and V. A. Liubimov for valuable advice, V. P. Dzhelepov for taking part in the work with the accelerator, and V. G. Zaitseva, N. S. Konoplev, I. A. Sosunov, V. M. Golubchikov, and V. N. Luzin for taking part in reducing the data.

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SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 4 OCTOBER, 1958

TEMPERATURE ANOMALY IN THE RESISTANCE AND THE HALL EFFECT IN GOLD

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Submitted to JETP editor November 26, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 836-842 (April, 1958)

The dependence of the Hall effect on temperature and magnetic field was studied in samples of gold with normal and abnormal temperature dependence of the resistance. A jump was observed in the Hall constant of an "anomalous" sample at a field of 8 kOe. The magnitude of the jump increased with decreasing temperature. A field strength of 8 kOe is the value at which the anomalous temperature dependence of the resistance vanishes.

1. INTRODUCTION

As is well known (see the references to the literature in Ref. 1) the Ohm's-law resistance in a series of metals (Au, Cu, Ag, Mg and, apparently, Mo)[2] shows an anomalous temperature dependence, consisting in the fact that as the temperature is lowered, the resistance of these metals falls, reaches a minimum at some temperature denoted by T_{min}, and then begins to rise. It was noticed in a series of articles[2-5] that the dependence of this rise on temperature could be satisfactorily represented in the form

$$\frac{\Delta r}{r_{min}} = \frac{r(T) - r_{min}}{r_{min}} = \text{const} + a \log(1/T) \quad \text{for } T < T_{min},$$

where r_{min} is the resistance at T_{min}. In the work of Ref. 5 carried out by us on gold samples, it was shown that $\Delta r/r_{min}$ decreased in a magnetic field and reached zero for some value H_k. In the same work it was noticed that, for a value of the field equal to H_k, a discontinuous change in the slope of the Hall electric field $E_y(H)$ was observed.

It was of interest to carry out a more detailed investigation of the Hall effect in dependence on temperature and magnetic field using gold samples with both normal and anomalous-type resistances, which allowed us to clarify the connection between anomalous resistance and the Hall effect.

2. METHOD OF MEASUREMENT

To prepare samples we had at our disposal two batches of gold naturally occurring: a foil of 0.05 mm and a plate 1 mm thick. Both batches were 99.99% pure. A spectral analysis of the gold is given in Table I.

The sample Au-1, together with current and potential leads was cut out of the foil, as shown in

Fig. 1. The thick plate was rolled to a thickness of 0.05 mm. A sample Au-4 was prepared from this foil. The samples had identical geometrical dimensions $0.05 \times 14 \times 30$ mm^3. To get rid of surface dirt, the samples were immersed in aqua regia.

TABLE I

Admixtures	Samples	
	Au-1	Au-4
Ag	$8 \cdot 10^{-5}$	$7.5 \cdot 10^{-5}$
Cu	$1 \cdot 10^{-5}$	$2.4 \cdot 10^{-5}$
Fe	$4.4 \cdot 10^{-7}$	$5 \cdot 10^{-7}$
Bi	$<3 \cdot 10^{-7}$	$<3 \cdot 10^{-7}$
Pb	$2.5 \cdot 10^{-7}$	$5 \cdot 10^{-7}$
Ni	$1.2 \cdot 10^{-7}$	$1.6 \cdot 10^{-7}$
Mg	$3 \cdot 10^{-7}$	$5 \cdot 10^{-7}$
Sb	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$
Si	$1.5 \cdot 10^{-7}$	$2 \cdot 10^{-7}$

The value of the residual resistance r_{min}/r_{295} for Au-1 was equal to 0.00971 and for Au-4, 0.00893.

Measurement of the Hall electric field was carried out at room temperature, temperatures of liquid nitrogen, hydrogen and helium and in the very low temperature region, reached by the method of adiabatic demagnetization of ferric-ammonium alums. Construction of the apparatus for obtaining very low temperatures, making it possible to carry out galvanomagnetic measurements at these temperatures, was described previously[5] by us. In the present work, the only change introduced was in the mounting of the sample (Fig. 1). To the

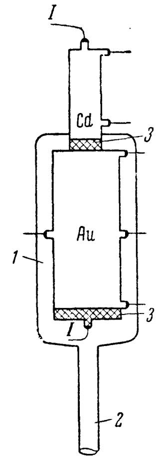

FIG. 1. Mounting of the gold and cadmium specimens.

