# Temperature dependence of positive-muon precession frequency in gadolinium

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It is shown that at 230–280 °K the temperature dependence of the precession frequency of positive muons in gadolinium is not described by a Brillouin function. An estimate $P_e > 0.04$ is presented for the polarization of the conduction electrons in gadolinium.

We investigated the precession of the positive-muon spin in gadolinium at temperatures $T = 90-280$ °K. In this temperature interval, an abrupt change takes place in the magnetic properties of gadolinium, namely, gadolinium is paramagnetic above the Curie temperature $\Theta = 289$ °K, and ferromagnetic below this temperature. The experimentally observed Larmor precession frequency, $\omega = eB_\mu/m_\mu c$, of the $\mu^+$ meson is determined by the local magnetic field $B_\mu$ at the positive muon. Therefore the experimental $\omega(T)$ relation shows how the field $B_\mu$ varies in this ferromagnet with temperature. It is of interest also to obtain other parameters of the positive-muon precession in gadolinium (see the table).

The gadolinium sample was a disk of 65 mm diameter and 12 mm thickness. The gadolinium was placed in an external magnetic field $H$ parallel to the plane of the disk, perpendicular to the positive-muon spin direction. The field $H$ was produced by an electromagnet with a gap 180 mm between poles and a pole diameter 220 mm. The muon spin precession was observed with the aid of scintillation counters that registered the positrons of the $\mu^+ \to e^+$ decay.[1]

The results are shown in the table and in the figure. The table lists, for different values of the gadolinium temperature, the muon precession frequency $\omega$ in the corresponding field $B_\mu$, the rate $\Lambda$ of damping of the precession amplitude or of the muon spin relaxation, and the experimental value of the amplitude $a$ of the precession or of the asymmetry coefficient at the initial instant of time. The table lists also the muon precession parameters in copper, measured under the same experimental conditions.

The figure shows a plot of $B_\mu(T)$ in units of $B_\mu/B_0$, where the field $B_0 = 1760$ G is arbitrarily assumed to be $B_0 = B_\mu(T \to 0)$. The experimental plot of $B_\mu(T)/B_0$ is compared in the figure with the Brillouin function $M/M_{sat} = f(T/\Theta)$, which describes the temperature dependence of the spontaneous magnetization of the ferromagnet. Here $M$ and $M_{sat}$ are the magnetization of the sample at the temperature $T$ and as $T \to 0$ °K (saturation magnetization), respectively, and $\Theta = 289$ °K is the Curie temperature for gadolinium.

It is seen from the figure that in general the experimental plot of $B_\mu(T)/B_0 = f(T/\Theta)$ agrees satisfactorily with the Brillouin curve. At the same time, there is also a pronounced deviation from the Brillouin function, in that $B_\mu$ is constant at $T = 230-280$ °K. It follows from the data in the table that this temperature interval is characterized also by a variation of the quantities $a$ and $\Lambda$. The deviation of the experimental plot of $B_\mu(T)$ from the Brillouin function (a deviation not observed in nickel[2]) may be the result of phase transition in gadolinium.

The experimental asymmetry coefficient of the $\mu^+ \to e^+$ decay in gadolinium ($a$) should be compared with the asymmetry coefficient $a_{Cu} = 0.29 \pm 0.01$ in copper. It is seen that $a \approx (2/3)a_{Cu}$ at $T < 220$ °K. This is precisely the ratio that should be observed when the

TABLE. Parameters of positive-muon precession in gadolinium. The notation is indicated in the text. The errors are statistical.

