μ^+-meson spin relaxation in germanium in longitudinal magnetic fields

I. I. Gurevich, B. A. Nikol'skiĭ, V. I. Selivanov, and B. V. Sokolov

I. V. Kurchatov Atomic Energy Institute

(Submitted October 1, 1974)
Zh. Eksp. Teor. Fiz. **68**, 806–810 (March 1975)

On the basis of measurements of the relaxation rate of the μ^+-meson spin it is concluded that a long-lived bound paramagnetic state Mu (μ^+e^-) should exist in germanium; at temperatures between 170 and 300°K it should be formed in about ~70% of cases. The parameters that determine the relaxation rate of the μ^+-meson spin in this state are estimated.

It was found earlier [1] that at low temperatures $T < 80°K$ a long-lived impurity muonium atom Mu(μ^+e^-) is observed in germanium. The two-frequency precession method was used to determine the "dimension," or more accurately the frequency ω_{Ge} of the hyperfine splitting of the muonium atom in germanium at this temperature [2]. We investigate here the relaxation of the spin of the μ^+ meson in germanium in longitudinal magnetic fields; it follows from the obtained data, in particular, that a bound paramagnetic state of Mu exists also at higher temperatures, up to room temperature.

The work was performed with the JINR synchrocyclotron at Dubna. Positive muons polarized against the momentum direction were decelerated and stopped in a single-crystal germanium target. The longitudinal magnetic field H, along the direction of the spin (and momentum) of the μ^+ meson, of intensity up to 6 kOe, was produced by an electromagnet with an opening along the pole axis for the entry of the beam. The spin relaxation rate of the polarized μ^+ mesons in germanium was determined by recording, with scintillation counters, the $\mu^+ \to e^+$ decay positrons emitted against the direction of the initial μ^+-meson polarization. A detailed description of the recording apparatus is given in [2].

Figure 1 shows one of the spectra and demonstrates the time dependence of the number of counts N(t) of the positron-counter telescope. The instant t = 0 corresponds to the stopping of the μ^+ meson in the germanium; the change of the counting rate N(t) of the $\mu^+ \to e^+$ decay positrons is due to depolarization of the μ^+ meson. The experimental spectra N(t) are set in correspondence with the calculated relations

$$N_{calc} = N_0(1 - ce^{-\Lambda t}) \qquad (1)$$

With parameters N_0, c, and Λ chosen by the maximum-likelihood method. Here Λ is the rate of relaxation of the μ^+-meson spin, $c = \beta a$, where a is the experimental asymmetry coefficient of the angular distribution of the positrons of the $\mu^+ \to e^+$ decay, and β is the fraction of the μ^+ mesons whose spin relaxes with a time $1/\Lambda$.

The values of Λ for different values of H and T are shown in Figs. 2 and 3; the parameter c turned out to be practically constant in the measured interval T = 470—300°K and H < 5 kOe, and equal to c = 0.19 ± 0.01. Figure 2 shows the dependence of the μ^+-meson relaxation rate on the intensity of the longitudinal field in units of $(1 + x^2)^{-1}$, where $x = H/H_0$. Here $H_0 = \omega_0/2\mu_e$ = 1594 Oe is the field produced by the magnetic moment of the μ^+ meson at an electron of the muonium atom in vacuum, i.e., for an undeformed electron wave function; $\omega_0 = 2.8 \times 10^{10}$ sec^{-1} is the frequency of the hyperfine

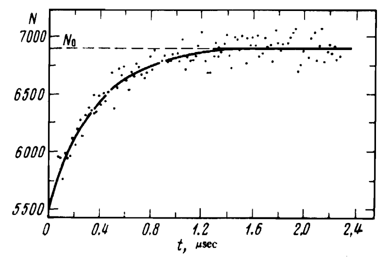

FIG. 1. Temporal spectrum of the $\mu^+ \to e^+$ decay positrons emitted against the direction of polarization of the μ^+ mesons at T = 233°K and $x = H/H_0 = 3.0$ (N is the number of counts in the channel). The instant of time t = 0 corresponds to the stopping of the μ^+ meson in germanium. The smooth curve is a plot of (1) with parameter N_0, c, and Λ chosen by the maximum-likelihood method: $N_0 = 6900 \pm 40$, $c = 0.196 \pm 0.003$, $\Lambda = 3.4 \pm 0.2$ μsec^{-1}. The presented data were "corrected" for the meson-decay exponent ($\tau_0 = 2.2$ μsec).

