$$\Delta = (I_{ph}/I_c)\cdot 10^3 = 5\cdot 10^{10}\bar{\varepsilon}_c MR^{-2} \approx 2\cdot 10^9 \overline{H^2} MR^{-2}$$

(if it is assumed that $\bar{\epsilon}_c = \overline{H^2}/8\pi$, where H is the intensity of the magnetic field). If, for example, we assume for the Crab nebula $H = 3\times 10^{-3}$ oe, $M = 10^{33}$ g, and $R = 10^{22}$ cm, then $\Delta = 2\times 10^{-7}$. If (as in the center of the galaxy) $H = 10^{-3}$, $M = 10^{38}$, and $R = 2\times 10^{22}$, then $\Delta = 5\times 10^{-4}$.

Thus, even the most favorable estimates yield rather low values for the photon intensity. Recognizing, however, that the cosmic-ray spectrum in many objects can be richer in high-energy particles than is the spectrum on earth, and also that only the order of magnitude of most astrophysical quantities is known, it seems advantageous to investigate by the above-described method the most promising objects (such as the center of the galaxy or the radio nebulae).

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TUNNEL EFFECT BETWEEN THIN LAYERS OF SUPERCONDUCTORS

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As is well known, the chemical potentials of the electrons of metals in electrical contact are equalized. Contact can also be accomplished by tunneling transfer of electrons through a layer of insulator separating the metals. If a potential difference is applied to the layer of insulator, the current produced depends not only on the dimensions of the insulator, but also on the distribution of electron states near the energy corresponding to the chemical potential. According to the present theory of superconductivity,[1,2] the transition of a metal from the normal into the superconducting state is accompanied by a change in the distribution density of electrons ρ; if $\rho = N(0)$ in the normal state, then in the superconducting state the density of "unpaired" electrons (for $E > 0$) or holes (for $E < 0$)*

$$\rho_s(E) = N(0)\,|E|\,[E^2 - \Delta^2]^{-1/2}, \quad E \geqslant \Delta,$$
$$\rho_s(E) = 0, \quad E < \Delta, \tag{1}$$

where E is the energy, measured from the chemical potential, and $\Delta(T)$ is the width of the gap in the energy spectrum of the electrons of the superconductor. A change in the electron density distribution will, evidently, produce a change in the current when the applied voltage is less than Δ/e. This effect has recently been found[3] and also confirmed.[4] In these experiments, however, the measurements were carried out in a temperature region where the smearing out of the electron distribution, due to the influence of temperature on the Fermi distribution, affects the results appreciably.

In the present paper we report on a study of the tunnel effect at temperatures down to $\sim 0.1°$ K. The specimens were metal films of thickness $\sim 10^{-5}$ cm, condensed at 300° K onto a glass surface in the form of a ~ 1 mm wide strip. The measurements were made on the overlap regions of strips of successively condensed metals. An oxidized aluminum layer, or in some experiments a BaF_2 film, was used as insulator. The resistance of the specimens was $10^4 - 10^6$ ohm. The tunneling transfer between Al and Al, In, Sn, and Pb was mainly studied. The temperature of the specimens was reduced by adiabatic demagnetization of a paramagnetic salt.[5] It was possible with the apparatus to achieve brief heating of the specimen to $\sim 4°$ K before the measurements.† In an experiment, current-voltage characteristics were measured between metals in the normal ($J_n - V$) and superconducting ($J_s - V$) states. The dependence of the current on temperature and on a magnetic field parallel to the plane of the specimen was measured.

The $J_n - V$ characteristic is linear up to $\sim 10^{-3}$ v for the tunneling transfer of electrons between metals in the normal state (at a temperature above the transition temperature or in a field greater than the critical magnetic field).

*The paired electrons are only important in the equalization of chemical potentials. Their contribution in the tunneling current is negligibly small.

†The heating served to remove the frozen-in fields from the specimens. These fields, frozen-in during the adiabatic demagnetization, led to a spreading of the $\sigma(V)$ dependence.

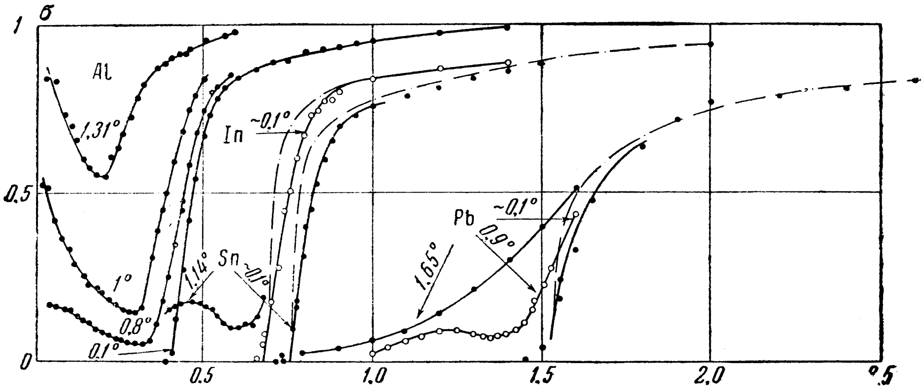

FIG. 1. The reduced conductivity $\sigma = J_s/J_n$ for tunneling transitions between Al and Al, In, Sn, and Pb films. The dashed lines indicate results calculated from relation (2).