| H, Oe | | T, K | $a$ | $\Lambda$, μsec$^{-1}$ | $\omega$ μsec$^{-1}$ | $B_\mu$, G |
|---|---|---|---|---|---|---|
| Gd | 0 | 93 | 0.23 ±0.03 | 16 ± 3 | 124 ± 3 | 1460 ± 40 |
| Gd | 4000 | 108 | – | 78 ± 16 | 201 ± 20 | 2360 ± 230 |
| Gd | 2000 | 108 | – | 18 ± 2 | 1500 ± 20 | 128 ± 2 |
| Gd | 450 | 108 | 0.18 ±0.03 | 13 ± 2 | 137 ± 2 | 1610 ± 20 |
| Gd | 450 | 153 | 0.20 ±0.02 | 10 ± 2 | 144 ± 1 | 1690 ± 10 |
| Gd | 450 | 191 | 0.19 ±0.02 | 9 ± 1 | 139 ± 1 | 1630 ± 10 |
| Gd | 450 | 213 | 0.21 ±0.02 | 14 ± 2 | 129 ± 2 | 1510 ± 20 |
| Gd | 450 | 223 | 0.20 ±0.04 | 22 ± 4 | 117 ± 5 | 1370 ± 60 |
| Gd | 450 | 233 | 0.09 ±0.04 | 18 ± 7 | 74 ± 5 | 870 ± 60 |
| Gd | 450 | 252 | 0.07 ±0.02 | 7 ± 2 | 81 ± 2 | 950 ± 20 |
| Gd | 450 | 273 | 0.06 ±0.02 | 5 ± 3 | 74 ± 2 | 870 ± 20 |
| Gd | 450 | 283 | 0.08 ±0.01 | 7 ± 2 | 78 ± 2 | 920 ± 20 |
| Gd | 450 | 287 | 0.29 ±0.03 | 10 ± 1 | 33 ± 1 | 390 ± 10 |
| Gd | 450 | 289 | 0.25 ±0.01 | 3 ±0.2 | 35 ±0.2 | 410 ± 2 |
| Gd | 450 | 293 | 0.28 ±0.01 | 3 ±0.2 | 35 ±0.2 | 410 ± 2 |
| Cu | 450 | 303 | 0.29 ±0.01 | 0.1 ±0 | 1 38 ±0.1 | 450 ± 1 |

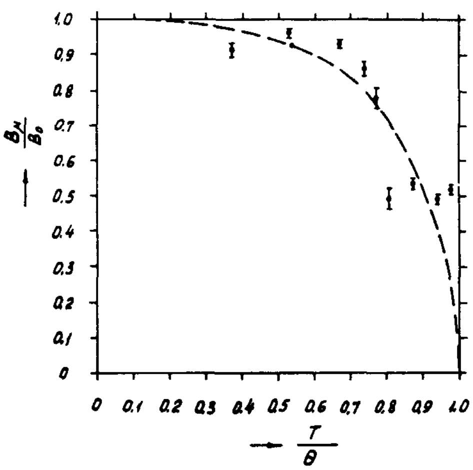


FIG. Plot of $B_\mu/B_0$ against temperature, $B_0 = 1760$ G. Smooth curve—Brillouin function for the ratio $M/M_{sat}$. $\Theta = 289$ °K is the Curie temperature of gadolinium.

direction of magnetization of the individual domains in gadolinium is arbitrary. Above the Curie point we have $a \approx a_{Cu}$. The relatively small value $B_0 = B_\mu(T \to 0) = 1.76$ kG means that in gadolinium, as in other ferromagnets,[1] the local field at the positive muon is determined essentially by the contact field of the conduction electrons $B_c$:

$$\mathbf{B}_\mu = \mathbf{B}_d + \mathbf{B}_c . \qquad (1)$$

Here $\mathbf{B}_d$ is the dipole field of the atoms of the ferromagnet. The field $\mathbf{B}_d$ in gadolinium can be set equal to $\mathbf{B}_d = (4/3)\pi\mathbf{M}$, inasmuch as the dipole fields from the atoms closest to the positive muon in the octa- and tetrapores of the hexagonal gadolinium lattice are equal to zero. Assuming $M = M_{sat}$ we get $B_d = (4/3)\pi M_{sat} = 8$ kG, and in accordance with (1) the contact field is $B_c = B_d - B_\mu = 8 - 1.76 = 6.2$ kG. Knowing $B_c$, we can estimate the degree of conduction-electron polarization $P_e$, which is proportional to $B_c$ and inversely proportional to the density $\rho$ of the conduction electrons at the $\mu^+$ meson. The maximum possible value of $\rho$ corresponds to the bound state—the muonium atom. At the muonium density of the totally polarized electrons, the contact field is $(B_c)_{Mu} = 160$ kG. Therefore the minimum value of $P_e$ corresponding to $B_c = 6.2$ kG is $(p_e)_{min} = 6.2/160 = 0.04$, and corresponds to a bound state of the $\mu^+ - e^-$ system in gadolinium.

[1] I. I. Gurevich, A. I. Klimov, V. N. Maĭorov, E. A. Meleshko, I. A. Muratova, B. A. Nikol'skiĭ, V. S. Roganov, V. I. Selivanov, and V. A. Suetin, Zh. Eksp. Teor. Fiz. 66, 374 (1974) [Sov. Phys.-JETP 39, No. 1 (1974)].
[2] M. L. G. Foy, N. Heiman, and W. J. Kossler, Phys. Rev. Lett. 30, 1064 (1973).