Relaxation of μ^+-meson spin in silicon in longitudinal magnetic fields

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The μ^+-meson spin relaxation in silicon in longitudinal magnetic fields of intensity ~6 kOe was investigated experimentally at a temperature 290° K. It follows from the result that the μ^+ meson produces in silicon a long-lived paramagnetic state (μ^+e^-). The lifetime of this state is estimated.

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Gurevich *et al.*[1] measured the dependences of the μ^+-meson spin relaxation rate $\Lambda(H)$ in germanium of the intensity of the longitudinal magnetic field H at temperatures $T=200-300$°K. It followed from the obtained experimental $\Lambda(H)$ dependences that at the indicated temperatures the μ^+ meson produces in germanium an orbitally coupled paramagnetic state (μ^+e^-), which can be interpreted as a muonium atom. The frequencies ω_0 of the hyperfine splitting of the muonium atom in germanium and the rates ν of the muonium electronic-spin relaxation due to the interaction with the electrons of the medium were determined by comparing the experimental and theoretical $\Lambda(H)$ dependences at $T=230$ and $T=270$°K. It is of great interest to ascertain whether an orbitally coupled paramagnetic state (μ^+e^-) exists also in other semiconductors, and to determine the parameters of this state at various temperatures. To this end, we investigated in the present study the relaxation of the μ^+-meson spin in silicon in longitudinal magnetic fields $H=0-6$ kOe at $T=290$°K. The work was performed with the JINR synchrocyclotron in Dubna.

Positive muons polarized against the direction of the momentum were slowed down and stopped in the investigated sample. A longitudinal magnetic field H in the direction of the spin (and momentum) of the μ^+ meson was produced by an electromagnet with an opening along the pole axis for the entry of the beam. The investigated silicon sample was a single crystal of n-type with resistivity 30 Ω-cm and an impurity content ~10^{14} cm^{-3}. The spin relaxation of the polarized μ^+ mesons in silicon was investigated by recording, with the aid of scintillation counters, the $\mu^+\to e^+$ decay positrons emitted in a direction opposite to the initial polarization of the μ^+ mesons.

Figure 1 shows two spectra that illustrate the time dependence of the number of counts $N(t)$ of the positron counter telescope, for different values of the longitudinal field intensity H. The instant of time $t=0$ corresponds to stopping a μ^+ meson in silicon. The change of the count $N(t)$ of the $\mu^+\to e^+$ decay positrons is due to depolarization of the μ^+ meson. All the experimental spectra $N(t)$, as illustrated in Fig. 1, are well described by the calculated relation

$$N_{calc}=N_0\exp(-t/\tau_0)(1-ce^{-\Lambda t}). \tag{1}$$

Here $\tau_0=2.2\times10^{-6}$ sec is the μ^+-meson lifetime; Λ is the spin relaxation rate of the μ^+ meson; $c=\beta a$, where a is the experimental asymmetry coefficient of the angular distribution of the $\mu^+\to e^+$ decay positrons, and $\beta\leq1$ is a parameter that takes into account the variation of the coefficient c with the longitudinal field intensity H as observed for silicon.

The quantity a was determined in the form $a=2a_0=0.32\pm0.5$ where a_0 is the muonium precession amplitude observed in this silicon sample at $T=80$°K. This value of a coincides within the limits of errors with the experimental asymmetry coefficient in copper, $a_{Cu}=0.312\pm0.03$. Unfortunately, it was impossible in this experiment to compare with the necessary degree of accuracy the count of the positron telescope for different spectra $N(t)$. Therefore the spectra $N(t)$ shown in Fig 1 were arbitrarily normalized to one value $N(t=0)$. An experimental normalization of the $N(t)$ spectra would in this case be of great interest, since the change

