## *EFFECT OF HYDROSTATIC COMPRESSION ON THE ELECTRICAL CONDUCTIVITY OF METALS AT LOW TEMPERATURES*

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In our previous work on the effect of isotropic compression on the superconductivity of tin and indium,[1] it was noted parenthetically that there was a difference in conductivity of these metals when under pressure and in the normal state. In succeeding work this has been confirmed.[2]

Very recently we have also observed that hydrostatic compression has a considerable effect on the magnetic[3] and galvanomagnetic properties of metals[4,5] at low temperatures. From these later studies we conclude that the density of the conduction electrons is noticeably affected by pressure.

All of the above investigations were carried out by the use of a freezing technique to produce the pressure.[6] It is well known that this method can produce pressures up to a maximum of 1730 kg/cm$^2$, and the large effect of such a relatively small pressure upon almost all of those properties of metals depending on the conduction electrons was very interesting and unexpected. It is therefore essential to study in detail the effect of pressure on the electrical conductivity over a wide range of temperature.

In this letter we shall report some results of studies on the effect of pressure on the conductivities of metals in the low temperature region. Measurements have been made on zinc, tin, gold, and bismuth. All samples (except for gold) were prepared as single crystals. Zinc was studied in two orientations (in sample Zn I the principal axis was perpendicular to the sample axis, and in Zn II the two axes were parallel). The principal axis of symmetry of the tin sample was parallel to the long axis of the sample, and the axes of the bismuth were oriented at about 45° from the length of the sample. The metals were very pure; the ratio of the resistance at 4.2° K to the resistance at 293° K, which characterizes the purity, was $5.3 \times 10^{-4}$ for the Zn I sample, for example, $6 \times 10^{-5}$ for the tin, and $3.25 \times 10^{-3}$ for the gold. Measurements were made at the temperatures of liquid helium, hydrogen, and nitrogen, and also at higher temperatures in the case of bismuth.

The bismuth was studied only in order to compare our results with those of Alekseevskii and his co-workers.[4] In our measurements, as well as theirs, pressure caused an increased resistivity over the whole temperature range for this metal.

The other metals which we investigated behaved in a different way. At sufficiently low temperatures, all of them showed increased resistance under pressure. At higher temperatures, this resistance increment decreased, and at some temperature (peculiar to each metal) it became equal to zero. Upon further raising the temperature, the effect changed sign — the resistance under pressure became less than the resistance without pressure, thus agreeing with the results of Bridgman's work[7] at temperatures above 90° K.

In zinc (sample Zn I) at 4.2° K the increment of resistance due to the pressure amounted to $\Delta R/R \sim 30\%$. The effect decreased with rise in temperature and had almost disappeared at 20.4° K. At 77° K the effect was already reversed in sign, and its magnitude was approaching Bridgman's value for monocrystalline zinc with this orientation at a temperature of 90° K ($\Delta R/R \sim 1.5\%$).

In tin at 4.2° K the resistivity under pressure was also larger than normal — $\Delta R/R$ was about 30%. But at 14° K the sign of the effect had reversed; i.e., the sign change for the effect in tin occurs somewhere between 4.2° and 10° K.

For gold at 4.2° K the effect amounts to about 11%; its reversal takes place in the liquid hydrogen temperature region. As already indicated, the gold sample was quite pure ($R_{4.2}/R_{293} = 3.25 \times 10^{-3}$); its resistivity did not go through a minimum at any temperature, as it does when gold contains impurities, and neither did the resistivity of the sample under pressure.

Thus for all the metals studied in this work, an increase in resistivity was observed when hydrostatic pressure was applied. The effect is reversible.

For the time being, it does not seem possible to explain this effect; but its mechanism is probably quite different from that responsible for the effect of pressure on electrical resistivity at higher temperatures. It is possible that the low-temperature increase of resistivity with pressure has the same origin as the effect of pressure on the magnetic and galvanomagnetic properties of the metals.

It is interesting that the effect should disappear at higher temperatures. In this case the pressure-induced change in conductivity follows an exponential law of dependence on the temperature very closely. For example, in the range 14 to 20° K, the conductivity of sample Zn I was given with good approximation by $\Delta\sigma \propto e^{-\Delta E/kT}$ with $\Delta E = 2 \times 10^{-2}$ ev/mole. Bismuth behaves in a similar manner.

