Singularities of the magnetoresistance of neodymium at low temperatures

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The electric resistivity ρ and the longitudinal and transverse magnetoresistance $\Delta\rho/\rho$ of 99.9% pure polycrystalline Nd are investigated in the temperature interval 1.9–70 K in magnetic fields up to 45 kOe. The $\Delta\rho/\rho$ curves exhibit anomalies due to the change of the magnetic structure of the neodymium. The critical fields corresponding to these anomalies are determined, and their dependence on the temperature is established. The magnetic phase diagram of neodymium is constructed.

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The magnetic properties of light rare-earth metals are more complicated than those of metals in the second half of the lanthanide series. The unique character of the properties of these metals has increased the interest in the study of their magnetic structures and phase transitions. In view of the considerable difficulties of obtaining light rare-earth metals and their single crystals, their investigations are far from complete.

The present paper is devoted to the light rare-earth metal neodymium (Nd). Under normal conditions neodymium crystallizes into a double-hexagonal-close-packed structure with alternating of *ABAC* layers along the *c* axis. The ions located in the *A* layers have an approximately cubic environment (we designate them I), and the ions of layer *B* and *C* have a hexagonal environment (we designate them II).

Neutron-diffraction investigations of Nd have shown that in the absence of a magnetic field at $T_1 = 7.5$ K the magnetic moments of the ions I form a periodic structure of the type

$$\boldsymbol{\mu}_A = -\boldsymbol{\mu}_{A'} = \mu_{cub}\mathbf{b}_2 \cos(2\pi\boldsymbol{\Theta}_{cub}\mathbf{R}),$$

where $\mu_{cub} = 1.8 \mp 0.2\mu$ at $T = 4.2$ K, $\mathbf{b}_2$ is the vector of a reciprocal lattice of the type $(1\bar{2}10)$, $\boldsymbol{\Theta}_{cub}$ is a cubic vector lying in the plane of the basis and making an angle 30° with the vector $\mathbf{b}_2$. At $T_2 = 19$ K, the magnetic moments of the ions II also form a periodic structure:

$$\boldsymbol{\mu}_B = -\boldsymbol{\mu}_C = \mu_{hex}\mathbf{b}_1 \cos(2\pi\boldsymbol{\Theta}_{hex}\mathbf{R}),$$

where $\mu_{hex} = 2.3 \mp 0.2\mu$ at $T = 4.2$ K, $\mathbf{b}_1(1\bar{1}00)$ is the reciprocal-lattice vector, $\boldsymbol{\Theta}_{hex}$ is a wave vector parallel to $\mathbf{b}_1$ and $\boldsymbol{\Theta}_{cub}$ $(\mathbf{b}_1 \parallel \boldsymbol{\Theta}_{cub})$.[1]

It is shown in Refs. 2 and 3 that at liquid-helium temperatures single-crystal neodymium goes over into a ferromagnetic state in an external magnetic field. Nagasawa[4] investigated the longitudinal and transverse magnetoresistance of neodymium in magnetic fields up to 20 kOe at four temperatures from 1.38 to 20 K. The longitudinal magnetoresistance at $T = 4.2$ K was investigated[5] in fields up to 80 kOe. In these papers[4,5] the $\Delta\rho_{\parallel}/\rho$ curves revealed anomalies which were attributed by the authors to a change in the magnetic structure of neodymium under the influence of the magnetic field. The weak magnetic field in Ref. 4 and the narrow temperature interval Refs. 4 and 5 did not make it possible to observe the behavior of the magnetoresistance in the magnetic phase transitions in neodymium in a wide range of temperatures and magnetic fields.

The purpose of the present study was to investigate the scattering of the conduction electrons by various Nd structures as a function of the temperature and of the the magnetic field and to construct the magnetic phase diagram on the basis of these data and the neutron-diffraction data. To this end we measured the electric resistivity and the longitudinal and transverse magnetoresistance in the temperature interval 1.9–70 K and in magnetic fields up to 45 kOe.

The samples were made of polycrystalline neodymium 99.9% pure ($\rho_{293\ \mathrm{K}}/\rho_{4.2\ \mathrm{K}} = 10$) in the form of parallelepipeds measuring $1 \times 1 \times 4$ mm. The contacts were welded to the sample by the electric-spark method. All samples were subjected to an x-ray phase analysis, which revealed the absence of a face-centered cubic phase.

