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MEASUREMENT OF RESIDUAL POLARIZATION OF NEGATIVE MUONS IN GASEOUS HYDROGEN

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The process of negative muon depolarization in hydrogen has specific features which are due to the possible influence of the interactions of excited μ-atoms with external hydrogen atoms and also due to exchange collisions of $p\mu$- or $d\mu$-atoms with protons or deuterons. From this point of view the study of μ^--meson depolarization in hydrogen is of inherent interest. Besides this the knowledge of the value of residual polarization $P_\mu(\mathcal{H})$ and $P_\mu(\mathcal{D})$ is necessary for choosing the optimum conditions of experiments on nuclear mu-capture by protons and deuterons. Finally, the measurement of the values of P_μ in hydrogen is a possible way of obtaining some information on the mu-atom spin states which is very important for interpretation of the experimental data on nuclear muon capture in hydrogen and also for understanding of the results studying the resonance muonic molecule formation.

Until recently the process of negative muon depolarization in hydrogen has been poorly investigated. "Standard" depolarization theory /1,2/ is in good agreement with the experimental data for many elements with $Z > 2$ but for helium the experimental result /3,6/ of the P_μ measurements is approximately 5 times smaller, than the theoretically predicted one. According to the theory /2/, the value of polarization ($P_{\ell-S}$) for hydrogen obtained with accounting only for spin-orbital interaction (ℓ - orbital quantum number and S - spin of muon), must be bigger than the value of $P_{\ell-S} \simeq 0.17$ obtained for the initial values of $\ell_0 \gg 1$ and must be equal to $P_{\ell-S}(D,H) \simeq 0.30$. Additional decreasing of negative muon polarization is due to the hyperfine I-S interaction (I - spin of proton or deuteron), thus at the formation of mu-atom in the ground state the residual polarization of muon must be equal to

$$P^{o}_{\mu}(H,D) = \alpha\, 0.15, \qquad (1)$$

where the value of α accounts for the possible influence of some unknown effects on the polarization value.

In the ground state of mu-atom polarization can decrease due to exchange collisions of mesic atoms with protons or deuterons. Theory /4-7/ predicts for the depolarization rate in the process $p\mu + p' \rightarrow p'\mu + p$ the value

$$\lambda_d(H) \sim 10^{10}\ s^{-1} \qquad (2)$$

and for the process $d\mu + d' \rightarrow d'\mu + d$, the value

$$\lambda_d(D) \sim 10^7 \ s^{-1} \qquad (3)$$

(for the density liquid hydrogen).

Experimentally the value of P_μ has been found only for liquid protium /8,9/. The data of these measurements are given in Table 1. As is seen from this table, the accuracy of the P_μ (H) measurements has been 3-4%. The aim of our measurements was to determine the values of P_μ(H) and P_μ(D) in gaseous hydrogen with an accuracy of $\simeq$ 1%. The use of gaseous hydrogen gave us a possibility of increasing the sensitivity of our data to the value of exchange collision rate and gave us a hope to detect the nonzero value of P_μ (D).

Table 1. The results of the measurements of negative muon polarization in hydrogen.

	Residual polarization,%	Source of data
Liquid H_2	3 ± 3	/8/
"	7 ± 4	/9/
Gaseous H_2 (40 atm)	0.3 ± 0.9	present
Gaseous D_2 (40 atm)	0.6 ± 0.9	experiment

For measurements of the polarization the parameters of muon spin precession in a transverse magnetic field have been found by means of fitting of time distributions of electrons from mu-decay.

The experiment has been carried out on the muon beam of the JINR 680 MeV synchrocyclotron. The schematic view of the experimental set-up is presented in Fig. 1. The muons were detected by monitor counters 1-3, slowed down by the moderator (6) and stopped in the target (8). Muon stoppings in the target were registered by counters 4 and 5 with CsJ(Tl) scintillator. The target was filled with hydrogen (protium or deuterium) of high purity. The contamination by admixtures of other elements with $Z > 1$ in hydrogen was less than 10^{-7}. Scintillation counters E1 and E2 located symmetrically around the target were designed for detecting electrons from decay of muons stopped inside the target. Electronic apparatus has been used to measure the electron time distributions.

