Paschen–Bach effect for muonium atom in crystalline nitrogen

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The polarization of muons is measured as a function of longitudinal magnetic field strength in solid nitrogen. It is shown that the hyperfine interaction energy of a muonium atom in nitrogen is smaller than the vacuum value by a factor of two. In a weak field the polarization of muons is less than half the value, which is evidently due to the nuclear hyperfine interaction.

When muons are thermalized in certain materials, muonium atoms (Mu) form with a high probability.[1] The state of a muonium atom as a model of atomic hydrogen is of great interest in the study of the interaction of one-electron atoms with a crystal lattice. Rapid depolarization of muons in condensed nitrogen was observed in Ref. 2. Rapid depolarization of muons could be caused by the formation of muonium atoms or by the interaction of muons with paramagnetic impurities. It was shown in Ref. 3 that paramagnetic impurities are not the cause of the rapid depolarization of muons in nitrogen.

The formation of a metastable muonium atom can be detected by observing triplet precession of muonium in a perpendicular magnetic field. However, only precession at the muon frequency was observed in Refs. 2 and 3. The absence of precession of muonium with the triplet frequency is evidently due to the fact that after a short time ($\tau \sim 10^{-10}$ sec) muonium participates in a chemical reaction resulting in the formation of the diamagnetic compound $N_2\mu^+$ (Ref. 2). The reaction can proceed if the muonium atom in condensed nitrogen is in an excited state,[2] since the binding energy of muonium in the ground $1S$ state (13.6 eV) is much larger than the binding energy of the ion $N_2\mu^+$ (~ 5 eV). The hypothesis of an excited muonium atom was supported by measurements of the dependence of the initial phase of muon precession on a perpendicular magnetic field.[4] However, the interpretation of the results is complicated by the fact that it is required to measure small phase shifts and the systematic errors are large. Measurement of the polarization of muons as a function of a longitudinal magnetic field would make it possible to uniquely determine the state of the muonium atom in condensed nitrogen.

In the case of complete longitudinal polarization of the muon beam, muonium is formed in the triplet and singlet states. In triplet muonium depolarization of muons does not occur. The formation of singlet muonium atoms leads to complete muon depolarization after a time $t \sim 1/\omega$, where $\omega \sim 10^{10}$ sec^{-1} is the transition frequency between hyperfine levels. In strong longitudinal magnetic fields the coupling between the magnetic moments of the muon and the electron is destroyed (the Paschen–Bach effect), and such processes become forbidden. The experimentally observed consequence is the absence of depolarization of muons in strong longitudinal fields. The region of weak magnetic fields, where the hyperfine interaction dominates, is separated from the region of the Paschen–Bach effect by the magnetic field strength H_0, which is defined by equating the hyperfine interaction energy to the Zeeman energy of the electron and muon. For an isolated muonium atom $H_0^{\text{vac}} = 1858$ Oe (Ref. 5). If we neglect spin rotation of the muonium electron due to interaction with the medium, and if the probability of forming a muonium atom is 100%, then the dependence of the muon polarization on the longitudinal magnetic field has the form[5]

$$P = \frac{1 + 2x^2}{2 + 2x^2}, \quad \text{where} \quad x = H/H_0. \tag{1}$$

This relation contains a single parameter H_0, which is uniquely determined from the dependence $P(H)$. The basic parameters of the muonium atom, i.e., the hyperfine constant A and the radius r_0, can be obtained from the measured value of the critical magnetic field H_0 using the relation

$$2(\mu_e - \mu_\mu)H_0 = hA \cong 32/3\frac{\mu_\mu \mu_e}{r_0^3}, \tag{2}$$

where μ_e and μ_μ are the magnetic moments of the electron and muon.[5] The state of the muonium atom in matter can be obtained by comparing the values of H_0, A, or r_0 obtained from measurements of muon polarization in matter with the vacuum values of these quantities.

The experiment was conducted using the phasotron at JINR. The magnetic field parallel to the muon spin was varied in the region 0–4 kOe. The relative stability of the field and its nonuniformity from sample to sample was of order 10^{-3}. The experimental apparatus, the method of preparation of the sample, and the control and measurement of the temperature have been described in Ref. 2. Nitrogen containing an oxygen impurity of 10^{-6} was used as the sample.

