Measurement of the residual polarization of negative muons in gaseous deuterium at a pressure of 10 atm

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The residual polarization of negative muons was measured using an apparatus with a gas target filled with deuterium to a pressure of 10 atm. A value of $P_\mu = 7.2 \pm 2.1\%$ was obtained. This value is in agreement with the theory. The measurements were carried out in a muon beam of the JINR phasotron.

Experimental study of the depolarization of negative muons in hydrogen (protium, deuterium, tritium) is of considerable interest because it yields information about the initial stage of life of the mesic atom: it describes mechanisms involved in its formation and de-excitation. The information obtained from such studies can, in principle, also be used to determine the populations of the spin states of the mesic atoms and the rates of transitions between them, which is of crucial importance in the study of the μ-capture processes and in muon catalysis.[1–3]

After a muon stops in matter, a considerable fraction of the polarization is lost in the cascade de-excitation of the muonic atom due to the spin-orbit and hyperfine interactions. According to Ref. 3, the theoretically predicted polarization at the time the muonic atom of deuterium forms in the 1*s* state is (at a gas pressure of 10 atm)

$$P_\mu(D_2) \approx 9\% . \qquad (1)$$

The collisions of mesic atoms with hydrogen nuclei cause a further depolarization. As was initially shown in Ref. 4, an effective mechanism for the loss of polarization involves collision processes of the type

$$p\mu(F=1) + p \to p\mu(F=0) + p, \qquad (2a)$$

$$d\mu(F=3/2) + d \to d\mu(F=1/2) + d, \qquad (2b)$$

in which a muon is exchanged between identical nuclei with a change in the total spin of the mesic atom (F). The rates of these processes have so far not been measured directly. Experimental determination of the rate γ_d of reaction (2b) is based on the dependence of the rate of resonance formation of $dd\mu$ molecules on the spin state of the $d\mu$ atom. The results of measurements of γ_d (Refs. 5 and 6) lie in the range 3–$5\times 10^7\ \varphi s^{-1}$, in satisfactory agreement with theory[7,8]:

$$\gamma_p = 1.6 \times 10^{10} \phi s^{-1}, \quad \gamma_d = (3-5) \times 10^7 \phi s^{-1}$$

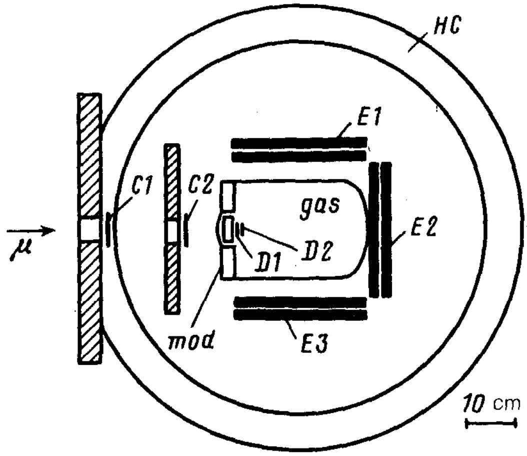

FIG. 1. Experimental arrangement. HC—Helmholtz coil magnet; $C1$ and $C2$—monitor counters; $E1$–$E3$—telescope electron scintillation detectors; $D1$ and $D2$—semiconductor muon detectors; mod—muon moderator.

(ϕ is the relative hydrogen density; $\phi = 1$ corresponds to the nuclear density $N = 4.22 \times 10^{22}$ nuclei/cm^3).

Three experimental measurements of the polarization of muons in hydrogen have so far been carried out. Two of these measurements[9] involved liquid protium and one of them[1] involved gaseous deuterium at a pressure of 40 atm. None of these studies revealed any presence of polarization consistent with the expected values of the depolarization rates.

Our purpose in this study was to measure the residual polarization of muons in gaseous deuterium at a gas pressure of 10 atm. Experimental setup, represented schematically in Fig. 1, was described in Ref. 10. Its main components are the gas target with silicon semiconductor detectors ($D1$ and $D2$) placed inside it, electron scintillation detector telescopes ($E1$–$E3$), and a magnet (Helmholtz coils). The distinguishing feature of this method is the use of the spectrometric information from detectors $D1$ and $D2$ to clearly identify the muon stoppings in gas.

The measurements were carried out in the muon channel of the JINR phasotron. The target was filled with an isotopically pure deuterium (which contained $< 1\%$ protium, $< 10^{-10}$ tritium, and fewer than 10^{-5} nuclei with $z > 1$) to a pressure of 10 atm. The strength of the magnetic field was $H = 200$ Oe, which corresponded to the precession frequency of muon spin in the $d\mu$ atom with $F = 3/2$ and $\omega = 5.1$ rad/μs.

The logic of the experiment can be summarized as follows. The signal announcing the stopping of a muon in the target triggers the 10-μs time "gates" which enable the electrons from the muon decay to be detected. The time spectra of electrons are analyzed with the help of the expression

$$dN_e(t)/dt = A_{\mathrm{Fe}} F_{\mathrm{Fe}}(t) + A_{\mathrm{Si}} F_{\mathrm{Si}}(t) + A_{\mathrm{D}_2} F_{\mathrm{D}_2}(t) + B, \qquad (3)$$

where the functions $F_i(t)$ describe the time dependence of the electrons detected from the decay of muons which are stopped in the target (Fe), in the detector $D2$ (Si), and in gas (D_2), A_i are the normalization constants which are proportional to the number of muon stops in a given substance, and B is the random-coincidence background. The functions $F_i(t)$ are

