Effect of Uniform Compression on the Ettingshausen-Nernst Effect in Zinc at Low Temperatures*

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The influence of hydrostatic pressure on the oscillatory Ettingshausen-Nernst effect in a zinc single crystal has been studied in magnetic fields ranging from 2 to 11 kilogauss at 4.2°K. With the field along the hexagonal axis, the long period oscillations decrease in period by 5% as the pressure is increased from 300 to 2300 psi. There is an average increase in amplitude of about 10% for each 250-psi increase of pressure. There is no evidence of phase change with pressure.

In order to see the effect of elastic deformation of a metal crystal on the shape of the surfaces of constant energy of its conduction electrons, several authors have made measurements on the de Haas-van Alphen effect in various metals under moderately high pressure.[1–3] Of the various galvanomagnetic and thermomagnetic effects[4] which show de Haas-van Alphen type oscillations, the Ettingshausen-Nernst effect, in which oscillations have been recently observed and examined,[5,6] shows especially clean oscillations and lends itself readily to measurement in a pressurized system. Reported here are measurements on this effect in zinc under pressures up to 2350 psi.

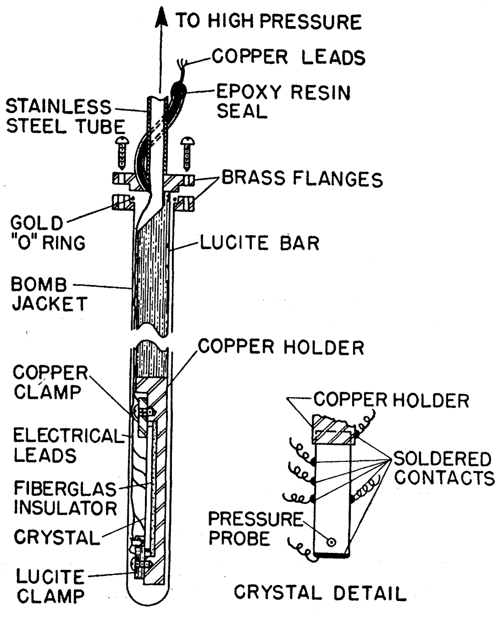

FIG. 1. Crystal holder and pressure chamber.

I. EXPERIMENTAL

The zinc crystal was in the form of a thin right parallelepiped of dimensions 20.0×6.0×0.3 mm. X-ray reflections showed the hexagonal axis to be in a plane normal to the long axis of the crystal and inclined 46° from the normal to the flat surface of the crystal. The crystal was mounted on a copper and Lucite holder in a copper bomb (Fig. 1) which, in turn, was suspended in a cryostat by a $\frac{3}{16}$-in. o.d. stainless steel tube, through which the bomb could be pressurized. The stainless steel tube passed through the cap of the cryostat and was connected through a manifold to a high-pressure helium cylinder. The cryostat rested in a $1\frac{5}{8}$-in. gap between 8-in. diameter flat poles of an electromagnet. The magnet, measuring circuit, and all other apparatus not contained in the cryostat were those employed by Bergeron et al.[6] To avoid heat influx from room temperature to the crystal along the leads, the leads passed first into the liquid helium bath and then directly from the helium bath into the pressure bomb through an epoxy resin seal.[7] Other experimental procedures were the same as those of Bergeron et al.[6]

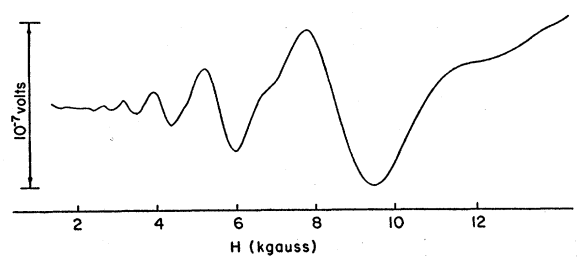

FIG. 2. Typical recorder trace of the Ettingshausen-Nernst potential. This curve was taken with the magnetic field parallel to the hexagonal axis of the crystal and with the crystal under 1000-psi pressure.

