Measurement of the residual polarization of negative muons in gaseous hydrogen

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The residual polarization of negative muons in the ground state of the $p\mu$ and $d\mu$ atoms was measured in experiments with a gas target filled with ultrapure hydrogen at 40 bar in a muon beam of energy 680 MeV at the JINR synchrocyclotron. The values obtained for the residual polarization are $P\mu(H) = 0.3 \pm 0.9\%$ for protium and $P\mu(D) = 1.0 \pm 0.9\%$ for deuterium.

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1. INTRODUCTION

The study of the depolarization of negative muons in hydrogen is especially interesting. In addition to the usual mechanisms of cascade depolarization due to the spin-orbit interaction[1,2] and depolarization due to the interaction of the muon and nucleus spins,[2,3] in hydrogen there can be important contributions from exchange collisions[4–6] (charge exchange) in the ground state and also apparently from Stark collisions in an excited state of the muonic atom.[7]

Since the values of the residual polarization and the magnetic moment of a muonic hydrogen atom are different for the upper and lower states of the hyperfine structure, measurement of the muon polarization makes it possible in principle to obtain information on the spin states of the $p\mu$ and $d\mu$ atoms (with the condition that the polarization remaining after the occurrence of the cascade is not too small). Such information is extremely important[8] for interpreting the results of measurements of the rate of nuclear capture of a muon by a proton and a deuteron. Up to now no direct experimental information has been obtained on the spin state of the muonic hydrogen atoms. It is usually assumed in accordance with the existing theory[4,5,9] that the fast, irreversible transition $F=1 \to F=0$ (F is the spin of the muonic atom) occurs in protium. This conclusion is in agreement with the data from measurements[10] of the cross section for the elastic scattering of $p\mu$ atoms on protons and also with the results of measurements[11] of the rate of muon capture by protons at different hydrogen densities. The situation with the spin states of $d\mu$ atoms is not as clear-cut. Calculations[6,9] indicate that in gaseous deuterium at a pressure on the order of several atmospheres the rate of the transition $F=\frac{3}{2} \to F=\frac{1}{2}$ is relatively small and does not exceed the muon decay rate. This conclusion is in agreement with the results of measurements[12] of the yield of the fusion reaction in the $pd\mu$ molecule. At the same time, a reasonable explanation of the data from measurements[13] of the rate of muon capture by deuterons carried out in gaseous hydrogen ($95\% H_2 + 5\% D_2$) at a pressure of 7 bar can be given only when it is assumed that the muon capture occurs from the lowest state of the hyperfine structure due to the fast transition $\frac{3}{2} \to \frac{1}{2}$.

At the present time two studies have been carried out to measure the residual polarization of negative muons in hydrogen. The experiment of Ref. 14 was carried out with liquid protium and the one in Ref. 15 was carried out with liquid protium and deuterium. It is important to note that in Ref. 14 the purity of the hydrogen was not kept at the necessary level (10^{-6}–10^{-7}). This makes the interpretation of the data difficult because a large part of the muons can be captured by impurity nuclei with $Z>1$. The purity of the hydrogen was controlled in Ref. 15. Here it turned out that in protium the relative impurity content was acceptably low ($\sim 10^{-6}$) while the purity of the deuterium was not high enough, so that more than half of the muons were captured by impurity atoms.

The data from Refs. 14 and 15 for the precession amplitude and residual polarization in percent are

liquid protium (Ref. 14):	1±1	3±3
liquid protium (Ref. 15):	1.9±1.4	7±4
liquid deuterium (Ref. 15):	1.4±1.7	— .

It can be seen that the accuracy of the earlier measurements of the muon polarization in hydrogen was 3–4%. The purpose of the present study was to measure the muon residual polarization in gaseous protium and deuterium at a pressure of 40 bar with an accuracy $\lesssim 1\%$. The use of gaseous hydrogen made it more difficult to obtain the necessary statistics, but made it possible to decrease significantly (by a factor of 20) the rates of depolarization processes involving Stark collisions and exchange collisions, which gave grounds for hoping to register a finite residual polarization for deuterium.