Figure 1 shows the measured results of the muon polarization as a function of the longitudinal magnetic field strength in crystalline nitrogen at the temperature $T = 28$ K. The solid curve in the region 100–2000 Oe was calculated using (1). The critical magnetic field is $H_0 = 750 \pm 170$ Oe, which is smaller than the vacuum value by a factor of two. For comparison, Fig. 1 also shows the dependence of the muon polarization on longitudinal field for an isolated muonium atom with $H_0 = 1585$ Oe (dashed curve). The Bohr radius of the muonium atom in nitrogen can be obtained with the help of (2): $r_0 = r_B(H_0^{\text{vac}}/H_0)^{1/3} = 0.64$ Å, where $r_B = 0.5$ Å is the Bohr radius of a single muonium atom in the $1S$ state.

Hence it has been experimentally established that the muonium atom in crystalline nitrogen is in an excited state. We note that in a longitudinal field in solid nitrogen a slow depolarization is observed with a characteristic rate of 0.2 μsec^{-1}. The rate of depolarization decreases with increasing magnetic field.

In the magnetic field region 0–100 Oe the muon polarization in crystalline nitrogen is less than 1/2. A similar effect has been observed in a number of materials, including corundum.[5] Evidently the cause of the decrease of muon polarization below

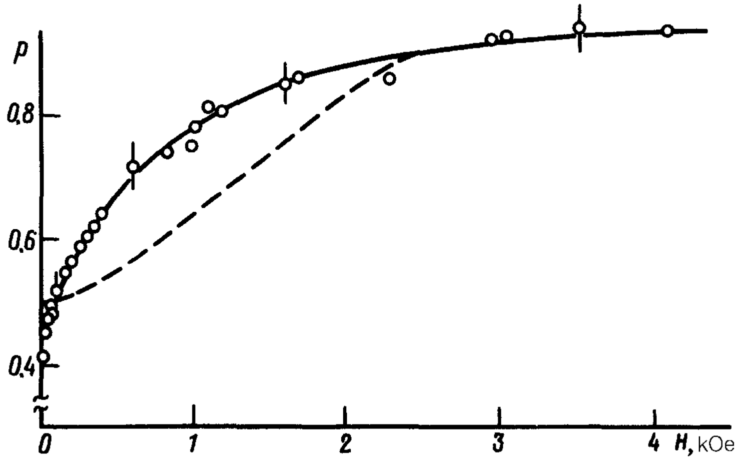

FIG. 1. Dependence of the muon polarization in crystalline nitrogen at $T = 28$ K on longitudinal magnetic field. The dependence for a muonium atom in a vacuum is shown by the dashed curve.

1/2 in weak longitudinal fields is the nuclear hyperfine interaction,[5] i.e., the interaction of the electron of the muonium atom with the nuclear magnetic moments of the nitrogen molecules. When the nuclear hyperfine interaction is taken into account, the spin Hamiltonian of the muon has the form

$$H = hA\vec{S}_e\vec{S}_\mu - g_e\mu_B\vec{S}_e\vec{H} - g_\mu\mu_\mu\vec{S}_\mu\vec{H} + h\sum_n A'\vec{S}_e\vec{S}_n - \sum_n g_n\mu_n\vec{S}_n\vec{H}, \qquad (3)$$

where the first and fourth terms describe the hyperfine interaction and nuclear hyperfine interaction, while the second, third, and fifth terms correspond to the electron, muon, and nuclear Zeeman interactions. The value of the nuclear hyperfine interaction constant A' can be estimated from the measured dependence of the muon polarization on longitudinal magnetic field. For weak magnetic fields the nuclear hyperfine interactions is stronger than the Zeeman interaction. An increase in the longitudinal magnetic field leads to a break in the coupling between the magnetic moment of the muonium electron and the nuclear magnetic moments of nitrogen. This effect is the analog of the Paschen–Bach effect of the muonium atom, in which the coupling between the magnetic moments of the electron and muon is destroyed. The constant A' is determined by setting the Zeeman energy equal to the nuclear hyperfine interaction energy for a polarization $P = 1/2$. Neglecting the muon and nuclear Zeeman interactions, we obtain $A' \simeq 10^9$ rad/sec. The hyperfine interaction constant in crystalline nitrogen is an order of magnitude larger.

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