The measurements were made with a potentiometer setup. We used an R-348 potentiometer with an amplifier, in which the level of the intrinsic noise was decreased, so that maximum sensitivity 5×10^{-9} V/mm could be obtained when the measurement results were automatically recorded.

1. TEMPERATURE DEPENDENCE OF THE RESISTIVITY $\rho(T)$

The resistivity of neodymium at temperatures 1.9 and 2 K is 5.33 $\mu\Omega$-cm. With increasing temperature, ρ increases sharply and has an inflection in the region of $T_1 = 7.5$ K. Above T_1, in the entire investigated temperature interval, the $\rho(T)$ curve is nonlinear. In the region $T_2 = 19$ K no anomaly is observed. The character of the $\rho(T)$ curve of Nd is similar to the $\rho(T)$ dependence given in Ref. 6.

2. FIELD DEPENDENCES OF THE MAGNETORESISTANCE AT CONSTANT TEMPERATURE

Figure 1 shows plots of $\Delta\rho_{\perp}/\rho$ against H at constant T. At 1.9 K the quantity $[\Delta\rho_{\perp}(H)/\rho]_T$ in a magnetic field up to 10 kOe is positive and has a maximum at $H_1 = 7$ kOe. With further increase of the magnetic field $\Delta\rho_{\perp}/\rho$ decreases drastically and two inflections are observed

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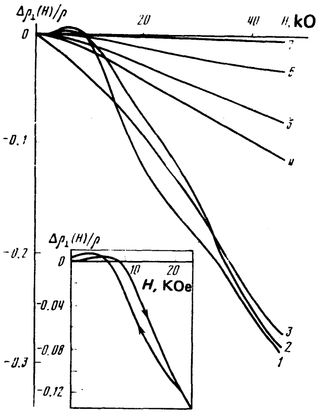

FIG. 1. Plots of the transverse magnetoresistance against the magnetic field at constant temperature $[\Delta\rho_\perp(H)/\rho]_T$: curves 1) $T = 1.9$ K; 2) 4.2 K; 3) 7.0 K; 4) 15 K; 5) 19.5 K; 6) 40.3 K; 7) 55.9 K; the inset shows the $[\Delta\rho_\perp(H)/\rho]_T$ curves in increasing and decreasing magnetic fields at a temperature $T = 1.9$ K.

on the curve near the fields $H_2 = 21$ kOe and $H_3 = 33$ kOe, the values of which were determined from the plots of $\ln(\Delta\rho_\perp/\rho)$ against $\ln H$ (see Fig. 2).

When the temperature is raised to $T_1 = 7.5$ K the character of the $\Delta\rho_\perp/\rho$ curves changes. In fields up to H_1 the positive section decreases with increasing temperature and at $T = 4.5$ K the value of $\Delta\rho_\perp/\rho$ becomes entirely negative. With increasing temperature, the value of the magnetic field H_1 remains practically unchanged (a slight increase is observed), while H_2 and H_3 increase strongly.

The dependences of the longitudinal magnetoresistance $[\Delta\rho_\parallel(H)/\rho]_T$ are similar to those of $[\Delta\rho_\perp(H)/\rho]_T$ in the entire investigated magnetic-field interval, with $\Delta\rho_\parallel/\rho$ smaller than $\Delta\rho_\perp/\rho$ by approximately 30%. The quantities $\Delta\rho_\parallel/\rho$ and $\Delta\rho_\perp/\rho$ are of the same sign.

In fields below 21 kOe, hysteresis of the longitudinal and transverse magnetoresistance as observed (inset in Fig. 1). The residual magnetoresistance $(\Delta\rho_\perp/\rho)_{\text{res}} = 0.011$ and $\Delta\rho_\parallel/\rho)_{\text{res}} = 0.007$ at 4.2 K. In order of magnitude, $(\Delta\rho_\parallel/\rho)_{\text{res}}$ is close to the value obtained in Ref.

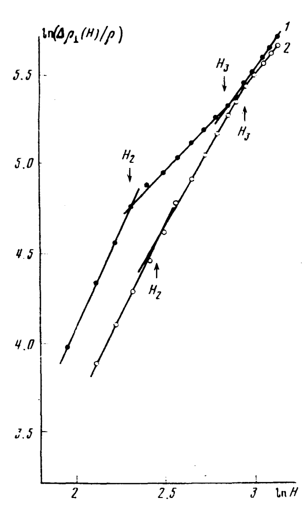

FIG. 2. Plots of $\ln(\Delta\rho_\perp/\rho)$ against $\ln H$: 1) $T = 1.9$ K; 2) $T = 4.2$ K.