copper plate 1, which ended at the cooling system 2, we soldered BiCd* 3 to one of the ends of the sample studied. To the other end of the gold sample we fixed a specimen of cadmium of the same origin as those in Refs. 6 and 7. It was used in determining the temperature of gold in the region $0.05 - 0.5°$K, in which it was assumed that the curve of critical fields of this specimen coincided with the analogous curves previously measured for the other specimens.[6,7] The critical fields of cadmium were determined from the curves of the appearance of resistance upon destruction of superconductivity in a magnetic field. Measurements were carried out with a potentiometer set up. The current through the sample was equal to 0.1 amp, with the specimen of cadmium in series with that of gold. Comparison of the curve of critical fields with the data of Refs. 6, 7 made it possible to determine the difference in temperature between the cadmium and the alum block. This difference was negligible for a current of 0.1 amp. Therefore, in our measurements the temperature of the gold sample was taken equal to the temperature of the alum block. The inaccuracy introduced in this way did not influence the results of the measurements essentially. The temperature of the alum block was determined by measuring its susceptibility, carried out by a ballistic method.

In the study of the Hall effect in metals of group I, the essential difficulty is the small magnitude of the measured electric field, connected with the small value of the Hall constant. In order to increase the Hall electric field, higher currents and stronger magnetic fields are usually used. However, in our case such a way was not possible because use of currents ($I > 0.3$ amp) led to considerable overheating of the sample and to a rapid rise in temperature of the alum block, and the need to study the dependence of the Hall effect on magnetic field required that the measurements be carried out in both strong and weak fields. As a consequence, it was necessary to increase the sensitivity of the measuring scheme. For this, a two-cascade photoelectric multiplier FEOU-15 of the Kozyrev type[8] was used.

In order to increase the sensitivity and stability of the work still further, this multiplier was subjected to several changes. Thus, for example, the low power illumination lamp (0.5 W) was replaced by a stronger one (2 W). The zeroing apparatus was completely changed, and the insulation of the chassis wiring was improved. The multiplier was included in a KL-48 potentiometer set up. Measurement of the Hall electric field in the very low temperature region was carried out with a sensitivity of 2×10^{-19} V/(mm/m) of the scheme and a field through the sample of 0.1 amp. At temperatures

*A eutectic alloy 60% Bi + 40% Cd; $T_{melt} \approx 140°$C, $T_k = 0.55°$K.

above 1°K it was possible to carry out the measurements at a higher current (0.3 amp) which made it possible to decrease the sensitivity of the scheme to 3×10^{-9} v/(mm/m).

At such high voltage sensitivities of the measuring apparatus, random electric fields began to show up strongly. The largest of these was the electric field induced on the potential ends of the sample by fluctuation in the magnetic field. In order to attain sufficient accuracy in the measurement of the Hall electric field, a number of special measures were taken. Thus, in order to exclude large fluctuations, a stabilizer of the magnetic field* was worked out, which was distinctive because of the following. Fluctuations in the current of the generator feeding the electromagnet, produced a change in the difference of potentials on a resistor placed in series with the windings of the electromagnet. These changes, after considerable amplification, corrected the current of the generator, making it possible to keep up the feeding current (up to 150 amp) with an accuracy of 0.01%.

In order to get rid of the influence of small fluctuations of the magnetic field, an additional loop was placed in series with the Hall potential leads. This loop was outside the air Dewar, between the poles of the electromagnet. The turning of this loop relative to the magnetic field made it possible to compensate almost completely for the induced alternating electric fields.

In order to exclude from the measured electric field the thermoelectric field and the difference of potentials $E_x(H)$ arising because of the asymmetrical disposition of the Hall potential terminals, the usual commutation of the measuring current and magnetic field was carried out.

The relative error of measurement, beginning with a field of 8 kOe, did not exceed 1%.

3. RESULTS OF THE MEASUREMENTS

Study of the temperature dependence of the resistance showed that, whereas the resistance of the Au-1 sample rose noticeably with the lowering of the temperature (Fig. 2), the growth of the resistance of the Au-4 sample in the region 4.2 — 1.4°K was less than the error of measurement (0.2%). In the study of the depth of the temperature minimum resistance with respect to its dependence on magnetic fields, $[r_{0.07;H} - r_{\min;H}]/r_{\min;H}$, it turned out that for Au-1 it became zero for a value of the field H = 8 ± 0.5 kOe, in good agreement with the values H_k obtained in Ref. 5. Measurements of the dependence of the Hall effect on magnetic field were carried out for temperatures of 295.77; 20.4; 10.1; 4.2 and 0.07°K. Relative to the final temperature, it should be remarked that in the region below 1°K measurements took place with a slow rise in temperature of the gold sample, as a consequence of which, we took the mean between the initial and final temperatures as the temperature of the experiment. Usually, during the time in which the dependence of $E_y(H)$ on fields of 1.5 to 18.3 kOe was obtained, the temperature of the sample rose from 0.05°K to 0.1°K.

