

MAGNETIC PROPERTIES OF METALS AT LOW TEMPERATURES. IV.

INFLUENCE OF HOMOGENEOUS COMPRESSION ON THE DE HAAS - VAN ALPHEN EFFECT IN ZINC CRYSTALS

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A method and apparatus have been developed to investigate the influence of homogeneous compression on the anisotropy of the magnetic properties of crystals at low temperatures. The angular dependence of the oscillation periods of the magnetic susceptibility of free zinc crystals due to the two smallest groups of mobile charges has been established. The effect of homogeneous compression at a pressure of 1700 kg/cm^2 on the period and amplitude of the oscillations due to the smallest group of mobile charges has been investigated. A large (40 to 48%) increase in the periods of these oscillations has been found for all values of the angle θ between the field vector and the direction of the principal axis. The homogeneous compression of the crystal is found to cause a strong decrease of the oscillation amplitude and a change in the temperature dependence of the oscillation amplitude. The experimental data are compared with the semi-phenomenological theory of the influence of deformations on oscillation effects in metals at low temperatures.

1. INTRODUCTION

THE homogeneous compression of crystals, or in other words, the homogeneous and large elastic deformation of the lattice, is one of the most direct methods of external action on the periodic electric field within the crystal, meaning also on the electronic properties of metals (conductivity, magnetic and galvanomagnetic phenomena, etc.)

For a long time experimental investigations of the effect of homogeneous lattice compression on the electric properties of metals have been carried out at high temperatures (room temperature and higher), because Bridgman had developed for these experimental conditions a method for the production and measurement of sufficiently high pressures. The development by one of the authors and by Kan² of the "ice method" for producing high pressures made it possible, for the first time, to extend experimental investigations of this kind to the more interesting low-temperature region and, in particular, to investigate in detail the effect of homogeneous lattice compression on the superconductivity of a number of metals.³ The results of these experiments, together with the study of the isotope effect in superconductivity phenomena (e.g. reference 4), gave evidence of the specific interaction of the electrons with the metal lattice, which later on proved so important for the devel-

opment of a microscopic theory of superconductivity.

In recent years Alekseevskii and his co-workers used the "ice method" to produce high pressures in order to investigate the effect of homogeneous compression on the electromagnetic phenomena in bismuth⁵ at low temperatures. Very recently an investigation has been carried out on the effect of homogeneous lattice compression on the temperature variation of the electrical conductivity of a number of metals.⁶

The effect of homogeneous compression on the magnetic properties of crystals was not studied for a long time even at higher temperatures, because the known methods for producing high pressures could not be applied to the measurement of magnetic susceptibility. The systematic investigation of the magnetic properties of unconstrained crystals of feebly magnetic metals at low temperatures led to the discovery of the de Haas - van Alphen effect in a large group of metals^{7,8} and to the establishment by Lifshitz et al.⁹ of a connection between this phenomenon and the problem of the energy distribution of charge carriers in metals - one of the most important problems of metal physics. It became essential to clarify the effect of the homogeneous compression of the crystal on the de Haas - van Alphen effect, and thus on the energy distribution of charge carriers in metals.

A method and apparatus were developed in the

low-temperature laboratory of the Physico-Technical Institute of the Academy of Sciences of the U.S.S.R. to study the effect of homogeneous compression on the anisotropy of the magnetic properties of crystals at low temperatures. Some results of such investigations, made on crystals of bismuth and zinc, have been published previously (references 10 and 11).

This paper is devoted to the description of a method for investigating the effect of homogeneous compression on the anisotropy of the magnetic properties of crystals, to the discussion of the results of investigations concerning the de Haas — van Alphen effect on zinc crystals under homogeneous compression, and also to the comparison of the experimental data with the theory of the phenomenon. Furthermore, some new information is given on the de Haas — van Alphen effect in unconstrained zinc crystals.

2. METHOD AND APPARATUS

The method of investigation consisted of measuring the torque acting on a small anisotropic crystal placed inside a massive but magnetically isotropic high pressure bomb, suspended by means of a thin elastic thread in a homogeneous magnetic field. The homogeneous compression of the crystal was brought about by the "ice method," i.e., by freezing water inside the bomb.¹⁰

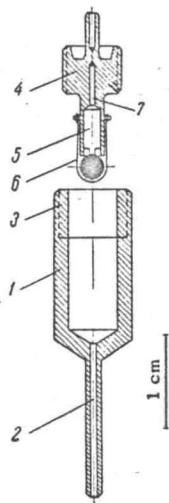


FIG. 1. Pressure bomb for investigation of the magnetic anisotropy of homogeneously compressed crystals.