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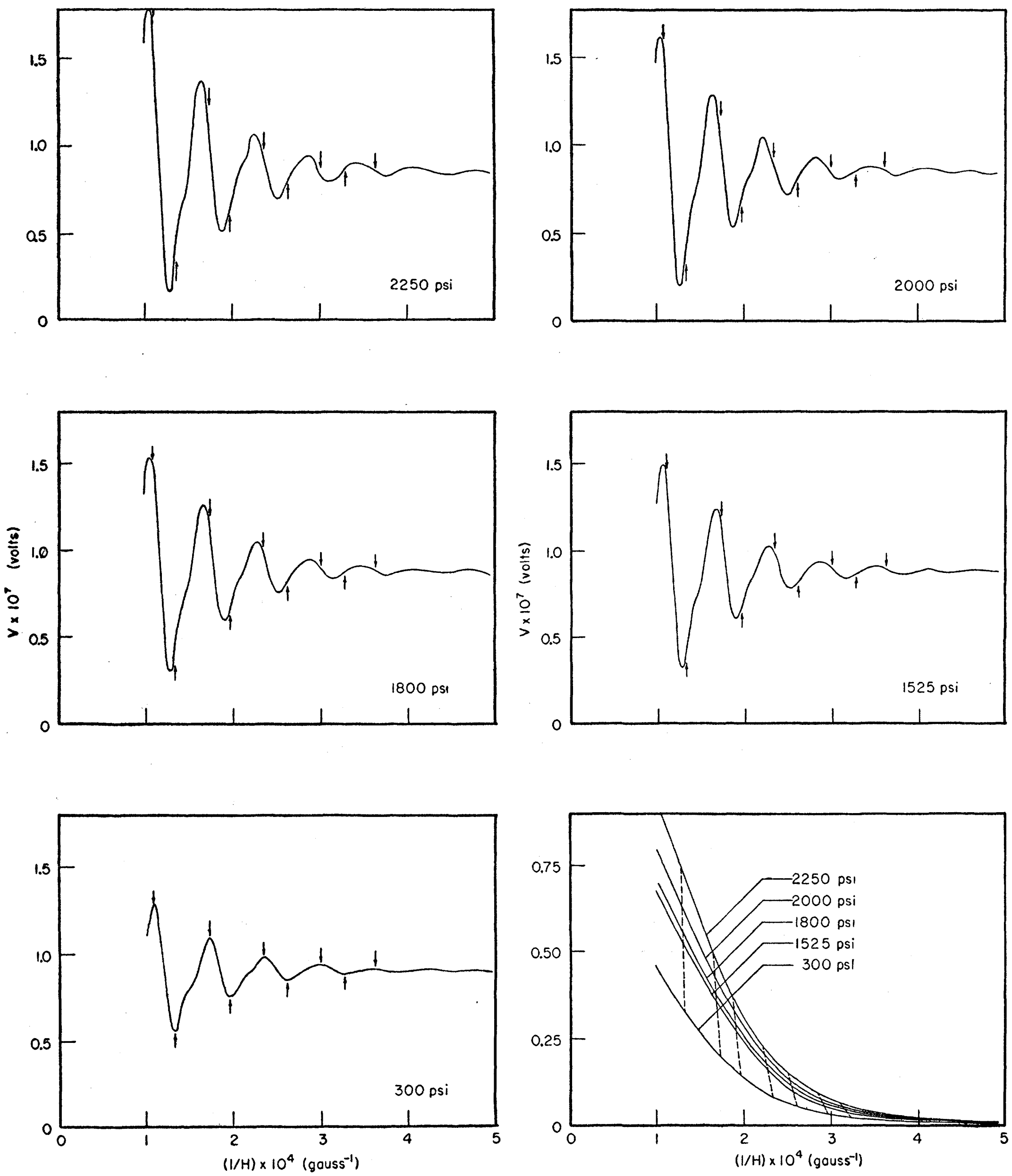

FIG. 3. Ettinghausen-Nernst potential vs reciprocal magnetic field. In the lower right-hand frame the amplitudes of the other curves are plotted. The arrows indicate positions of maxima and minima at atmospheric pressure.

II. RESULTS

One of the recorder traces of the Ettingshausen-Nernst potential, taken with the crystal under 1000-psi pressure and with the field parallel to the hexagonal axis of the crystal, is seen in Fig. 2. In Fig. 3 Ettingshausen-Nernst potentials are plotted against the reciprocal of the magnetic field for various pressures. The amplitudes of the oscillations in these curves are plotted in the lower right-hand corner of the figure. It can be seen that the effect of pressure is to increase the amplitude and decrease the period of the oscillations. The values of H^{-1} corresponding to maxima in three of the curves in Fig. 3 are plotted against integers in Fig. 4. The period (designated as β^*/E_0) of the oscillations is given by the slope of each of these lines, while the phase is given by the intercept (n_0) with the $H^{-1}=0$ axis, such that:

