Measurement of positive-muon spin-precession phase shift

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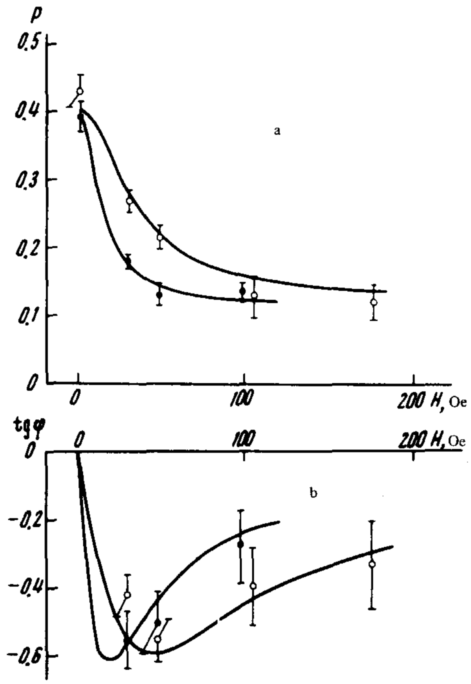
We measured the modulus and the initial phase of the vector of the residual polarization of positive muons in single-crystal germanium as functions of the transverse magnetic field intensity. We calculated the parameters of the muonium theory of depolarization of positive muons.

We investigated the influence of an external field on the muonium stage of depolarization of positive muons in single-crystal germanium using the beam of the meson channel of the synchrocyclotron of the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research, with the aid of apparatus for the observation of the spin precession of positive muons in a magnetic field that is transverse to the initial beam direction.[1] In the experiments we measured, varying the field intensities in the interval 0—200 Oe, the modulus P and the initial phase ϕ of the polarization vector $\mathbf{P}(t) = P_{\cos}(\omega t + \phi)$ as it varied periodically in time at the meson frequency $\omega = gH$, where g is the gyromagnetic ratio for the positive muon and H is the intensity of the electric field. The purpose of these experiments was to study the possibility of determining the aggregate of the phenomenological parameters of the theory of the muonium stage of depolarization of positive muons,[2–3] namely the lifetime τ of the free muonium atoms, the frequencies ν of the spin-exchange interactions of the latter with the sample, and the fraction P_{ip} of the positive-muon polarization due to "instantaneous" processes. If the muonium atom precessing in a transverse magnetic field with frequency $\omega' = g'H$, where ω' is the muonium precession frequency and g' is the gyromagnetic ratio for muonium ($g'/g \approx 103$), enters in a chemical reaction with the surrounding medium in such a way that the interaction results in a diamagnetic compound, then a jumplike decrease of the precession frequency takes place at the instant of the interaction,



Plots of P (Fig. a) and $\tan\phi$ (Fig. b) against the intensity of the transverse magnetic field. The solid curves were calculated in accordance with the theory of muonium depolarization; light and dark circles—177 °K and 161 °K, respectively.

since the process of formation of the diamagnetic bond in the condensed medium can be regarded as instantaneous. The rapid rotation of the spin system of the triplet muonium within the average characteristic time of the chemical reaction causes the appearance of an initial phase shift in the mesic precession, if the latter is observed after the completion of the muonium stage. The connection between the experimentally measured quantities and the parameters of the theory and the external-field intensity were analyzed in detail in[3]. It follows from the analysis that the region of values of the field intensity in which the phase shift is maximal corresponds to the value of the product $\omega'\tau \approx 1$, under the condition that the intensity of the external field remains much smaller than that produced by the magnetic moment of the positive muon at a distance on the order of the first Bohr orbit of the muonium in the germanium.[4] In this case the formulas of[3] become much simpler:

$$P = \frac{1}{2}\left[\frac{(1+P_{ip}+2P_{ip}\nu\tau)^2+4P_{ip}^2(\omega'\tau)^2}{(1+\nu\tau)^2+(\omega'\tau)^2}\right]^{1/2}$$

$$\mathrm{tg}\,\phi = -\frac{\omega'\tau}{1+\nu\tau+\dfrac{2P_{ip}}{1-P_{ip}}\left[(1+\nu\tau)^2+(\omega'\tau)^2\right]}.$$

The experiments were performed with a target of single-crystal n-type germanium with conduction-electron density $[n] \approx 1\times 10^{14}$ cm^{-3} at two values of the temperature, $(161 + 2)$ and (177 ± 2) °K. We have established earlier that for this sample the duration of the muonium stage can be varied from 10^{-7} to 10^{-10} sec by varying the target temperature in the interval 90—300 °K.[5] During the course of the experiments, we took into account the possible asymmetry of the positron-recording telescope, which was placed at an angle 0° to the positive-muon beam, and other geometrical sources of systematic errors in the determination of the initial phase shift of the precession. To this end we reversed regularly the magnetic field. The monitoring of the stability of the apparatus and the normalization of the results were carried out by using bromoform as a standard. The results are shown in the figure. The obtained values of the parameters were $P_{ip} = 0.12 \pm 0.01$, $\tau = (17 \pm 3)$ nsec, $\nu = (4 \pm 1)\times 10^7$ sec^{-1}, and $\chi^2 = 3.5$ (7 experimental points) at 161 °K and $P_{ip} = 0.13 \pm 0.01$, $\tau = (7 \pm 1)$ nsec, $\nu = (8 \pm 1)\times 10^7$ sec^{-1}, and $\chi^2 = 7.9$ (9 experimental points) at 177 °K.

Our experiments have revealed, for the first time, the meson-precession phase shift produced in semiconducting material as a result of the existence of the muonium stage. This has made it possible to determine all of the parameters of the muonium theory of depolarization of positive muons in a medium. This method can yield the most precise and reliable data for the investigation of the mechanisms of physicochemical interaction of positive muons with matter.

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