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# PHYSICS

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**Abstract**

**Full Text**

**PHYSICS**

**B. I. VERKIN, L. N. PELIKH, V. V. EREMENKO**

## **QUANTUM OSCILLATIONS OF THE CONTACT POTENTIAL DIFFERENCE OF A BISMUTH-NIOBIUM PAIR**

*(Presented by Academician P. L. Kapitsa, 10 VII 1964)*

The oscillatory dependence on magnetic-field strength of the magnetic susceptibility of metals, their electrical conductivity, thermoelectric power, etc., is known to be connected with the nonmonotonic dependence of the number of electron states near the limiting Fermi energy. But, in addition to oscillations of the density of states, oscillations of the very value of the limiting energy (the chemical potential) are possible; the order of magnitude of their amplitude is determined by the expression <sup>(1,2)</sup>

$$\xi^{\text{osc}} \sim \theta \left( \frac{\mu H}{\xi_0} \right)^{1/2} \exp(-2\pi^2 \theta / \mu H), \quad (1)$$

where  $\xi^{\text{osc}}$  is the oscillating component of the chemical potential;  $\xi_0$  is the chemical potential;  $\theta = kT$ ,  $k$  is Boltzmann's constant,  $T$  is the temperature;  $\mu$  is the effective magneton;  $H$  is the magnetic field.

For  $T = 10^\circ \text{ K}$ ,  $H = 10^4$  oersted, for small groups this estimate gives  $\xi^{\text{osc}} \sim 10^{-3} \div 10^{-4}$  eV; for large groups this value decreases to  $10^{-6}$  eV.

Observation of quantum oscillations of the chemical potential is possible by measuring the effect of a pulsed magnetic field on the contact potential difference of a pair of metals, one of which possesses a small group of current carriers.

I. O. Kulik and G. A. Gogadze <sup>(2)</sup> formulated experimental conditions under which such observation is possible. The present note reports the performance of the experiment. In accordance with the recommendations of Kulik and Gogadze <sup>(2)</sup>, the potential difference arising on the plates of a sample-capacitor was measured when a pulsed magnetic field was switched on, the duration of which was  $t \ll \tau$ , where  $\tau = RC$  is the relaxation time of the circuit sample-load.

One plate of the sample-capacitor was a bismuth single crystal (grade V000, purity 99.99999%), chosen as the object of study, since the amplitude of oscillations of its chemical potential should be significant owing to the low concentration of

current carriers, in accordance with estimates from formula (1). It is also essential that for bismuth it is not difficult to satisfy the condition of quasistaticity (<sup>3,2</sup>), under which the results of measurement in a pulsed field practically do not differ from the stationary case. In addition, because of the poor conductivity of bismuth, screening of the pulsed magnetic field was reduced to a minimum.

Niobium was used as the second plate of the sample-capacitor. This choice was due to the consideration that the amplitude of oscillations of the chemical potential of niobium is several orders of magnitude smaller than that of bismuth, and their contribution to the overall effect lies beyond the sensitivity limits of the measuring circuit. In addition, on niobium it is fairly simple, by electrolytic anodization, to create a film of niobium pentoxide, which is—

is a good dielectric. It was used as the spacer between the plates of the sample-capacitor, and its thickness was monitored from its interference color. In this way samples were obtained in which, for dielectric-film thicknesses of 400–550 Å, the capacitances were 1000–5000 pF.

When the samples were cooled to liquid-helium temperature, their capacitances were preserved and the resistance between the plates was greater than 500 MΩ. After several cooling cycles of a sample, its capacitance decreased by 1–3%. The parameters of the most characteristic samples are given in Table 1. In the table,  $R_{300}$  is the resistance of the sample at room temperature;  $R_{4.2}$  is the resistance of the sample at liquid-helium temperature;  $C_{4.2}$  is the capacitance of the sample at liquid-helium temperature;  $S$  is the area of the plates of the sample-capacitor;  $d$  is the thickness of the dielectric.