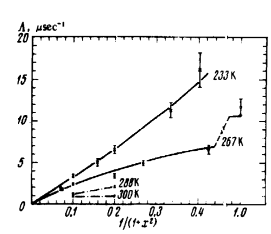

FIG. 2

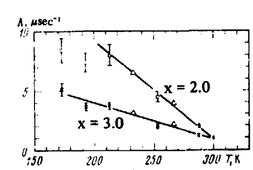

FIG. 3

FIG. 2. Dependence of the μ^+-meson spin relaxation rate in germanium on the intensity of the longitudinal magnetic field at different temperatures ($\Lambda = f(1/1 + x^2)$), $x = H/H_0$, H_0 = 1594 Oe). The errors are statistical. The solid curves represent the theoretical relations (3) ($\nu \gg \omega_{Ge}$) with parameters ν and ω_{Ge} chosen by the maximum-likelihood method (see the table). The dash-dot lines are shown for clarification.

FIG. 3. Plot of $\Lambda(T)$ at two values of the longitudinal field $x = H/H_0$; H_0 = 1594 Oe. The values of Λ at T = 233 and 267°K, designated by triangles, were obtained from the theoretical plots of $\Lambda(x)$ [Eq. (3)] shown in Fig. 2 at these temperatures. The straight lines are drawn for the sake of clarity.

splitting of muonium in vacuum; μ_e is the magnetic moment of the electron. This scale along the abscissa axis of Fig. 2 is connected with the possible interpretation of the experimental Λ(H) dependence and will be considered below. Figure 3 shows the temperature dependence of Λ(T) at two values of the field H. Let us examine the consequences ensuing from the presented experimental data.

It is seen from Fig. 2 that when the longitudinal field intensity is increased the relaxation rate Λ decreases. However, even in fields H > 1 kOe we have $\Lambda \sim 10^7$ sec. So large a relaxation rate in strong longitudinal fields shows that the depolarization of the μ^+-meson spin in germanium is due to interaction with electrons.

The fact that Λ varies with the intensity of the longitudinal magnetic field at H < 5 kOe means that the relaxation of the μ^+-meson spin is due to interaction with a bound electron in a paramagnetic state. We shall assume for the sake of argument that this bound paramagnetic system is a muonium atom in the S state. The relaxation of the μ^+-meson spin is due in this case to polarization of the electron of the muonium interacting with the electrons of the medium. We denote by ν the frequency of the spin flip of the muonium electron. The function $\Lambda(\omega_{Ge}, \nu, H)$ obtained in this case was calculated by Ivanter and Smilga [3]. In the general case, the expression for $\Lambda(\omega_{Ge}, \nu, H)$ is very cumbersome. The formulas for the limiting cases $\nu \ll \omega_{Ge}$ and $\nu \gg \omega_{Ge}$ are given below:

$$\Lambda=\frac{\nu}{1+x^2(\omega_0/\omega_{Ge})^2}, \quad \nu\ll\omega_{Ge}, \qquad (2)$$

$$\Lambda=\frac{\nu(\omega_{Ge}/\omega_0)^2}{4(\nu/\omega_0)^2+x^2}, \quad \nu\gg\omega_{Ge}. \qquad (3)$$

In accordance with the structure of formulas (2) and (3), the experimental $\Lambda(x)$ dependence is shown in Fig. 2 as a function of $1/(1 + a^2)$.

It is seen from (3) that in the absence of a bound state of the Mu system the relaxation rate Λ should remain practically unchanged with changing x in the measured interval x < 4. Indeed, the $\Lambda(x)$ dependence of the μ^+ meson, due to the interaction with the conduction electrons, can be qualitatively described by formula (3) if we assume $\nu = 1/\tau$, where $\tau = l/v \sim 10^{-16}$ sec is the time of interaction of the μ^+ meson with the electron. Here $l \sim 10^{-8}$ cm is the dimension of the interaction region, $v \sim 10^8$ cm/sec is the electron velocity. The value $\nu \sim 10^{16}$ sec^{-1} leads to a very large value of the ratio $\nu/\omega_0 \sim 10^{16}/10^{10} = 10^6$, and consequently to independence of Λ of x in formula (3). We recall that the condition under which formula (3) is valid, namely $\nu \gg \omega_G$, is satisfied if $\nu \gg \omega_0$, since the frequency ω_0 of the hyperfine splitting in vacuum is always larger than in the medium (ω_{Ge}).