A diagram of one of the most convenient high-pressure bombs is shown in Fig. 1. The bomb, made of pure beryllium bronze,* consists of the body 1 with capillary 2 and thread 3 into which

*We wish to take this opportunity to thank I. Bolgov for casting the bronze from copper and beryllium with a high degree of purity.

bronze stopper 4 with crystal holder 5 can be screwed. The crystal holder consists of a thin-walled copper tube (copper tube and stopper are made in one piece) with four perpendicular lugs and with side windows. The cavity 7 in the stopper serves to center the crystal in the crystal holder.

The crystal is initially oriented on the platform of a goniometer and a thin quartz stick is attached to it (in the direction coinciding with the axis of suspension in the apparatus). The sample is then transferred to the crystal holder in such a way that the quartz stick fits into the cavity 7, and wire harness 6 is firmly secured to the lugs. After mounting the crystal, the quartz stick can be detached. The error in the orientation of the crystal axes relative to the axis of suspension of the bomb does not exceed 1°.

The stopper 4 is screwed into the body 1 of the bomb while covered with pure molten indium, which makes the thread gas tight after hardening. This avoids the use of gaskets and enables the bomb and the stopper to be subjected to a sufficiently strong acid etch after the machining is completed, in order to remove ferromagnetic impurities.

After the bomb has been mounted in the apparatus, it is evacuated and filled with water through the capillary 2. The bomb is cooled from the capillary side, and the ice plug which forms in the capillary then securely contains the pressure developing inside the bomb. The ice inside the bomb is thawed from above, from the side of stopper 4; if it were thawed from below, the movement of the ice would upset the suspension of the crystal holder. When the whole suspension system rotates in the magnetic field, a light spot is displaced on a scale; the displacement is measured on a traveling microscope.

The experiments were carried out at pressures of $p \sim 1700 \text{ kg/cm}^2$ in a magnetic field $H \leq 20,000 \text{ Oe}$ over the temperature range from 1.6 to 4.2°K.

3. THE SAMPLES

Zinc supplied by the firm Hilger (spectroscopically pure) served as starting material for the preparation of the crystals. Five zinc crystals: Zn-1, Zn-2, Zn-3, Zn-4 and Zn-7, were prepared and investigated; they differed in the method of preparation and the growth rate. Crystals Zn-2, Zn-3, and Zn-4, spherical in shape, were prepared by the method of Obreimov — Shubnikov in quartz tubes at a growth rate of 10, 15 and 50 mm/hr respectively. The crystal Zn-1 was prepared by the same method from Hilger zinc that had been

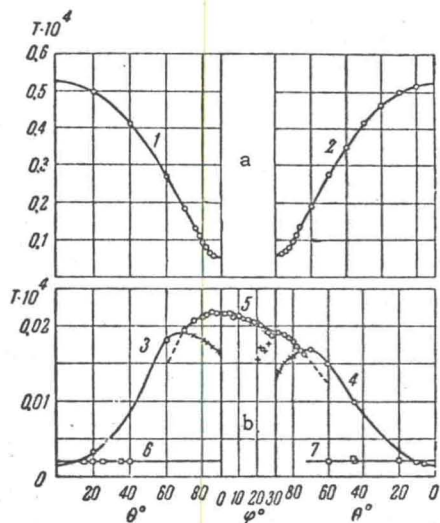


FIG. 2. Angular dependence of the oscillation period of the susceptibility of zinc caused by: a) the smallest group of mobile charges (1 - first, 2 - second orientation of the crystal); b) the group which determines one of the high frequency components (fine structure) of the de Haas - van Alphen effect (curves 3, 4, and 5 refer to the first, second and third orientation of the crystal, respectively), and the group which determines the hyperfine structure of the effect (curves 6 and 7 refer to the first and second orientation of the crystal, respectively). θ = angle between vector H and principal crystal axis; φ = angle between vector H and the diagonal crystal axis in the basal plane. x, o - two fine-structure branches observed on the experimental $\Delta\chi(1/H)$ curves at the large angles θ .

recrystallized seven times. A rather detailed study of Zn-1 was made in one of the preceding papers.¹² The crystal Zn-7, with the hexagonal axis along the geometric axis of the sample, was prepared by Kapitza's method on a plate subjected to a temperature gradient at a growth rate of 5 mm/hr. The

maximum sample diameter was 4 mm.

A widely-used method for the qualitative estimate of crystal strain is the microscopic investigation of slip along the basal plane.¹³ The microscopic investigation of slip in crystals Zn-1, Zn-2, Zn-3, Zn-4, and Zn-7 showed that Zn-7 was the least strained and Zn-4 the most strained.

The crystals were oriented by means of an optical double-arc goniometer.¹² Three orientations of the zinc crystals were investigated: (1) The diagonal axis of the crystal was taken parallel to the axis of suspension - the first orientation. (2) The direction perpendicular to the diagonal axis and lying in the basal plane was taken parallel to the axis of suspension - the second orientation. (3) The principal axis of the crystal was taken parallel to the axis of suspension - the third orientation.