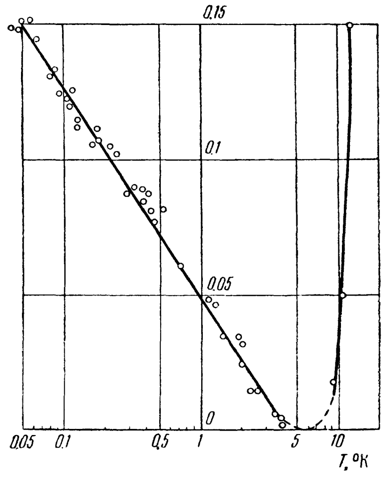

FIG. 2. Specimen Au-1. Dependence of $\frac{r(T) - r_{\min}}{r_{\min}}$ on temperature.

Results of the dependence of the Hall electric fields on magnetic fields for the samples Au-4 and Au-1 are given in Figs. 3 and 4 for a series of temperatures. The Hall constant R(H) for Au-1 is given on Fig. 5, where

$$R = E_y d / HI \qquad \text{for } H < 8\,\text{kOe},$$

$$R = E_y d / (H - 8000) I \qquad \text{for } H > 8\,\text{kOe},$$

where d is the thickness of the sample and I is the current through the sample.

In Table II the numerical values of the Hall constant for Au-1 and Au-4 are given in the CGSM system for all temperatures studied.

Analogous results were obtained with a series of other gold samples.

4. DISCUSSION OF RESULTS

Measurements showed that the Hall constant of the sample Au-4, which did not have an anomaly in the curve r(T), did not depend on the magnetic field up to 18 kOe at all temperatures. In the region from 77 to 20.4°K its value rose 25% and then remained constant with further decrease in temperature. For the sample Au-1, having an anoma-

*The author is grateful to A. N. Vetchinkin for working out the stabilizing scheme.

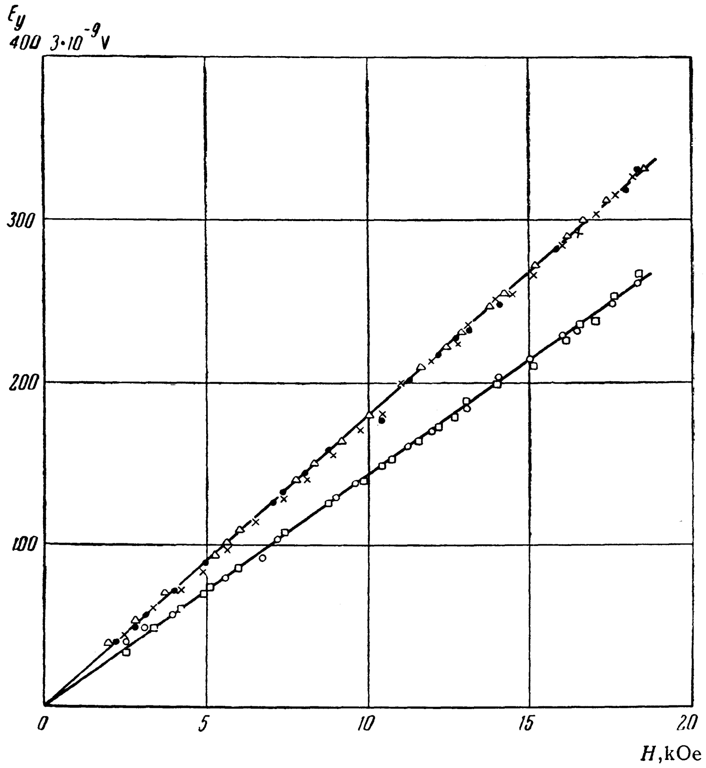

FIG. 3. Sample Au-4. Dependence of $E_y(H)$: o – T = 295°K; □ – T = 77°K; Δ – T = 20.4°K; • – T = 4.2°K; × – T = 1.45°K.

lous resistance, in fields of less than 8 kOe, the Hall constant also did not depend on magnetic field and here the Hall constants for Au-1 and Au-4 coincided within the limits of error for all temperatures.

