Magnetic breakdown trajectories in beryllium

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(Submitted July 11, 1975)
Zh. Eksp. Teor. Fiz. 69, 2231–2235 (December 1975)

A sample of beryllium was subjected to fields of ~70 kOe producing magnetic breakdown and measurements were made of oscillations of the susceptibility (de Haas–van Alphen effect) and magnetoresistance. Magnetic breakdown was observed for noncentral extremal sections of a cigar-shaped Fermi surface.

PACS numbers: 75.30.Cr, 75.10.Gm, 71.30.Hr

It was reported earlier[1] that large-amplitude oscillations of the transverse magnetoresistance were observed in beryllium under magnetic breakdown conditions not only for field directions close to $\mathbf{H} \parallel \mathbf{C}$ ($\mathbf{H}$ is the applied magnetic field and $\mathbf{C}$ is the hexagonal axis) but also in a fairly wide range of angles ϑ between $\mathbf{H}$ and $\mathbf{C}$. This was attributed to the appearance of elongated magnetic breakdown trajectories connecting two or three coronets through a cigar-shaped Fermi surface (see Fig. 5 in[2]), whose contribution to the conductivity for relatively short lifetimes τ was comparable with the conductivity due to open trajectories. The relative amplitude of these oscillations should decrease with increasing τ.[3]

It seemed desirable to carry out more accurate, than those reported in[1], measurements of the magnetic frequency F of these oscillations, particularly since, even in[1], we pointed out some disagreement between the results of such measurements and the data for the central section of the cigar Fermi surface $F_c(\vartheta)$, obtained from the de Haas-van Alphen effect.[4]

The magnetoresistance and susceptibility measurements were carried out on the same sample of beryllium and recorded in turn by a single-pen X–Y plotter. A magnetic field was produced in a superconducting solenoid with a small internal gap, where modulation coils were placed (the main purpose of this gap was to create a homogeneous field and, in this particular case, the homogeneity was at least $\pm 1.5 \times 10^{-5}\ \text{cm}^{-3}$). The solenoid winding was made of the KÉTV 2-NT-50 cable of varying diameter from 1.2 mm inside to 0.7 mm outside. The external diameter of the solenoid was 180 mm, its length was 200 mm, and the usable internal diameter was 40 mm. The maximum magnetic field was ~92 kOe for a 113 A current.

The magnetic field was deduced from the current in the solenoid. Direct current was provided by a storage battery through a current regulator (Fig. 1). The output stage of a four-stage composite transistor (emitter follower) consisted of 20 hf KT-803 silicon transistors cooled with running water. The operational-amplifier gain was 10^4 and the negative feedback voltage was provided by a manganin shunt $R_{fb} \sim 10^{-3}\ \Omega$ placed in a kerosene-filled water-cooled container. The control voltage was applied by means of a rheostat R_r made of manganin wire, 0.3 mm in diameter and ~3 m long, supplied from a heating battery. The rheostat wire was wound on a block and rotated by a low-power dc motor through a reduction gear unit; the wire rubbed against an immobile rigid slider; this made it possible to vary the control voltage extremely smoothly. The instability of the current due to the amplifier input noise was ~1 mA for any current (i.e., ~0.8 Oe) and the use of a filter resistor $R_f \sim 0.1\ \Omega$ suppressed all but very slow oscillations (~10 sec) about an average value. The average value of the current was governed by the control voltage whose drift was negligible because the ~10 mA current through the rheostat flowed continuously throughout this operation.

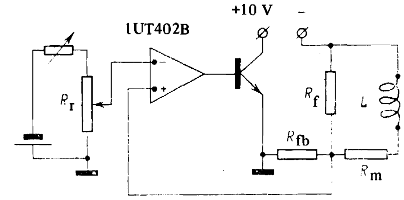

FIG. 1. Block diagram of the power supply of a solenoid L, including a storage battery of 10 V, a composite transistor, a 1UT402B feedback amplifier, a feedback resistor R_{fb}, a filter resistor R_f, a measuring resistor R_m, and a control rheostat R_r.

The voltage across a measuring shunt $R_m = 10^{-3}\ \Omega$, proportional to the current in the solenoid, was applied to the X input of the plotter and measured by a digital voltmeter with an error not exceeding 1.5×10^{-4}. The voltage was first calibrated, by means of the NMR signal of running water,[1)] right up to a field of 80 kOe and this was done to within ±1 Oe. (A special "reverse" cryostat, which made it possible to operate in a "warm" field, was constructed for the water-flow system.) Subject to corrections for the diamagnetic hysteresis loop of the superconducting material of the solenoid winding,[5] this method for measuring the magnetic field on the basis of the solenoid current was preferable to the use of a Hall probe. The relative error in the quantity $F = nH_1H_2/(H_2 - H_1)$ (n is the number of periods between H_1 and H_2) was, in fact, governed only by the error in the reading of the positions of the minima in the record of the signal, which did not exceed 0.2 mm for $\vartheta = 0$ when the length of the whole record was about 300 mm, so that the error in F was of the order of 1.5×10^{-3}; for higher values of ϑ, the error was somewhat higher.

The investigated sample was a beryllium single crystal cut in the basal plane by spark machining and its dimensions were $\sim 3 \times 0.25 \times 0.28$ mm. The orientation was determined by x-ray diffraction. The resistance ratio was $\rho_{300^\circ K}/\rho_{4.2^\circ K} = 105$. The sample had a small side projection which carried a ~ 1 mm pick-up coil for measuring the susceptibility; the coil consisted of 500 turns of ~0.02 mm diameter copper wire on a cut beryllium bronze cylinder whose walls were also ~0.02 mm thick. A compensating coil was somewhat larger and had about 50 turns.

