Relaxation of the μ^+-meson spin in tellurium

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From measurements of the relaxation of the μ^+-meson spin in strong magnetic fields it is concluded that a paramagnetic state (μ^+e^-) is formed in tellurium at temperatures 250–290 K.

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Relaxation of the μ^+-meson spin in tellurium has been observed in a longitudinal magnetic field H and transverse magnetic field $H_\perp$. The work was carried out in the synchrotron at the Joint Institute for Nuclear Research, Dubna. The results are shown in Figs. 1–3. The relaxation rates shown in these figures Λ in a longitudinal magnetic field and $\Lambda_\perp$ in a transverse field, and also the experimental asymmetry coefficients C of the angular distribution of positrons from $\mu^+\to e^+$ decay in a longitudinal magnetic field, were determined by the method of maximum likelihood with comparison of the experimental dependences $N(t)$ of the number of positrons from $\mu^+\to e^+$ decay emitted opposite to the direction of the primary polarization of the μ^+ meson, and the corresponding theoretical expressions:

$$N(t)=N_0e^{-t/\tau_0}(1-Ce^{-\Lambda t}) \quad (1)$$

for a longitudinal magnetic field and

$$N(t)=N_0e^{-t/\tau_0}(1-Ce^{-\Lambda t}\cos\omega t) \quad (2)$$

for a transverse magnetic field. Here $\tau_0=2.2\times10^{-6}$ sec is the lifetime of the μ^+ meson; ω is the Larmor precession frequency of the μ^+ meson in a field $H_\perp$. In the expressions (1) and (2) it is assumed that relaxation of the μ^+-meson spin in tellurium occurs according to an exponential law: $P(t)=e^{-\Lambda t}$. The exponential dependence of $P(t)$ in tellurium has been confirmed experimentally.

From the experimental dependence $\Lambda(H)$ given in Fig. 1 for the relaxation rate as a function of the longitudinal magnetic field strength at $T=290$ K and $T=250$ K it follows that in tellurium at these temperatures a paramagnetic state (μ^+e^-) is formed. An experimental study of the (μ^+e^-) paramagnetic state by means of a longitudinal magnetic field was first carried out for germanium.[1] A long-lived paramagnetic state (μ^+e^-) in tellurium follows from the high relaxation rate $\Lambda\sim10^6$ sec^{-1} of the μ^+-meson spin, which is not suppressed even by a longitudinal field $H\sim10^3$ Oe. Such a large value of Λ can occur only in the interaction of the μ^+ meson with the electronic magnetic moment. The fact that Λ changes with change of magnetic field for $H\approx10^3$ Oe means that the observed relaxation of the μ^+-meson spin cannot be the result of interaction with conduction electrons.[1] A natural explanation of the observed relaxation is the assumption of existence of an orbital bound state (μ^+e^-) in this semiconductor. Precession of the μ^+-meson spin in a transverse magnetic field $H_\perp$ with frequency ω is explained in this model by the high frequency $\nu>\omega_0$ (Ref. 2) of flipping of the electron spin as the result of incoherent interactions with matter.

Let us now consider the process of μ^+-meson spin relaxation in tellurium more in detail. It is evident from Fig. 2 that the coefficient C on increase of H first rises and then decreases. The rise of C can be explained if we assume that formation of the long-lived paramagnetic state (μ^+e^-) occurs as the result of interaction with matter of a short-lived experimentally unobserved atom of muonium. On increase of the longitudinal magnetic field H the depolarization of the μ^+ meson during the lifetime of the short-lived muonium atom decreases, which leads to an increase of the coefficient C in low fields $H\lesssim500$ Oe. The decrease of C in longitudinal fields $H>500$ Oe can occur only as the result of a nonzero polarization of the μ^+-meson spin as $t\to\infty$, i.e.,

