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A STUDY OF MAGNETIC SUSCEPTIBILITY OF SINGLE-CRYSTAL GADOLINIUM UNDER ALL-ROUND COMPRESSION

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We measured the dependences of the initial magnetic susceptibility on the temperature $\chi(T)$ of a Gd single crystal along the c and b crystallographic axes in external magnetic fields and up to 1 GPa. The $\chi(T)$ curves were found to have maxima at the Curie temperature Θ_C, the spin-reorientation transition temperature Θ_{SR}, and the temperature $\Theta_A = 140$ K. The derivatives $\partial\Theta_C/\partial P$ and $\partial\Theta_{SR}/\partial P$ are determined, which are -13 and -67 K GPa^{-1} along the c axis and -12 and -29 K GPa^{-1} along the b axis, respectively.

The study of the effect of all-round compression on the magnetic susceptibility $\chi(T)$ gives useful information on the transformation of a magnetic structure exposed to a uniform stress. Although temperature shifts of magnetic phase transitions under pressure in heavy rare-earth metals have been well studied (see, e.g., [1]), the effect of compression on the shape of the $\chi(T)$ curves has not so far been investigated in detail for all rare-earth metals. This paper reports a study of the effect of pressure and magnetic field on the temperature dependences of the initial magnetic susceptibility measured along different crystallographic directions.

The description of the experimental procedure is given in [2]. The measurements were carried out at the ambient pressure and at pressures up to 1 GPa. The constant magnetic field in this case could vary to 2 kOe. The specimen used was grown by the Czochralski method. The specimens were oriented by the Laue method to an accuracy of ±3° and were cut by the electric spark method.

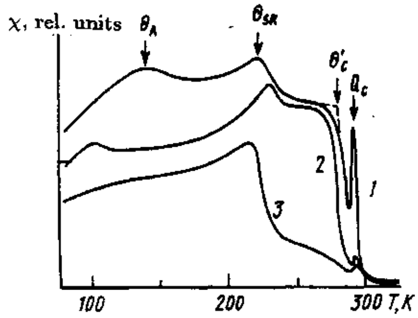

Fig. 1

Temperature dependences of the initial magnetic susceptibility χ of a Gd single crystal at the ambient pressure in a field applied along the c crystallographic axis: $H = 0$ (1), 0.33 kOe (2), and 0.57 kOe (3).

Figure 1 shows the $\chi(T)$ temperature dependences in magnetic fields up to 500 Oe applied along the c crystallographic axis. It is evident that exposure to the magnetic field transforms appreciably the $\chi(T)$ curves. According to neutron diffraction data [3], the c axis is an easy magnetization axis within the interval from the Curie temperature $\Theta_C = 294$ K to the temperature of spin-reorientation transition $\Theta_{SR} = 232$ K. At $T < \Theta_{SR}$ the easy magnetization direction deviates from the c axis through the angle θ, whose value varies with temperature. At $H = 0$ the $\chi(T)$ curves exhibit four characteristic properties. The maximum at the temperature $\Theta_C = 292$ K corresponds to the specimen transition from paramagnetic to ferromagnetic state. The maximum drastically diminishes with increasing field (by a factor of about 2 in the 0.1 kOe field), it also becomes broader and in strong fields shifts toward high temperatures (294 K at $H = 0.57$ kOe). In fields higher than 0.7 kOe the maximum disappears completely. At $T = \Theta'_C$ the second anomaly, in contrast to the first, shifts with increasing field toward lower temperatures and completely vanishes in a field $H \approx 0.6$ kOe. Similar anomalies on the $\chi(T)$ curves that accompany a transition of a uniaxial ferromagnetic from paramagnetic to ferromagnetic state were observed earlier (see, e.g., [4]). Near the spin-reorientation transition temperature χ increases and a third feature appears: a maximum at $T = \Theta_{SR} = 224$ K. This maximum is not broadened by the field and remains the sole anomaly at $H \gtrsim 0.7$ kOe.

The fourth anomaly is detected at $T = 140$ K (see Fig. 1). When the field increases to about 0.6 kOe, this maximum disappears, as do the anomalies at the temperatures Θ_C and Θ'_C.