A departure from linearity is observed for large potential differences, related to the penetration of electrons through the potential barrier. Figure 1 shows the change in the J – V characteristic when the metals go over into the superconducting state.

Let us consider the results obtained at $\sim 0.1°$ K. It is evident that if the spread of the Fermi distribution $f(E/T)$ is negligibly small, the current due to the tunnel effect between superconductors will only appear if the applied voltage $V \geq (\Delta_1 + \Delta_2)/e$, where Δ_1 and Δ_2 are the gap widths in the superconductors being studied. With this condition we can deduce $\Delta_1 + \Delta_2$ from the data of Fig. 1 and then Δ for Al, In, Sn and Pb. It was found that for the Al specimens only the ratio $2\Delta/kT_c = 3.37 \pm 0.10$ remains constant, while the value of Δ changed correspondingly with the critical temperature of the specimen (T_c varied from 1.35 to 1.45° K). For the remaining metals the following values were found: (Δ is given in millielectron volts):

$$\Delta_{In} = 0.505 \pm 0.01, \quad \Delta_{Sn} = 0.56 \pm 0.01,$$

$$\Delta_{Pb} = 1.33 \pm 0.02\,\text{Mev}, \quad 2\Delta_{In}/kT_c = 3.45 \pm 0.07,$$

$$2\Delta_{Sn}/kT_c = 3.47 \pm 0.07, \quad 2\Delta_{Pb}/kT_c = 4.26 \pm 0.08.$$

The electron distribution density in the superconductor $\rho_s(E)$ can be determined from the voltage dependence of the conductivity ratio $\sigma = J_s/J_n$. It is easy to show[4] that if the probability of tunneling penetration of the barrier is the same for the normal and superconducting states, then

$$\sigma = \frac{1}{V}\int \rho_{s1}(E)\,\rho_{s2}(E-V)\left\{f\left(\frac{E-V}{kT}\right) - f\left(\frac{E}{kT}\right)\right\}dE. \quad (2)$$

Using the values of Δ obtained above, the $\sigma(V)$ dependence for the pairs of superconductors studied can be calculated from (2). The results of this calculation are shown in Fig. 1, from which it is seen that the values of σ calculated theoretically and obtained in the experiments are close to one another. Some difference is only observed in the immediate neighborhood of $\Delta_1 + \Delta_2$.

We now discuss the change in $\sigma(V)$ on increasing the temperature. It can be seen from Fig. 1 that for Al in the temperature region $T \lesssim T_c$, an increase in σ is observed not only for $eV \sim \Delta_1 + \Delta_2$, but also for $eV \sim \Delta_1 - \Delta_2$. The effect of the appearance of a current for $\Delta_1 - \Delta_2$, as a result of the spread of the $f(E/T)$ distribution, was discussed in detail.[3,4] Our data for the pair Al-Pb agree with those given in these papers. Similar results were obtained for the Al-Sn pair. The existence of the additional maximum in σ at $eV = \Delta_1 - \Delta_2$ is most clearly seen in the Al-Al pair. The ratio σ decreases several fold in the range from $V = 0$ to $eV = 2\Delta$.

As can be seen from Fig. 1, the potential difference at which the sharp increase in σ for Al-Al occurs changes with temperature. This variation is evidently produced by the variation of the width of the gap Δ with temperature, which can therefore be determined from the data of Fig. 1. The $\Delta(T)$ dependence is shown in Fig. 2. The form of the variation with temperature is close to that which follows from the present theory.