5. With decreasing temperature, the residual magnetoresistance decreases, and at 1.9 K it is equal to 0.002 regardless of the magnetic-field direction.

3. TEMPERATURE DEPENDENCE OF THE MAGNETORESISTANCE $[\Delta\rho_\perp(T)/\rho]_H$

Figure 3 shows plots of $[\Delta\rho_\perp(T)/\rho]_H$ for different fields. At low temperatures ($T < T_1$) and in weak magnetic fields ($H < 10$ kOe) $\Delta\rho_\perp/\rho$ is positive and reverses sign at $T = 4.5$ K. In strong magnetic fields ($H > 10$ kOe) $\Delta\rho_\perp/\rho$ is negative in this temperature region. In the region $T \sim 4.5$ K all the $\Delta\rho_\perp/\rho$ curves have a local maximum, which is not shifted by the magnetic field. Near $T_1 = 7.5$ there is observed a minimum, whose depth depends little on the magnetic field. In the field interval $H_1 < H < H_3$ the minimum of the magnetoresistance is shifted by the magnetic field into the region of lower temperatures. No shift of the minimum was observed in fields $H > H_3$.

Next, with increasing temperature the magnetoresistance increases and in the region $T_2 = 19$ K the $\Delta\rho_\perp/\rho$ curves show at all the magnetic fields a weak anomaly. Above $T_2 = 19$ K the magnetoresistance of neodymium decreases smoothly with increasing temperature and remains negative up to 78 K.

The dependences of the longitudinal magnetoresistance on the temperature are similar to $[\Delta\rho_\perp(T)/\rho]_H$ in the entire temperature interval.

4. DISCUSSION OF MEASUREMENT RESULTS

The increase observed by us on the $\Delta\rho_\perp(H)/\rho$ curves in weak fields at temperatures 1.9–4.5 K can be attrib-

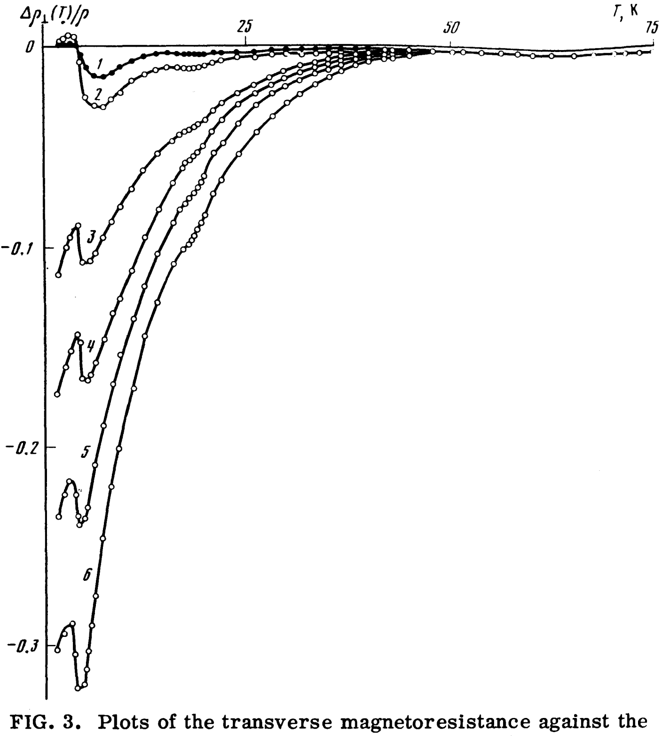

FIG. 3. Plots of the transverse magnetoresistance against the temperature in different magnetic fields $[\Delta\rho_\perp(T)/\rho]_H$; curves: 1) $H = 4.0$ kOe; 2) 7.9 kOe; 3) 21.7 kOe; 4) 27.7 kOe; 5) 35.6 kOe; 6) 45.5 kOe.

uted to an increase of the disorder in the system of localized magnetic moments. The reason is that in weak fields ($H < H_1$) two processes occur simultaneously: a reorientation of the structure of the magnetic moments of the ions I (the vector Θ_{cub} is rotated perpendicular to the external field), and a rotation of the magnetic moments of the ions II parallel to the direction of the magnetic moments of the ions I. These domain reorientation processes are similar to the reorientation processes in technical magnetization of ferromagnets. Our results do not contradict the conclusion of Refs. 2, 3, and 7.