$$\alpha = 2\pi n_0,$$

where α is the phase angle. The common intercept of these lines gives a pressure independent value of α equal to $(0.92\pm0.04)\pi/2$ for a cosine oscillation. In Fig. 5

the dependence of the period on pressure is shown. The values plotted in Fig. 5 are listed in Table I, along with comparative amplitudes. Because of error in determination of the values of the magnetic field and of the pressure in the bomb, the absolute values of the period are not determined to the accuracy indicated by the numbers in Table I. Even so, it is expected that the relative accuracy between data at different pressures in a given run is good to the number of places shown. In Fig. 5 the points for 40 and 1000 psi were obtained in a different run from that of the other points. However, they also fall in reasonably well with the other pressure points.

III. DISCUSSION

For ellipsoidal energy surfaces, the period of the de Haas-van Alphen type oscillations is given by β^*/E_0 where β^* is the effective double Bohr magneton and E_0 is the chemical potential. It is possible to attribute part of the pressure induced decrease in β^*/E_0 (about 5% for 2000-psi pressure) to a change in E_0. Taking E_0 from the results of Donahoe[8] and Mackinnon,[9] as 4.1×10^{-4} erg or 0.026 ev at 4.2°K and a ξ (Fermi energy) of 11 ev at room temperature, the ratio E_0/ξ is:

$$E_0/\xi = 23\times10^{-3}. \qquad (1)$$

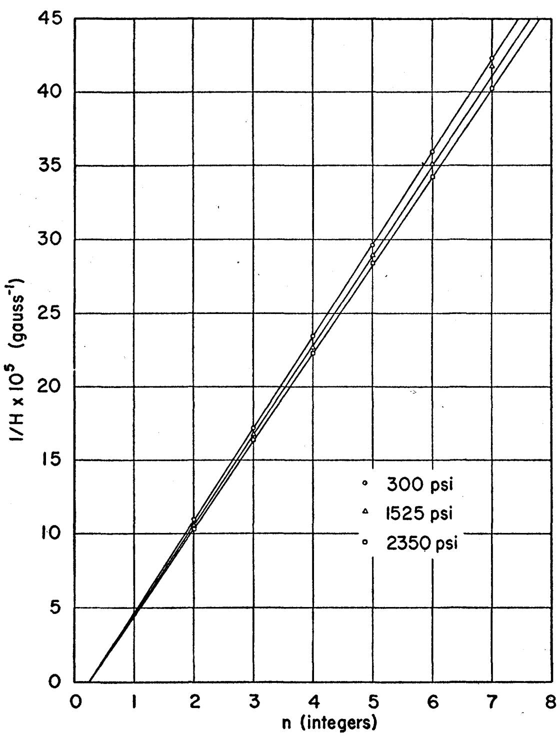

FIG. 4. The $1/H$ values for maxima in Fig. 3 plotted against integers.

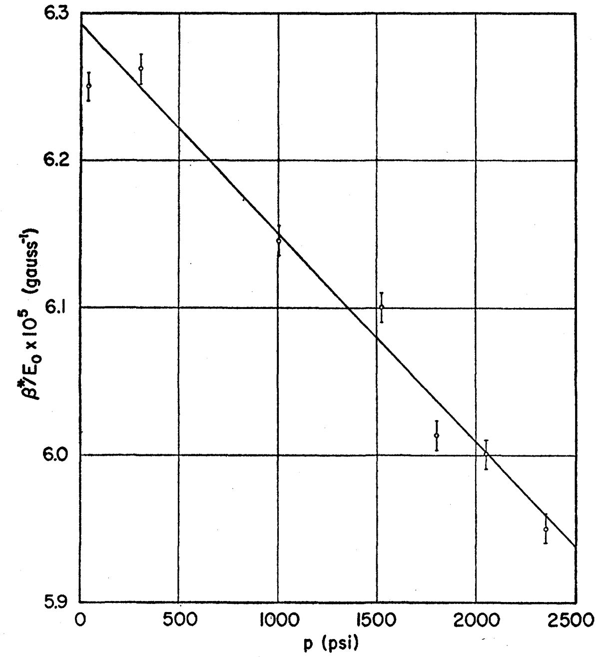

FIG. 5. The dependence of the period on pressure.

