Precise determination of the frequency of hyperfine splitting of muonium in quartz

I. I. Gurevich, A. I. Klimov, V. N. Maĭorov, E. A. Meleshko, B. A. Nikol'skiĭ, and V. I. Selivanov
I. V. Kurchatov Institute of Atomic Energy

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We have measured the frequency of hyperfine splitting ν_0 for a muonium atom impurity in quartz, $\nu_0^{SiO_2} = 4438 \pm 8$ MHz. This value for ν_0 is negligibly different from the vacuum value $\nu_0^0 = 4463$ MHz. The experiment is carried out in an applied magnetic field H = 400 Oe using equipment with a time resolution $\Delta t \approx 0.32$ nsec.

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A technique for determining the frequency of hyperfine splitting of muonium $(\mu^+ e^-)$ using two-frequency precession was proposed in Ref. 1. The frequency of hyperfine splitting $\nu_0^{SiO_2}$ of muonium in quartz in a magnetic field $H = 100$ Oe was determined in Ref. 2 with an accuracy of 1.7%. Further improvement in the accuracy

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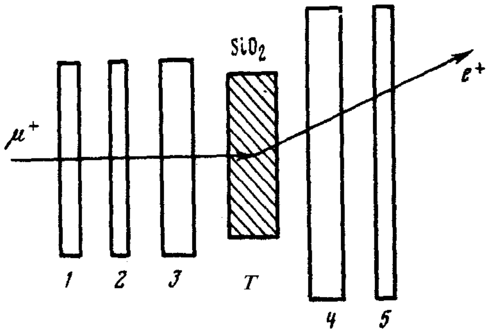

FIG. 1. Experimental setup. T is the quartz target, and 1–5 are the scintillators. Scintillator dimensions are: 1,2–100×100×10 mm^3; 3–100×100×20 mm^3; 4–150×150×20 mm^3; 5–150×150×10 mm^3. The magnetic field $H = 400$ Oe is perpendicular to the plane of the figure.

of determining ν_0 is possible by observing two-frequency precession in magnetic fields substantially greater than 100 Oe. However, observation of the Larmor precession of muonium $\omega = eH/2m_e c$ (m_e is the electron mass) in fields $H > 100$ Oe is difficult, since the precession period of muonium $T = 2\pi/\omega$ becomes comparable to the time resolution $\Delta t \approx 1.0$ nsec which is characteristic of the scintillation counters usually employed for the $\mu^+ \to e^+$-decay.[3]

The purpose of this work is to substantially improve the accuracy of determining ν_0. In order to carry out this experiment special scintillation counters and recording apparatus were developed. The work was carried out on the Joint Institute for Nuclear Research (JINR) synchrocyclotron; a diagram of the experiment is given in Fig. 1. Signals from scintillation counter 1–5 were processed by the recording apparatus discussed in detail in Ref. 3. In order to increase the time resolution, the "opposed-photomultiplier" technique was used. This consisted of viewing scintillators 3 and 4 from two opposite sides with photomultipliers through light guides whose lengths were 20 cm for counter 3 and 60 cm for counter 4. Signals from the two photomultipliers, detecting a burst in scintillator 3, were fed into a "geometry compensation scheme"[5] whose output signal (the time t_μ for the stopping of a μ^+-meson in the target) is independent of the particle impact point in the scintillator. The signal t_e from counter 4 was generated in a similar manner, corresponding to the escape time of the $\mu^+ \to e^+$-decay positron from the target. The remaining scintillator were viewed by one photomultiplier each. Signals from these scintillators served for the logical selection of events. The time distribution $t = t_e - t_\mu$ was analyzed by a time encoder with a differential nonlinearity of less than 1%. The integral nonlinearity of the encoder used was better than 10^{-4}.[6,7] The time encoder channel value was measured with the help of a specially-developed scheme[8] with an accuracy better than 10^{-4}. An encoder with a channel width of 0.10425 nsec was used in the experiment. The total number of channels was 4096. Using this apparatus we succeeded in obtaining a time resolution $\Delta t \approx 0.32$ nsec, and in this way observing the two-frequency precession of muonium at $H \approx 400$ Oe.

Let us consider the dependence of the polarization of the μ^+-meson on time, $P(t)$, for muonium in an applied magnetic field. It is known that the function $P(t)$ is described by the frequencies ν_{ik} for transitions between muonium states with different quantum numbers[1]:

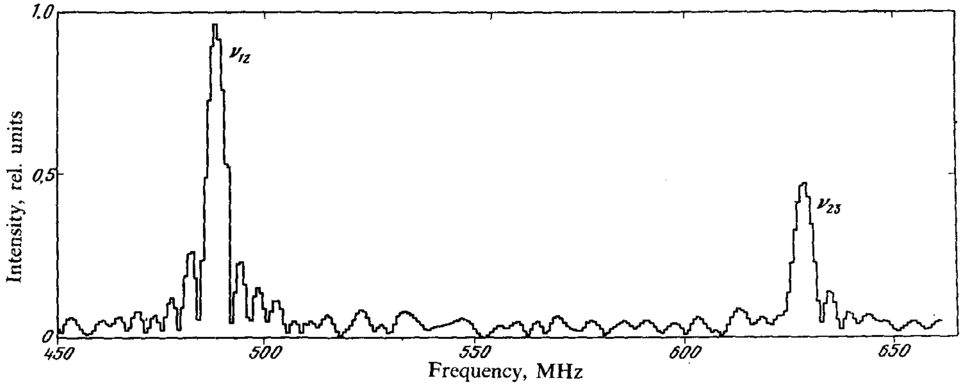

FIG. 2. Fourier transform of the experimental spectrum for $\mu^+ \to e^+$-decay in quartz in the field $H = 400$ Oe.