2. THE MEASUREMENT TECHNIQUE. THE EXPECTED EFFECT

We used the standard μSR (muon spin precession) method to determine the muon residual polarization. In this method we record and analyze the temporal distribution of electrons from the decay of muons stopped in a certain volume of space contained in a magnetic field perpendicular to the direction of the initial polarization. This distribution is described by an expression of the form[16]

$$N(t) = B\exp(-\lambda t)\left[1 + A\exp(-\lambda_d t)\cos(\omega t + \varphi)\right] + C, \quad (1)$$

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where λ is the muon decay rate in the matter [for hydrogen $\lambda(\mathrm{H}), \lambda(\mathrm{D}) = 4.55\times10^5$ sec^{-1}], λ_d is the depolarization rate, A and ω are the precession amplitude and frequency, respectively, φ is the initial phase, B is a normalization constant, and C is the level of background from random coincidences. The precession amplitude is $A = \beta P/3$, where P is the muon residual polarization in a muonic hydrogen atom and β is the degree of polarization of the muons in the beam. For a free muon (gyromagnetic ratio $\gamma = 2$) the precession frequency is[17]

$$\omega_\mu = 85.3\cdot10^3\ H \text{ rad/sec}, \tag{2}$$

where H is the strength of the magnetic field in Oersteds.

Expression (2) gives the precession frequency for muonic atoms with nuclear spin $I = 0$. For nuclei with $I \neq 0$ the gyromagnetic ratios are different for the upper (+) and lower (−) states of the hyperfine structure[3]:

$$\begin{aligned} \gamma_+ &= \frac{1}{I+{}^1/_2}(\mu_\mu+\mu_N),\\ \gamma_- &= -\frac{1}{I+{}^1/_2}\left(\mu_\mu-\frac{I+1}{I}\mu_N\right), \end{aligned} \tag{3}$$

where μ_μ and μ_N are the magnetic moments of the muon and the nucleus, respectively. Using (3), we find the following values for the precession frequencies in the upper and lower states of the hyperfine structure of muonic hydrogen atoms:

$$\omega(F_{p\mu}=1) = 0.34\omega_\mu, \tag{4a}$$

$$\omega(F_{d\mu}={}^3/_2) = 0.30\omega_\mu, \tag{4b}$$

$$\omega(F_{d\mu}={}^1/_2) = 0.40\omega_\mu. \tag{4c}$$

What are expected values of the precession amplitude A? Since the time t_a for the production and deexcitation of a mesic atom is several orders of magnitude smaller than the muon lifetime [at a hydrogen pressure of 40 bar the value of t_a is $\sim10^{-10}$ sec (Ref. 18)], the value of A in expression (1) is determined by the amount of the depolarization occurring during the deexcitation cascade and due to the hyperfine structure [accordingly, the parameter λ_d in (1) represents the rate of depolarization in the ground state]. According to the theory in Refs. 1 and 2, the cascade depolarization depends on the ratio of the cross sections for atomic muon capture for different values of the orbital angular momentum l, that is, on the form of the initial l distribution and in the general case (large initial values of l and statistical population of states with different l) is 17–20%.

The cascade depolarization process in hydrogen has certain features. We recall that depolarization occurs in those levels whose width is much smaller than the fine splitting. The radiative width is always much smaller than the fine splitting (by roughly a factor of 100), so in practice depolarization occurs in those levels for which the rate of the other deexcitation mechanism, that is, Auger ionization (λ_A), which dominates in the upper levels, becomes equal in order of magnitude to the rate of radiative transitions (λ_{rad}). Since $\lambda_{\mathrm{rad}} \sim Z^4$, where Z is the atomic number, and λ_A depends weakly on Z, the condition $\lambda_A \sim \lambda_{\mathrm{rad}}$ is satisfied for heavy and light atoms at different values of the principal quantum number $n = n_0$. For hydrogen[1)] these are $n_0 = 3$–4 (Ref. 2), because the value of the polarization when only the spin-orbit interaction is taken into account (P_{l-S}) turned out to be larger than the value $P_{l-S} = 0.17$ calculated for $l \gg 1$ and according to Ref. 2 is (for statistical population in l)

