

GALVANO-MAGNETIC EFFECTS IN METALS WITH NEARLY EQUAL NUMBERS OF ELECTRONS AND HOLES

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A general theory of galvanomagnetic effects in metals, which explains the asymptotic behavior of the resistance tensor ρ_{ik} in high magnetic fields, is developed in reference 1. It has been shown that all metals (with closed Fermi surfaces) can be divided into two groups; one (Cu, Na, In, Al, . . .) with unequal number of electrons (n_1) and holes (n_2), and one (Bi, Be, Zn, Mg, . . .) with $n_1 + n_2$.*

Besides these limiting cases, we would expect approximate equality of the number of electrons and holes (i.e., $n_1 \approx n_2$) for a number of metals with small impurity content.² The relative difference $\Delta n/n$ ($\Delta n = n_1 - n_2$; $n = (n_1 + n_2)/2$) is a parameter which enables us to express the dependence of the resistance tensor on the magnetic field.

A calculation analogous to that described in reference 1 leads to the following results for the resistance ρ and the Hall constant R :

$$\rho \approx \rho' \frac{(H/H_1)^2}{1 + \left(\frac{\Delta n}{n} \frac{H}{H_1}\right)^2}, \quad H \gg H_1; \quad (1)$$

$$R \approx \frac{1}{nec} \frac{a + \frac{\Delta n}{n} (H/H_1)^2}{1 + \left(\frac{\Delta n}{n} \frac{H}{H_1}\right)^2}, \quad H \gg H_1; \quad (2)$$

$H_1 \sim m^*c/et_0$ (the notation is the same as in reference 1). The parameters ρ' , H_1 , and a depend on the angle between the magnetic field and the crystallographic axes, with a on the order of unity.

From (1) and (2) we obtain

$$\rho = \begin{cases} \rho' (H/H_1)^2 & (H_1 \ll H \ll H_1 |n/\Delta n|) \\ \rho' (n/\Delta n)^2 & (H \gg H_1 |n/\Delta n|) \end{cases}, \quad (3)$$

$$R = \begin{cases} \frac{a}{nec} + \frac{\Delta n}{n^2 ec} (H/H_1)^2 & (H_1 \ll H \ll H_1 |n/\Delta n|) \\ \frac{1}{\Delta nec} & (H \gg H_1 |n/\Delta n|) \end{cases} \quad (4)$$

We note furthermore that the present results agree well with the experiments of Alekseevskii, Brandt, and Kostina² on bismuth with small concentrations of impurities. In fact, independently of the law of dispersion, the ratio $HE_y/E_x = H^2 R/\rho$ (see reference 2) varies linearly with the square of the magnetic field, and the sign of the coefficient of H^2 is determined by the sign of Δn .

*Note added in proof (September 1, 1958). Recent results of I. M. Lifshitz and V. G. Peschanskii on the one hand, and of N. E. Alekseevskii and Iu. P. Gadukov on the other, show that the division of metals into two groups is very provisional.¹ Apparently many metals have open Fermi surfaces.

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² Alekseevskii, Brandt, and Kostina, Dokl. Akad. Nauk SSSR **105**, 46 (1955).

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TRANSITION FROM THE ANTIFERROMAGNETIC INTO THE FERROMAGNETIC STATE IN CoSO_4

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WE have investigated, jointly with Karasik,¹ the magnetic properties of anhydrous polycrystalline CoSO_4 . We have established that this substance goes into an antiferromagnetic state near 15°K. In the present investigation we prepared single crystals of anhydrous CoSO_4 by weighing approximately 1.5 milligrams, using a procedure previously described.^{2,3} The magnetic properties of these single crystals have been investigated at temperatures from 1.3 to 70°K. The crystals were obtained in bipyramidal form. The measurements were made along the axis joining the vertices of the pyramid (the c axis) and along axes that are coincident with the sides of the base