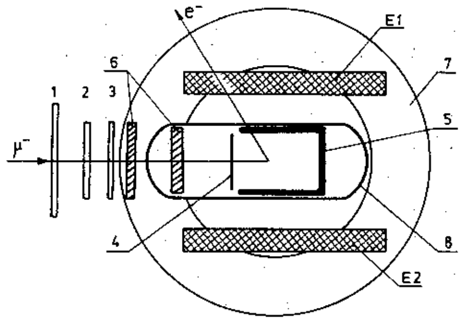

Fig. 1.
Schematic view of the experimental set-up.
1-3 - monitor counters (plastic scintillator),
4 and 5 - counters with CsJ(Tl) scintillators, 6 - moderator, 7 - Helmholz coils, 8 - gaseous hydrogen target, E1 and E2 - electron detectors.

Magnetic field was provided by Helmholz coils with a mean radius of R = 42 cm. In the main runs the magnetic field value has been equal to H = 140 Oe which corresponds to the next spin precession frequency (ω) for muon in hydrogen mesic atom

$$\omega\,(F_{p\mu} = 1) = 4.1 \text{ rad/mcs}, \qquad (4a)$$

$$\omega\,(F_{d\mu} = 3/2) = 3.6 \text{ rad/mcs}, \qquad (4b)$$

$$\omega\,(F_{d\mu} = 1/2) = 4.8 \text{ rad/mcs} \qquad (4c)$$

(F - the total spin of $p\mu$ - or $d\mu$-atom).

The allowed time instability of magnetic field strength and its nonuniformity in the target volume were $\lesssim$ 1%.

The main runs have been performed with protium and deuterium under the gas pressure of 40 atm and magnetic field value of H = 140 Oe. To check the parameters of our apparatus there have been carried out runs with a graphite disc inside the target under H = 140 Oe, 70 Oe and H = 0. The total statistics in the electron time distributions was equal to $\simeq 10^6$ counts for each of these runs. Besides, the exposures have been performed with vacuum target and with hydrogen under H = 0.

Electron time distributions were analyzed using the expression

$$dN_e/dt = B\exp(-\lambda t)\left[1 + A\exp(-\lambda_d t)\cos(\omega t + \varphi)\right] + C, \qquad (5)$$

where λ is the muon disappearance rate (for hydrogen $\lambda = \lambda_0 = 4.55 \cdot 10^5\ s^{-1}$); λ_d, the value of depolarization rate for the ground state of $p\mu$- or $d\mu$ -atom; $A=\beta P_\mu/3$, the amplitude of muon spin precession; β = 0.85, initial muon polarization; ω, the precession frequency; φ, initial phase; B, normalization parameter; and C, the background level parameter.

The electron time distributions obtained in the runs with graphite (a), protium (b) and deuterium (c) are shown in Fig. 2. In Fig. 3 the results of the frequency analysis (the optimization of the expression (5) parameters under fixed values of ω) are presented for distributions obtained in the random coincidence measurements (a) and in the runs with graphite at H = 140 Oe (b), H = 70 Oe (c) and with protium (d), deuterium (e) at H = 140 Oe. The results of a common fit of time distribution for detectors E1 and E2 are presented in Fig. 4 for the runs with graphite, protium and deuterium.

The optimum values of expression (5) at λ_d = 0 parameters for distribution delivered in the runs with graphite, protium and deuterium are listed in Table 2. It should be pointed out, that the values of λ obtained by us are in good agreement with the measurements /10-12/ of muon lifetime in hydrogen and carbon and our values of A,

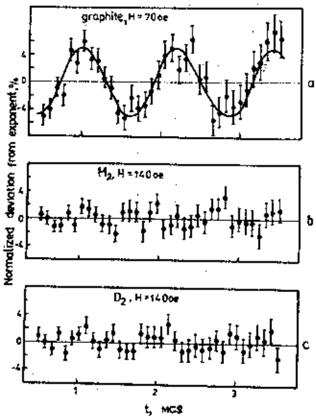

Fig. 2. Electron time distribution registered by one of the electron detectors in the runs with graphite under H=70 Oe (a), with protium (b) and deuterium (c) at H=140 Oe. Each distribution was corrected to the exponent $e^{-t/\tau}$, where τ is muon lifetime in carbon or hydrogen. Solid curve in Fig. 2a is the inter dependence (5) with parameters defined in computer analysis.