If ξ is taken for a Fermi sphere as a first approximation, then ξ is proportional to $n^{2/3}$ (n being the density of valence electrons) with $nV=N$. N is the total number of electrons and V is the volume, which is equal to $l_1l_2l_3$. Then:

$$d\xi/\xi = -\frac{2}{3}\left(2\frac{dl_1}{l_1}+\frac{dl_3}{l_3}\right). \qquad (2)$$

For an electron overlap $E_0=\xi-A_0$ where A_0 is the energy of the Brillouin zone boundary in momentum (k) space. One of the most probable places for an overlap is in a direction perpendicular to the hexagonal axis. So as a first approximation, write

$$\frac{dA_0}{\xi} \cong \frac{dA_0}{A_0} \cong \frac{2dk_x}{k_x} \cong -2\frac{dl_1}{l_1}. \qquad (3)$$

Since $dE_0/\xi = d\xi/\xi = dA_0/\xi$, by using Eqs. (2) and (3),

TABLE I. Effect of pressure on the period and amplitude of Ettingshausen-Nernst oscillations in zinc.

Pressure (psi)	Period β^*/E_0 (gauss^{-1})	Amplitude (in arbitrary units) at $H=8$ kilogauss
2350	59.50×10^{-6}	14.2
2025	60.00×10^{-6}	12.7
1800	60.15×10^{-6}	11.4
1525	61.00×10^{-6}	10.8
1000	61.45×10^{-6}	10.3
300	62.65×10^{-6}	9.1

[8] F. Donahoe, University of Pennsylvania Annual Report, 1952 (unpublished).
[9] L. Mackinnon, Proc. Phys. Soc. (London) **B62**, 170 (1949).

we have

$$\frac{dE_0}{E_0}=\frac{dE_0}{\xi}\times\frac{\xi}{E_0}\cong\frac{2\xi}{3E_0}\left(\frac{dl_1}{l_1}-\frac{dl_3}{l_3}\right).$$

It is possible to approximate the value of dl_1/l_1 and dl_3/l_3 by using Bridgman's[10] data for the coefficient of compressibility of zinc at 75°C and 30°C. Extrapolating linearly to 4.2°K:

$$dl_3/l_3=-9.18\times10^{-7}\text{ per atm},$$

$$dl_2/l_2=dl_1/l_1=-1.42\times10^{-7}\text{ per atm}.$$

Therefore: $dE_0/E_0\cong2.25\times10^{-4}$ per atm and for a pressure of 2000 psi: $dE_0/E_0\cong0.03$. Hence,

$$\frac{d(\beta^*/E_0)}{\beta^*/E_0}=\frac{d\beta^*}{\beta^*}-\frac{dE_0}{E_0}=\frac{d\beta^*}{\beta^*}-0.03,$$

which should be compared to the experimentally observed value of decrease in period of about 5%. We have not considered the effect of the change in overlap on β^* which could also be important. In general, from this kind of overlap one should expect that $d\beta^*/\beta^*<0$.

In a calculation very similar to that above, Berlincourt and Steele[11] showed that the large temperature dependence of period, which they observed in the susceptibility of zinc, could be largely accounted for by the change in E_0 due to the anisotropic thermal contraction of the zinc lattice, assuming the same kind of energy overlap employed above.

It should be pointed out that the results of Dmitrenko et al.[3] with moderate high pressure and the results of Verkin and Dmitrenko[12] with unilateral compression, both on zinc's susceptibility, show an effect on the period of the same order of magnitude but of opposite sign to that reported here. Also, their amplitude decreases with pressure. In a more recent brief publication these authors[13] reported that the period of the de Haas-van Alphen effect in zinc is itself periodic in pressure. Their maximum pressure (1750 atm) was obtained by freezing water in a constant volume while lower pressures were produced by freezing water solutions of ethyl alcohol of varying concentrations in the same bomb. Since each pressure point required a new solution in the bomb, points were taken at 250-atm intervals, while the measurements reported here cover only the range of pressure 0 to 170 atm. The periods observed in this range can be fitted to Verkin and Dmitrenko's oscillatory curve by adding 1150 atmospheres to each pressure point. This would seem offhand to indicate that our crystal was initially under a severe compression strain or that theirs was under a tension strain. Their zero pressure period (adjusted to correspond to H parallel to the hexagonal axis) is 5.3×10^{-5} gauss^{-1} while the crystal used in this study has a zero pressure period of 6.3×10^{-5} gauss^{-1}. Referring to Table I of the preceding paper, it is seen that these constitute the two common values for this period. A Bridgman-type ram is being constructed in this laboratory to allow galvanomagnetic and thermomagnetic measurements over a continuous range of pressure from 0 to 5000 atm. It is hoped that these measurements will help to resolve the discrepancies.

ACKNOWLEDGMENTS

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