The experimental value c = 0.19 ± 0.01 (see expression (1)) must be compared with the asymmetry coefficient $a_{Cu} = 0.264 \pm 0.004$ of the angular distribution of the positron of the $\mu^+ \to e^+$ decay in a copper target, obtained in a transverse magnetic field under the same experimental conditions. Assuming that $c = \beta a_{Cu}$, we obtain the fraction β of the μ^+ mesons whose spin experiences the experimentally observed slow ($\Lambda = 2 \times 10^7$–10^6 sec^{-1}) relaxation in germanium: $\beta = c/a_{Cu} = 0.7$. It can be assumed that the remaining ~30% of the μ^+ mesons form in the germanium a diamagnetic compound and their spin relaxes slowly during the lifetime of the μ^+ meson.

We now use formulas (2) and (3) to determine the parameters ν and ω_{Ge} that characterize the bound state of Mu in germanium. The parameters ν and ω_{Ge} are obtained by comparing the experimental $\Lambda(x)$ dependence and the theoretical expressions (2) and (3) for the cases $\nu \ll \omega_{Ge}$ and $\nu \gg \omega_{Ge}$, respectively. The values obtained for these parameters in this manner for T = 233 and 267° K, when the $\Lambda(x)$ dependence is determined in sufficient detail (see Fig. 2), are listed in the table.

Values of the parameters* ν and ω_{Ge}, determined from a comparison of formulas (2) and (3) with the experimental $\Lambda(x)$ dependence at 233 and 267°K.

	T, K	ν/ω_0	ω_{Ge}/ω_0	ν/ω_{Ge}	χ^2
$\nu\gg\omega_{Ge}$	233	0,37±0,09	0,054±0,005	7	4.3
$\nu\gg\omega_{Ge}$	267	0,79±0.04	0,0346±0.0005	23	8.2
$\nu\ll\omega_{Ge}$	233	0,002±0.0002	0.74±0,17	0.0027	4.3

*The Pearson parameter χ^2 corresponds to six experimental points; $\omega_0 = 2.8 \times 10^{10}$ sec^{-1}.

The table does not list the case $\nu \ll \omega_{Ge}$ for T = 267°K, since it leads to a value $\omega_{Ge}/\omega_0 = 1.57 \pm 0.08$, which contradicts the condition $\omega_{Ge} \ll \omega_0$. Therefore only the case $\nu \gg \omega_{Ge}$, corresponding to formula (3), is possible at T = 267°K. At T = 233°K, the experimental $\Lambda(x)$ dependence can be compared both with formula (2) and with formula (3). For comparison we recall that the value of ω_{Ge} obtained for an impurity muonium atom in germanium at T = 80°K by the two-particle precession method turned out to be $\omega_{Ge} = (0.58 \pm 0.01)\omega_0$ [2].

It is seen from the table that the values of ω_{Ge} at the two investigated temperatures differ from each other. An attempt to describe $\Lambda(x)$ at T = 233 and 267°K with the aid of formula (3) with one and the same value of ω_{Ge} leads to a value $\chi^2 \approx 100$, i.e., it contradicts the experimental data. The change of ω_{Ge} with changing temperature means that the electronic wave function of the paramagnetic state of Mu in germanium changes with changing temperature.

Figure 3 shows the experimental plot of $\Lambda(T)$ at the two values x = 2.0 and x = 3.0. The same values of Λ at two values of the temperature T are shown in Fig. 2. It is seen from Figs. 2 and 3 that with increasing temperature the difference between $\Lambda(x = 2)$ and $\Lambda(x = 3)$ decreases; at T = 300°K these quantities coincide. Such a regularity is possible only if $\nu \gg \omega_{Ge}$, and the agreement of $\Lambda(x = 2)$ with $\Lambda(x = 3)$ at T = 300°K means that at this temperature $\nu/\omega_0 \gg x$ (see formula (3)) or that there is no Mu bound state. It is of interest to investigate in greater detail the $\Lambda(x)$ dependence in germanium at T > 260°K, when the determination of the parameters ν and ω_{Ge} is unambiguous.

The authors are grateful to A. I. Klimov, V. N. Maĭorov, I. A. Muratova, A. V. Pirogov, V. S. Roganov, and V. E. Suetin for help with the work.

[1]D. G. Andrianov, G. G. Myasishcheva, Yu. V. Obukhov, V. S. Roganov, V. G. Firsov, and V. I. Fistul', Zh. Eksp. Teor. Fiz. 56, 1195 (1969) [Sov. Phys.-JETP 29, 643 (1969)].
[2]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)].
[3]I. G. Ivanter and V. P. Smilga, Zh. Eksp. Teor. Fiz. 55, 1521 (1968) [Sov. Phys.-JETP 28, 796 (1969)].

Translated by J. G. Adashko
89