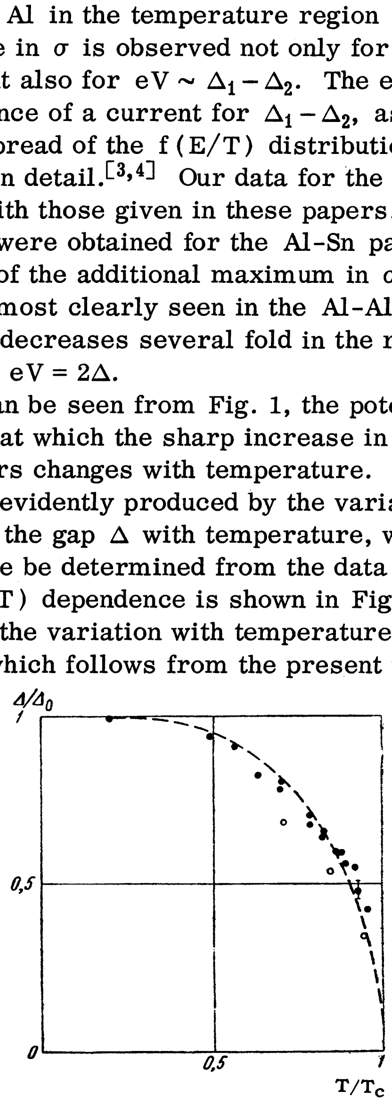

FIG. 2. The dependence of the gap width Δ in Al on temperature: ● – from measurements on the Al–Al pair ($\Delta_0 = 0.41$ Mev, $T_c = 1.4 \pm 0.02$°K); ○ – for the Al–Sn pair ($T_{cAl} = 1.34$°K); the dashed curve shows the theoretical $\Delta(T)$ dependence.

The results obtained thus show that the tunneling effect between $\sim 10^{-5}$ cm thick superconducting films can be explained satisfactorily by the present theory of superconductivity, and the ratio $2\Delta/kT_c$ is not a universal constant. The ratio $2\Delta/kT_c$ obtained on thin films is close to the value determined by other methods on bulk specimens. However, while results of investigations on bulk specimens indicate the existence of strong anisotropy of Δ in a number of metals, no noticeable anisotropy was found in the investigation of the tunnel effect in thin films of superconductors. For example, although the anisotropy of Δ in tin is as much as $\sim 30\%$, according to measurements on the heat capacity[5] and on the absorption of ultrasonics,[6] the $\sigma(V)$ dependence is close to that which follows from an isotropic model. It is possible that this arises because the thickness of the films studied was much smaller than the coherence distance of the electrons of the superconductor.

In conclusion, I express my thanks to P. L. Kapitza and A. I. Shal'nikov for their interest in this work.

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THE SPECIAL ROLE OF OPTICAL BRANCHES IN THE MÖSSBAUER EFFECT

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1. Recently two experimental groups have detected an anomalous temperature behavior of the Mössbauer effect in SnO_2[1] (radiator Sn^{119}) and Dy_2O_3[2] (radiation Dy^{161}). It appeared that in these materials the effect exists at high temperatures, and its fall-off with increasing T occurs much more slowly than would be expected starting from the actual values of the Debye temperature and a simple theoretical description of the effect.[3]

In the present note we give the results of an analysis of the effect of optical branches of the crystal on the magnitude of the Mössbauer effect, which makes it possible in particular to explain the observed regularities.

2. The probability of the Mössbauer effect in a crystal of arbitrary symmetry, when the radiator is one of the atoms in the elementary cell (j), is given by the expression[4]

$$W_j = \exp\{-Z_j\}, \tag{1}$$

$$Z_j = R\frac{v_0}{(2\pi)^3}\sum_\alpha{}'\int\frac{|\mathbf{q}\mathbf{V}_j(\mathbf{f},\alpha)|^2}{\hbar\omega(\mathbf{f},\alpha)}[2\bar{n}(\mathbf{f},\alpha)+1]\,d^3f \tag{2}$$

(where the notation is all the same as in [4]).

If we use the orthonormality of the complex amplitudes $V_j^\xi(\mathbf{f},\alpha)$, one can show that for any atom in the cell and for arbitrary direction of the γ quantum we have the relation

$$(2\pi)^{-3}v_0\sum_\alpha\int|\mathbf{q}\mathbf{V}_j(\mathbf{f},\alpha)|^2\,d^3f = 1. \tag{3}$$

It then follows from (2) and (3) that at T = 0 the effect is determined by the average over branches and phase space of the value of $1/\omega(\mathbf{f},\alpha)$, where the probability density distribution is given by the quantity $|\mathbf{q}\cdot\mathbf{V}_j(\mathbf{f},\alpha)|^2$.

This result enables us to draw the important conclusion that the probability of the Mössbauer effect will be the larger the greater the relative magnitude of the amplitude of oscillation of the atom in the highest-lying optical branches in the fundamental region of the phase space of the reciprocal lattice.

Let us compare crystals with one and with several atoms in the unit cell, which have similar characteristic acoustic frequencies (that is, similar Debye temperatures). If we have the same radiator in both cases, it follows from (2) and (3) that the Mössbauer effect in the polyatomic lattice will, in general, occur with higher probability.