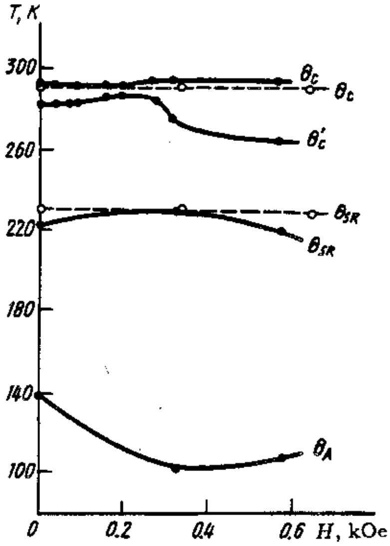

Fig. 2

Field dependences of the temperatures corresponding to the anomalies on the $\chi(T)$ curves: $H \| c$ (solid lines) and $H \| b$ (dashed lines).

Figure 2 demonstrates the relationships between the temperatures of the above anomalies of $\chi(T)$ and the field. It can be seen that the temperature Θ_C is affected by the magnetic field the least. The points of the other three anomalies depend on the magnetic field to a greater extent.

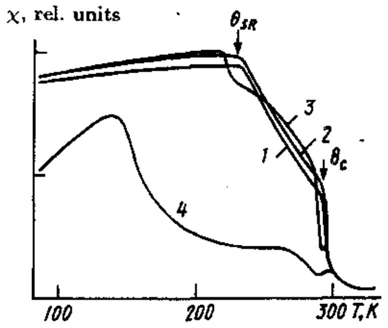

Fig. 3

Temperature dependences of the initial magnetic susceptibility of a Gd single crystal at the ambient pressure in an external field applied along the b crystallographic axis: $H = 0$ (1), 0.34 kOe (2), 0.89 kOe (3), and 1.37 kOe (4).

The temperature dependences of the susceptibility $\chi(T)$ measured along the b axis, in the absence of the field show only two anomalies: at $\Theta_C = 291$ K and $\Theta_{SR} = 230$ K (Fig. 3). As the field increases there appears on the $\chi(T)$ curves a typical paramagnetic peak (at $T \approx 291.5$ K in the field $H = 0.65$ kOe). The effect of the field on the ordering temperatures for the given specimen is also indicated in Fig. 2 by the dashed line.

According to [5, 6] the position of the $\chi(T)$ maximum near the Curie temperature depends on the field strength. This conclusion is supported by our experimental data (see Fig. 2).

Certain difficulties arise in interpreting the nature of the maximum near $T = \Theta_A \approx 140$ K. Analysis of the literature data reveals that anomalies of other physical nature occur in this temperature range (see, e. g., [7–10]). Thus, the temperature dependence of the lattice parameter c of gadolinium [7] in this temperature range exhibits a fairly broad maximum. An anomalous behavior in the vicinity of this point is also shown by the energy of magnetic anisotropy, which is related to a minimum on the temperature dependence of the anisotropy constant K_1 [8–9]. Certain peculiarities of the temperature dependence of Young's modulus $E(T)$ in the indicated temperature range were also observed in [10].

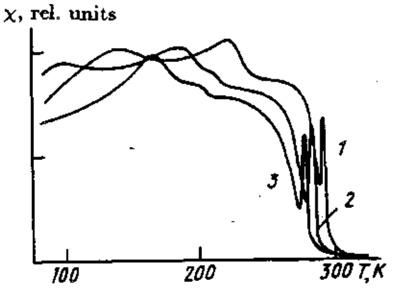

Fig. 4

Temperature dependences of the initial magnetic susceptibility of a Gd single crystal ($H||c$) at different pressures: ambient (1), 0.6 GPa (2), and 0.96 GPa (3).

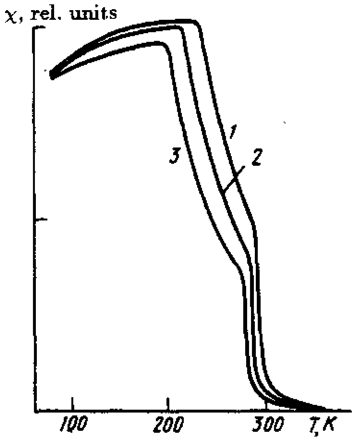

Fig. 5

Temperature dependences of the initial magnetic susceptibility of a Gd single crystal ($H||b$) at different pressures: ambient (1), 0.6 GPa (2), and 1 GPa (3).