**Table 1**

$R_{300}$ , kΩ	$R_{4.2}$ , MΩ	$C_{4.2}$ , pF	$S$ , mm <sup>2</sup>	$d$ , Å	Orientation of the sample plates relative to H
510	> 500	~ 2700	5.1	550	⊥
480	> 500	~ 3000	5.6	550	⊥
220	> 500	~ 4000	6	450	
200	> 500	~ 4200	6	450	

Figure 1 shows a block diagram of the apparatus. The pulsed magnetic field was produced by discharging a battery of capacitors with a capacitance of 3000 μF through a small solenoid cooled with liquid helium (hydrogen). The maximum magnetic field was 70 kOe for a pulse duration (from zero to maximum) of 4 ms. Two variants of the measuring circuit were used. In the first variant the sample was loaded by the input resistance of a cathode follower, whose value was 10 MΩ. Approximately the same parasitic resistance was possessed by the

Fig. 1. Block diagram of the apparatus

Figure 1: Fig. 1. Block diagram of the apparatus

Fig. 2

Figure 2: Fig. 2

coaxial line between the sample and the cathode follower for the mean oscillation frequency. The signal then went to a narrow-band amplifier, whose passband could be adjusted within the range 1-10 kHz. From the narrow-band amplifier the signal went to an oscilloscope with triggering of the waiting sweep from an electronic delay circuit; in this way it was possible to measure the oscillations in any interval of magnetic fields. The sensitivity of the measuring circuit in the narrow band (1 kHz) was  $10^{-4}$  V/mm.

### Fig. 1. Block diagram of the apparatus

Figure 2 shows an oscillogram of the oscillations obtained. With a passband of the narrow-band amplifier of 1 kHz, against the background of pickup from the pulsed magnetic field there were observed oscillations whose amplitude was comparable with the width of the electron beam on the oscilloscope screen. Measurement of the oscillations in the narrow band was associated with the necessity of reducing the signal from the pickup of the pulsed magnetic field, whose frequency differed by an order of magnitude from the mean frequency of the oscillations; at the same time it was not possible to estimate reliably the period of the oscillations obtained, to say nothing of their amplitude.

The second variant of the measuring circuit consisted in replacing the active load of the sample by an inductive one,  $R = \omega_{av}L$ , where  $\omega_{av}$  is the mean oscillation frequency and  $L$  is the load inductance. In this variant it was possible to reduce the pickup signal by approximately  $10^3$  times and to increase the sensitivity of the circuit to  $8 \cdot 10^{-6}$  V/mm over a wide band and, consequently, to obtain the oscillation pattern in an undistorted form (see Fig. 3).

The results of measurements carried out by means of the method described may be summarized essentially as follows:

1. The amplitude of the oscillations of the contact potential difference depends sharply on temperature. If at 4.2° K it reaches  $10^{-4}$  V and more (in a field  $H = 2 \cdot 10^4$  Oe), then at 20° K the amplitude of the oscillations does not exceed  $5 \cdot 10^{-6}$  V.
2. The amplitude of the oscillations increases with increasing magnetic-field strength  $H$ , but at the same time it also depends on the rate of change of the field with time,  $dH/dt$ . Thus, in the region where the maximum of the magnetic-field pulse is reached, where  $dH/dt = 0$ , the amplitude of the oscillations is strongly reduced (see Fig. 2).

Fig. 3

Figure 3: Fig. 3

Fig. 2. Oscillations of the contact potential difference of the Bi–Nb pair at 4.2° K. The load is active. Duration of the magnetic-field pulse  $t = 4$  msec. In the upper part of the photograph the magnetic field is traced

3. There is no noticeable dependence of the amplitude and period of the oscillations on the orientation of the magnetic field relative to the plane of the dielectric interlayer of the sample-capacitor.
4. A sharp dependence is observed of the amplitude and period of the oscillations on the orientation of the magnetic field relative to the crystallographic axes of bismuth, which agrees with the strong anisotropy of the de Haas–van Alphen and Shubnikov–de Haas effects.