4. RESULTS OF THE MEASUREMENTS

a. The de Haas - van Alphen Effect in Unconstrained Zinc Crystals

It is known that the experimental curves $\Delta\chi(1/H)$ for Zn crystals represent the superposition of three frequency components of the variation of the susceptibility with the field.¹² Each of these frequency components is caused by a certain group of charge carriers in the metal; the component with the longest period is caused by the smallest group of charge carriers. The high frequency components are usually called the fine and the hyperfine structure of the de Haas - van Alphen effect. Before investigating the effect of homogeneous compression on the de Haas - van

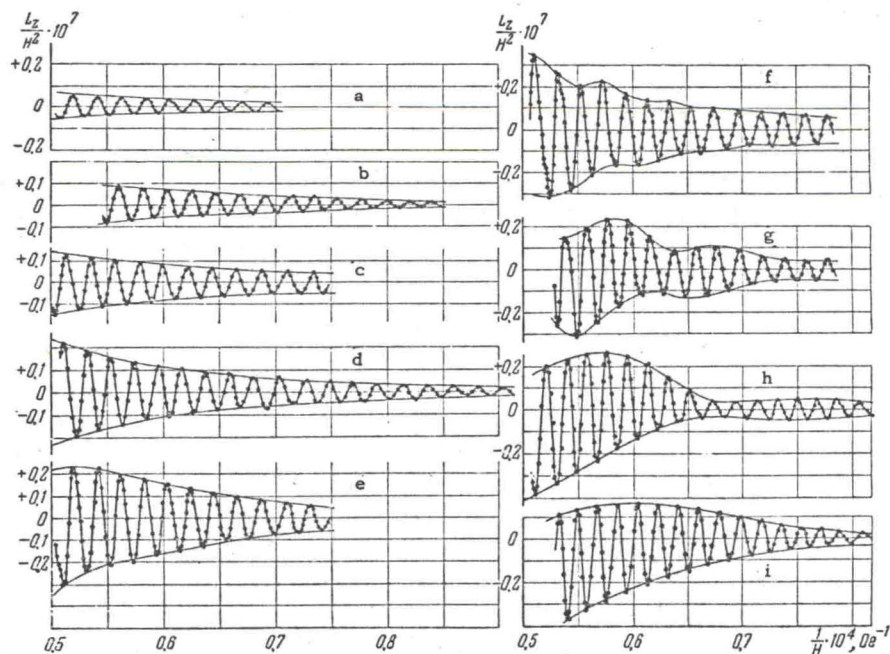


FIG. 3. Variation with $1/H$ of the torque L_z/H^2 , acting on the crystal in its third orientation in the field, at a temperature of $T = 4.2^\circ\text{K}$. Crystal Zn-1: a - $\varphi = 2^\circ$; b - $\varphi = 4.5^\circ$; c - $\varphi = 7^\circ$; d - $\varphi = 9.7^\circ$; e - $\varphi = 15^\circ$; f - $\varphi = 18^\circ$; g - $\varphi = 22^\circ$; h - $\varphi = 26^\circ$; i - $\varphi = 28^\circ$.

