Precession of positive muons in ferromagnets

I. I. Gurevich, A. I. Klimov, V. N. Maĭorov, E. A. Meleshko, I. A. Muratova, B. A. Nikol'skiĭ, V. S. Roganov,[1)] V. I. Selivanov, and V. A. Suetin

I. V. Kurchatov Atomic Energy Institute
(Submitted August 1, 1973)
Zh. Eksp. Teor. Fiz. **66**, 374–378 (January 1974)

The polarization, precession frequency, and spin relaxation rate are determined for positive muons in magnetized iron, cobalt, and nickel specimens in transverse external magnetic fields up to 1900 Oe. The magnetic fields inducing precession of positive muons in ferromagnetic substances are discussed.

The precession of positive muons in ferromagnets is of twofold interest: First, it can provide information about the properties of the metal-hydrogen system, since the positive muon can be regarded as a light hydrogen isotope; and second, the muon method supplements other methods for investigating the magnetic properties of ferromagnets. Methodologically, the muon method is convenient because of its simplicity and because it can be used to study different specimens under quite identical conditions.

We have investigated the precession of positive muons in iron, cobalt, and nickel specimens at room temperature in external magnetic fields H up to 1900 Oe. The magnetic field was produced in the 180 mm gap between the 220 mm diameter pole pieces of an iron-encased electromagnet; it was uniform within 2% at distances up to 100 mm from the center of the gap. The targets were oblate spheroids 60 mm in diameter and 10 mm thick made of at least 99% pure polycrystalline iron, cobalt, and nickel.

The experimental setup is diagramed in Fig. 1. The beam of longitudinally polarized positive muons from the synchrocyclotron of the Joint Institute for Nuclear Research was stopped in the target T of the investigated ferromagnetic material. A $123\bar{4}$ signal (counters, 1, 2, and 3 in coincidence and 4 in anticoincidence) indicated that a muon stopped in the target, and a $456\bar{3}$ signal recorded the escape of a positron from $\mu^+ \to e^+$ decay. The muon spin precession was observed in a standard manner [1].

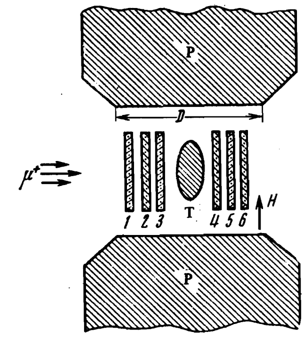

FIG. 1. Experimental setup: T–ferromagnetic target, P–magnet polepiece, 1-6–scintillation counters.

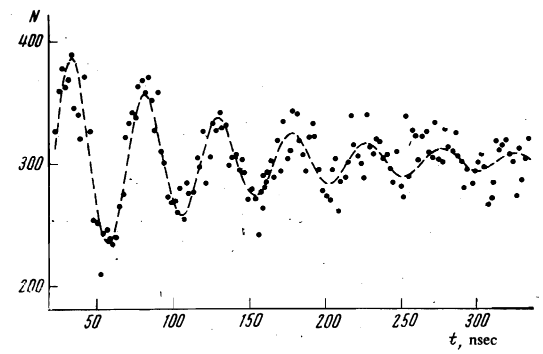

FIG. 2. Precession of a positive meson in nickel in an external field H of 750 Oe (N is the number of counts per channel). The curve was calculated for the following parameter values (obtained by a least-squares fit): precession amplitude a = 0.310 ± 0.030, precession frequency $\omega = 124.5 \pm 0.7$ MHz, precession damping rate $\lambda = 8.5 \pm 0.8$ μsec^{-1}. The corresponding parameters for a similar target of copper at H = 1900 Oe are $a_{Cu} = 0.320 \pm 0.010$, $\omega_{Cu} = 165.2 \pm 0.1$ MHz, and $\lambda_{Cu} = 0.22 \pm 0.10$ μsec^{-1}.