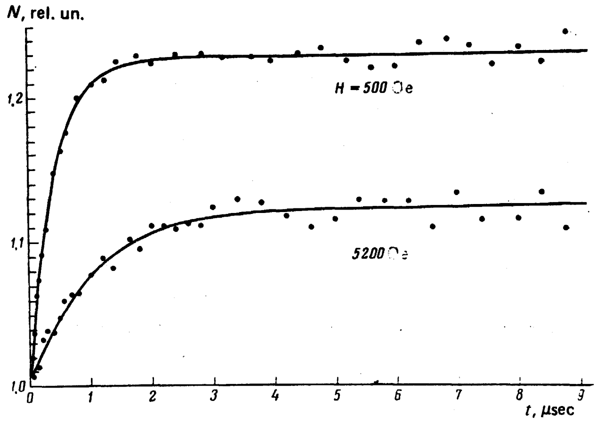

FIG. 1. Time spectra $N(t)$ of the $\mu^+\to e^+$ decay positrons emitted in a direction opposite to μ^+-meson polarization at $H=500$ Oe and $H=5200$ Oe. The spectra are normalized to a single value of N at $t=0$. The smooth curves are plots of (1) with parameters N_0, c, and Λ, chosen by the maximum likelihood method. The presented data were corrected for the time constant of the μ^+-meson decay ($\tau_0=2.2$ μsec).

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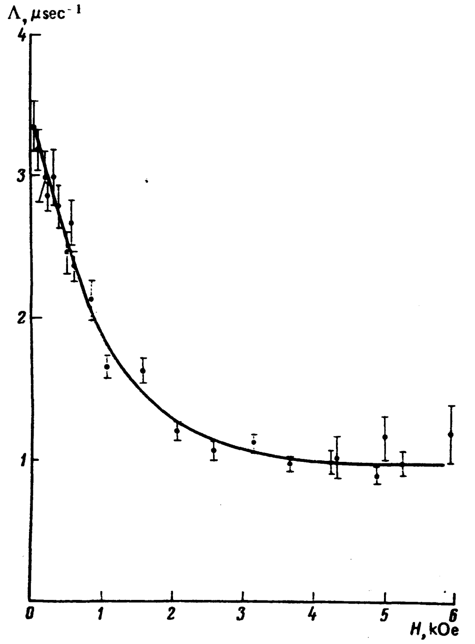

FIG. 2. Experimental plot of $\Lambda(H)$ in silicon at $T = 290$ °K. The solid line is an interpolation of the experimental points in the form of a smooth curve.

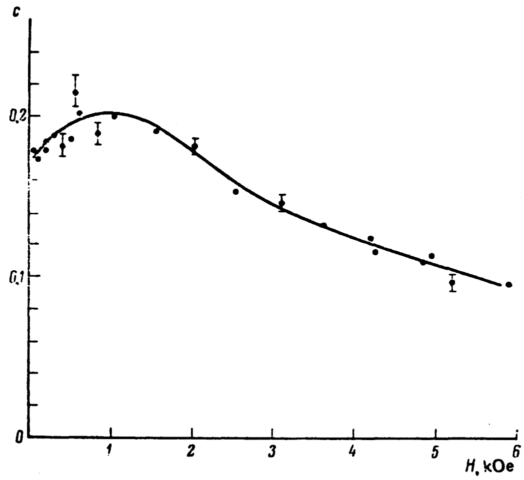

FIG. 3. Experimental dependence of $c(H)$ in silicon at $T = 290$ °K. The solid line is an interpolation of the experimental points in the form of a smooth curve.

of the coefficient c with changing H, observed for silicon, can be due both to a change of $N(t=0)$ and of $N(t \to \infty)$.

Figures 2 and 3 show plots of $\Lambda(H)$ and $c(H)$ in silicon at $T = 290$°K. The experimental values of Λ and c shown in these figures were determined by the maximum-likelihood method from a comparison of the experimental spectra $N(t)$ and expressions calculated (1). It is seen from Fig. 2 that with increasing longitudinal field H the relaxation rate Λ in silicon decreases. However, even in fields $H \approx 6$ kOe the value of Λ remains quite appreciable: $\Lambda \approx 10^6$ sec^{-1}. So large a μ^+-meson spin relaxation rate in longitudinal magnetic fields of several kOe intensity shows that the depolarization of the μ^+-meson spin in silicon is due to interaction with the electrons. The substantial change of Λ in fields H in the interval $H = 0$–3 kOe means that the spin depolarization of the μ^+ meson occurs upon interaction with the orbitally coupled electron in the paramagnetic state (μ^+e^-).[1] This state can be a muonium atom or some more complicated paramagnetic formation. We shall hereafter regard this state as a muonium impurity atom.