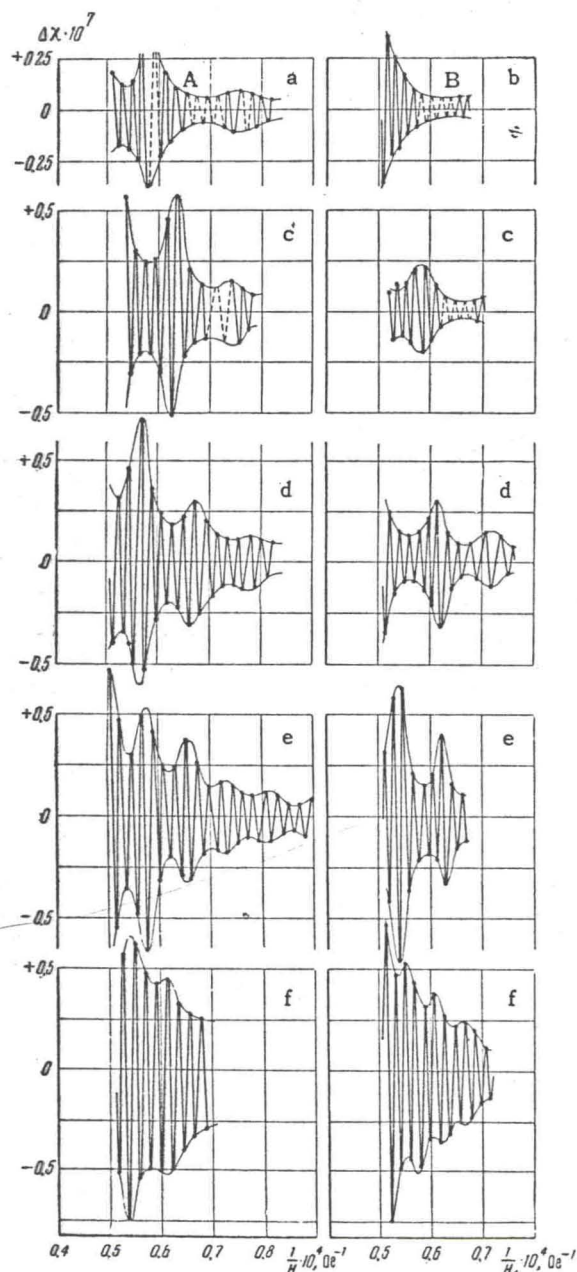


FIG. 4. Resolved oscillations of the high frequency component of the de Haas - van Alphen effect (fine structure): A) in the first, and B) in the second orientation of the crystal Zn-1: a- $\theta = 75^\circ$; b- $\theta = 78^\circ$; c- $\theta = 80^\circ$; d- $\theta = 82^\circ$; e- $\theta = 85^\circ$; f- $\theta = 88^\circ$; T = 4.2°K.

Alphen effect it was necessary to establish more accurately the angular dependence of the periods of susceptibility oscillations, caused by different groups of charge carriers in unconstrained zinc crystals.

The curves of Fig. 2 illustrate the angular dependence of the periods of oscillation of the susceptibility for three orientations of the zinc crystals in the magnetic field.

From the preceding investigations of the crystal Zn-1 it is known¹² that when the sample is oriented in the magnetic field in either the first

or second direction, the smallest group of charge carriers produces practically coinciding curves for the angular dependence of the period of oscillation of the susceptibility of zinc. This fact was checked more carefully by an investigation of the crystal Zn-7. The curves of Fig. 2a represent the angular dependence of the periods of oscillation of the susceptibility in this crystal, produced by the smallest group of charge carriers, for the first (1) and the second (2) orientations in the magnetic field respectively. It can be seen that the curves coincide over practically the whole range of values of θ . This smallest group of carriers does not appear at all when investigating the magnetic properties in the basal plane of the zinc crystals. All the above favors the assumption that the Fermi surface for the charges of this group is a surface of revolution elongated along the axis k_z , which approximates an ellipsoid of revolution over a wide range of angles $0 < \theta \leq 60^\circ$, and for large θ changes gradually first to a cone, and then to a cylinder.¹⁴

The anisotropy of the magnetic properties of zinc crystals in the basal plane is due to the same group of charge carriers that is responsible for the fine structure of the effect in the first and second orientations of the zinc crystals in the magnetic field. In fact, an analysis of the magnetic

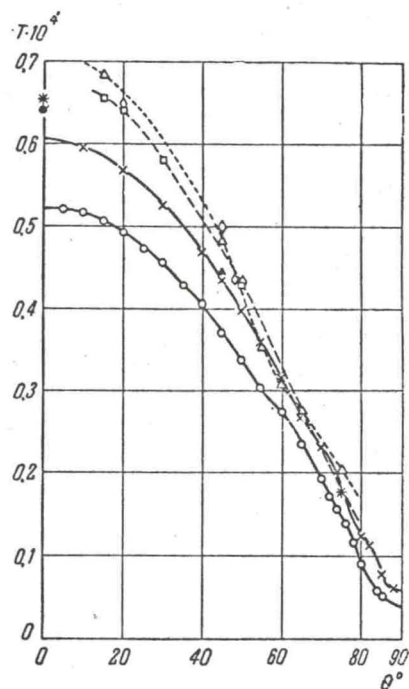


FIG. 5. Angular dependence of the oscillation period of the susceptibility caused by the smallest group of mobile charges in different zinc crystals, obtained from: x - crystal Zn-1, o - crystals Zn-2, 3, 4, 7 (this paper); Δ - Sidoriak and Robinson,¹⁸ Δ - Mackinson,¹⁹ \bullet - Berlincourt and Steele,²⁰ \square - Donahoe and Mix,²¹ * - Dhillon and Shoenberg.²²

anisotropy in the basal plane of the crystal Zn-1 (the curves of Fig. 3), as well as an analysis of the resolved fine structure of the effect in this crystal (the curves of Fig. 4) made it possible to elucidate the complete angular variation of the periods of oscillation of the susceptibility, caused by the larger group of charge carriers, as shown in Fig. 2b. All the fine-structure $\Delta\chi(1/H)$ curves show modulations, with the modulation period decreasing appreciably as θ increases. An analysis of the curves of Fig. 2 shows that the Fermi surface corresponding to this second larger group of charge carriers has quite a complicated shape far removed from the simple scheme of three ellipsoids, rotated in the plane $k_x k_y$ through an angle of $\pm 120^\circ$ relative to each other. It will be the object of further investigations to determine more precisely the shape and the dimensions of the Fermi surface for this group of charge carriers in zinc crystals.