In a field equal to 8 kOe, the Hall constant of the sample Au-1 underwent a jump, the magnitude of which increased with decreasing temperature. The dependence of these jumps $\Delta R = R(H > 8\,kOe) - R(H < 8\,kOe)$ on temperature is shown in Fig. 6.

Thus, in the gold sample which had an anomaly in the curve r(T), an anomaly was also observed in the Hall effect. In comparing the anomaly in the resistance with the anomaly in the Hall effect, one cannot help but notice that ΔR, upon extrapolation with respect to temperature, becomes zero for T ≈ 140°K, where T_{min} lies between 4 and 6°K. However, T_{min} may be a characteristic point for an anomalous branch of resistance. One can imagine a temperature at which the sum of two processes — one connected with the fall and the other with the rise of the resistance with decreasing temperature — has a minimum. From this point of view, the temperature at which ΔR becomes zero, it seems to us, may definitely characterize anomalous galvanomagnetic properties of the metal.

It is of interest to compare results of this work with those of other workers.[9,10] In these works, measurements of the Hall effect have been carried out for gold samples for a wide range of temperatures. But in both Ref. 9 and Ref. 10 these measurements were carried out for only one value of the magnetic field.

TABLE II. $R \times 10^{-4}$ CGSM

T°K	Au - 1		Au - 4	
	H < 8 kOe	H > 8 kOe	H < 8 kOe	H > 8 kOe
295	6.7	6.7	6.75	6.75
77	6.7	6.95	6.75	6.75
20.4	8.5	9.3	8.4	8.5
10	8.5	10.1		
4.2	8.5	10.6	8.4	8.4
1.4	8.5	11.15	8.35	8.5
0.075	8.5	12.5		

Comparing results of these two works with results of this work, it may be assumed that the anomalous rise in the Hall constant with decreasing temperatures observed in Ref. 9 is connected with the fact that these authors used a field of 20 kOe, larger than H_k. That is, in that region of fields, where an anomalous change in the Hall constant with temperature was observed in our case. The fact that the anomalous behavior of the Hall constant was not observed by the authors of Ref. 10 is connected with the fact that their measurements took place in a field of 8 kOe, where there is not yet an anomalous temperature dependence of the Hall constant.

In conclusion, it is my pleasant duty to express sincere gratitude to Academician P. L. Kapitza for the interest that he showed in this work, to N. E.

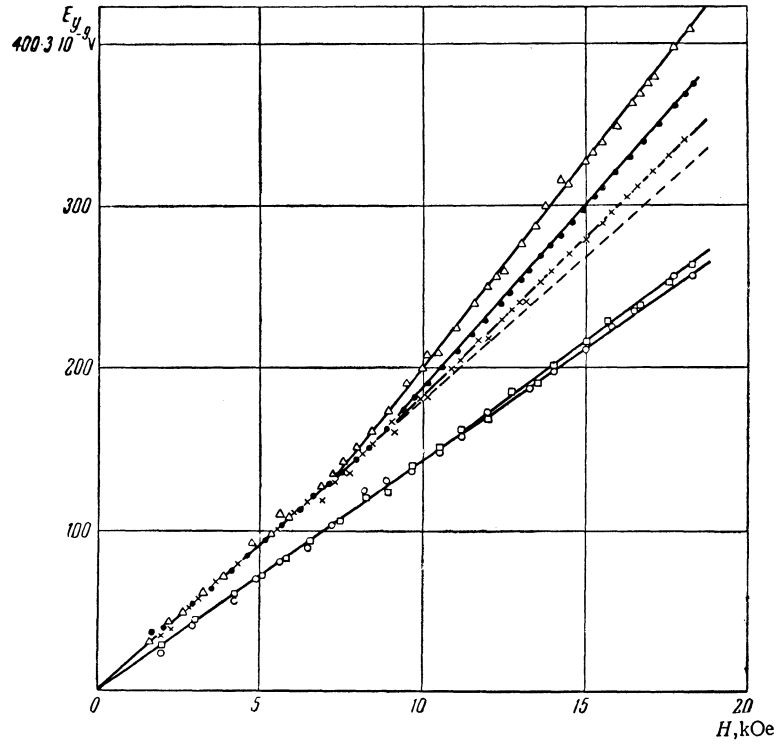

FIG. 4. Sample Au-1. Dependence of $E_y(H)$: o – T = 295°K; □ – T = 77°K; × – T = 20.4°K; • – T = 4.2°K; Δ – T = 0.07°K.

