EFFECT OF UNIFORM COMPRESSION ON THE OSCILLATION OF THE MAGNETIC SUSCEPTIBILITY OF BISMUTH AT LOW TEMPERATURES

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The influence of approximately 1000 atmospheres of hydrostatic pressure on the oscillation of the magnetic susceptibility of bismuth in magnetic fields up to 13,000 oersteds has been investigated at 4.2° to 1.6°K. The character of variation of the effective mass tensor, the Fermi energy E_0, the Dingle factor, and the electron concentration have been estimated by means of Landau's equations. Suggestions are made regarding the nature of the electron energy spectrum in bismuth.

In earlier papers[1-3] concerning the influence of pressure on the galvanomagnetic properties of bismuth it was suggested that it might be possible to observe an appreciable pressure effect on the quantum oscillations of the magnetic susceptibility of metals in a magnetic field H at low temperatures, even under not very high pressures. Such an investigation would make it possible to determine the character of deformation of the effective mass tensor in compressed Bi, and would provide an interesting comparison with experimental and theoretical work studying the effect of pressure on the de Haas-van Alphen effect.[1-6]

Measurements were obtained for the three principal orientations of very pure Bi single crystals. The samples were fastened in a special holder inside a magnetically isotropic pressure vessel (Fig. 1),[4] which was joined to the suspension of a torsion balance. Pressures were produced by the method of Lazarev and Kan.[7] However, for the purpose of improving the uniformity of the pressure, aqueous solutions of ethyl alcohol were used instead of water, thus greatly reducing the nonuniform stresses in compressed samples and approximating uniform compression.[8] Pressures were measured according to the elongation of the vessel by means of a simple indicator consisting of two narrow flat springs welded on the vessel at two different heights.

For each sample we recorded the relation between the moment of the forces C acting on the sample in a static magnetic field and the magnetic field direction in a plane perpendicular to the axis of suspension, as well as the dependence of C on the field strength for different directions of the sample at the temperatures 4.2° and 1.6°K. All of these measurements were performed before the samples were subjected to pressure, then under hydrostatic pressure of about 1000 atmos, and finally after release of the pressure. Excellent

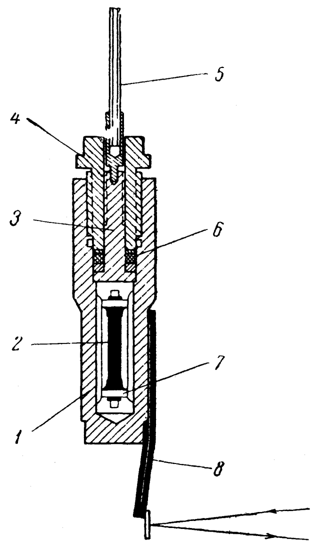


FIG. 1. Construction of pressure vessel: 1) shell; 2) sample; 3) mushroom-shaped pin; 4) cap; 5) glass rod; 6) gaskets; 7) sample holder; 8) pressure indicator with mirror.

reproducibility of the results was obtained when the procedure was repeated, which was done four times in some instances. Figure 2 shows some curves of $C/H^2 = \Delta\chi \cdot \sin\psi \cdot \cos\psi$ as a function of $1/H$, where $\Delta\chi$ is the anisotropy of the magnetic susceptibility and ψ is the angle between the principal axis and the magnetic field. The figure shows that a pressure of about 1000 atmos reduces the amplitude of oscillation by about 30%, with the effect increasing somewhat when $\psi \to 0$ and H is reduced; the oscillation frequency E_0/β is also reduced (see Landau's equations in reference 9). Figure 3 shows the change of oscillation frequency under compression as ψ is varied.