Figure 5 shows the angular dependence of the period of the low-frequency component of the de Haas - van Alphen effect in zinc crystals, studied in this paper and by other authors. It can be seen that for different samples of the same metal the magnitude of the period of oscillations of $\Delta\chi(1/H)$, caused by the smallest group of charge carriers, does not remain constant, with the differences being greatest in the region of small angles θ between the field vector and the principal crystal axis. The periods of oscillation practically coincide in crystals Zn-2, Zn-3, Zn-4 and Zn-7; in the crystal Zn-1 (see also¹²) the periods are appreciably larger.

The facts mentioned above lead to the conclusion that an increase in purity of the samples causes an appreciable increase (up to several tens percent) in the period of oscillation of the susceptibility in the magnetic field, whereas differences in the state of strain of the samples, arising from differences in the method and from thermal conditions during the growth of the crystals, do not have any effect on the magnitude of the period of oscillations. An analysis of the experimental data shows that this conclusion is correct also for the fine structure of the de Haas - van Alphen effect in zinc crystals.

It should be noted that lattice distortions related to the method and conditions of the crystal growth appreciably influence the amplitude of the susceptibility oscillations. The amplitude of the oscillations is largest in the free-grown crystal Zn-7, and is 40 to 50% smaller in crystal Zn-4, obtained under less favorable conditions. On annealing crystal Zn-4, some increase was produced in the amplitude of the susceptibility oscillations.

b. The de Haas - van Alphen Effect in Homogeneously Compressed Zinc Crystals

The crystal Zn-2 was used to investigate the effect of the homogeneous compression of the lattice on the de Haas - van Alphen effect. The second orientation of the crystals has been studied in detail; this is sufficient (see Fig. 2) for a rather complete investigation of the effect of homogeneous compression on the oscillations caused by the smallest group of mobile charges.

Figure 6 shows some $\Delta\chi(1/H)$ curves for the crystal Zn-2 in the second orientation in the field, unconstrained (A) and under homogeneous compression, $p \approx 1700 \text{ kg/cm}^2$ (B). These curves