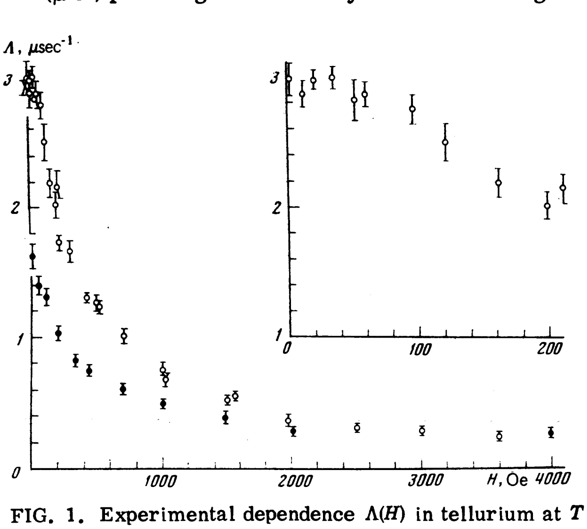

FIG. 1. Experimental dependence $\Lambda(H)$ in tellurium at $T=290$ K (○) and $T=250$ K (●). In the insert we have given the dependence $\Lambda(H)$ at $T=290$ K for $H<200$ Oe.

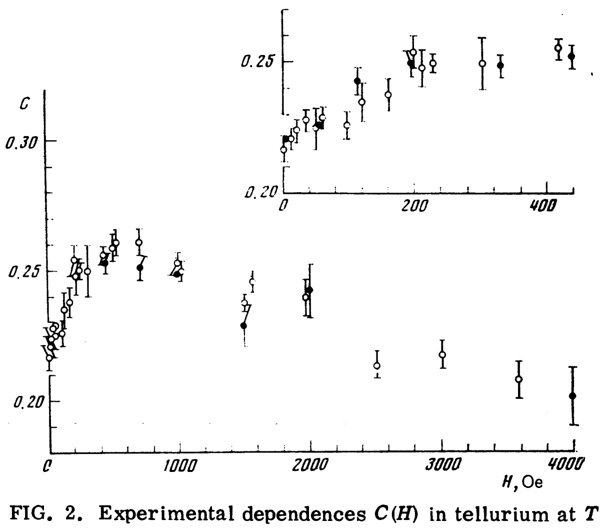

FIG. 2. Experimental dependences $C(H)$ in tellurium at $T=290$ K (○) and $T=250$ K (●). The dependence $C(H)$ for $T=250$ K for $H<400$ Oe is given only in the upper figure.

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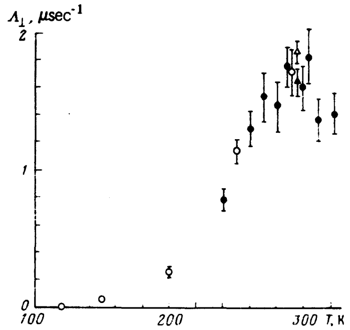

FIG. 3. Dependence $\Lambda_\perp(T)$ in tellurium for various transverse field values $H_\perp$: △—50 Oe, ○—120 Oe, ●—300 Oe, ▲—700 Oe.

as the result of stopping of the depolarization of the μ^+-meson spin after some time t following formation of the (μ^+e^-) paramagnetic state, for example, on entry into a diamagnetic compound. Here the decrease of C should apparently be accompanied by a decrease of the relaxation rate Λ.

The existence of a short-lived muonium atom and the stopping of the μ^+-meson depolarization according to a law $e^{-t/\tau}$ lead to the following expression for the experimentally observable dependence $N(t)$:

$$N(t)=N_0e^{-t/\tau_0}[1-aP_0(H)P(t)], \tag{3}$$

where

$$P(t)=P_\infty+(1-P_\infty)e^{-(\Lambda_1+\Lambda_2)t}=\Lambda_1\Lambda^{-1}[1+\Lambda_2\Lambda^{-1}e^{-(\Lambda_1+\Lambda_2)t}]$$

is the time dependence of the μ^+-meson polarization. Here a is the experimental asymmetry coefficient of positrons from $\mu^+\to e^+$ decay which has been observed at $t=0$ in the absence of any unobserved μ^+-meson depolarization processes; the value $a=0.278\pm0.005$ for tellurium was determined in a special experiment, where instead of tellurium a similar target of copper was installed; $P_0(H)$ is the polarization of the μ^+ meson of the short-lived muonium atom remaining at the moment of formation of the long-lived ferromagnetic state; P_∞ is the polarization of the μ^+ meson as $t\to\infty$; $\Lambda_1=\tau^{-1}$ is the probability of formation of a diamagnetic compound; Λ_2 is the μ^+-meson spin relaxation rate in the paramagnetic state (μ^+e^-), which depends on H; $\Lambda=\Lambda_1+\Lambda_2$ is the experimentally observed relation rate.