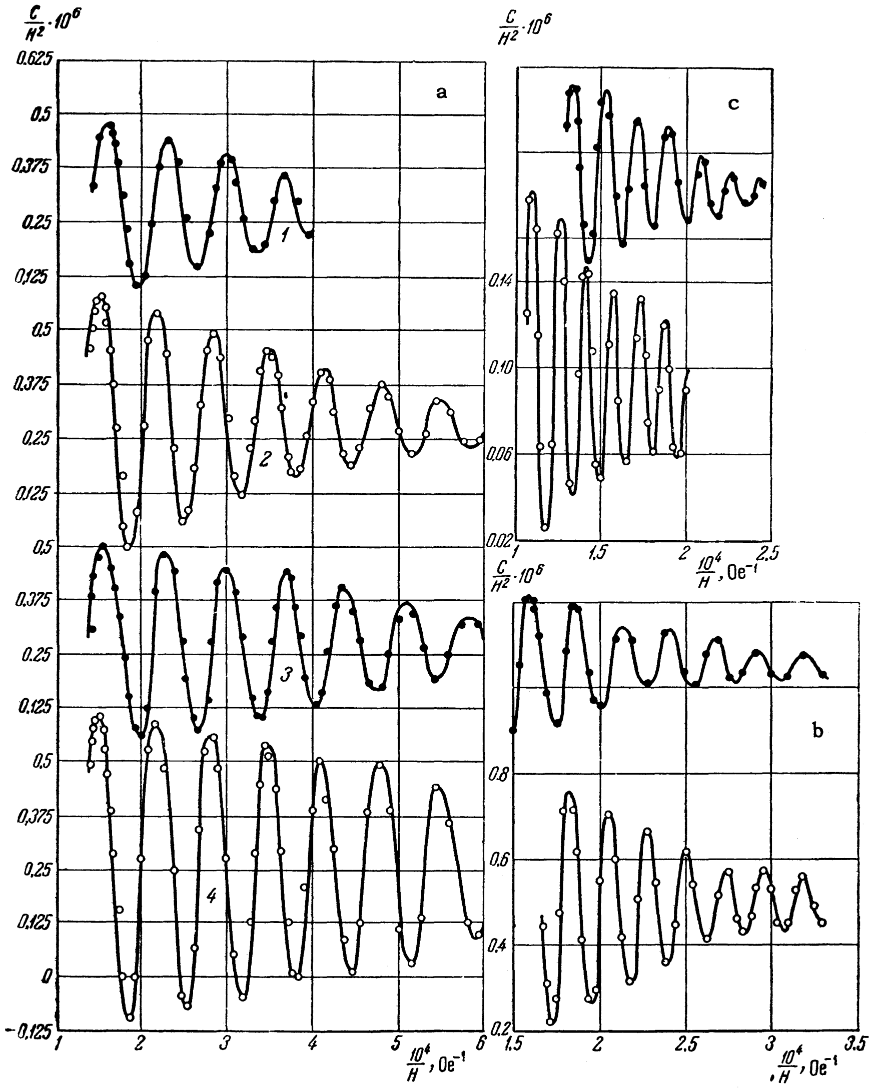


FIG. 2. Anisotropy of the susceptibility of bismuth (with the principal and binary axes perpendicular to the axis of suspension) as a function of magnetic field strength: ○) p = 0, ●) p = 1000 atmos: a) $\psi = 76°$, curves 1 and 2 – T = 4.2°K; curves 3 and 4 – T = 1.6°K; b) $\psi = 170°$, T = 1.6°K; c) $\psi = 175°$, T = 1.6°K.

Curve 1, which is for a sample not under pressure, is a good fit of measurements obtained after pressure was released one or more times. Curves a and b were plotted from the equations used in reference 9. For the two other orientations of the sample we also observed good agreement between the experimental dependence of E_0/β on ψ and the theoretical curves. In addition, the variation of E_0/β under pressure was in qualitative agreement with the data shown in Fig. 4.

Our results are thus in good agreement with Shoenberg's three-ellipsoid model of the Fermi surface for electrons. Since E_0/β is proportional to the extremal area S_m of a section of the Fermi surface cut by a plane perpendicular to the magnetic field direction,[10] we can conclude from Fig. 4 that the deformation of the Fermi surface for bismuth under pressure is not uniform.[4]

It was also found that the change of oscillation phase $\Delta\chi$ under 1000 atmos does not exceed $\pm 10°$, and that the change of the anisotropy $\Delta\chi_0$ of the constant part of the magnetic susceptibility is $\pm 2\%$.

A calculation shows that $\Delta\chi_0 = \chi_\perp - \chi_\parallel$ for bismuth at the temperature of liquid helium corresponds to the anisotropy of the effective mass tensor for the group of electrons which produce the de Haas—van Alphen effect, but that the calculated absolute values of $\chi_\perp$ and $\chi_\parallel$ differ from the observed values by an amount of the order of 0.8×10^{-6} emu. Using this fact and assuming that the rotation angle of the Fermi surface ellipsoids does not change under hydrostatic pressure by more than 1 to 2%, we can use Landau's equations to determine the character of the changes in the effective masses m_1, m_2, m_3, and m_4 (in the coordinate system associated with the principal axes of the bismuth lattice) and m_1', m_2' and m_3' (in the coordinate system associated with the principal axes of the ellipsoid), the Fermi energy E_0, the electron concentration n, and the Dingle factor x under uniform pressure (see the table; at p = 0 the data are Shoenberg's[9] and our own; the