The complicated temperature dependence of the lattice parameter c and the existence of a local minimum of anisotropy energy in Gd apparently bring about a change in the character of magnetic structure in this temperature range. This may be responsible, in particular, for anomalies on the temperature dependence of the angle θ.

The study of the effect of pressure on the shape of the $\chi(T)$ curves suggests that the general appearance of the $\chi(T)$ curves near the phase transition temperatures practically does not change for either $H\|c$ or $H\|b$ (see Figs. 4 and 5, respectively). At the same time these anomalies are shifted by the pressure toward low temperatures. It has been found that at $H\|c$ $\partial\Theta_C/\partial P = -13$ K GPa^{-1} and $\partial\Theta_{SR}/\partial P = -67$ K GPa^{-1}, and when the field is oriented along the hard magnetization axis the shifts are -12 and -29 K GPa^{-1}, respectively.

It has been found in [11] by means of quantum mechanical calculations that in rare-earth metals compression transforms the band structure owing to the shift of the 6*s* band upward to the energy range above the Fermi level. In Gd pressure may induce (*s*, *p*)-*d* transitions, which makes a contribution to the shift of the points of magnetic phase transitions under pressure. However, the main contribution to the Curie point shift is made by a change of the exchange integrals, under all-round compression.

The effect of all-round compression on the opening of the cone of magnetic moments has been examined [12, 13]. It has been shown that a reduction of the unit cell volume substantially affects the constants of magnetic anisotropy and stabilizes the easy magnetization axis in parallel to the *c* axis.

Thus, a decrease in the temperature of spin-reorientation transition depends on the variation of magnetic anisotropy constants under pressure.

In conclusion it should be noted that a more detailed interpretation of the origin of the maximum on the $\chi(T)$ curve at $T \approx 140$ K ($H\|c$) requires a more thorough investigation of the dependences of the angle θ and the magnetic anisotropy constants of Gd on temperature.

REFERENCES

1. S. A. Nikitin, Yu. I. Spichkin, and A. M. Tishin, *Vest. Mosk. Univ. Fiz. Astron.*, vol. 32, no. 5, p. 90, 1991.
2. S. A. Nikitin, A. M. Tishin, M. D. Kuz'min, and Yu. I. Spichkin, *Phys. Lett.*, vol. 153A, no. 23, p. 155, 1991.
3. J. W. Cable and E. O. Wollan, *Phys. Rev.*, vol. 165, no. 2, p. 733, 1968.
4. Kh. K. Aliev, I. K. Kamilov, and A. M. Omarov, *Fiz. Tverd. Tela*, vol. 26, no. 3, p. 840, 1984.
5. J. Klamut and Z. Sznajd, *Phys. Lett.*, vol. 31A, p. 6, 1970.
6. E. Riedel and F. Wegner, *Z. f. Phyzik*, vol. 225, p. 195, 1969.
7. V. A. Finkel', *Structure of Rare-Earth Metals* (in Russian), Moscow, 1978.
8. W. D. Corner, W. C. Roe, and K. N. R. Taylor, *Proc. Phys. Soc. Japan.*, vol. 80, p. 927, 1962.
9. C. D. Graham, *J. Phys. Soc. Japan.*, vol. 17, p. 1310, 1962.
10. V. Yu. Bodryakov, S. A. Nikitin, and A. M. Tishin, *Fiz. Tverd. Tela*, vol. 32, no. 7, p. 2233, 1991.
11. L. V. Al'tshuller, A. I. Voropinov, G. M. Gendel'man, et al., *Fiz. Met. Metalloved.*, vol. 51, no. 1, p. 76, 1981.
12. J. J. M. Franse and V. Mihai, *Physica*, vol. 86–88B, p. 49, 1977.
13. H. Klimker and M. Rosen, *Phys. Rev.*, vol. B7, no. 5, p. 2054, 1973.

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