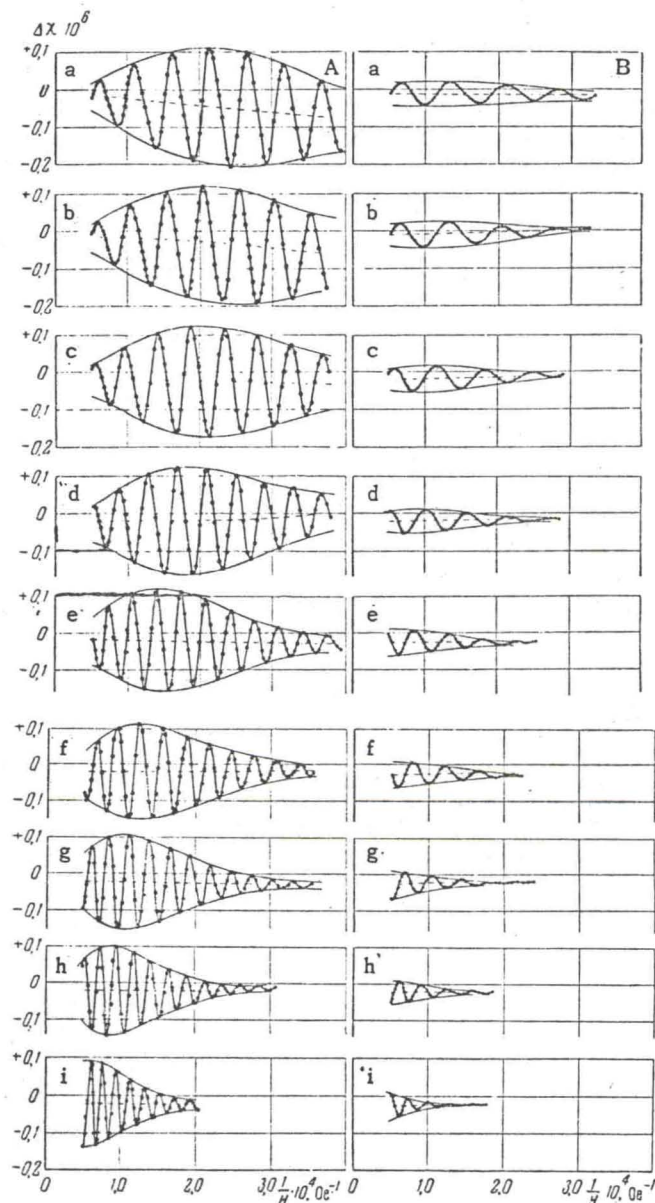


FIG. 6. "Periodic" variation of the susceptibility of the crystal Zn-2 with the magnetic field: A) unconstrained crystal, B) homogeneously compressed crystal at $p = 1700 \text{ kg/cm}^2$; a - $\theta = 10^\circ$; b - $\theta = 20^\circ$; c - $\theta = 30^\circ$; d - $\theta = 40^\circ$; e - $\theta = 50^\circ$; f - $\theta = 55^\circ$; g - $\theta = 60^\circ$; h - $\theta = 65^\circ$; i - $\theta = 70^\circ$; $T = 4.2^\circ\text{K}$.

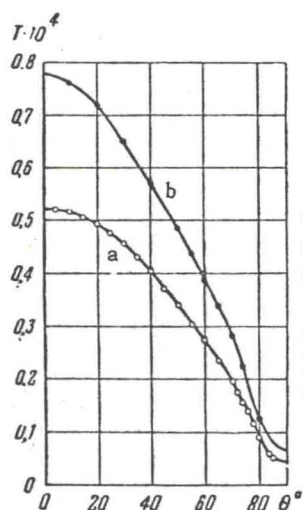


FIG. 7. Angular dependence of the oscillation period of the susceptibility caused by the smallest group of mobile charges: a — for the unconstrained crystal Zn-2 and b — for the homogeneously compressed crystal Zn-2 at $p = 1700 \text{ kg/cm}^2$.

give the low-frequency component of the effect, caused by the smallest group of mobile charges in zinc. It may be seen that the homogeneous compression of the crystals under a pressure of $p \approx 1700 \text{ kg/cm}^2$ changes very markedly all the characteristics of the $\Delta\chi(1/H)$ curves: the period of the oscillations increases noticeably, the amplitude of the oscillations decreases by a large factor (particularly in small fields), and the maximum of the attenuated $\Delta\chi(1/H)$ curves is displaced towards greater field strengths.

The curves of Fig. 7 illustrate the angular dependence of the period of oscillation of the susceptibility without pressure and for a homogeneously-compressed crystal. It can be seen that the period of oscillation has increased in the homogeneously compressed crystal for all values of the angle θ . This increase in the period of oscillation is somewhat larger for small angles, where it reaches 48%, and somewhat less for large angles, where it equals 40 to 43%.

The homogeneous compression of the crystal also changes the period and the amplitude of the oscillations of the fine structure of the de Haas — van Alphen effect. The high-frequency oscillations

do not disappear under pressure, but their period increases noticeably; at $\theta = 80^\circ$ the increase in the period of oscillation of the fine structure amounts to 12%. The amplitude of the high-frequency oscillations decreases under pressure.

The numerical values of the periods of oscillation for the low-frequency and high-frequency components of the $\Delta\chi(1/H)$ curves are listed in Table I for Zn-2 crystals, unconstrained and under homogeneous compression. On removing the pressure the values of the periods of oscillation are completely restored.

The homogeneous compression of the crystals leads to a strong decrease in the amplitude of the oscillations. The decrease in the amplitude of the oscillations under pressure is particularly pronounced for large values of θ and for small fields. On removing the pressure the amplitude of the oscillations is not completely restored. The hysteresis is greatest for small fields; it decreases with increasing field strength.

The temperature variation of the amplitude of the oscillations, caused by the smallest group of mobile charges in unconstrained and in homogeneously-compressed crystals, has been investigated at $\theta = 80^\circ$. Numerical values for the ratio of the amplitudes of the oscillations A_2/A_1 are given in Table II for different values of $1/H$ and for two different experimental temperatures.

5. DISCUSSION OF THE RESULTS

The de Haas — van Alphen effect is a feature common to a group of 15 elements, in which the absolute magnitude of the susceptibility increases with decreasing temperature and which crystallize in anisotropic structures (in many cases in lamellar structures). In crystal chemistry it is usually assumed that complicated mixed types of interaction (partially covalent or van der Waals forces)

TABLE I

Period of oscillation $T \times 10^4, \text{Oe}^{-1}$					
θ°	Low-frequency component $\Delta\chi(1/H)$		θ°	High-frequency component $\Delta\chi(1/H)$	
	$p = 0$	$p \approx 1700 \text{ kg/cm}^2$		$p = 0$	$p \approx 1700 \text{ kg/cm}^2$
10	0.516	0.763	80	0.0138	0.0154
20	0.494	0.724	84	0.0125	0.0145
30	460	650			
40	405	570			
50	340	484			
55	303	435			
60	276	387			
65	237	338			
70	196	283			
74	157	224			
80	93	126			