The period of the oscillations of the contact potential difference in the reciprocal field, determined for the most thoroughly studied orientation  $\mathbf{H} \parallel c_3$  (in our case  $\mathbf{H}$  is perpendicular to the bisectrix axis and the angle between  $\mathbf{H}$  and  $c_3$  is 15°), coincides with the period of the oscillations of the magnetic susceptibility and electrical resistance <sup>(5)</sup> and is  $2.9 \cdot 10^{-5} \text{ Oe}^{-1}$  (see Fig. 4).

Fig. 3. Oscillations of the contact potential difference of the Bi–Nb pair at 4.2° K. The load is inductive. Duration of the magnetic field  $t = 4$  msec. The bisectrix axis of the bismuth single crystal is perpendicular to the magnetic field, the trigonal axis at an angle of 15° to  $\mathbf{H}$

5. In addition to the oscillations determined by the electronic parameters of bismuth, at helium temperature (and only at it), in the region of small magnetic fields, a small spike is reproducibly observed, independently of the orientation of the bismuth single crystal (see Fig. 3). It should be noted that the region of magnetic field in which this spike is observed is very close to the field strength of the critical field for destruction of the superconductivity of niobium.

Experimental results 1–4 agree with the conclusions of the theoretical work <sup>(2)</sup> on the behavior of the contact potential difference in a pulsed magnetic field. Nevertheless, one might suspect that the observed oscillations are caused either by oscillations of the magnetic susceptibility or by oscillations of the electrical conductivity of bismuth.

The first concern is eliminated if one takes into account that the fairly massive niobium substrate was rigidly fixed, which completely eliminated any displacements of the specimen in the magnetic field that could have produced a specific oscillating pickup. In addition, a control experiment was carried out in which two single crystals of bismuth of different crystallographic orientation were mounted on one substrate. If the observed oscillations were caused by a nonmonotonic displacement of the specimen in connection with the de Haas–

Fig. 4. Graphical determination of the period in the reciprocal field for the oscillations shown in Fig. 3;  $\Delta(H^{-1}) = 2.9 \cdot 10^{-5}$  oersted

Figure 4: Fig. 4. Graphical determination of the period in the reciprocal field for the oscillations shown in Fig. 3;  $\Delta(H^{-1}) = 2.9 \cdot 10^{-5}$  oersted

van Alphen effect, then the pattern should have been a superposition of signals from the two specimens. In reality, however, the oscillograms obtained from each specimen differed sharply and were determined by their orientation.

**Fig. 4.** Graphical determination of the period in the reciprocal field for the oscillations shown in Fig. 3;  $\Delta(H^{-1}) = 2.9 \cdot 10^{-5}$  oersted

The second concern—that the Shubnikov-de Haas effect has an influence—is eliminated when one takes into account the circumstance that the current in the specimen circuit is sharply limited by the resistance of the dielectric interlayer of the specimen-capacitor. For the pulse frequency of the magnetic field, the capacitive resistance of the specimen-capacitor is about  $1 \text{ M}\Omega$ ; in this case the current in the specimen-load circuit does not exceed  $10^{-8} \text{ A}$ . The amplitude of the magnetoresistance oscillations when such a current passes through the bismuth coating was several orders of magnitude smaller than the maximum sensitivity of the circuit.

The occurrence of an unwound pickup in connection with oscillations of the magnetic moment of bismuth is also possible; N. V. Zavaritskii drew our attention to this. However, estimates show that the amplitude of such oscillations under the conditions of our experiment does not exceed  $5 \cdot 10^{-7} \text{ V}$ , i.e., is 2-3 orders of magnitude smaller than the observed amplitude.

Thus, it may be confidently asserted that the observed pattern is caused by oscillations of the contact potential difference, directly related to quantum oscillations of the chemical potential in a magnetic field.

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