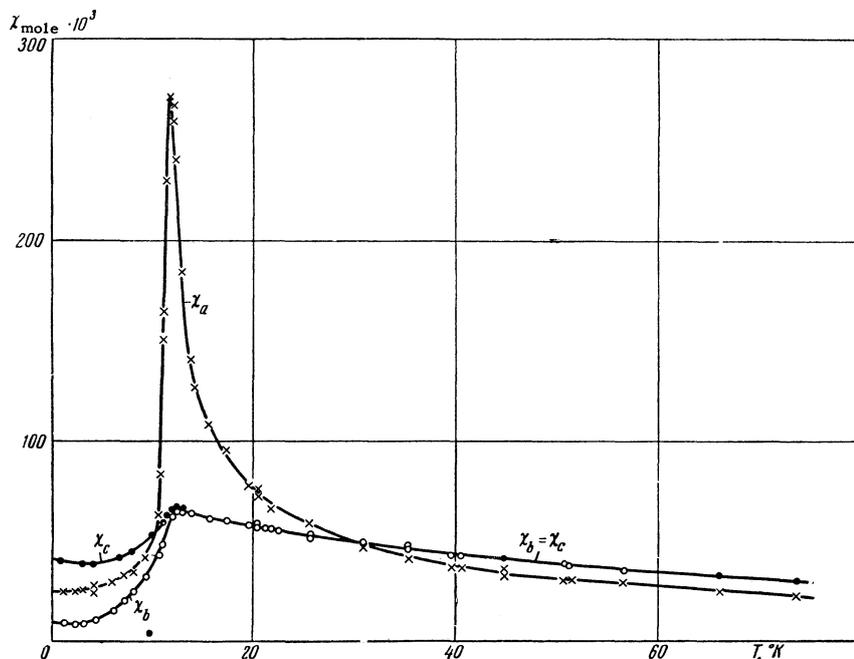


FIG. 1. Temperature dependence of molar susceptibility of single crystal of CoSO_4 .

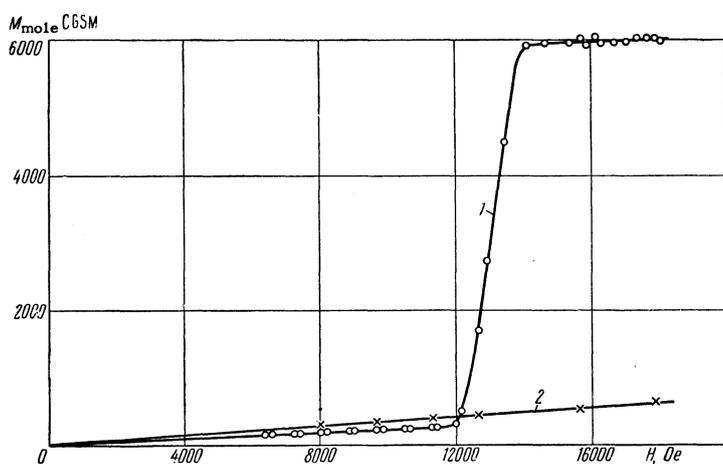


FIG. 2. Dependence of molar magnetic moment of CoSO_4 on the magnetic field at $T = 4.2^\circ\text{K}$. 1) along a axis, 2) along b axis.

(the a axis corresponds to the smaller side and the b axis to the larger).

The magnetic susceptibility is independent of the field at all temperatures, up to fields of ~ 4 kilo-oersteds. The measured values of the susceptibility along all three axes of the crystal are shown in Fig. 1. The character of the resultant curves confirms that CoSO_4 goes into an anti-ferromagnetic state at $T_N = 12^\circ\text{K}$. Attention must be called to the very sharp susceptibility peak along the a axis. It is probably due to the character of splitting of the Co^{++} in the crystal field. Another feature of the results is that as $T \rightarrow 0^\circ\text{K}$ the susceptibility does not tend to zero along any of the axes.

The most interesting are the results obtained in strong fields. We have found that while the susceptibility along the b and c axes is independent of the field up to 18 kilo-oersteds, the magnetic

properties along the a axis exhibit a sharp anomaly. Figure 2 shows the dependence of the molar magnetic moment on the field for two directions (a and c axes) at 4.2°K . We see that when a field is applied along the a axis the moment increases linearly until the field reaches 12 kilo-oersted. Increasing the field one kilo-oersted more causes a sharp jump in the moment, to $\sim 6,000$ cgs magnetic units, followed by a continuing very slight rise. The observed anomaly is obviously connected with the reversal of the magnetization vectors of the sublattices and the transition of the substance from anti-ferromagnetic into ferromagnetic state. Two interesting facts should be noted here. First the ferromagnetic moment does not reach saturation even at ~ 18 kilo-oersteds. Second, the value of the ferromagnetic moment amounts to merely 30% of the nominal moment, calculated under the assumption that

the orbital moments are completely frozen.

