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SINGULARITIES OF THE TEMPERATURE DEPENDENCE OF ELECTRIC CONDUCTIVITY OF ALUMINUM AT HELIUM TEMPERATURES

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It is still unclear [1] why the power-law dependence T^5, obtained from highly simplified theoretical considerations, is in good agreement with results of investigation of the temperature dependence of electric resistivity of nonmagnetic non-transition metals. It is perfectly possible that this is connected with the insufficient accuracy with which the resistivity is measured, especially at low temperatures where deviations from the T^5 law are to be properly expected, since the roles of the different electron scattering mechanisms become comparable.

On the basis of the experimental data [2], an empirical formula was proposed for aluminum [3] in the form of a superposition of the contributions of the electron-electron and electron-phonon scattering:

$$\delta_\infty(T) = (1.98 \times 10^{-2}\ [\text{deg}^{-2}]T^2 + 4.34 \times 10^{-6}\ [\text{deg}^{-5}]T^5) \times 10^{-5} \qquad (1)$$

The index ∞ denotes that expression (1) was obtained from data for bulky samples. This is a reasonable dependence, for it yields for the contribution of the electron-electron interaction to the electric resistivity at helium temperatures a value (~10%) which does not contradict estimates obtained from data on the infrared absorption [4]. If expression (1) is correct, then at helium temperature $\delta_{4.2}$ differs from δ_0 by 10^{-6} ($\delta_T = R_T/R_{273°K}$, $\delta_0 = R_0/R_{273°K}$, where R_0 is the residual resistivity of the sample, R_T the resistivity at the temperature of the experiment, and $R_{273°K}$ the resistivity at 0°C). An exact measurement of this quantity makes it necessary, in the case of bulky specimens of reasonable length, to measure resistance changes of the order of $\sim 10^{-11}$ ohm.

We have investigated the temperature dependence of the resistivity of aluminum by a procedure similar to that described in [5], which affords the required measurement accuracy (the voltage sensitivity of the apparatus is 10^{-11} - 5×10^{-12} V). We present here the first results.

The investigated metal was aluminum, whose carrier Fermi surface is either closed or, if open, contains narrow necks. The temperature-dependent part of the resistivity of such metals, if observed, cannot be explained at low temperatures solely in terms of electron-phonon collisions with umklapp [4].

Single-crystal samples of varying (but sufficiently high) purity can be regarded as bulky. Therefore their residual resistance is connected only with scattering of electrons by microscopic defects, such as impurities. The transverse dimension of the samples was 5 - 10 mm and was appreciably larger than l_{ei} (the mean free path of electron scattering by impurities).

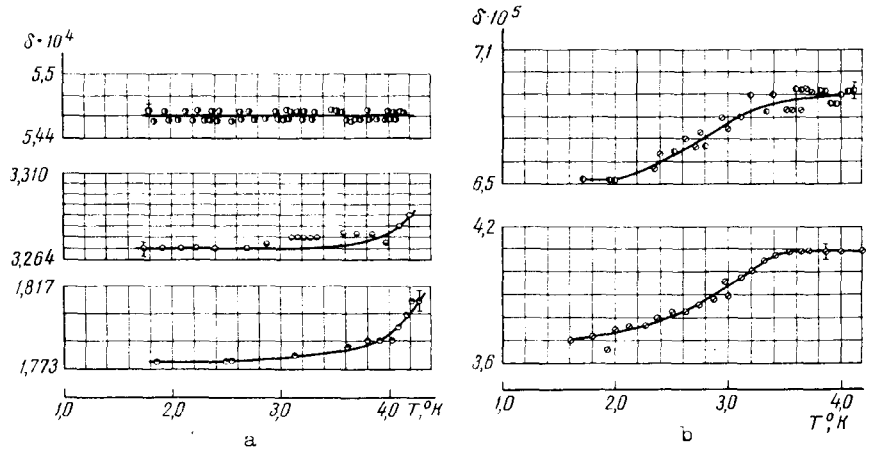

Fig. 1. Temperature dependence of the resistivity of "dirty" (a) and pure (b) samples of aluminum. a: ◑ -- $1/\delta_{4.2°K} = 5.5 \times 10^3$, the points denote the maximum peaks on a curve obtained with an automatic two-coordinate plotter; ◒ -- $1/\delta_{4.2°K} = 3.04 \times 10^3$, and ◒ -- $1/\delta_{4.2°K} = 5.5 \times 10^3$ (measured point-by-point). b: ◐ and ◕ -- $1/\delta_{4.2°K} = 14.5 \times 10^3$ (measured point-by-point). The solid curve corresponds to that recorded with a two-ccordinate plotter (peaks not shown); ● -- $1/\delta_{4.2°K} = 24.5 \times 10^3$ (measured point-by-point).

Sufficiently pure samples displayed at temperatures below 4.2°K (starting with samples for which $1/\delta_{4.2} \approx R_{273}/R_{4.2} = 3.04 \times 10^3$ and more) a noticeable change of resistivity with changing temperature (Figs. 1a,b).

If the electric resistivity is represented in the form

$$\delta_T = \delta_0 + \delta(T) \qquad (2)$$

(δ_0 - residual resistivity, $\delta(T)$ - temperature-dependent part of the resistivity), then $\delta_T - \delta_0$ = const for samples of different purity, in accord with the Matthiesen rule. Comparison of the values of $\delta_T - \delta_0$ at 4.2°K (Fig. 2) and at lower temperatures shows that this rule does not hold. The discrepancy is large and cannot be explained in the usual manner [6]. As is well known, a similar deviation was observed for aluminum at higher temperatures [7].

