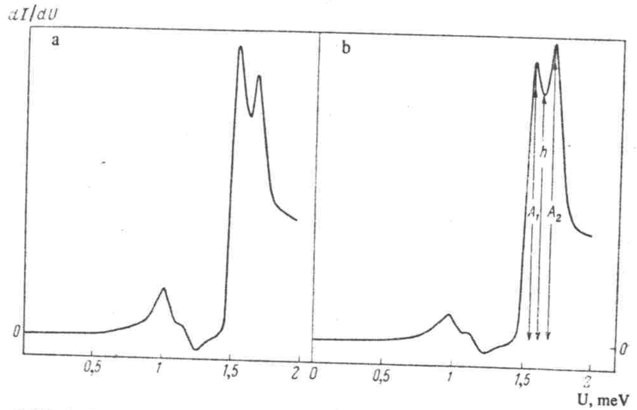

FIG. 1. Differential conductance of an Al-I-Pb* contact with a thick (~15000Å) film of lead (Pb*) at T = 1.17°K: a) $A_1/A_2 > 1$, $2\Delta_1 = 2.55$ meV, $2\Delta_2 = 2.83$ meV; b) $A_1/A_2 < 1$, $2\Delta_1 = 2.49$ meV, $2\Delta_2 = 2.78$ meV.

manometer.[17] The bomb containing the samples was cooled directly with liquid helium.

3. ENERGY GAP AND PHONON SPECTRUM OF LEAD

Although a direct proof of the anisotropy of the energy gap of superconductors was provided over a decade ago,[20] a complete understanding of this anisotropy has not yet been achieved[3], consequently detailed experimental and theoretical investigations of anisotropic superconductors are still desirable. Our aim was to obtain additional information on the gap anisotropy through experiments on anisotropic lead under pressure. The Fermi surface[21] and the phonon spectrum[22] of this metal have been investigated in detail. Bennett[23] suggested a theory of the anisotropy of the energy gap of superconducting lead, based on the assumption that the gap anisotropy was due to the anisotropy of the phonon spectrum. The fullest information on the gap anisotropy could be obtained by investigating single crystals. However, the anisotropy effects should be observed also in thick pure polycrystalline films if the mean free path of electrons is considerably longer than the coherence length, $l > \xi_0$.[23,24] This case was investigated experimentally by Campbell and Walmsley[25], and by Rochlin.[26]

A. Singularities in the Tunnel Conductance of Thick Films at Zero Pressure

An investigation was made on about 50 lead films, which were ~15 000 Å thick. The tunnel characteristics of the junctions exhibited clearly the singularities ($\Delta_{\mathrm{Pb}} \pm \Delta_{\mathrm{Al}}$) associated with the presence of two gaps Δ_1 and Δ_2 in the energy spectrum of lead (Fig. 1). The nature of the singularities in the characteristics $(dI/dU) = f(U)$ could be used to divide the samples investigated into two arbitrary groups: the first and larger group comprised those samples (~70% of all the samples) for which the ratio of the amplitudes at the singularities was $A_1/A_2 > 1$; the second group consisted of those samples for which this ratio was $A_1/A_2 < 1$. The structure of the characteristics at $eU = \Delta_{1,2}^{\mathrm{Pb}} \pm \Delta_{\mathrm{Al}}$ could be attributed to the presence of two groups of electrons with velocities normal to the barrier surface. Then, the ratio A_1/A_2 should be a measure of the contribution of a given group of electrons to the tunnel current. The value of A_1/A_2 was found to vary from sample to sample, ranging from a maximum of 1.35 to a minimum of 0.833. The best resolution of the singularities, i.e., high values of the ratio $A_{1,2}/h$ (h is the amplitude at the minimum between the two peaks), was achieved for lead films evaporated at a low rate (1–3 Å/sec) and annealed at 100°C for several hours after the fabrication of a junction. The maximum values of the ratio $A_{1/2}/h$ for these films were $(A_1/h)_{\max} = 2.52$ and $(A_2/h)_{\max} = 1.91$. The structure at $eU = \Delta_{1,2}^{\mathrm{Pb}} - \Delta_{\mathrm{Al}}$ was practically unresolved for samples with $A_{1,2}/h < 1.05$, which was explained satisfactorily by the theory due to Gorbonosov and Kulik,[24] according to which the amplitude of the singularities should shrink with decreasing temperature and should be

$$\left(1+\operatorname{th}\frac{\Delta_{\mathrm{Al}}}{2T}\right)\Big/\,2\left(1-\operatorname{th}\frac{\Delta_{\mathrm{Al}}}{2T}\right)$$

times smaller than the corresponding singularity at $eU = A_{1,2}^{\mathrm{Pb}} + \Delta_{\mathrm{Al}}$ (in our case, the two amplitudes differed by a factor of about 10).

The extremal values of the energy gaps, found from the dependences $(dI/dU) = f(U)$, were 2.49 ± 0.01 and 2.57 ± 0.01 meV for $2\Delta_1$, and 2.78 ± 0.01 and 2.85 ± 0.01 meV for $2\Delta_2$. As a rule, the samples belonging to the first group had larger values of Δ_1 and Δ_2. The results of the numerical calculations of Bennett[23] for polycrystalline samples (see Fig. 17a in[23]) were in satisfactory agreement with our data.

The theory[23,24] predicts singularities in the tunnel conductivity between polycrystalline films, due to the presence of critical points in the dependence $\Delta(n)$: there should be a local maximum, a minimum, and a saddle point. However, this theory is based on a model which presumes that tunnel transitions take place in films consisting of randomly oriented grains, so that the orientations of the momenta p and q with respect to the crystallographic axes are different. This case is difficult to realize experimentally because thick films deposited on various substrates exhibit a tendency to have a preferential orientation.[27] In particular, lead films deposited on glass are oriented preferentially along the [111] axis, perpendicular to the substrate surface.[28,29] We were able to prepare only two junctions, deposited simultaneously on the same substrate, which exhibited a complex structure (Fig. 2) similar to that predicted theoretically and which had the following critical points for 2Δ: 2.4, 2.49, 2.67, 2.78, and 2.92 meV.

B. Effect of Pressure

The samples with high values of the ratio $A_{1,2}/h$ were placed in the bomb and the measurements were carried out at high pressures. Figure 3 shows the $I = F(U)$ and $(dI/dU) = f(U)$ characteristics recorded at various pressures for the same sample. The results of a study of the influence of pressure on the energy gaps of lead are presented in Table I and in Fig. 4. At the maximum pressure employed, the difference $\Delta_2 - \Delta_1$ decreased slightly (see the inset in Fig. 3b):

$$eU = (\Delta_2-\Delta_1)_{P=0} - (\Delta_2-\Delta_1)_{p=14\,\mathrm{kbar}} = 16 \pm 4\ \mu\mathrm{V}.$$