Thus, close to room temperature, the μ^+ meson produces in silicon, just as in germanium, a paramagnetic muonium atom. Just as in germanium,[1] the muonium atom in silicon does not precess at $T \gtrsim 100$°K with the Larmor frequency of the free muonium, obviously as a result of the high relaxation frequency $\nu \gtrsim \omega_0$ of the electron spin.

We consider now in greater detail the spin relaxation of the μ^+ meson in silicon. It follows from Fig. 3 that the value of c depends substantially on the longitudinal magnetic field intensity H. Thus, when H changes from 1 to 5 kOe, the parameter c decreases to one-half. The decrease of c can be due only to the non-zero polarization of the μ^+ meson as $t \to \infty$, i.e., to the stopping of the depolarization of the μ^+-meson spin after a certain time τ following the production of the muonium, for example, when a diamagnetic compound is produced. The fall-off of the polarization of the μ^+-meson spin like $\sim e^{-t/\tau}$ leads to the following expression for the experimentally observed $N(t)$ dependence:

$$N(t) = N_0[1 - aP(t)]\exp(-t/\tau_0), \tag{2}$$

where

$$P(t) = P_\infty + (1 - P_\infty)\exp[-(\Lambda_1 + \Lambda_2)t] = \frac{\Lambda_1}{\Lambda}\left\{1 + \frac{\Lambda_2}{\Lambda_1}\exp[-(\Lambda_1 + \Lambda_2)t]\right\} \tag{3}$$

is the time dependence of the μ^+-meson polarization. Here P_∞ is the μ^+-meson polarization at $t \to \infty$; $\Lambda_1 = 1/\tau$ is the probability of formation of a diamagnetic compound; Λ_2 is the H-dependent relaxation rate of the muonium μ^+-meson spin; $\Lambda_1 + \Lambda_2 = \Lambda$ is the experimentally observed (see Fig. 2 and relation (1)) rate of change of the count $N(t)$.

Relation (2) leads to the following dependence of the parameter c on the values of Λ_1 and Λ_2, which determine the value of Λ:

$$c = \frac{\Lambda_2 a}{\Lambda_1(1 + \Lambda_2/\Lambda_1 - a)} = \frac{\Lambda_2 a}{\Lambda - \Lambda_1 a}. \tag{4}$$

It follows from (4) that in our model only one constant Λ_2, which is independent of the field H, determines the ratio of the experimental values of $\Lambda(H)$ and $c(H)$ in the entire interval of variation of H. This still leaves open, of course, the question of whether the $\Lambda_2(H)$ dependence obtained in this manner corresponds to the assumed physical model of the interaction of the muonium atom in matter. In this case, if the influence of the matter on the muonium atom can be described, as for germanium, only by the corresponding parameters ω_0 and ν, then

$$\Lambda_2(H)=\frac{A}{B+H^2}, \tag{5}$$

where A and B are constants.[2]

The model proposed above in incapable, however, of completely describing the experimental $\Lambda(H)$ and $c(H)$ dependences. A disparity arises at $H < 2$ kOe, when Λ increases sharply and c remains constant or even decreases as $H \to 0$. This change of the parameters Λ and c does not satisfy the relation (4) at any possible value of $\Lambda_1 < \Lambda(H=6)$, where $\Lambda(H=6)$ is the minimal value of Λ in the measured interval $H=0$–6 kOe.