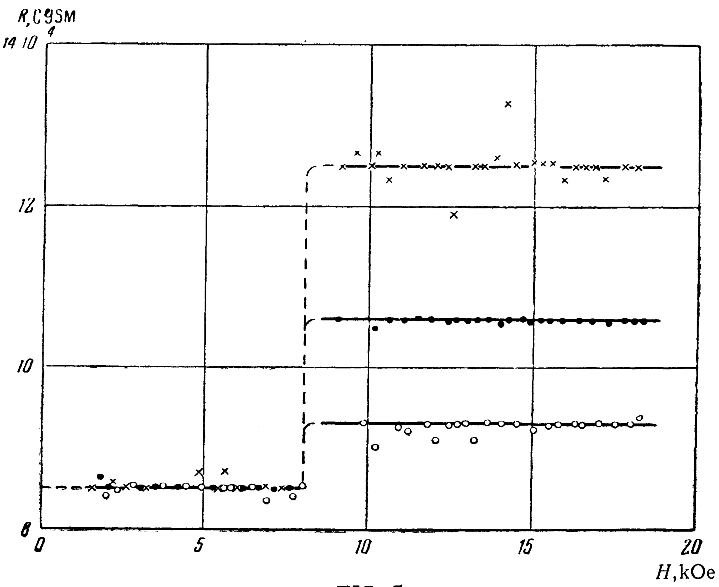

FIG. 5.

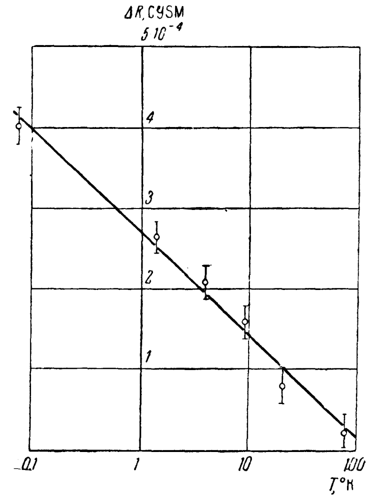

FIG. 6.

FIG. 5. Sample Au-1. Dependence of R(H): o – T = 20.4°K; • – T = 4.2°K; × – T = 0.07°K.
FIG. 6. Sample Au-1. Dependence of ΔR(T).

Alekseevskii for valuable advice and suggestions and to G. E. Karstens for carrying out the spectral analysis of the samples.

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SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 4 OCTOBER, 1958

NUCLEAR INTERACTION IN PHOTOGRAPHIC EMULSION ACCOMPANIED BY LARGE ENERGY TRANSFER TO THE ELECTRON – PHOTON COMPONENT

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Submitted to JETP editor November 26, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 843-848 (April, 1958)

A nuclear interaction event with primary energy $E_0 = 250^{+250}_{-125}$ Bev in which about 200 Bev was carried away by one of the π^0-mesons is investigated in detail. The lower limit of energy transferred to the soft component is approximately 30% of the total shower energy.

DATA on interactions between particles with energy of the order of few hundred Bev and atomic nuclei obtained by means of a cloud chamber[1] indicate the existence of very large fluctuations of the fraction of energy carried away by photons. The minimum value of the energy transferred to photons was found to be equal to a few tenths of a percent of the primary energy. The problem of the maximum energy transfer to the soft component is also of considerable interest.

In a stack of stripped Ilford G-5 emulsions exposed at the altitude of 2.5 km during the Italian expedition of Prof. C. F. Powell in 1955, we found and studied in detail an interaction event of the type 1 + 12n characterized by an unusually large fraction of the energy carried away by the electron-photon component. The path length of particles in each emulsion layer was ~1.5 cm and the total

TABLE I. Angular distribution of penetrating particles

No. of particles	θ (first method)	θ (second method)	No. of particles	θ (first method)	θ (second method)
	$\theta_i \cdot 10^3$, radians	$\theta_i \cdot 10^3$, radians		$\theta_i \cdot 10^3$, radians	$\theta_i \cdot 10^3$, radians
1	40	2.5	9	245	235
2	40	11	10	280	265
3	40	32	11	430	420
4	80	67	12	510	525
5	104	95	$\theta_{1/2}^{-1}$	6	7
6	140	135	$1/\theta_{min}$	25	400
7	190	160	$\Sigma 1/\theta_i$	125	580
8	218	220			