This gives some grounds for supposing that pressure creates a condition similar to that in a semiconductor, for some of the electrons; but with a very small energy gap, which would overlap even at low temperatures.


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## *EFFECT OF $\mu^-$-MESON POLARIZATION ON THE CORRELATION OF GAMMA RAYS EMITTED BY THE MESONIC ATOM*


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THE function describing the angular correlation of $\gamma$ rays from mesonic atom transitions was derived in Ref. 1. Recently it has been established experimentally[2] that polarized $\mu^-$ mesons are formed in the $\pi^-$-meson decay. It is therefore of interest to discuss the same question for a given degree of polarization of the $\mu^-$ meson.

In the case of heavy mesonic atoms, the correlation function for the cascade $\ell_A(L_1)\ell_B(L_2)\ell_C$ has the form:

$$W = \sum_{\nu_1\nu_2} F_{2\nu_1}(L_1 l_A l_B)\, F_{2\nu_2}(L_2 l_C l_B)$$
$$\times \sum_{F_B F'_B j_\beta l k \rho} \frac{(2F_B+1)(2F'_B+1)}{2I+1)\quad 1+(\nu_{FF'}\tau)^2]} W^2(j_\beta I 2\nu_2 F_B;\ F'_B j_\beta)$$
$$\times (2j_\beta+1)^2 W(l_B s 2\nu_2 j_\beta;\ j_\beta l_B)\, W(l_B s 2\nu_2 j_\beta;\ j_\beta l)$$
$$\times (2l+1)\, W(s2kj_\beta l;\ sl_B)\, W(2\nu_1 2\nu_2 l_B l;\ 2kl_B)\, C^{2k0}_{2\nu_1\rho;\ 2\nu_2-\rho}$$
$$\times \langle|(ss)2k0\rangle\, 4\pi Y^{\rho}_{2\nu_1}\left(\theta_1,\ \varphi_1-\frac{\pi}{2}\right) Y^{-\rho}_{2\nu_2}\left(\theta_2,\ \varphi_2-\frac{\pi}{2}\right); \tag{1}$$

$$F_{2\nu_1}(L_1 l_A l_B) = (-1)^{l_A-l_B-1}(2l_B+1)^{1/2}(2L_1+1) \times C^{2\nu_1 0}_{L_1 1;\ L_1-1} W(l_B l_B L_1 L_1;\ 2\nu_1 l_A); \tag{1a}$$

$$\langle|(ss)2k0\rangle = W^{-1}_{2k}(s)\, f_{2k}(s) = \sum_\mu a_\mu C^{2k0}_{s\mu;\ s-\mu}. \tag{1b}$$

Here $L_1$, $L_2$ are the angular momenta of the quanta; $\ell_A$, $\ell_B$, $\ell_C$ are the orbital angular momenta of the meson in the initial, intermediate, and final states; $j_\alpha$, $j_\beta$, $j_\gamma$ are the corresponding total angular momenta: $\mathbf{j} = \boldsymbol{\ell} + \mathbf{s}$ where s is the meson spin; $F_B$ is the sum of the meson ($j_\beta$) and nucleus (I) angular momenta; $\langle|(ss)2k0\rangle$ is the statistical tensor of Fano, proportional to the meson orientation degree of 2k-th order $f_{2k}(s)$;[3] $a_\mu$ is the probability amplitude that the meson in the initial state has a spin projection equal to $\mu$; $\nu_{FF'}$ is the hyperfine structure; $\tau$ is the lifetime of the intermediate state; C and W are the Clebsh-Gordan and Racah coefficients.

As can be seen from expression (1) the correlation function depends on the angles formed by the axis of rotational symmetry of the $\mu$ meson and the directions of emission of the first ($\theta_1$) and the second ($\theta_2$) quanta, as well as on the angle $\theta$ between the directions of the two quanta:

$$\cos\theta = \cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\cos(\varphi_2-\varphi_1). \tag{1c}$$

If $a_\mu = \text{const} = 1/(2s+1)$ then (1) reduces to formula (2) obtained in Ref. 1.

Since the summation in (1) is only over even orders of the orientation degree $f_{2k}(s)$ we shall also obtain the same result if we set $s = \frac{1}{2}$.[2] Thus the correlation does not depend on the degree of the $\mu^-$-meson polarization $f_1(s)$. If one allows for the possibility of the $\mu^-$-meson spin being $^3/_2$ then in this case the correlation function would depend on the degree of alignment $f_2(s)$.

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