$$F_{\rm Fe}(t)=e^{-\lambda_{\rm Fe}t} \tag{4a}$$

$$F_{\rm Si}(t)=e^{-\lambda_{\rm Si}t}[1+a_{\rm Si}\cos(\omega_{\rm Si}t+\delta_{\rm Si})] \tag{4b}$$

$$F_{\rm D_2}(t)=e^{-\lambda_{\rm D_2}t}[1+a_{\rm D_2}e^{-\gamma t}\cos(\omega_{\rm D_2}t+\delta_{\rm D_2})], \tag{4c}$$

where $\lambda_{\rm Fe}\approx 4.85\,\mu{\rm s}^{-1}$, $\lambda_{\rm Si}\approx 1.30\,\mu{\rm s}^{-1}$, and $\lambda_{D_2}\approx\lambda_0=0.455\,\mu{\rm s}^{-1}$ are the rates at which the muons disappear (with allowance for the decay and capture by a nucleus), a_i, ω_i, and δ_i are the precession amplitudes, frequencies, and phases, and γ is the depolarization rate of muons in deuterium, which is governed mainly by process (2b).

In the course of the analysis we constructed for telescopes $E\,1$ and $E\,3$ two time-resolved spectra which corresponded to various energy losses of muons in detectors $D\,1$ and $D\,2$. A suitable choice of the range of this energy loss has made it possible to select in the spectra of the first group the events almost entirely from the muon stopping in silicon, and to select in the spectra of the second group the events mainly from the muon stopping in deuterium (admixtures of events from silicon and iron were no greater than 7%).

The parameters of the function (4b) were determined from an analysis of the distributions of the first group:

$$a_{\rm Si}=5{,}1(7)\%,\qquad \delta_{\rm Si1}=-0.92(18),\qquad \delta_{\rm Si3}=0.79(21)$$

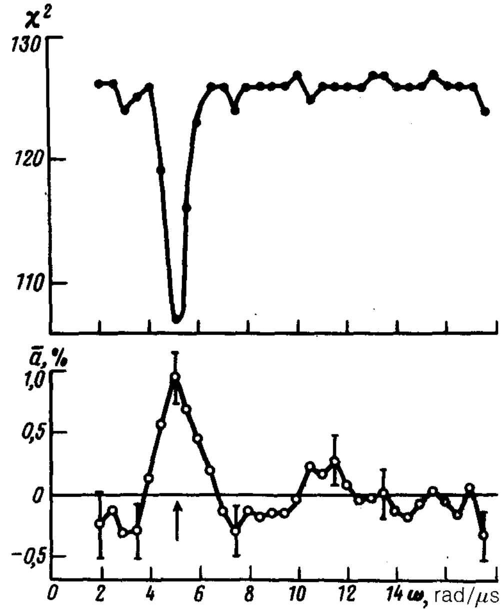

FIG. 2. Maximum values of the effective precession amplitude and the values of χ^2 corresponding to them versus the precession frequency. The traces were obtained from the joint analysis of the $E\,1$–$E\,2$ time spectra.

(the indices 1 and 3 correspond to telescopes $E1$ and $E2$); the measured values $\lambda_{Si} = 1.30\ (3)\ \mu s^{-1}$ and $\omega_{Si} = 17.0\ (2)$ rad/μs in this case are consistent with the expected values. The results obtained in this manner were used in the analysis of the spectra of the second group (deuterium). This analysis was carried out in two stages.

In the first stage we analyzed the time spectra by the method of least squares, using expressions (3) and (4) for various values of the frequency ω_{D_2}. The depolarization rate γ was assumed equal to zero. The results of such an analysis of $\chi^2(\omega_{D_2})$ and $\bar{a}_{D_2}(\omega_{D_2})$ are shown in Fig. 2. As can be seen in this figure, at the state expected for $F = 3/2$, $\omega_{D_2} = 5.1$ rad/μs, there is a pronounced minimum of χ^2, which corresponds to the "effective," i.e., averaged over the observation time, precession amplitude

$$\bar{a}_{D_2} = (0{,}94 \pm 0{,}21)\% . \tag{5}$$

This value is, in fact, the lower boundary of the true asymmetry coefficient.

Additional control of the hardware was accomplished through an analysis of the distribution obtained by means of a channel-by-channel summing of the $E1$ and $E3$ spectra. The oscillations die out mutually in this case, since the phase difference for $E1$ and $E3$—for the distributions δ_1–δ_2—is equal to π. The analysis was carried out for several arbitrary precession phases. No oscillations were observed in any one of those phases. In the case of the expected frequency $\omega = 5.1$ rad/μs, the phase was maximized, giving $\delta = 0.49 \pm 0.27$ and $\bar{a} = -0.28 \pm 0.22\%$. In the analysis of the total distribution we found the loss rate of muons in deuterium to be $\lambda_{D_2} = 0.453 \pm 0.005\ \mu s^{-1}$, in agreement with the value $\lambda_0 = 0.455\ \mu s^{-1}$.

In the second stage of the analysis we took the depolarization rate into account. As a result, we found the maximum value of γ and the initial polarization amplitude corresponding to it

$$\gamma = (4 \pm 2) \times 10^7 \phi\ s^{-1};\quad a = (1.83 \pm 0.53)\% \tag{6}$$

In going from the precession amplitude to the polarization we made use of the relation $a = 0.25 \pm 0.06 P\mu$, which we obtained in the calibration measurements with a carbon target. For the residual polarization in the 1s state of the $d\mu$ atom with a spin $F = 3/2$ we thus find

$$P_\mu(D_2) = (7.2 \pm 2.1)\% . \tag{7}$$

A comparison of the experimental value, (7), and theoretical value, (1), of the polarization of muons in deuterium shows that these values are in agreement with each other.

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