Investigation of the magnetic properties of gadolinium by means of μ^+ mesons

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Magnetic phase transitions in gadolinium are investigated at temperatures $T = 100$–300 K by observing precession of μ^+ mesons. It is shown that a sharp change in the magnetic structure of this ferromagnetic material occurs at $T \approx 235$ K.

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Gadolinium is not a normal ferromagnetic material. In the ferromagnetic state below the Curie temperature $\Theta = 289$ K it reveals an unusual change of its magnetic properties,[1-3] associated with a rearrangement of the magnetic structure. In the present work the magnetic properties of gadolinium are investigated in the temperature range T = 100—300 K by the method of observing the precession of μ^+ mesons in this ferromagnetic material. The work was carried out at the synchrocyclotron of the Joint Institute for Nuclear Research at Dubna. Preliminary results have been published previously.[4]

The sample of gadolinium was a disk of diameter 65 mm and thickness 12 mm. An external magnetic field **H** was directed parallel to the plane of the disk and perpendicular to the spin of the precessing μ^+ mesons. The precession of the μ^+ mesons was observed by means of scintillation counters which detected[5] the positrons of the $\mu^+ \to e^+$ decay. The counting rate dN/do of the positron counter telescope, which describes the precession of the spin of μ^+ mesons in gadolinum, can be represented in the following form:

$$dN/do \approx (1 - ae^{-\Lambda t}\cos\omega t)\, e^{-t/\tau_0}. \quad (1)$$

Here a is the μ^+-meson precession amplitude, Λ is the rate of damping of the precession, ω is the precession frequency, and τ_0 is the μ^+-meson lifetime.

The amplitude a determines the polarization of the μ^+ mesons in gadolinium: $P = a/a_0$, where a_0 is the amplitude of precession of μ^+ mesons in a nonmagnetic and nondepolarizing material—in the present case, copper. The frequency ω is determined by the average magnetic field B_μ at the μ^+ meson: $\omega = eB_\mu/mc$, where m is the μ^+-meson mass. The damping rate Λ characterizes the degree of nonuniformity of the magnetic field δB_μ at the individual μ^+ meson in gadolinium.

The dependence of the experimental values of the parameters P, Λ, and B_μ on temperature is shown in Fig. 1. In Fig. 2 we have shown the dependence $B_\mu(T)$ in units of B_μ/B_0, where the field $B_0 = 1760$ G was arbitrarily taken equal to $B_0 = B_\mu(T \to 0)$. The experimental dependence $B_\mu(T)/B_0$ in Fig. 2 was compared with the Brillouin function $M/M_{sat} = f(T/\Theta)$, which describes the temperature dependence of the spontaneous magnetization of the ferromagnetic material. Here M and M_{sat} are the magnetization of the sample at T and $T \to 0$ K (saturation magnetization).

From Figs. 1 and 2 it is clearly evident that there is a sharp change in all of the precession parameters indicated in Eq. (1) at $T_0 \approx 235$ K. At this temperature the value of the field B_μ drops by a factor of two, the relaxation rate Λ rises sharply, and the observed polarization P of the μ^+ mesons decreases substantially.

The entire temperature interval T = 235—285 K is also unusual for a normal ferromagnetic material. The field B_μ at these temperatures remains approximately constant, which is not in agreement with the Brillouin function. The polarization P is unusually small, which indicates existence of a process fast in comparison

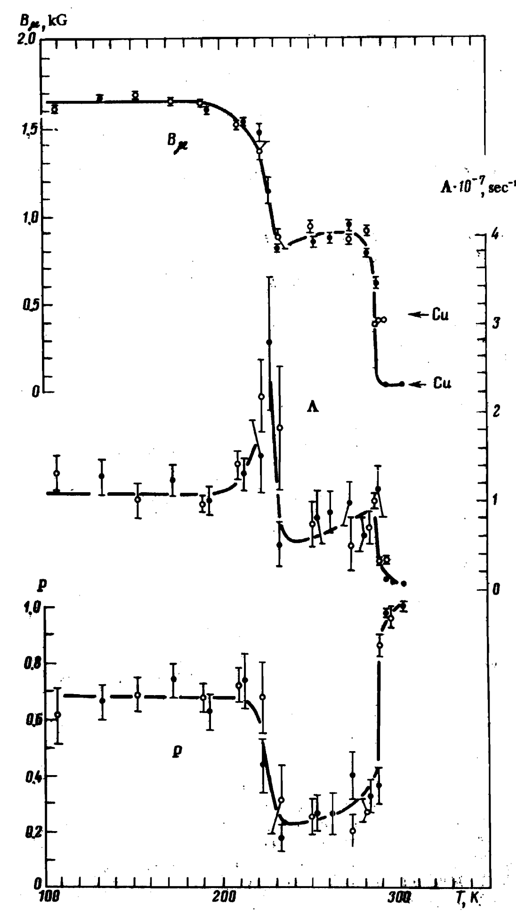

FIG. 1. The parameters P, Λ, and B_μ for precession of μ^+ mesons in gadolinium, as a function of temperature T. The points denote the corresponding experimental values in an external field H = 60 Oe (●) and in a field H = 450 Oe (○). The arrows indicate the experimental values of the field B_μ in copper for H = 60 and 450 Oe. The smooth curves P(T), Λ(T), and B_μ(T) have been drawn through the experimental points by eye.

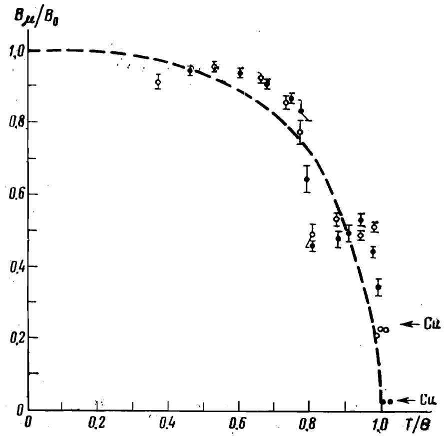

FIG. 2. The ratio B_μ/B_0 as a function of temperature for $B_0 = 1760$ G. The smooth curve is the Brillouin function for the ratios M/M_{sat}. $\Theta = 289$ K is the Curie temperature for gadolinium. The remaining designations are the same as in Fig. 1.

with the time of observation of relaxation of the spin of an appreciable fraction of the μ^+ mesons.

For $T < T_0$ the parameters P, Λ, and B_μ are practically independent of the temperature. The increase of the relaxation rate Λ at $T = T_0$ signifies, as was pointed out above, a sharp rise in the degree of nonuniformity of the field B_μ at the temperature T_0 of the phase transition.

It is also evident from Figs. 1 and 2 that all of the parameters characterizing the precession of a μ^+ meson in gadolinium coincide within experimental error for the values $H = 60$ and 450 Oe used in the present experiment. It should be noted that the external fields $H = 60$ and 450 Oe are substantially less than the maximum demagnetizing field $B_{demag} = \gamma B_{sat} \approx 3000$ G, where $\gamma = 0.12$ is the demagnetizing factor for this gadolinium sample and $B_{sat} = 24.5$ kG is the saturation induction of gadolinium at $T = 0$ K. Therefore almost over the entire temperature range studied the gadolinium was not magnetized to saturation ($M < M_{sat}$), i.e., it was a multidomain ferromagnet. The relation $M < M_{sat}$ for $H < \gamma B_{sat}$ explains in a natural way the experimental value $P = 2/3$ for $T < T_0$, which corresponds to an isotropic distribution of directions of magnetization of individual domains.

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