With further increase of the magnetic field ($H > H_1$), a decrease and change of sign of $\Delta\rho/\rho$ is observed. This is apparently due to the appearance of a ferromagnetic phase under the influence of the magnetic field at $H = H_1$, and to the suppression of the magnetic inhomogeneities with further increase of the field. The appearance of a ferromagnetic phase in a magnetic field was also observed in Ref. 2 and 3 (by neutral diffraction).

The observed hysteresis of the magnetoresistance in fields $H < 21$ kOe can be associated with the existence in neodymium of a domain structure and with its influence on the magnetization reversal (irreversibility of the processes). In weak fields, obviously, the main contribution to the magnetization is made by the moments of the ions I.

In the magnetic field H_2 an increase of the slope of the $\Delta\rho_\perp(H)/\rho$ curve is observed. This behavior of the curve can be attributed to two processes in the magnetic structure of neodymium, which were noted in Refs. 2 and 3. In the region of the field H_2, according to neutron-diffraction data, an abrupt increase takes place in the magnetic moments of the ions I and II. This jump (the growth of the magnetic moments of the ions I and II) is attributed by the authors to splitting of the levels of the crystal field of the ions II in the magnetic field and to their influence on the ions I. In addition, in these fields the reorientation of the structure of the magnetic moments of the ions II terminates.

The anomaly on the $\Delta\rho_\perp(H)/\rho$ curve in the field H_3 is apparently due to the total suppression of the modulated structure and to a transition of the neodymium into a ferromagnetic state. The subsequent weak decrease of $\Delta\rho_\perp(H)/\rho$, obviously, is connected with the para process.

The temperature dependence of the magnetoresistance of Nd in a constant field shows that at $T_1 = 7.5$ K there is observed a minimum that can be connected with the destruction of the magnetic structure of ions I. The position of the minimum shifts into the region of lower temperatures at $H_1 < H < H_3$. This behavior of the even galvanomagnetic effect is typical of antiferromagnets near the Néel point[8]—in this case near the temperature of the antiferromagnetic ordering of the magnetic moments of ions I. We can therefore conclude that the magnetoresistance in the temperature interval $T < T_1$ and in fields $H < H_2$ is determined by scattering of the conduction electrons by the antiferromagnetically ordered magnetic moments. The positive section of the $\Delta\rho_\perp(T)/\rho$ curves in weak fields at low temperatures are obviously connected with the existence of antiferromagnetic order in fields $H < H_1$. With further increase of temperature, the even galvanomagnetic effect increases, and in the region of $T_2 = 19$ K one observes a small anomaly that can be associated with the destruction of the magnetic structure of the ions II.

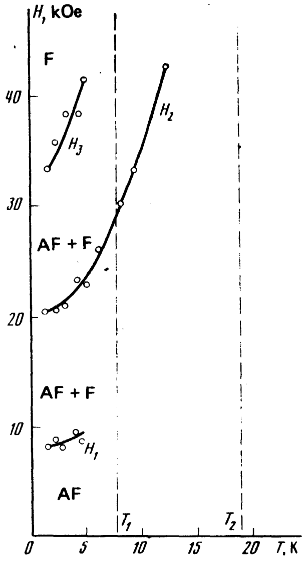

FIG. 4. Magnetic phase diagram of neodymium.

The anomalies on the $\Delta\rho_\perp(H)/\rho$ curve at $T = 4.2$ K were compared with the changes of the magnetic structure in Nd, determined in Refs. 2 and 3, and full agreement was obtained.

From our data we obtained the critical fields H_1, H_2, and H_3 for different temperatures, and from the values of the fields H_1, H_2, and H_3 we plotted the magnetic phase diagram of Nd, shown in Fig. 4.

As a result of our investigation, we determined from the magnetoresistance data the regions of existence of antiferromagnetism, ferromagnetism, and mixed structure in neodymium in the temperature interval 1.9–70 K in magnetic fields up to 45 kOe.

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