Quantum oscillations of the thermoelectric power and of the Nernst effect on magnetic-breakdown trajectories in ruthenium

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The thermoelectric power and the Nernst effect of the purest known ruthenium single crystals with $\rho_{273\,\mathrm{K}}/\rho_{4.2\,\mathrm{K}}$ as high as 3000 were measured at 4.2 K and in magnetic fields up to 90 kOe under magnetic-breakdown conditions. Giant oscillations of the thermoelectric power and of the Nernst effect, due to formaion of a narrow layer of open magnetic-breakdown orbits, are observed.

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It was shown theoretically in a recent paper[1] that effects nonlinear in the electric fields and connected with electron "heating" can appear in the kinetic properties of metals under magnetic-breakdown conditions. One of the principal requirements for observing these effects is that the magnetic breakdown lead to formation of a narrow layer of open trajectories. Since the results of Ref. 1 are of fundamental importance for the understanding of the behavior of conduction electrons under magnetic-breakdown conditions, it is of interest to search for objects on which to verify experimentally the results of the theoretical calculations.

We have therefore undertaken measurements of the thermoelectric power and of the Nernst effect in the transition metal ruthenium, which was shown by galvanomagnetic measurements to experience magnetic breakdown between the multiply connected hole surface and the "lens," which are separated by a small energy gap of spin-orbit origin.[2,3] The measurements of just thermoelectric effects is the most convenient method of finding narrow layers of magnetic-breakdown trajectories, inasmuch as according to Refs. 4–6, under magnetic-breakdown conditions, giant oscillations of the thermoelectric power can appear under magnetic-breakdown conditions and can undergo an anomalously large (by several orders) growth. It can be assumed that a similar action of magnetic breakdown will appear also in the Nernst-thermal analog of the Hall effect.

The measurements were performed at $T = 4.2$ K in magnetic fields up to 90 kOe on samples cut from single crystals with ratios $\rho_{273\mathrm{K}}/\rho_{4.2\mathrm{K}}$ up to 3000 by the electric-spark method followed by electric polishing. The samples in the form of square rods measuring $14\times0.5\times0.5$ mm were oriented with the long axis along the principal crystallographic directions ($\langle 0001\rangle$, $\langle 10\bar{1}0\rangle$, $\langle 12\bar{1}0\rangle$). The temperature gradient ∇T was produced by a nichrome-wire placed on one end of the sample, and monitored in the absence of a magnetic field with a differential copper-constantan thermocoupule. Its value ($\approx$0.9 K/cm) was chosen from the condition that the oscillation amplitude have a maximum. Measurements of the Nernst effect were carried out at two opposite directions of the magnetic field, thereby eliminating the thermoelectric-power contribution that results inevitably from the inaccurate placement of the "Nernst" potential contacts. The magnitude of this contact was smaller by two orders of magnitude than the Nernst emf. The dependence of the thermoelectric power and of the Nernst emf on the voltage and magnitude of the magnetic field was recorded automatically with an x-y potentiometer with sensitivity up to 10^{-8} V.

We present below the results of measurements in an experimental geometry with $\nabla\mathbf{T}\|\langle 0001\rangle$ and $\mathbf{H}\|\langle 2\bar{1}\bar{1}0\rangle$. The point is that according to Refs. 2 and 3 it is precisely at this direction of the magnetic field that magnetic breakdown between the "neck" and the "lens" produces in ruthenium a layer of open trajectories located in the *LMML* plane of the Brillouin zone and directed perpendicular to the $\langle 0001\rangle$ axis (the shapes of these trajectories are given in Refs. 2 and 3).

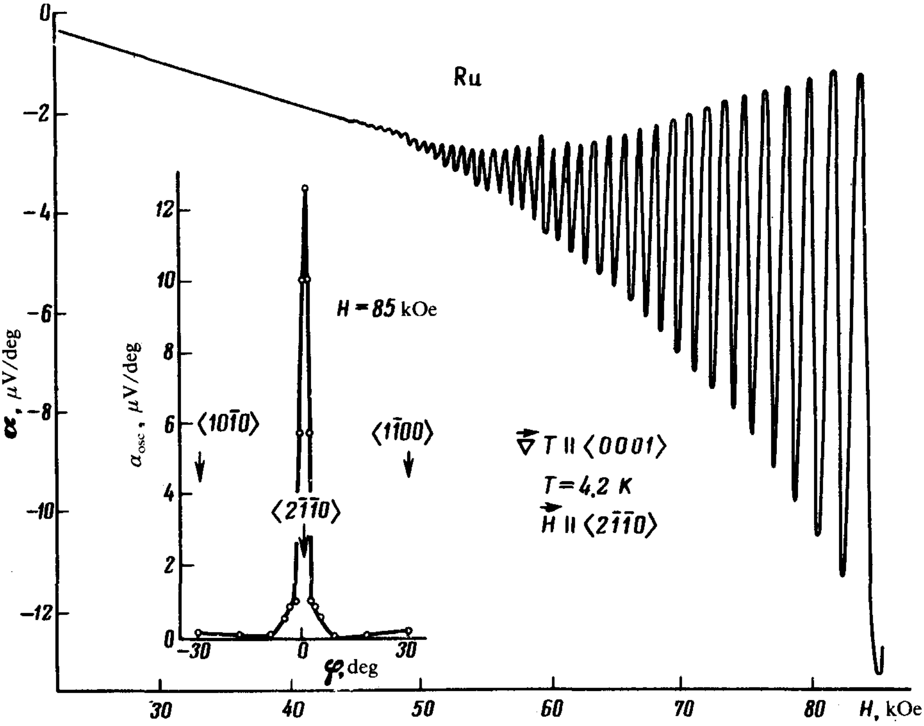

FIG. 1. Dependence of the thermoelectric power on the magnetic field at $\mathbf{H}\|\langle 2\bar{1}\bar{1}0\rangle$. Insert-anisotropy of the oscillation amplitude.