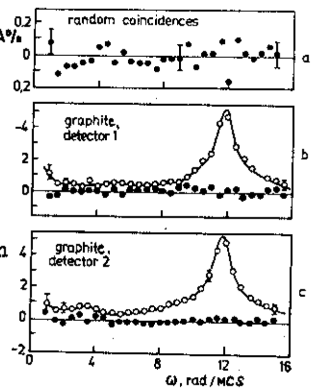

Fig. 3. The results of the analysis of electron time distributions obtained in the measurements of random coincidences (a) and in exposured with graphite (b,c). Open cycles - H=140 Oe, full cycles - H = 0.

obtained in the runs with graphite agree with the measurements /13/. It means that there are no systematic errors at sufficient level in our experiment.

As is seen from the data in Table 2 our results for protium and deuterium agree with expression (5) at A=0 and λ_d =0. Further analysis

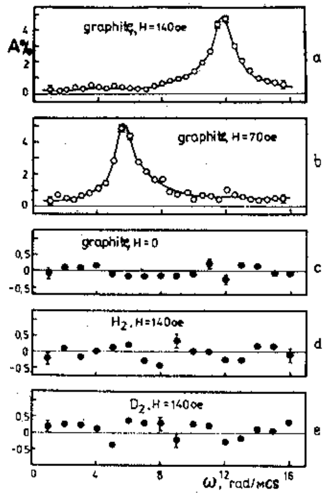

Fig.4. Common fit of electron time distributions for detectors E1 and E2 obtained in exposures with graphite at H=140 Oe (a), H=70 Oe (b) and with protium (c) and deuterium (d) at H=140 Oe.

Table 2. The results of analysis of electron time distribution obtained in the runs with graphite, protium and deuterium at H = 140 Oe.

Target	Frequency of precession ω, rad/mcs	Optimum parameters of expression $y = Be^{-\lambda t}[1 + A\cos(\omega t + \varphi)] + C$			Residual polarization, %
		λ, $10^6 s^{-1}$	A, %	χ^2 ($\bar{\chi}^2$=174)	
Graphite	11.8	0.493±0.002	4.9±0.2	190	19±1
Protium, 40 atm	(4a) ω =4.1	0.454±0.002	0.08±0.25	183	0.3±0.9
Deuterium, 40 atm	(4b) ω =3.6	0.453±0.002	0.16±0.25	208	0.6±0.9
"	(4c) ω =4.8		0.28±0.25	205	1.0±0.9

has made it possible to obtain the next estimates for the depolarization rates of negative muon in protium and deuterium

$$\lambda_d(H) > 4 \cdot 10^7 \ s^{-1} , \qquad (6)$$
$$\lambda_d(D) > 4 \cdot 10^7 \ s^{-1} \qquad (7)$$

(for the density of liquid hydrogen).

Experimental estimate (6) agrees with the theoretical value /4,7/ (2) and at the same time does not contradict to the assumption that negative muons lose their polarization in $p\mu$-atom excited state. The estimate (7) is not in consistency with calculation /6/ and experimental results /14,15/ indicate to a small exchange $d\mu + d$ collision rates in gaseous deuterium, but it agrees well with theoretical calculations /7/. There is only one possibility of fitting our data (7) to the results /6,14,15/, namely to assume that in hydrogen under the gas pressure $P \gtrsim 10$ atm negative muons lose practically all their initial polarization when they are in the excited mu-atom state. To make a final conclusion on this subject one has to carry out both new theoretical research including the excited mu-atom interactions with external atoms (Stark-collisions) and new experimental investigation of the negative muons depolarization at different densities of hydrogen.

It would have been most desirable to carry out these measurements with a substantially increased accuracy ($\simeq 0.1\%$ in quantity P_μ). The results obtained in ref. /15/ are an evidence to the possibility of performing measurements with the indicated accuracy. It is probable that in this case one may succeed in registering the nonzero residual polarization of muons in deuterium and will measure the rates of transitions $F = 3/2 \rightarrow F = 1/2$ in collisions $d\mu + d$. This will provide direct data on the $d\mu$-atom spin states which is essential both for interpreting the data on nuclear μ-capture by deuteron /17/ and for studying the spin dependence in resonance production of muon molecules $dd\mu$ /18/. At nonzero residual polarization of muons in deuterium it is possible in principle to find the transition rates $F = 1 \longrightarrow F = 0$ in collisions $p\mu + p$ - through measuring quantity P_μ in the gaseous mixture $H_2 + \alpha D_2$ (where $\alpha \sim 10^{-3}$ for the pressure in the mixture ~ 10 atm) and the characteristics of some other μ-molecular and μ-atomic processes.

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