$$\nu_{12} = \frac{\nu_0}{2} + \nu_- - \delta, \quad \nu_{14} = \frac{\nu_0}{2} + \nu_- + \delta,$$
$$\nu_{23} = -\frac{\nu_0}{2} + \nu_- + \delta, \quad \nu_{34} = \frac{\nu_0}{2} - \nu_- + \delta, \tag{1}$$

where $\delta = (\nu_0^2/4 + \nu_+^2)^{1/2}$, $\nu_\pm = \nu(1 \pm \xi)$, and $\xi = m_e/m_\mu = 4.837 \times 10^{-3}$, where m_μ is the mass of the μ^+-meson, and $\nu = \omega/2\pi$. For the case where the experimental time resolution does not allow the detection of the larger frequencies ν_{14} and ν_{34}, the dependence of the polarization $P(t)$ of the μ^+-meson on time in an applied field $H < H_0 \approx 1590$ Oe (H_0 is the hyperfine field at the muonium electron in the $1S$-state due to the magnetic moment of the μ^+-meson) is written as[1]:

$$4P(t) = \left(1 + \frac{\nu_+}{\delta}\right) \cos 2\pi\nu_{12} t + \left(1 - \frac{\nu_+}{\delta}\right) \cos 2\pi\nu_{23} t. \tag{2}$$

The frequency of the hyperfine splitting ν_0, according to Eq. (1), is expressed in terms of the observed frequencies ν_{12} and ν_{23}:

$$\nu_0 = \frac{2(\nu_{12} + \xi\nu_{23})(\nu_{23} + \xi\nu_{12})}{(\nu_{23} - \nu_{12})(1 - \xi)^2}. \tag{3}$$

The two-frequency precession of muonium was observed in our work in fused quartz in a field $H = 400$ Oe. The experimental dependence $N_{ex}(t)$ of the number of the escaping $\mu^+ \to e^-$-decay positrons in terms of beam momentum was described using a maximum probability technique by the expression

$$N(t) = N_0 e^{-t/\tau_0} [1 - a e^{-\lambda t} P(t)], \tag{4}$$

where $\tau_0 \approx 2.2 \times 10^{-6}$ is the μ^+-meson lifetime, α is the asymmetry coefficient for μ^+

$\to e^-$-decay, and λ is the μ^+-meson spin relaxation rate. In analyzing the experimental spectrum $N_{ex}(t)$ in the interval $t = 6$–280 nsec, the following values were obtained for ν_{12} and ν_{23}:

$$\nu_{12} = 487{,}08 \pm 0{,}07 \text{ MHz}, \quad \nu_{23} = 627{,}55 \pm 0{,}14 \text{ MHz}.$$

Figure 2 shows the Fourier transform of the resulting experimental spectrum $N_{ex}(t)$. From the experimental values for ν_{12} and ν_{23} and Eq. (3), it follows that the frequency of hyperfine splitting of the muonium atom in quartz is $\nu_0^{SiO_2} = 4438 \pm 8$ MHz. It should be noted that exchange interactions between the muonium electron and electrons in the medium lead to a damping of the muonium precession and introduce a systematic error in the experimental value for $\nu_0^{SiO_2}$. In this experiment the relaxation rate is $\lambda \approx 0.6\,\mu$sec which, according to Eq. (25) in Ref. 2, leads to a shift of $\nu_0^{SiO_2}$ by an amount $\Delta\nu/\nu \leqslant 10^{-4}$.

Therefore, using this technique we succeeded in determining the value of $\nu_0^{SiO_2}$ with an accuracy of 0.18%. The resulting value $\nu_0^{SiO_2} = 4438 \pm 8$ MHz is three sigma less than the vacuum value $\nu_0^0 = 4463$ MHz. This indicates that the interactions of the hydrogen-like atomic impurity (muonium) with the quartz lattice lead to an insignificant distortion of its electron structure. Since the Bohr radius of the atom in the 1S-state is $r_0 \sim \nu_0^{-1/3}$ then, from the value $\nu_0^{SiO_2} = 4438 \pm 8$ MHz, it follows that the Bohr radius of muonium in quartz is $r_0^{SiO_2} = 1.0017 \pm 0.0006 r_0$, where $r_0 = 0.5$ Å is the Bohr radius of the muonium atom in vacuum.

In conclusion, we note that the technique suggested for determining the frequency of the hyperfine splitting of the muonium atom in medium magnetic fields may be used successfully for a precise measurement of ν_0 for muonium in semiconductors.

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