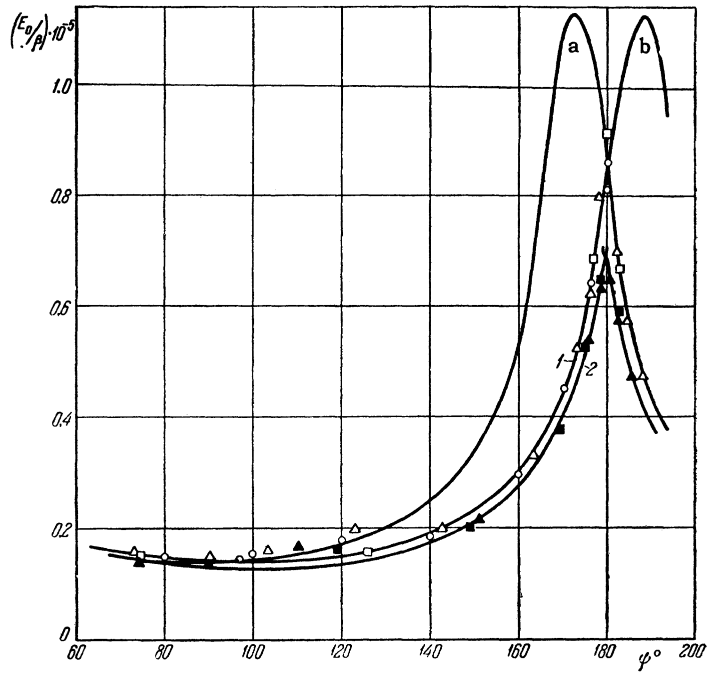


FIG. 3. $E_0/\beta \approx Sm$ for bismuth (principal and binary axes perpendicular to the axis of suspension) as a function of the angle ψ. ⊙) p = 0, △) p_1 removed, ▲) $p_2 \sim 100$ atmos, □) p_2 removed, ■) $p_3 \sim 1000$ atmos.

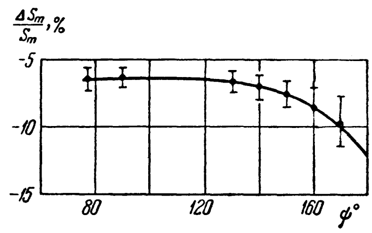
masses are given in units of the electron mass m_0).

	p = 0	p = 1000 atmos	Relative change under pressure, in %
$m_1 \cdot 10^3$	2.4	1.8±0.2	−25±10
m_2	2.5	2.55±0.12	2±5
m_3	0.05	0.056±0.003	12±5
m_4	−0.25	−0.255±0.012	2±5
$m'_1 \cdot 10^3$	2.4	1.8±0.2	−25±10
m'_2	2.53	2.58±0.12	2±5
m'_3	0.025	0.03±0.001	20±5
$E_0 \cdot 10^{14}$ erg	2.81±0.07	2.68±0.07	−5±5
$\frac{E_0}{k}$, °K	204±5	194±5	−5±5
$n \cdot 10^5$	1.42±0.07	1.275±0.075	−10±10
x, °K	1.7±0.1	2.18±0.05	28±10

The good qualitative agreement of the variation of n under pressure with the data in references 1 to 3 is evidence that in bismuth there exists only one electron group corresponding to the Jones-Shoenberg model, and that the character of the deformation of its Fermi surface agrees with the basic ideas of Jones,[11] who considers bismuth to be a metal with an irregular structure. On the basis of this model we may assume that bismuth can contain two groups of holes whose Fermi surfaces are surfaces of revolution located at the corners of the Brillouin zone. One type of holes is represented by one such surface while the second type of holes is represented by two surfaces which transform into each other under rotation around the binary axis.

It is quite possible that one group of holes with a nearly spherical Fermi surface, effective mass

FIG. 4. Relative variation $\Delta S_m/S_m$ at ≈ 1000 atmos.



$\sim 0.002\ m_0$ and Fermi energy $\sim 14 \times 10^{-12}$ erg is associated with the isotropic part of the magnetic susceptibility (0.8×10^{-6}) and that the other group is associated with a large value of the linear term in the specific heat of bismuth.[12] It is of interest that cyclotron resonance experiments have revealed holes with the mass $\sim 0.0015\ m_0$.[13]

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235