SHIFT OF THE CURIE TEMPERATURE OF GADOLINIUM BY HYDROSTATIC PRESSURE UP TO 35 KILOBARS

L. D. LIVSHITZ and Yu. S. GENSHAFT

Institute of Earth Physics, Academy of Sciences, U.S.S.R.

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Experiments are described for determining the influence of hydrostatic pressure up to 35 kbar on the Curie temperature of gadolinium. It was established that the Curie temperature of gadolinium decreases linearly over the whole range studied. The experimentally determined coefficient of proportionality between the amount of shift of the Curie temperature and the pressure is -1.34 deg kbar^{-1}.

THE influence of hydrostatic pressure on the Curie temperature of gadolinium was studied earlier in the range 1 to 8000 atm [1] and 1 to 6000 atm [2]. According to the results of these studies, the Curie temperature of gadolinium decreases in proportion to the pressure,

$$-\Delta\Theta = \Theta_p - \Theta = ap, \qquad (1)$$

where Θ and Θ_p are the values of the Curie temperature under atmospheric pressure and under pressure p, respectively, and a is a proportionality coefficient, equal to 1.2 ± 0.005 deg katm^{-1} (1.225 deg kbar^{-1}) according to the data of [1] and to 1.55 deg katm^{-1} (1.58 deg kbar^{-1}) according to the data of [2]. A value of $d\Theta/dp$ near these was also obtained in experiments conducted under quasi-hydrostatic pressure up to 26 kbar, and reported in preliminary form in an earlier paper [3], and also to 21.5 kbar in [4]. The agreement of these results with those cited above shows that in determination of the influence of pressure on the magnetic transformation temperature, the liquid or gas used for transmission of the pressure to the specimen can be successfully replaced by a solid plastic material.

Reported below are some additional data on the shift of the Curie point of gadolinium with pressure in the range up to 35 kbar. As was described earlier [3,5], the pressure was produced in a piezometer by the method of "piston displacement"; silver chloride served as the medium being compressed. The specimens were minature toroids, cut from cast polycrystalline metal, which was reported to contain the following controlled impurities: Yb and Tb (in all) 0.1%, Ca 0.02%, Fe 0.01%, Cu 0.005%.

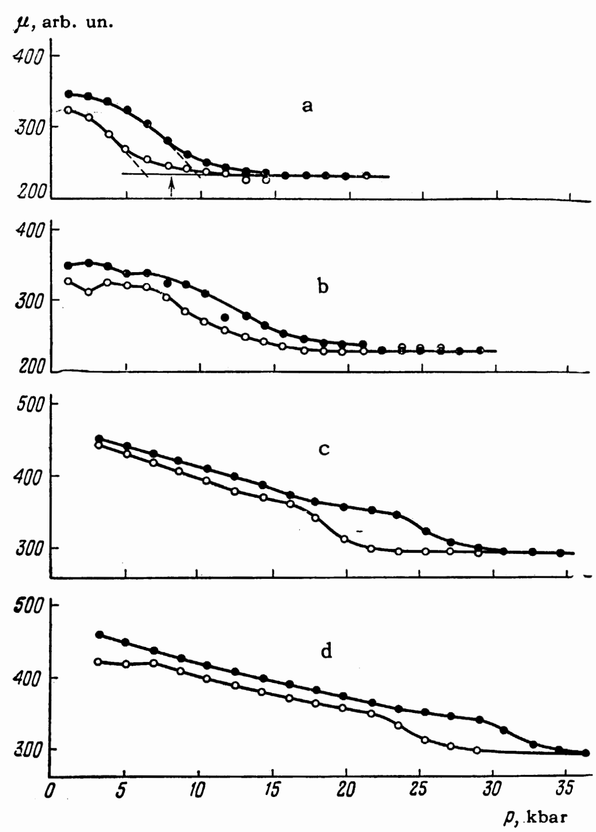

FIG. 1. Dependence of magnetic permeability of gadolinium on pressure at various temperatures: a, $-1.5°C$; b, $-15°C$; c, $-23°C$; d, $-30°C$. Dark circles, experimental values obtained on increase of pressure; open circles, on decrease. The arrow in Fig. 1a gives the value of the magnetic transition pressure at the indicated temperature.

In the course of the experiment, curves showing the dependence of magnetic permeability (μ) on pressure were taken, at constant temperature (the temperature fluctuations during the time of an experiment did not exceed 0.5 to 1°). The

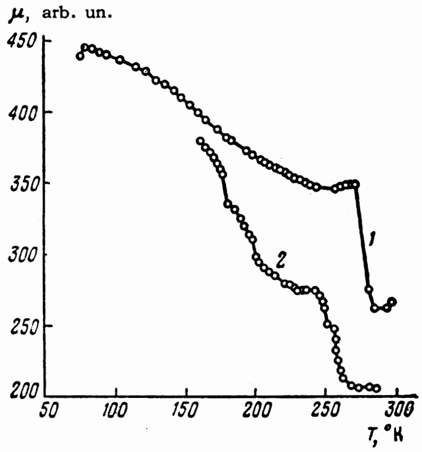

FIG. 2. Dependence of magnetic permeability of gadolinium on temperature at atmospheric pressure (1) and at pressure 15 kbar (2). The curves were taken under increasing temperature.