Figure 2 shows an example of the precession of a positive muon in nickel in an external field H = 750 Oe. As the figure shows, the muon precession amplitude a in nickel decreases with time, i.e., the muon becomes depolarized. In all cases the precession amplitude decayed according to the exponential law $a(t) = a_0 e^{-\lambda t}$. The polarization P of the positive muon in the ferromagnet was determined from the precession amplitude a using the formula $P = a/a_{Cu}$, where $a_{Cu} = 0.320 \pm 0.010$ is the precession amplitude of positive muons in a copper target of the same shape and size as the ferromagnetic target.

The principal experimental results are presented in the table. The polarization P_0 given in the table is the polarization of the positive muon at the initial instant $t = 0$, defined by the relation $P_0 = a_0/a_{Cu}$. From the observed muon Larmor precession frequency ω we can evaluate the magnetic field B_μ at the muon in the ferromagnet: $B_\mu = mc\omega/e$, where m is the muon mass. We may compare the B_μ values found in this way with the field $B_{sph} = (4/3)\pi M_{sat} = (1/3)B_{sat}$ at the center of a sphere of uniformly magnetized ferromagnetic material (here M_{sat} and B_{sat} are the saturation magnetization and induction, respectively). The values H = 0 given in the table are nominal, since the residual field of the electromagnet was compensated only in the absence of the target and with an accuracy $\delta H < 0.5$ Oe.

The following conclusions concerning the precession of positive muons in iron, cobalt, and nickel can be drawn from the data in the table:

1) The polarization P_0 of the stopped positive muon is close to unity in nickel and smaller than unity in cobalt and iron; it increases somewhat as the external field is increased from zero to 1900 Oe.

2) The spin of the muon becomes depolarized; the depolarization rate λ depends on H and is not the same in iron, cobalt, and nickel.

3) The spin precession frequency ω of a positive muon in a ferromagnet is substantially lower than the Larmor precession frequency in the saturation field B_{sat}, or even in the field $B_{sph} = (1/3)B_{sat}$.

4) The precession frequency ω for a positive muon in iron is independent of the external field over the range from zero to 1900 Oe, and in nickel ω appears to depend on H only when $H \gtrsim 700$ Oe.

Spin Precession Parameters for Positive Muons in Iron, Cobalt, and Nickel

Metal	H, Oe	P_0	λ, μsec^{-1}	ω, MHz	B_μ, G	B_{sat}, G
Fe	0	0.66 ± 0.03	2.9 ± 0.3	298.5 ± 0.3	3504 ± 3	
	750	0.72 ± 0.03	3.4 ± 0.3	298.6 ± 0.3	3506 ± 3	21500
	1900	0.78 ± 0.06	4.5 ± 0.5	296.9 ± 0.5	3486 ± 6	
Co	0	0.82 ± 0.03	25.5 ± 8.0	73.1 ± 7.0	858 ± 80	17600
Ni	0	0.88 ± 0.06	8.3 ± 0.9	113.7 ± 0.9	1134 ± 10	
	750	0.97 ± 0.09	8.5 ± 0.8	124.5 ± 0.7	1462 ± 8	6100
	1900	1.05 ± 0.06	6.4 ± 0.5	224.6 ± 0.5	2637 ± 6	

The precession of the muon in the ferromagnet is determined by the local magnetic field B_μ, which can be expressed as the sum of five different fields: a) the dipole field B_D due to the magnetic moments of the lattice atoms nearest to the muon; b) the field B_{sph} at the center of a small sphere of the polarized ferromagnetic material (B_{sph} is the resultant field of all the distant magnetic moments); c) the contact field [2] $B_c = (16/3)\pi\beta P_e|\Psi(0)|^2$ of the polarized conduction electrons at the positive muon (here β is the magnetic moment of an electron, P_e is the polarization of the conduction electrons, and $|\Psi(0)|^2$ is the electron density at the positive muon); d) the demagnetizing field B_d, which depends on the shape of the ferromagnetic target; and e) the external field H.

The demagnetizing field B_d for an oblate spheroid in an external field H parallel to its equatorial plane is small. The demagnetizing factor for the spheroidal targets used in our experiments is 0.12.