TABLE II

$p = 0; T_1 = 4.2^\circ\text{K}, T_2 = 2.0^\circ\text{K}$		$p = 1700 \text{ kg/cm}^2; T_1 = 4.2^\circ\text{K}, T_2 = 1.6^\circ\text{K}$	
$(1/H) \cdot 10^4, \text{Oe}^{-1}$	A_2/A_1	$(1/H) \cdot 10^4, \text{Oe}^{-1}$	A_2/A_1
1.2	3.2	0.8	2.2
1.1	2.7	0.75	2.7
1.0	1.9	0.7	2.2
0.9	1.5	0.65	2.0
0.8	1.0	0.6	1.8
0.7	1.05	0.55	1.42
0.6	1.09	0.5	1.23

are playing an important part in the lattices of the above elements along with the metallic type of bond.

The basic experimental data on the de Haas-van Alphen effect (the complicated frequency spectrum, large periods and amplitudes of the susceptibility oscillations), as well as the variation of the susceptibility of these elements with temperature, are explained by the well-known assumption that these elements contain one or more exceptionally small groups of mobile charges besides the large fundamental group. The origin of these exceptionally small groups has not been explained; it is possible that the complicated energy spectrum of the mobile charges is connected with the above-mentioned mixed types of bonds in the lattices of these elements.¹⁴

The period of oscillation T of the magnetic susceptibility, caused by the small group β of the mobile charges, is determined by the area of the extremal section $S_m^\beta(\xi_\beta)$ through the Fermi surface for these charges:

$$T = eh / cS_m^\beta(\xi_\beta), \quad (1)$$

where ξ_β is the chemical potential, measured from the "bottom" of the β -energy zone. The investigation of the temperature variation of the oscillations of the magnetic susceptibility makes it possible to determine still another important characteristic of the energy spectrum of the mobile charges:

$$m_\beta = \frac{1}{2\pi} (dS_m^\beta / d\xi_\beta). \quad (2)$$

For the general case of an arbitrary dispersion law, m_β is a function of the lattice parameters a_i and of the chemical potential. In the special case of a quadratic dispersion law, m_β coincides with the effective mass of the charge carrier as usually defined. This mass depends only on the lattice parameters and not on the energy.

Very recently Kosevich¹⁵ has treated the effect of an elastic lattice deformation on the electron spectrum in a semi-quantitative manner and has considered the peculiarities of the de Haas-van Alphen effect in a deformed metal. The elastic deformation of the lattice (in particular the homogeneous compression of the lattice) leads to a change in the chemical potential

$$\delta\xi = \delta S_m^\beta / 2\pi \bar{m}_\beta, \quad (3)$$

where $\bar{m}_\beta = \frac{1}{2}(m_\beta^0 + m_\beta^p)$, and δS_m^β is the variation of the section through the Fermi surface under pressure.* In the case of a homogeneous compression

$\delta\xi = ap$, where

$$a = \delta\xi/p \quad (4)$$

is of the same order of magnitude as the volume occupied by one particle of the charge-carrier "gas" in the metal.

$\delta\xi$ may be of the order of ξ_β and then the elastic deformation of the lattice will change little the properties that are determined by the majority group of charges, and will change very strongly those properties which are determined by the minority group of charges. Thus, in spite of the fact that the deformation and consequently the relative changes of the lattice parameters are small, the chemical potential and the oscillation period of the susceptibility will change by a factor comparable to ξ_β and S_m^β , respectively. In the special case of a quadratic dispersion law, m_β depends neither on the energy nor, consequently, on the pressure.

The investigation of the temperature variation of the oscillation period of the susceptibility in the constrained and in the deformed crystal, carried out at $\theta = 80^\circ$, makes it possible to determine m_β^0 and m_β^p in this orientation, without any assumptions concerning the form of the dispersion law for the charge carriers in the small group, and hence to calculate $\delta\xi$ and a . The results of these calculations are given below.

$$\begin{array}{ll} T_p/T_0 = 1.355. & m_\beta^p \cdot 10^{29} = 7.5; \\ S_m^p/S_m^0 = 0.740. & \bar{m}_\beta \cdot 10^{29} = 6.3; \\ \delta S_m/S_m^0 = -0.260. & \delta\xi \cdot 10^{14} = -0.62 \text{ erg}; \\ m_\beta^0 \cdot 10^{29} = 4.9. & a \cdot 10^{23} = 0.36. \end{array}$$

A comparison of the quantities m_β^0 and m_β^p gives evidence of a considerable dependence of m_β on the pressure, i.e. of a non-quadratic dispersion law for the small group of mobile charges in zinc crystals.