$$P_{l-s}(\mathrm{H}), P_{l-s}(\mathrm{D}) = 0.30\text{–}0.35. \tag{5}$$

Another feature of the cascade in a muonic hydrogen atom is related to the process of inelastic Stark collisions.[7] The use of this deexcitation mechanism made it possible[7] to explain the experimental data on the rates of absorption of negative pions in hydrogen. The mechanism of Stark collisions was also studied in Ref. 19 in an attempt to explain the observed shape of the energy spectrum of mesic x-rays in hydrogen. Apparently, the conclusions reached qualitatively in Ref. 19 are valid, that is, the mechanism of Stark collisions can explain the relatively large intensity of radiation with energy greater than the energy of the ($2P$–$1S$) transition. It should, however, be noted that there can be a different explanation of this if it is assumed that the initial l population is not statistical.[20,21] This is the conclusion arrived at by the authors of Ref. 22 in explaining the results of measurements of the mesic x-ray spectrum in liquid helium. Their cascade calculations were in good agreement with experiment when the l distribution studied in Ref. 20, which is quite different from the statistical distribution, was used.

Nevertheless, it seems that there are serious indications of the importance of the effect of Stark collisions on cascade deexcitation, at least for hydrogen mesoatoms. However, it is difficult to account even qualitatively for the effect of this process on depolarization without carrying out special calculations.[15,23]

Finally, we should point out yet another possible reason for depolarization in an excited state of a mesoatom—the initial alignment of the orbital angular momentum.[21] According to Ref. 21, this effect can explain the anomalously small value of the residual polarization in helium $P_\mu(\mathrm{He}) = 6 \pm 1\%$ that was measured in Ref. 23.

The interaction of the muon and nucleus spins leads to an additional polarization loss. In Ref. 3 the hyperfine interaction was studied only for the K shell. In this case it is easily shown that the polarization (taking into account the level population) for the two states $F = I \pm \frac{1}{2}$ (where I is the nuclear spin) of the $p\mu$ and $d\mu$ atom has the following values:

$$P_{I-s}(F_{p\mu}=1) = {}^1/_2, \quad P_{I-s}(F_{p\mu}=0) = 0, \tag{6a}$$

$$P_{I-s}(F_{d\mu}={}^3/_2) = {}^{10}/_{27}, \quad P_{I-s}(F_{d\mu}={}^1/_2) = {}^1/_{27}. \tag{6b}$$

In Ref. 2 the hyperfine interaction effects were taken into account not only for the ground state, but also for the excited states of muonic atoms and it was shown that these effects can change the polarization, but at small l_0, which is the case for hydrogen, this change is small. It should be noted that the theoretical study of the effect of the hyperfine interaction on the muon polarization in light mesoatoms has been confirmed by experiment.[24]

Therefore, after a muon goes through an atomic cascade its polarization in the K shell is $P=\alpha P_{l-S}P_{I-S}$, where according to (5) and (6) $P_{l-S}P_{I-S}=0.11-0.17$ and the coefficient α takes into account the effects on the polarization due to Stark collisions, to the l-alignment, and, possibly, to other unaccounted-for effects. Then the precession amplitude is

$$A=\alpha\beta(0.04-0.06). \tag{7}$$

A hydrogen muonic atom in its ground state collides with the nuclei of other atoms (protons or deuterons). The characteristic feature of these collisions is the possibility of the exchange of a muon between two nuclei,[4-6] which leads to loss of the muon polarization. A transition from an upper to a lower state of the hyperfine structure of a muonic atom can occur as a result of an exchange collision. The theoretical values of the rate $\lambda_{1\to0}$ of the transition $F=1\to F=0$ in collisions of $p\mu$ atoms with protons and the rate $\lambda_{3/2\to1/2}$ of the transition $F=\frac{3}{2}\to F=\frac{1}{2}$ in collisions of $d\mu$ atoms with deuterons are given in Table I. There we also give the data from the experiments of Ref. 12, where the value of $\lambda_{3/2\to1/2}$ was found from measurements of the yield of the fusion reaction in the $pd\mu$ molecule. We see from these data that the theory predicts a large (compared to the muon decay rate $\lambda_0=4.5\times10^5$ sec^{-1}) value for $\lambda_{1\to0}$ (and therefore, for the depolarization rate), which for liquid protium is