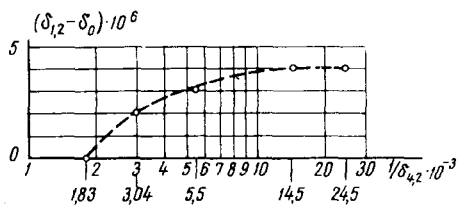

Fig. 2. Values of $\delta_\infty(T)$ at T = 4.2°K, determined for samples of different purity from the data of Figs. 1a,b.

As seen from Figs. 1a,b, the temperature variation of the resistivity of the investigated samples cannot be described by relation (1). Our comparison has shown that the experimental curves have a different (higher) power dependence on T than (1).

In addition, comparison of the curves for "dirty" and "pure" samples (Figs. 1a and 1b, respectively) shows that the temperature at which the residual resistivity is reached (within the limits of experimental accuracy) shifts towards lower temperatures with increasing sample purity. The relative change of the resistivity $(\delta_{4.2} - \delta_0)/\delta_0$ increases with purity, reaching ~10% in the purest samples. The curves of the latter (Fig. 1b) show saturation at temperatures close to 4.2°K.

This apparently points out a singularity in the temperature dependence of the resistivity of aluminum. As is well known [4], such a singularity can be ascribed to normal collisions (without umklapp) between electrons and phonons in the temperature region where the corresponding mean free path l_{ep}^{N} becomes comparable with the mean free path l_{ei} connected with the scattering of the electrons by the microscopic defects responsible for the residual resistivity. It is obvious that the manifestation of this singularity should be sensitive to the purity of the metal and shift towards lower temperatures for purer samples, as is indeed observed on the experimental curves. The order of magnitude of this effect can be estimated by the following relation:

$$l'_{ei}/l''_{ei} \sim (T''_0/T'_0)^5 \qquad (3)$$

(l'_{ei} and l''_{ei} are the electron-impurity mean free paths of the compared samples with different purity, and T'_0 and T''_0 are the characteristic temperatures at which $l_{ep} \sim l_{ei}$). On this basis we can expect, for example, a change in the sample purity by a factor of 10 to shift the temperature by a factor 1.5, i.e., the effect is not very large.

Comparison of the curves allows us to assume that for pure samples the indicated singularity appears almost entirely in the helium region of temperatures (Fig. 1b), and for "dirtier" ones at higher temperatures (Fig. 1a).

The dependence of the resistivity of pure samples on the temperature (Fig. 1b) is satisfactorily described by the formulas [4]

$$\begin{aligned} \delta &= \delta_0[1 + \alpha(T/T_0)^5] = \delta_0 + \delta(T), \quad T \ll T_0, \\ \delta' &= \delta'_0[1 - \beta(T_0/T)^5] = \delta'_0 - \delta'(T), \quad T \gg T_0, \end{aligned} \qquad (4)$$

where T_0 is the temperature at which l_{ep}^{N} becomes comparable with l_{ei}, δ_0 is the residual resistivity, and δ'_0 the resistivity that does not depend on the temperature in a certain region $T \gg T_0$ ($\delta_0 < \delta'_0$); $\alpha, \beta \sim 0.1$.

This is seen, for example, from a comparison of the temperature interval of the singularity $\Delta T = T_1 - T_2$ (T_1 and T_2 are the limits of the interval, $T_1 > T_2$) as obtained from formulas (4) and experimentally (Fig. 1b). The comparison must obviously be made such as to satisfy the relation

$$\delta'(T_{1e})/\delta(T_0) = \delta(T_{1c})/\delta(T_0), \quad \delta(T_{2e})/\delta(T_0) = \delta(T_{2c})/\delta(T_0)$$

(T_{1e} and T_{2e} are the experimental values of the temperature, and T_{1c} and T_{2c} the calculated ones). The limited accuracy of the experiment makes it possible to select $\delta'(T_{1e})$ and $\delta(T_{2e})$

that differ from $\delta(T_0)$ by a factor not larger than 10 (Fig. 1b). We then get $(\Delta T_c - \Delta T_e)/\Delta T_e \sim 13\%$, i.e., the discrepancy is small.

It follows from these estimates that a study of the dependence of this singularity on the purity of the metal at helium temperatures is hindered by the difficulty of obtaining the required range of sample purity necessary to keep the singularity in this region at all times. In order to estimate in this case the role of the usual scattering mechanisms accompanied by umklapp it is obviously necessary to broaden the temperature interval (to ~14°K), as will be done in the future. This is also necessary to ascertain the possibility of observing another interesting singularity - a minimum of resistivity, which should be observed in thin samples [4].

In conclusion we thank B. I. Verkin for continuous interest in the work, R. N. Gurzhi for a valuable discussion of the measurement results, and O. G. Shevchenko for help with the experiments.

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SHELL EFFECTS IN THE CROSS SECTION OF THE REACTION $Zn^{67}(\gamma p)$

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Study of the energy and angular distributions of photoprotons emitted by nuclei having one or two protons in excess of the $1f_{7/2}$ filled shell, corresponding to the magic nucleus with Z = 28, has pointed to the existence of shell effects [1,2]. The contribution from the individual shells is apparently also manifest in the cross section of the (γp) reaction [3]. It is of interest to obtain more accurate data with respect to the connection between the photoproton cross section and the shell structure of the nucleus.

We have chosen for this purpose the nucleus Zn^{67}, which has two protons in the state $2p_{3/2}$ in excess of the filled $1f_{7/2}$ shell. Data on the angular distribution of the photoprotons from natural zinc, where the main role is played by Zn^{64} [2], show that the contribution of the direct photoeffect amounts to more than 30% of the photoproton yield. The ratio of the nucleon binding energies in Zn^{64} and Zn^{67}, taking into account the different density of the