An anomaly analogous to that observed by us for CoSO_4 was previously observed for FeCl_2 by Shalyt⁴ in polycrystals and by Bizette et al.⁵ in single crystals. However, FeCl_2 is a layered antiferromagnet with strong ferromagnetic interaction inside the layer and weak antiferromagnetic interaction between layers, a fact that manifests itself in the ferromagnetic sign of the constant Θ in the Curie-Weiss law. The reversal of the moments of the layer is quite natural in such a structure, even in weak fields. A similar behavior was also observed in the metallic MnAu_2 compound.⁶ CoSO_4 is the first ionic crystal with such an antiferromagnetic sign of Θ that the antiferromagnetism is destroyed by a relatively weak magnetic field ($\mu H \ll kT_N$).

A detailed discussion of the observed anomaly will be made after a thorough study is completed of the phenomenon over the entire temperature range and after the structures of the crystals are established.

The authors express their deep gratitude to Academician P. L. Kapitza for a continuous interest in this work and to Professor P. G. Strelkov for many valuable hints.

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²A. S. Borovik-Romanov and N. M. Kreines, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1119 (1957), Soviet Phys. JETP **6**, 862 (1958).

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⁴S. S. Shalyt, J. Exptl. Theoret. Phys. (U.S.S.R.) **15**, 246 (1945).

⁵Bizette, Terrier, and Tsai, Compt. rend. **243**, 895 (1956).

⁶A. Y. P. Meyer and P. Taglang, Compt. rend. **239**, 961 (1954).

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COULOMB EXCITATION OF ALUMINUM

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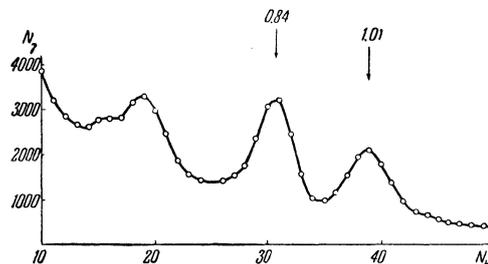
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WE have investigated the Coulomb excitation of Al^{27} using heavy ions accelerated in a cyclotron — 15.9-Mev triply charged nitrogen ions and 18.1-Mev triply-charged oxygen ions. The γ radiation emitted during the bombardment of aluminum was studied using a scintillation γ spectrometer having a NaI (Tl) crystal 40 mm in diameter and 40 mm high. A detailed description of the method, as well as the procedure for calculating $B(E2)\dagger$, i.e., the reduced probability for electric quadrupole transition of the nucleus from its ground state to an excited state, was given earlier.^{1,2}

The figure shows the spectrum of γ lines obtained from Coulomb excitation of aluminum by nitrogen ions. Two lines are observed, with $E = 0.84$ and 1.01 Mev. A study of the low energy

region of the spectrum under the same conditions showed that the relative intensity η of the 0.84 + 0.17 Mev cascade does not exceed 4% of the direct transition to the ground state. According to reference 3, η is 2.2%.



An attempt to excite the two levels of Al^{27} using 25-Mev nitrogen ions was unsuccessful, owing to the marked increase in γ -ray background from nuclear reactions.

The results obtained using nitrogen and oxygen ions are in good agreement with one another.

In computing the values of $B(E2)\dagger$ from the yield of γ quanta from a thick target we assumed, on the basis of reference 4, that the stopping power of aluminum for nitrogen ions is 5.9 Mev-cm²/mg. The values of $B(E2)\dagger$ for the levels with $\Delta E = 0.84$ and 1.01 Mev are, respectively, 0.0019 and 0.0031 e² × 10⁻⁴⁸ cm⁴. Using the known values of the spins of the ground state and first two excited states of Al^{27} ,⁵ we find that the partial lifetime