For the field due to the distant magnetic moments we have $B_{sph} = (4/3)\pi M$, and if the target is completely polarized, $B_{sph} = (4/3)\pi M_{sat} = (1/3)B_{sat}$.

The dipole field B_D depends on where the muon lies in the unit cell. The simplest case is that of nickel (fcc), in which $B_D = 0$. This result is based on the assumption that a positive muon in nickel lies in an octapore, as does a hydrogen ion[3]. In this case $B_D = 0$ regardless of the orientation of the unit-cell axes with respect to the external field H, i.e., regardless of the orientation of the individual crystals composing the polycrystalline specimen. In the iron lattice, B_D is of the order of 10 kG, both in the octapore and in the tetrapore. In iron, B_D depends substantially on the directions of the unit-cell axes as well as on the disposition of the octapores and tetrapores with respect to the unit cell concerned. In cobalt, B_D is also large and depends substantially on the orientation of the unit-cell axes.

The contact field B_c is determined by the polarization P_e of the conduction electrons and the squared modulus $|\Psi(0)|^2$ of the electron wave function at the positive muon. To estimate $|\Psi(0)|^2$ we used the results of Pathak [4], who calculated the density of an electron gas at a charged inclusion (in our case the inclusion is the positive muon), and assumed that iron, cobalt, and nickel each has two conduction electrons per atom. These calculations gave nearly the same value of $|\Psi(0)|^2$ for each of the metals, namely $(0.33-0.35)\rho_{Mu}(0)$, where $\rho_{Mu}(0)$ is the electron density at the muon in a free muonium atom. Of course these calculations are not rigorous, but it should be noted that the range of possible values of $|\Psi(0)|^2$ is not very wide: $|\Psi(0)|^2$ must be greater than the mean density of conduction electrons in the metal, and in our case this is about 8% of the maximum possible value $\rho_{Mu}(0)$ for the squared modulus of the electron wave function at the positive muon. Thus, the calculation indicates an approximately fourfold increase of the electron density at a positive muon in iron, cobalt, and nickel.

Now let us turn to the interpretation of the experimental results. First, it would seem that the large scatter of the dipole magnetic fields B_D in the magnetized polycrystalline iron and cobalt specimens must lead to very rapid depolarization of the muon in times of the order of 1–10 nsec, whereas no such rapid depolarization is observed. Another effect that seems strange is the relatively slow precession of a positive muon in these ferromagnets, in which the field B_μ at the muon is much smaller than B_{sph} and B_D. A possible explanation of these effects might be found in a rapid diffusion of the muon through the crystal lattice: the dipole field at the diffusing muon would be largely averaged out, and this would considerably reduce its effect on the precession frequency and damping rate. But even if such rapid diffusion actually takes place, we still have to explain how B_μ comes to be so much smaller than B_{sph}.

The only field available to compensate B_{sph} is the oppositely directed contact field B_c, and here there are two possibilities: $B_\mu = B_c - B_{sph}$ and $B_\mu = B_{sph} - B_c$. The correct choice between these possibilities can be made if the direction of B_μ with respect to the external field H is measured, i.e., if the direction of precession of the positive muon is measured. The direction of B_μ in iron was determined from measurements made with counters 5 and 6 (Fig. 1) displaced to the side; from the shift of the initial phase of the precession observed incident to the displacement of the counters one can determine the direction of the precession of the positive muon, and hence the direction of B_μ. It was found that in iron, B_μ is parallel to H. One could test the hypothesis that positive muons diffuse rapidly through ferromagnets by observing the muon precession at reduced temperature, for then the diffusion velocity would be lower and the depolarization rate λ should therefore be higher. An increase in λ on reducing the temperature has actually been observed for iron.