$$\lambda_{1\to0}>2\cdot10^9\ \text{sec}^{-1} \tag{8}$$

or for gaseous protium at a pressure of 40 atm is

$$\lambda_{1\to0}>10^8\ \text{sec}^{-1}. \tag{9}$$

According to the calculations of Refs. 6 and 9, the expected value of $\lambda_{3/2\to1/2}$ is considerably smaller than that of $\lambda_{1\to0}$. It follows from Ref. 6 that in gaseous deuterium at 40 atm $\lambda'_{3/2}=3.5\times10^5$ sec^{-1}. Later calculations[9] of $\lambda_{3/2\to1/2}$ give for this rate a value larger than that in Ref. 6. Depolarization can occur not only in inelastic but also in elastic (without change of the spin of the muonic atom) exchange collisions. It was shown in Ref. 6 that the cross section for exchange elastic collisions of $d\mu$ atoms with deuterons is $\sigma_{\text{el}}^{\text{ex}}\approx0.5\sigma_{\text{inel}}^{\text{ex}}\equiv0.5\sigma_{3/2\to1/2}$. From this it follows that according to Ref. 6 the depolarization rate in liquid deuterium is expected to be

$$\lambda_d(\mathrm{D})\approx10^7\ \text{sec}^{-1} \tag{10}$$

or at a deuterium pressure 40 atm

$$\lambda_d'(\mathrm{D})\approx5\cdot10^5\ \text{sec}^{-1}. \tag{11}$$

To make this discussion complete, we should mention the fact that polarization is partially lost in the formation of $pp\mu$ molecules in protium and $dd\mu$ molecules in deuterium. The production rates of these molecules for hydrogen at 40 atm are[18] $\lambda'_{pp\mu}=1.3\times10^5$ sec^{-1} and $\lambda'_{dd\mu}=4\times10^4$ sec^{-1}.

It follows from the above discussion that the temporal distribution of electrons from muon decay in hydrogen must in principle be described by the sum of several expressions of the type (1) with different precession frequencies. For protium we must use the frequencies corresponding to the state of the $p\mu$ atom with $F=1$ and the state of the $pp\mu$ molecule, and for deuterium we must use those corresponding to the two states of the hyperfine structure of the $d\mu$ atom with $F=\frac{3}{2}$ and $F=\frac{1}{2}$ and the state of the $dd\mu$ molecule. However, if we recognize that $\lambda'_{pp\mu}, \lambda'_{dd\mu}<\lambda_0$ and that the polarization in the state of the $d\mu$ atom with $F=\frac{1}{2}$ is one-fifth that in the state with $F=\frac{3}{2}$, we can use as a first approximation for the electron temporal spectrum formula (1), in which ω denotes the spin precession frequency of the muon in the upper spin state of the $p\mu$ or $d\mu$ atom, and λ_d is the depolarization rate in exchange collisions. The expected values of λ_d for gaseous protium and deuterium at a pressure of 40 atm are given by expressions (9) and (11), respectively.

TABLE I. Calculated values of the rate ($\lambda_{1\to0}$) of the transition $F=1\to F=0$ in collisions of $p\mu$ atoms with protons and the rate ($\lambda_{3/2\to1/2}$) of the transition $F=3/2\to F=1/2$ in collisions of $d\mu$ atoms with deuterons.

	$\lambda_{1\to0}$, sec^{-1}	$\lambda_{3/2\to1/2}$, sec^{-1}
Theory	$2.4\cdot10^9$ (Ref. 4)	$7\cdot10^6$ (Ref. 6)
	$5.0\cdot10^9$ *	$2.8\cdot10^7$ *
	$1.7\cdot10^{10}$ (Ref. 9)	$4.7\cdot10^7$ (Ref. 9)
Experiment	—	$<15\cdot10^6$ (Ref. 12)

Note. All the data are given with respect to the density of liquid hydrogen; the data of Refs. 4 and 6, where the values of the scattering lengths found in Ref. 9 are taken into account, are starred.