In Fig. 4 we have shown the dependence obtained from Eqs. (1) and (3) for $T=290$ K:

$$P_0(H)=C(1+\Lambda_2\Lambda_1^{-1})/a(C+\Lambda_2\Lambda_1^{-1}). \tag{4}$$

The parameter $\Lambda_1=0.080\pm0.005$ μsec^{-1} entering into this

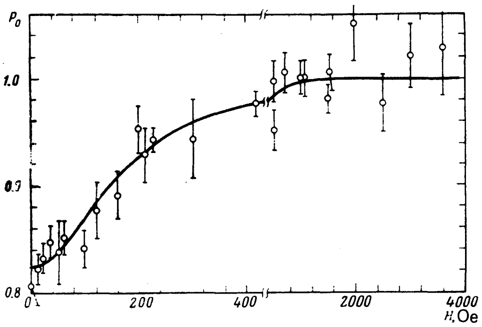

FIG. 4. Experimental (4) and theoretical (5) dependences $P_0(H)$ in tellurium at $T=290$ K.

TABLE I. Parameters of expression (5) for $P_0^{\text{theo}}(H)$ obtained by the method of maximum likelihood in comparison with the exceptional values (4).

T, K	τ, μsec	$\omega'_0\tau'$	H_0', Oe	$\tau'\times10^{10}$, sec	χ^2	n
290	12.5±0.8	0.74±0.02	101±8	4.2±0.4	17	25
250	12.5±1.6	0.75±0.05	76±11	5.6±1.2	9	11

expression was chosen in such a way that the values of P_0 determined by Eq. (4) increase monotonically within the statistical errors with increase of the field H and satisfy the condition $P_0<1$. The experimental dependence $P_0(H)$ in Fig. 4 is compared with the theoretical expression[2]

$$P_0^{\text{theo}}(H)=\frac{1+(\omega_0'\tau')^2(1/2+x^2)}{1+(\omega_0'\tau')^2(1+x^2)} \tag{5}$$

for the residual polarization of the short-lived muonium in a longitudinal field $x=H/H_0'$ for $\nu=0$. Here $\omega'=2\beta H_0'/\hbar$ and τ' are the hyperfine-splitting frequency and the lifetime of the muonium atom; β is the magnetic moment of the electron.

It is evident from Fig. 4 that the theoretical expression (5) satisfactorily describes the experimental dependence (4) $P_0(H)$ for $T=290$ K. The same good agreement is observed also for $T=250$ K with $\Lambda_1=0.080\pm0.010$ μsec^{-1}. The corresponding values of the parameters $\omega_0'\tau'$, H_0', and τ', and also the values of the Pearson parameter χ^2, are given in the Table. We have also given in the Table the values $\tau=\Lambda_1^{-1}$ of the mean life of the long-lived paramagnetic state (μ^+e^-) determined from Eq. (4); n is the number of experimental values of $P_0(H)$.

It must be emphasized that the use of Eq. (5) for $P_0^{\text{theo}}(H)$ does not assume the equality $\nu=0$. Use of this formula means only that the relation $\nu<(\tau')^{-1}=0.24\times10^{10}$ sec^{-1} ($T=290$ K) is satisfied, which is consistent with the rather high frequency $\nu>\omega_0$.

In addition it should be noted that the mechanism of depolarization of the long-lived paramagnetic state (μ^+e^-) remains unclear. The experimental dependence $\Lambda(H)$, which is not described by the expression

$$\Lambda_2=\nu/[4(\nu\omega_0^{-1})^2+x^2],\quad \nu>\omega_0, \tag{6}$$

obtained for the case in which the μ^+ meson is depolarized in interaction with a single paramagnetic electron,[2] needs explanation. Also requiring explanation is the dependence shown in Fig. 3 of $\Lambda_\perp(T)$ in a transverse magnetic field $H_\perp$. It is evident from Fig. 3 that the value of $\Lambda_\perp$ increases with increasing temperature, remaining 1.5–2 times less than the values $\Lambda(H=0)$.

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