From an analysis of the data quoted it can be seen that the changes of the chemical potential by homogeneous compression of the lattice under a pressure of $p \approx 1700 \text{ kg/cm}^2$ are of the same order of magnitude as the chemical potential of the charge carriers of the small group.^{12,16} The value of the parameter α , calculated on the basis of the experimental data, is also in good agreement with the value estimated for it by Kosevich¹⁵ from general considerations.

Since the theoretical determinations of these quantities are based on the assumption that there exist exceptionally small groups of charge carriers, one may conclude that the experiments on the homogeneous compression of the zinc crystals and the large changes in the oscillation periods and in the chemical potential detected in these experi-

*In what follows a zero in the superscript indicates a given quantity in the unconstrained crystal, and p in the superscript indicates the same quantity in the deformed crystal.

ments support the validity of such an assumption.

Further investigations on the pressure variation of the oscillation period of the susceptibility in zinc will make it possible to establish the dispersion law for the small group of charge carriers.¹⁵

The calculations by Kosevich¹⁵ permit a quantitative determination of the oscillation period of the magnetic susceptibility in a constant magnetic field as a function of the external load. In the case of a homogeneous compression of the crystals the change in pressure Δp , which corresponds to the oscillation period, equals

$$\Delta p = e\hbar H / cam_0. \quad (5)$$

This quantity can be determined for the zinc crystals from the experimental data. The results of the calculation are given in Table III ($\theta = 80^\circ$).

TABLE III

H, Oe	Δp , kg/cm ²
1000	75
5000	370
10000	750

It can be seen from the table that it is possible to observe the variation with pressure of the susceptibility oscillations in zinc crystals in a constant field by using the "ice" method for generating high pressures at low temperatures and by varying the pressure in the apparatus.

Two cases have been studied quantitatively and treated theoretically so far, i.e. changes induced in the chemical potential of the charge carriers by some external factor, and the conditions when such changes strongly affect the properties determined by small groups of charge carriers. The discussion here deals with the effect of the temperature on the magnetic properties of those elements which exhibit the de Haas — van Alphen effect,¹⁷ and with the effect of elastic deformations on the oscillations of the magnetic susceptibility caused by small groups of charge carriers.¹⁵

In Sec. 4 it was noted that small amounts of impurities change the oscillation period of the susceptibility in zinc crystals very strongly. It is probable that the impurities also induce in the chemical potential a change that affects appreciably the filling of the small group of charge carriers, and, correspondingly, the most important characteristic of the de Haas — van Alphen effect, i.e. the oscillation period of the susceptibility.

In conclusion, we wish to express our gratitude to A. M. Kosevich for discussing the experimental results.

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ENERGY DEPENDENCE OF $\mu^+ - e^+$ DECAY ASYMMETRY

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The energy dependence of the asymmetry of electrons originating in the decay of polarized μ mesons was studied with a set of scintillation counters biased against bremsstrahlung. The measurements were carried out for electron energies above 20 Mev. The observations are in a quantitative agreement (within a few percent) with the two-component neutrino theory. The experiments indicate that the degree of polarization of the μ meson beam is 0.81 ± 0.11 .

INTRODUCTION

THE hypothesis of parity nonconservation in weak interactions¹ has led² to a special variant of the neutrino theory, called the two-component or longitudinal neutrino theory. The attractiveness of such a theory makes it desirable to conduct experiments to decide whether the theory is correct or not.

A study of the spectrum of electrons produced in the decay of polarized μ meson at various angles offers such an opportunity. It is, however, necessary to note that such an investigation can, in principle, only disprove the two-component neutrino theory, but cannot provide a final proof of its validity. In other words, a four-component neutrino theory can, for an appropriate choice of the coupling constants,³ give a spectrum similar to that predicted by the two-component theory, namely

$$f(E, \theta) = 2E^2\{(3 - 2E) + \lambda(2E - 1) \cos \theta\}. \quad (1)$$

Here $f(E, \theta)$ denotes the electron energy-distribution function, θ is the angle between the elec-

tron momentum and the μ -meson spin, E is the ratio of the electron energy to the maximum energy possible, and λ is a parameter that depends on the coupling constants.

Parity nonconservation in $\pi - \mu - e$ decay was discovered in the classical experiments of Garwin, Lederman, and Weinrich⁴ who showed, using electronic methods of particle detection, that μ -meson beams from an internal target of a synchrocyclotron are polarized to a large degree, and that the angular distribution of electrons in $\mu - e$ decay is of the form $1 + a \cos \theta$. It follows from the above that the two-component neutrino theory predicts a definite dependence of the factor a on the electron energy.

The energy dependence of the factor a found in reference 4 is weaker than that given by Eq. (1). The energy of the electrons was estimated in these experiments by determining the penetrating power of electrons passing through a graphite absorber. Taking it into account that the arrangement of counters in reference 4 was such that the bremsstrahlung radiation of the electrons could be re-