \omega}{\partial T}\right)_V + \frac{\beta}{\kappa}\left(\frac{\partial \ln \omega}{\partial p}\right)_T,$$

i.e., at constant pressure the frequency shift is due also to a change in temperature without change in volume V, i.e., to phonon-phonon interaction. The experimental errors in the determination of $(\partial \ln \omega/\partial T)_p$ in [11] do not allow us to separate reliably this term $(\partial \ln \omega/\partial T)_V$.

The dependence of ω on the lattice volume is frequently described in terms of the Gruneisen parameter γ. The values of γ obtained by us (see the table) greatly exceed the values calculated from the thermal expansion and the heat capacity of lead at low temperatures [10], $\gamma = 2.7$. It is possible that this discrepancy is also due to phonon-phonon interaction. The different values of $(\partial \ln \omega/\partial p)_T$ for $\omega_\perp$ and $\omega_\parallel$ offer evidence that the spectrum changes under pressure.

The shift of the phonon spectrum under pressure can be used to verify the deduction of the theory of superconductors with strong coupling. As is well known [12,13], the analysis of the experimental data shows that the ratio $2\Delta_0/kT_c$ of different superconductors depends on the ratio T_c/Θ, where Θ is the Debye temperature. This experimental result is best explained by the calculations of Geilikman and Kresin [1], who have shown that

$$\frac{2\Delta_0}{kT_c} = 3{,}52\left[1 + 5{,}3\,\frac{T_c^2}{\omega_0^2}\ln\frac{\omega}{T_c}\right], \qquad (1)$$

where ω_0 is the limiting frequency of the longitudinal phonons, whose interaction with the electron, in their opinion, plays the principal role. Since the electron-phonon interaction with the transverse phonons is large in lead [7], it is natural to substitute $\omega_\perp$ in (1). This

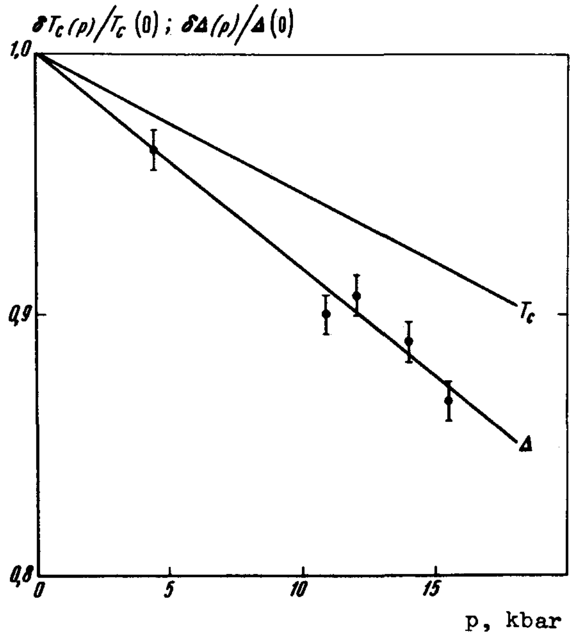

Fig. 3. Relative pressure dependence of the critical temperature T_c and of the gap width Δ of lead. The straight line for Δ was calculated from (2).

will make the agreement between the value of $2\Delta_0/kT_c$ with experiment even better than in the case of the value $\omega_0 = 0.7\Theta$ used in [1]:

$$\left(\frac{2\Delta_0}{kT_c}\right)_{0,7\Theta} = 4,1,\ \left(\frac{2\Delta_0}{kT_c}\right)_{\omega_\perp} = 4,26,\ \left(\frac{2\Delta_0}{kT_c}\right)_{\exp} \simeq 4,3. \qquad (2)$$

In comparing the relation (2) in differential form with experimental results, the external pressure p plays the role of a parameter. We used for the $T_c(p)$ dependence Smith's data [14], $dT_c/dp = -3.86 \times 10^{-5}$ deg/bar, which agree well with other measurements on both bulk samples and thin films [9]. The results of the calculation of $d \ln \Delta/dp$ with the aid of formula (1) using the foregoing values of dT_c/dp, $\omega_\perp$, and $d\omega_\perp/dp$ are shown in Fig. 3. We see that the relation derived by Geilikman and Kresin describes completely the experimental data on the $\Delta(p)$ dependence.

In conclusion, it is our pleasant duty to thank P. L. Kapitza and L. F. Vereshchagin for interest in the work, Yu. M. Kagan for discussions, and A. M. Shpel'ter for technical collaboration.

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* Preliminary results of these measurements, at pressures up to 5 kbar, were reported to the 14th All-union Conference on Low-temperature Physics, Khar'kov, June 1967.

DIRECT PHOTODISINTEGRATION OF Li^6

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Submitted 8 February 1968
ZhETF Pis'ma 7, No. 8, 277-280 (20 April 1968)

Recent experimental investigations of the process $Li^6(\pi^+, 2p)He^4$(ground)* [1] have shown that the decisive role in this reaction is a pole mechanism in which the π^+ mesons interact with a virtual deuteron from the Li^6 nucleus. These experimental data can be used to obtain information on the vertex part of the virtual breakup of Li^6 into an α particle and a deuteron, if the vertex part corresponding to the process $\pi^+ + d \to p + p$ is known. Independent data concerning such a vertex part of the virtual breakup of Li^6 can be obtained by studying other reactions with Li^6, particularly photonuclear ones.

It is impossible as a rule to asses the possible mechanisms of the photodisintegration of Li^6 on the basis of the available experimental data [2-5] (the results are ambiguous). Any particular photodisintegration mechanism can be decisive only for a definite reaction channel and only in a definite range of variation of the kinematic variables.

For this reason, calculation of the total cross sections of the photodisintegration of Li^6, based on the use of one or two diagrams (see [6]), seems to be unjustified.

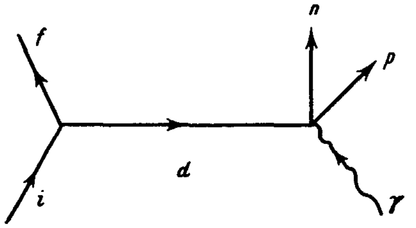

Fig. 1

We consider in this paper the photodisintegration reaction $Li^6(\gamma, np)He^4$(ground) in the electric dipole approximation. This approximation is valid up to γ-quantum energies on the order of 20 MeV. The problem consists of finding the regions of the kinematic variable in which the pole mechanism with photodisintegration of the virtual deuteron can be domi-