It was found earlier [12] that at low temperatures \( T < 80^\circ \text{K} \) a long-lived impurity muon atom \( \text{Mu}(\mu^- e^-) \) is observed in germanium. The two-frequency precession method was used to determine the "dimension," or more accurately the frequency \( \omega_{\text{Ge}} \) of the hyperfine splitting of the muon atom in germanium at this temperature \([12]\). We investigate here the relaxation of the spin of the \( \mu^- \) 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 \( \mu^- \) 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 \( \mu^- \) mesons in germanium was determined by recording, with scintillation counters, the \( \mu^- \rightarrow e^- \) decay positrons emitted against the direction of the initial \( \mu^- \) meson polarization. A detailed description of the recording apparatus is given in \([12]\).

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 \( \mu^- \) meson in germanium; the change of the counting rate \( N(t) \) of the \( \mu^- \rightarrow e^- \) decay positrons is due to depolarization of the \( \mu^- \) meson. The experimental spectra \( N(t) \) are set in correspondence with the calculated relations

\[
N_{\text{calc}} = N_0 (1 - ce^{-\Lambda t})
\]

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

The values of \( \Lambda \) 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 \( T = 740-300^\circ \text{K} \) and \( H < 5 \text{kOe} \), and equal to \( c = 0.19 \pm 0.01 \). Figure 2 shows the dependence of the \( \mu^- \) meson relaxation rate on the intensity of the longitudinal field in units of \((1 + x^2)^{-1/2}\), where \( x = H/H_0 \). Here \( H_0 = \omega_{\text{Ge}}/2\mu_B \) = 1594 Oe is the field produced by the magnetic moment of the \( \mu^- \) meson at an electron of the muonium atom in vacuum, i.e., for an undeformed electron wave function; \( \omega_{\text{Ge}} = 2.8 \times 10^{13} \text{ sec}^{-1} \) is the frequency of the hyperfine splitting of muonium in vacuum; \( \mu_B \) 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 \( \Lambda(H) \) dependence and will be considered below. Figure 3 shows the temperature dependence of \( \Lambda(T) \) 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 \( \Lambda \) decreases. However, even in fields \( H > 1 \text{kOe} \) we have \( \Lambda \sim 10^7 \text{ sec}^{-1} \). So large a relaxation rate in strong longitudinal fields...
shows that the depolarization of the $\mu^*$-meson spin in germanium is due to interaction with electrons.

The fact that $\Lambda$ varies with the intensity of the longitudinal magnetic field at $H < 5$ kOe means that the relaxation of the $\mu^*$-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 $\mu^*$-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 $\nu$ the frequency of the spin flip of the muonium electron. The function $\Lambda(\omega_{Ge}, \nu, \beta)$ obtained in this case was calculated by Ivanter and Smilga [3].

In accordance with the structure of formulas (2) and (3), the experimental $\Lambda(\beta)$ dependence is shown in Fig. 2 as a function of $1/(1 + \lambda^2)$. It is seen from (3) that in the absence of a bound state of the Mu system the relaxation rate $\Lambda$ should remain practically unchanged with changing $x$ in the measured $\omega_{Ge}$. Therefore only the case $\nu \ll \omega_{Ge}$ corresponding to formula (3), is possible at $T = 260^\circ$K. At $T = 233^\circ$K, the experimental $\Lambda$ dependence can be compared both with formula (3) and with formula (2). For comparison we recall the value of $\omega_{Ge}$ obtained for an impurity muonium atom in germanium at $T = 80^\circ$K by the two-particle precession method turned out to be $\omega_{Ge} = (0.58 \pm 0.01)\omega_{e}\beta^2$.

It is seen from the table that the values of $\omega_{Ge}$ at the two investigated temperatures differ from each other. An attempt to describe $\Lambda(\beta)$ at $T = 233$ and $267^\circ$K with the aid of formula (3) with one and the same value of $\omega_{Ge}$ leads to a value $\chi^2 \approx 100$, i.e., it contradicts the experimental data. The change of $\omega_{Ge}$ 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 $\Lambda$ 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 $T = 300^\circ$K these quantities coincide. Such a regularity is possible only if $\nu \gg \omega_{Ge}$, and the agreement of $\Lambda(\beta = 2)$ with $\Lambda(\beta = 3)$ at $T = 300^\circ$K means that at this temperature $\nu \gg \omega_{Ge}$ (see formula (3)) or that there is no Mu bound state. It is of interest to investigate in greater detail the $\Lambda$ dependence in germanium at $T > 260^\circ$K, where the determination of the parameters $\nu$ and $\omega_{Ge}$ is unambiguous.

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

---

Values of the parameters $\nu$ and $\omega_{Ge}$, determined from a comparison of formulas (2) and (3) with the experimental $\Lambda(x)$ dependence at $233$ and $267^\circ$K.

<table>
<thead>
<tr>
<th>$T$, K</th>
<th>$\nu$(\omega_{Ge})</th>
<th>$\omega_{Ge}$</th>
<th>$V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>233</td>
<td>$0.37 \pm 0.00$</td>
<td>$0.064 \pm 0.005$</td>
<td>7</td>
</tr>
<tr>
<td>267</td>
<td>$0.79 \pm 0.04$</td>
<td>$0.086 \pm 0.005$</td>
<td>33</td>
</tr>
<tr>
<td>233</td>
<td>$0.02 \pm 0.002$</td>
<td>$0.71 \pm 0.07$</td>
<td>0.0027</td>
</tr>
</tbody>
</table>

*The Pearson parameter $\chi^2$ corresponds to six experimental points; $\omega_{Ge} = 2.8 \times 10^8$ cm sec$^{-1}$. 

---