The de Haas–van Alphen effect was measured by the modulation method. The magnetic field was modulated by a sinusoidal signal; the modulation amplitude was

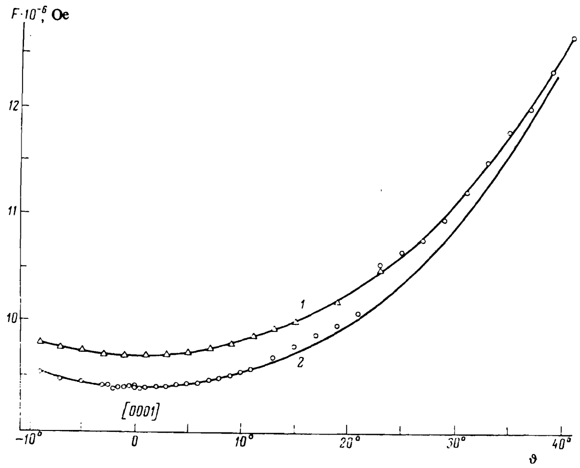

FIG. 2. Dependences of the magnetic frequency F on the angle ϑ between H and C. The continuous lines represent the dependences $F(\vartheta)$ for noncentral (1) and central (2) sections determined on the basis of the de Haas–van Alphen effect; the triangles are used to denote several control points and the circles are the results of measurements of the magnetoresistance oscillations.

±5 Oe and the frequency was 343 Hz. The pick-up coil signal was applied to a selective amplifier and to a detector and then to the Y input of the recorder. The constant component in the rectified signal, due to undercompensation of the pick-up coil, was balanced out by a potentiometer at the recorder input.

The magnetoresistance was measured by a four-contact method. The contacts were small beryllium bronze springs soldered to a plate made of laminated glass-fiber-reinforced Textolite, which served as the sample support. The potential contacts were located so as to minimize any possible Hall emf. The voltage signal was amplified with a photoamplifier and applied to the Y input of the recorder. The influence of the anomalous thermo-emf, which was a nonlinear function of the current,[6] was eliminated by using a sufficiently small measuring current $I \sim 20$ mA. A sample was rotated in a magnetic field of the $I \perp H$ configuration by a worm-drive mechanism. All the measurements were carried out at 4.2°K.

The results of the measurements are plotted in Fig. 2. The continuous curves represent the dependence $F(\vartheta)$ in the de Haas-van Alphen effect for central (curve 2) and extremal noncentral (curve 1) sections of the cigar-shaped Fermi surface, whereas the triangles are the control points of $F(\vartheta)$ deduced from the susceptibility measurements. In these measurements, the value of $F(0)$ was $(9.71 \pm 0.01) \times 10^6$ Oe, in good agreement with the result reported in[7]. The circles give the values of the frequency $F(\vartheta)$ deduced from the magnetoresistance oscillations. As pointed out in[1], the amplitude of these oscillations fell sharply away from the angle $\vartheta = 0$ but the oscillations were observed right up to $\vartheta \sim 50°$, i.e., as long as elongated magnetic breakdown trajectories, similar to those shown in Fig. 5 in[2], were still possible. Beginning from $\vartheta \sim 10°$, a significant modulation of the signal amplitude (beats) was observed, which indicated a contribution of different sections of the cigar to the oscillations. Since the measured points corresponded to the leading frequency, the jumps of these points to the upper curve at $\vartheta = 22°$ indicated that the contribution of the extremal noncentral orbit became predominant at this angle. Clearly, the magnetic breakdown in the noncentral orbit started at an even lower value of the angle ϑ. Hence, we concluded that the separation between a noncentral orbits of the cigar should be fairly small and, in any case, not much greater than the dimensions of the round projections along the C axis. On the other hand, it should not be less than this dimension because magnetic breakdown in noncentral orbits was not observed by Watts[4] or by us[8] for $\vartheta = 0$. This result was fairly close to the calculations of Terrell,[9] who placed the maximum section of the cigar at the top of a coronet.

Using the graphical representation of the Fermi surface of beryllium,[10] we could assume that the distance between these sections was 0.29 ± 0.03 au, i.e., about a quarter of the length of the whole cigar. It was interesting to note that this distance could not be measured by any other experimental method.

It should also be pointed out that the positions of the experimental points in the range $\vartheta = 12-18°$ suggested that, in this range of angles ϑ, the oscillations were dominated by the magnetic breakdown orbits in intermediate nonextremal sections of the cigar confined to narrow "necks" in the coronet, as shown in Fig. 5b in[2].

APPENDIX

Since magnetic breakdown oscillations have a sufficiently large amplitude for their use in magnetometry[11] (in this case, the effective magnetic field standard would be the Fermi surface section), we should mention here the more accurate values of the cigar sections obtained by measuring oscillations of the anomalous thermo-emf[6] in a pure beryllium whisker with resistivity ratio $\rho_{300°K}/\rho_{4.2°K} \sim 1000$, used earlier in[8]. In this application, the anomalous thermo-emf could be measured more conveniently and accurately than the resistivity because the oscillations were symmetric relative to zero so that we could use a wider range of magnetic fields and a correspondingly larger number of periods. Thus, a record showed clearly periods beginning from $n = 148$ right up to $n \gtrsim 400$ ($n = 0$ for $H \sim \infty$). The results of these measurements were as follows: central section $F_c = (9.422 \pm 0.003) \times 10^6$ Oe, beat frequency $F_{nc} - F_c = (0.287 \pm 0.002) \times 10^6$ Oe, and hence the noncentral orbit section was $F_{nc} = (9.709 \pm 0.005) \times 10^6$ Oe.

The author is grateful to B. N. Samoĭlov and N. A. Chernoplekov for their interest and encouragement.

1)The author is grateful to E. N. Lysenko for help in these measurements.

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Translated by A. Tybulewicz
241