Agreement with experiment at all values of H can be attained by assuming that the experimentally observed value $P(t=0)<1$ (or $c<a$) is connected with muonium production first in an unstable excited state, which then goes over rapidly to a long-lived ground state. Such an unstable state leads, first, to a decrease of the observed value of the polarization $P(t=0)$ of the μ^+ meson at $t=0$ and, second, to a dependence of the quantity $P(t=0)$ on the field intensity H. Expressions (2) and (4) for such a two-stage formation of long-lived muonium take the following form:

$$N(t)=N_0[1-aP_0(H)P(t)]\exp(-t/\tau_0), \tag{6}$$

$$c=\frac{\Lambda_2 aP_0(H)}{\Lambda_1[1+\Lambda_2/\Lambda_1-aP_0(H)]}=\frac{\Lambda_2 aP_0(H)}{\Lambda-\Lambda_1 aP_0(H)}. \tag{7}$$

Here $P_0(H)=P(t=0)$ is the H-dependent experimentally observed value of the polarization of the μ^+ meson at $t=0$.

Fig. 4 shows the experimental dependence obtained from relation (7),

$$P_0^{\text{exp}}(H)=\frac{c(1+\Lambda_2/\Lambda_1)}{a(c+\Lambda_2/\Lambda_1)}, \tag{8}$$

Corresponding to the experimental values of $\Lambda(H)$ and $c(H)$ shown in Figs. 2 and 3 at $\Lambda_1=0.69$ μsec^{-1} and $a=0.32$. To decrease the relatively large statistical errors, six experimental values of P_0 at $H>4$ kOe were summed pairwise on Fig. 4.

The experimental $P_0^{\text{exp}}(H)$ dependence is compared in Fig. 4 with the theoretical expression

$$P_0^{\text{teor}}(H)=\frac{1+(\omega_0'\tau')^2(1/2+x^2)}{1+(\omega_0'\tau')^2(1+x^2)}, \tag{9}$$

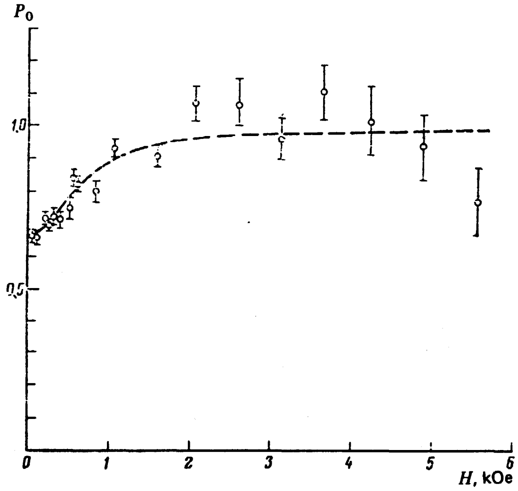

FIG. 4. Experimental (8) and theoretical (9) dependences of the residual polarization $P_0(H)$ of the short-lived muonium on the longitudinal field H.

which describes the residual polarization of short-lived muonium in a longitudinal magnetic field at $\nu\tau'<1$. Here ω_0' and τ' are respectively the frequency of the hyperfine splitting and the lifetime of the excited muonium, $x=H/H_0$, $H_0=\hbar\omega_0'/2\beta$, β is the magnetic moment of the electron. The parameter $\Lambda_1=0.69\pm0.01$ sec^{-1}, as well as the parameters $(\omega_0'\tau')=1.4\pm0.1$ and $H_0=0.56\pm0.03$ kOe which enter in (9), were determined by the maximum-likelihood method in a comparison of relations (8) and (9). The correspondence parameter obtained in this case turned out to be $\chi^2=28$ at the $n=20$ experimental values of $P_0^{\text{exp}}(H)$ shown in Fig. 4. From Fig. 4 and the presented value of χ^2 it is seen that the experimental $P_0^{\text{exp}}(H)$ dependence agrees well with the theoretical expression that describes the two-stage model of production of a long-lived paramagnetic state (μ^+e^-) in silicon with a lifetime $\tau=1/\Lambda_1=1.45\pm0.02$ μsec.

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