Figure 1 shows the dependence of the thermoelectric power $\alpha(H)$ on the value of the magnetic field at $\mathbf{H}\|\langle 2\bar{1}\bar{1}0\rangle$. It is seen that in strong magnetic fields the main contribution in this dependence is the one due to the magnetic breakdown. The frequency of the observed thermoelectric-power oscillations is $(4.05 \pm 0.05)\times 10^6$ Oe and agrees well with the frequency 4.1×10^6 Oe of the magnetoresistance oscillations and with the de Haas–van Alphen frequency (4.0×10^6 Oe) corresponding to the area of the extremal intersection of the "lens" with the *LMML* plane.[7] The agreement between the oscillation frequencies shows that the magnetic-breakdown layer of the trajectories passes through the "lens" and lies precisely in the *LMML* plane. We note also the good agreement between the frequencies of the thermoelectric power at **H**|| $\langle 2\bar{1}\bar{1}0\rangle$ and the result $(4.01 \pm 0.05)\times 10^6$ Oe of a recent paper.[8]

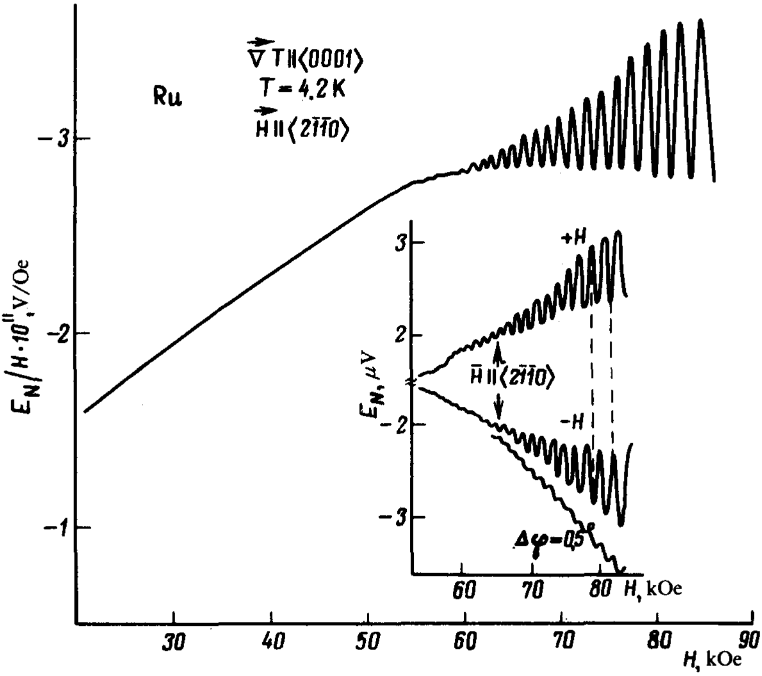

FIG. 2. Dependence of the Nernst emf on the magnetic field at H|| ⟨2110⟩. The insert shows a plot of the Nernst-effect signal at different directions of the magnetic field.

The amplitude of the magnetic-breakdown oscillations α_{osc} of the thermoelectric power is quite large and exceeds by almost two orders of magnitude both the "classical" thermoelectric power of ruthenium (at $H = 0$) and the amplitude of the magnetic-breakdown oscillations of the resistance; this agrees with the theoretical predictions.[4] If the layer of open magnetic-breakdown trajectories is eliminated by deflecting **H** away from the $\langle 2\bar{1}\bar{1}0\rangle$ axis, the amplitude of the oscillations decreases sharply (see the insert in Fig. 1). It is seen that deflection of the vector **H** from the $\langle 2\bar{1}\bar{1}0\rangle$ axis by merely 2° decreases the oscillation amplitude by one order of magnitude, and a deflection of 10° decreases the amplitude by a factor of 250.

Measurements of the Nernst effect have revealed an analogous oscillatory picture, which is shown in Fig. 2. The oscillations of the Nernst emf at mutally opposite directions of the magnetic field, in contrast to the thermoelectric power, are in counterphase. The frequency of the oscillations at **H**|| $\langle 2\bar{1}\bar{1}0\rangle$ agrees with the frequency of the thermoelectric-power and magnetoresistance oscillations at the same direction of **H** and is equal to $(4.05 \pm 0.05)\times 10^6$ Oe. As seen from Fig. 2, a negligible deviation of the magnetic field from the $\langle 2\bar{1}\bar{1}0\rangle$ axis leads to an abrupt decrease of the oscillation amplitude, in analogy with the situation for the thermoelectric power and the magnetoresistance.[3]

Thus, the presented experimental fact offer evidence that the layer of the open magnetic-breakdown trajectories in ruthenium is quite narrow. According to our estimates its relative width is $\delta p_z/p_z \sim 10^{-2}$ (p_F is the characteristic Fermi momentum of the electrons in ruthenium). This circumstance, as well as the large amplitude of the magnetic breakdown oscillatory effects makes ruthenium a promising material for observing the nonlinear effects predicted in Ref. 1.

We note in conclusion that, to our knowledge, these are the first observations of oscillations of the Nernst effect under magnetic-breakdown conditions.

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