Dependence of the μ^+ meson precession frequency in ferromagnets on the intensity of the external magnetic field

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It is shown that the local magnetic field at a μ^+ meson is directed opposite to the magnetization vector **M** in iron and along **M** in nickel. The polarization of the conduction electron in iron is estimated at $p_e > 0.065$.

The precession of μ^+ mesons in ferromagnets was investigated in a number of studies.[1-5] The experimentally observed precession frequency

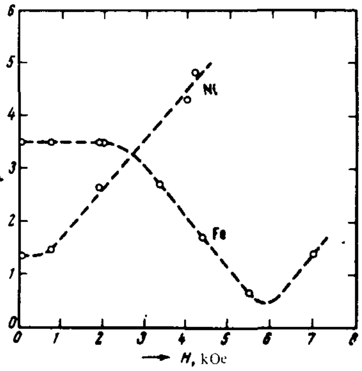
$$\omega = \frac{e}{m_\mu c} B_\mu \tag{1}$$

determines the local magnetic field B_μ at a μ^+ meson in a ferromagnet. We describe here the dependence of $B_\mu(H)$ on the external magnetic field H.

The investigation was performed with a beam of polarized muons from the JINR synchrocyclotron in Dubna. The experimental setup is described in[1]. The sample in which the μ^+ mesons were stopped was an ellipsoid of revolution of 60 mm diameter and maximum thickness 10 mm. The dimagnetizing factor for an ellipsoid of this shape is 0.12. The poles of the electromagnet producing the external magnetic field H had a diameter 270 mm; the distance between poles was 180 mm. The field H was perpendicular to the μ^+-meson polarization direction. The precession of the μ^+-meson spin was observed with the aid of scintillation counters by registering the $\mu^+ \to e^+$ decay positions.

Experimental plots of $B_\mu(H)$ for iron and nickel are shown in the figure. The $B_\mu(H)$ dependence for $H < 1900$ Oe was published earlier.[1] It is seen from the figure that at small H ($H < 700$ Oe for Ni and $H < 2000$ Oe for Fe) the value of B_μ is independent of H. This is possibly due to the screening effect. At larger H, the $B_\mu(H)$ dependence is such that the change ΔB_μ due to the change ΔH corresponds to the gyromagnetic ratio of the free μ^+ meson, as should be the case for a saturated ferromagnet. The nonmonotonic $B_\mu(H)$ dependence for iron (B_μ decreases with increasing H at $H = 2$ to 6 kOe) means that the magnetized iron produces at the μ^+ meson a magnetic field directed opposite to the magnetization vector **M**. In nickel at $H > 700$ Oe, B_μ increases with increasing H, i.e., the directions of $\mathbf{B}_\mu$ and **H** are always the same.

It should be noted that the direction of $\mathbf{B}_\mu$ determined for iron in this study does not agree with the direction of the μ^+-meson spin precession (i.e., the direction of $\mathbf{B}_\mu$) obtained by the method of moving aside the telescope of the counters that register the $\mu^+ \to e^+$ decay positrons.[1] To be sure, the reliability of the direction of $\mathbf{B}_\mu$ determined by the last method in[1] was low.



Plot of $B_\mu(H)$ for iron and nickel. The smooth curves are drawn through the experimental points for the sake of clarity. The statistical errors of B_μ do not exceed 1%.

The antiparallelism of the vectors $\mathbf{B}_\mu$ and $\mathbf{M}$ in iron can be attributed to the action exerted on the μ^+-meson spin by the contact field

$$\mathbf{B}_c = \frac{8}{3}\pi\beta|\psi(0)|^2\mathbf{p}_e \tag{2}$$

of the conduction electrons polarized opposite to the magnetization direction. Here $\mathbf{p}_e$ is the polarization of the conduction electrons, $|\psi(0)|^2$ is the electron density at the μ^+ meson, and β is the magnet moment of the electron. The contact field B_c constitutes part of the local field $\mathbf{B}_\mu$:

$$\mathbf{B}_\mu = \mathbf{B}_c + \mathbf{B}_g, \tag{3}$$

where $\mathbf{B}_g$ is the dipole magnetic field of the magnetized iron atoms. In the determination of $\mathbf{B}_g$ it is necessary to take into account the fast diffusion of the μ^+ mesons in iron at room temperature,[2] owing to which the dipole fields from the atoms closest to the μ^+ meson average out and only the dipole field in the Lorentz sphere $\mathbf{B}_g = 4\pi\mathbf{M}/3$ remains. Assuming that the magnetization $\mathbf{M}$ is maximal and equal to the saturation magnetization $\mathbf{M}_{sat}$, we obtain for iron $B_g = 7$ kG. Using the experimental value $\mathbf{B}_\mu = 3.5$ kG (see the figure and[1]), we get $\mathbf{B}_c$ from (3): $B_\mu = B_c - B_g$, and $B_c = 7 + 3.5 = 10.5$ kG.

The obtained value $B_c = 10.5$ kG makes it possible to determine the polarization p_e of the conduction electrons in iron. p_e is determined from (2) and depends on the electron density $|\psi(0)|^2$ at the μ^+ meson. The maximum value $|\psi(0)|^2 = |\psi(0)|^2_{Mu}$, corresponding to the bound state (the muonium atom) corresponds to $p_e = 1$ to $B_c = 160$ kG. Thus, the minimum possible polarization p_e at $B_c = 10.5$ kG turns out to be $(p_e)_{max} = 0.065$. At a smaller value of $|\psi(0)|^2$, which can correspond to "swollen" muonium or to the absence of a bound state of the muon-electron system in iron, p_e turned out to be quite high. It should be noted that the minimum possible value of $|\psi(0)|^2$ is close to the average conduction-electron density in iron, which is smaller only by a factor ~10 (assuming two conduction electrons per atom) than the electron density of the vacuum muonium. An approximate estimate[1] shows that in the case when muonium is not produced we have for iron $|\psi(0)|^2 \approx 0.3\,|\psi(0)|^2_{Mu}$, leading to a value $p_e = 0.2$.

The large value of p_e obtained in these calculations possibly indicates the existence of a bound state of muonium in iron.

The value of p_e for nickel was determined in[1].

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