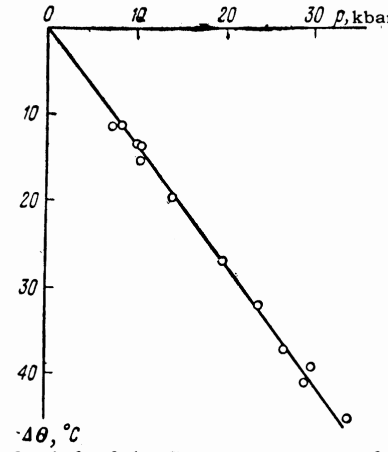

FIG. 3. Shift of the Curie temperature of gadolinium with pressure.

measurements were made at frequency 500 cps, at effective field intensity 5 to 6 Oe.

The pressure at which a ferromagnetic transition occurs, at a given temperature, was determined by the point of intersection of the prolongation of the steep parts of the $\mu(p)$ curves with the straight line to which these curves go over in the paramagnetic region (see the dashed curves in Fig. 1a).[1)] The value of the magnetic transition pressure was taken to be the arithmetic mean of the values obtained for it on increase and on decrease of pressure—as is customary in the method of "piston displacement." Tests of this method of pressure determination, by comparison of values of the polymorphic-transition pressure in cerium [5], teflon [6], and bismuth [7], obtained under purely hydrostatic conditions and under so-called quasihydrostatic pressure, show that in this method of pressure determination, the error allowed in the piston-displacement method usually does not exceed ±150 bar over the whole pressure range.

The value of the Curie point at atmospheric pressure was determined by extrapolation of the curves $\mu = f(T)$ into the paramagnetic region. As is known [8], the magnetization of polycrystalline gadolinium in weak fields (up to 10 to 15 Oe, and especially up to 1 to 2 Oe) has a complicated dependence on temperature: it increases in the temperature interval 100 to 200°K, passes through a maximum (the position and form of which depend on the field intensity), decreases sharply with temperature in the interval 210 to 250°K, and drops a second time upon transition to the paramagnetic state.

The temperature dependence of the permeability, on the whole, repeats the temperature behavior of the magnetization described above. Under these conditions the drop of permeability with temperature ceases at a temperature about 30° below Θ. Control experiments, conducted at a pressure of about 15 kbar, showed that the size of this temperature interval and the general character of the $\mu(T)$ dependence are retained also under pressure (Fig. 2).

As the result of twelve independent determinations of the pressure at transition into the paramagnetic state, there was obtained a p-T diagram of the magnetic transition in gadolinium up to pressures of 35 kbar and down to temperature −36°C (Fig. 3). The shift of the Curie temperature with pressure is expressed satisfactorily by Eq. (1); the value of a according to our data, defined as $\Sigma\Delta\Theta/\Sigma p$ ([9], formula (11.35)), is 1.34 ± 0.06 deg kbar^{-1}. The mean deviation of the experimental points from the straight line (1) amounts in temperature to 0.8° and in pressure to 0.6 kbar.

In connection with our discussion of the results of our measurements, we remark that there was published comparatively recently an investigation by a group of authors [4] who, working with a method in many respects similar to ours, reached the conclusion that the Curie-point line in the p,

[1)]The magnetic transition pressure obtained in this way refers to the mean temperature between the ascending and descending branches of the $\mu(p)$ curves. It is obvious that the greater the absolute value of dp/dT along the phase-transition line, the greater is the necessity for maintenance of a constant temperature in the experiments. In the case of the p-vs-T line of the Curie point of gadolinium, a departure of 0.2° from isothermal conditions corresponds to a shift of the transition pressure by about 150 bar.

T plane has a break in the pressure interval 21 to 26 kbar.

This interesting phenomenon is connected with the formation under pressure of a nonmagnetic modification of gadolinium. Such an idea is supported by experimental indications of the existence of a polymorphic transition in the pressure region 20 to 40 kbar at room temperature and at elevated temperatures [10-12].

Our measurements do not permit making a similar deduction; on the contrary, over the whole pressure range studied, the $\mu(p)$ curves retain the jump in permeability that corresponds to the magnetic transition, and the $\Theta(p)$ line undergoes no break. All that can be noticed is a certain diminution (by a factor of one and a half to two) of the size of the jump in μ at the Curie point, at pressures exceeding 20 kbar.

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