The discussion of the precession of positive muons in nickel is simpler because here $B_D = 0$ and the only unknown is the contact field B_c. Having evaluated B_c experimentally, we can find the polarization $(P_e)_{Ni}$ of the conduction electrons in nickel. Let us evaluate $(P_e)_{Ni}$ for the case $B_{sph} > B_c$. We have $B_\mu = B_{sph} - B_c$, i.e., $B_c = B_{sph} - B_\mu = 2030 - 1334 = 696$ G (we used the value $B_\mu = 1334$ G for the region $H \lesssim 700$ G in which the experimental value of B_μ is practically independent of H). Using the value $|\Psi(0)|^2 = 0.35\rho_{Mu}(0)$ from [4] in the equation $B_c = (16/3)\pi\beta P_e|\Psi(0)|^2$, we find $(P_e)_{Ni} = 0.7\%$.

To estimate P_e for iron and cobalt we have to make some assumption about the dipole field B_D. We shall assume that in these metals the average value of B_D at the positive muon is zero. Then for the case $B_c = B_{sph} - B_\mu$ ($B_{sph} > B_\mu$), calculations like that just made for nickel yield $(P_e)_{Fe} = 3.4\%$ and $(P_e)_{Co} = 4.3\%$.

We emphasize again that the values obtained for P_e are only rough estimates since a rather crude model [4] was used to calculate $|\Psi(0)|^2$.

There is still another interesting feature of the precession of positive muons in ferromagnets: the precession frequency ω is virtually independent of the external magnetic field H (in iron, ω is constant within

1% over the entire range of H from zero to 1900 Oe, and in nickel ω is also weakly dependent on H in the region $H \lesssim 700$ Oe). We do not know how to explain this effect.

The experimental value of the polarization P_0 of the positive muon in the ferromagnet is of considerable importance. The fact that $P_0 < 1$ in iron and cobalt shows that in these metals some rapid process takes place that is not observed in our experiments and that leads to the partial depolarization of the muon. It is also possible that individual muons on being stopped in iron and cobalt come to rest in some part of the lattice where B_μ differs substantially from the value in the table and that we do not observe the corresponding precession. Another explanation could be that the field B_μ is not parallel to the external field H. It is interesting that the observed polarization $P_0 = 2/3$ of a positive muon in iron at $H = 0$ corresponds to the picture of magnetized domains randomly disposed in space. In nickel, P_0 reaches unity at $H \approx 700$ Oe, i.e., at this value of H there are no fast muon depolarizing processes in nickel and B_μ is parallel (or antiparallel) to H.

Quite recently there appeared a paper[5] in which measurements of the precession of positive muons in nickel and iron are also reported. In this study [5] the values $(B_\mu)_{Ni} = 1550$ G and $(B_\mu)_{Fe} = 4100$ G were obtained; these values are close to those found in our work. Our values of the depolarization rate λ are also in good agreement with those of [5]. However, the values of P_0 found in the two studies differ widely, the values $(P_0)_{Ni} = 0.2$ and $(P_0)_{Fe} = 0.1$ being obtained in [5]. The reason for this discrepancy is not clear to us. The direction of the precession of a positive muon in nickel was determined in [5], and it was found that B_μ is parallel to H. This result shows that $B_{sph} > B_c$ in nickel, as we assumed in evaluating $(P_e)_{Ni}$.

One of the authors (B.A.N.) is grateful to V. G. Vaks for valuable discussions.

[1] I. I. Gurevich, I. G. Ivanter, E. A. Meleshko, B. A. Nikol'skiĭ, V. S. Roganov, V. I. Selivanov, V. P. Smilga, B. V. Sokolov, and V. D. Shestakov, Zh. Eksp. Teor. Fiz. 60, 471 (1971) [Sov. Phys.-JETP 33, 253 (1971)].
[2] L. D. Landau and E. M. Lifshitz, Kvantovaya mekhanika (Quantum Mechanics), Gostekhizdat., 1948, p. 574 [Pergamon, 1958].
[3] E. O. Wollan, J. W. Cable, W. C. Koeler, and C. E. Stronach, J. Phys. Chem. Solids 24, 1141 (1963)
[4] A. P. Pathak, Phys. Rev. 2B, 3021 (1970).
[5] M. L. G. Foy, Neil Heiman, and W. J. Kossler, and C. E. Stronach, Phys. Rev. Lett. 30, 1064 (1973).

Translated by E. Brunner
39