3. THE EXPERIMENT

The measurements were carried out in a muon beam from the JINR synchrocyclotron. The experimental setup is sketched in Fig. 1. Muons of initial energy 70 MeV were detected by the monitor counters 1–3 (a plastic scintillator), then were slowed down in an absorber (6) and allowed to enter the gas target. The detectors 4 and 5 with CsI(Tl) scintillators, which were located inside the target, were used to record

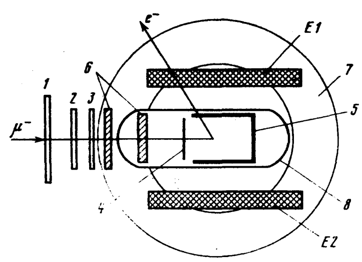

FIG. 1. Diagram of the experimental setup. 1–3) monitor counters (a plastic scintillator), 4, 5) detectors with CsI(Tl) scintillators, 6) muon absorber, 7) magnet, 8) gaseous target, E1 and E2) electron detectors.

muon stoppings in the gas. The dimensions of these scintillators were 100 diam. × 0.3 mm and 120 diam. ×200×5 mm, respectively. The target was filled with protium or deuterium at a pressure of 40 atm. In the experiments we used ultrapure hydrogen, which was rid of other impurity atoms with $Z>1$ to a level $\lesssim 10^{-7}$. The gas target with internal CsI(Tl) scintillators and the system for controlling the hydrogen purity were described by us in an earlier study.[25]

The electrons from muon decay were detected by two scinillation counters $E1$ and $E2$ (350×250×60 mm) symmetrically placed on either side of the target.

A magnetic field perpendicular to the muon beam axis was produced by two Helmholtz coils, the average radius of each being the same as the distance between the coils and equal to $R=42$ cm. The dimensions of the coils were chosen to obtain a magnetic field of the necessary magnitude and uniformity within the working volume of the target. From expression (1) we see that the best accuracy in determining the precession amplitude and frequency is attained for $\omega(H_0)\gtrsim 2\pi\lambda$, that is, when the muon spin makes more than one complete revolution during the muon lifetime. An increase of the magnetic field $H>H_0$ does not in practice improve the accuracy. Therefore, the magnet was designed to obtain fields up to $H=150$ Oe. The data from calibration measurements indicated that in the basic measurements the magnetic field was $H=140$ Oe. According to Eqs. (4a, b, c) this value of H corresponds to the following expected precession frequencies for $p\mu$ and $d\mu$ atoms:

$$\omega(F_{p\mu}=1)=4.1\ \text{rad}/\mu\text{sec}, \tag{12}$$

$$\omega(F_{d\mu}=3/2)=3.6\ \text{rad}/\mu\text{sec}, \tag{13}$$

$$\omega(F_{d\mu}=1/2)=4.8\ \text{rad}/\mu\text{sec}. \tag{14}$$

The inhomogeneity of the magnetic field in the working volume of the target did not exceed 1%. The temporal stability of the magnetic field was monitored against the current feeding the coils and was maintained at a level $\lesssim 1\%$ throughout the measurements.

A simplified block diagram of the electronics is given in Fig. 2. The muon-stopping signal $234\bar{5}$, which was generated in the "ST" block, triggered a time gate (measurement interval) of duration 10 μsec. This pulse was fed to the coincidence circuits C1 and C2, which selected signals from the detectors $E1$, $E2$, and 5 which were sent during the time gates. The time lag from the instant of a muon stopping (the start of the signal 23) to the beginning of the measurement interval was selected according to the value of the resolution time of the anticoincidences $234\bar{5}$, and also with allowance for the necessity of suppressing the background of direct muon stoppings in the scintillator of counter 4 [the muon lifetime $\tau_\mu(\text{CsI})\approx 0.1$ μsec] and was 0.5 μsec.

The time-to-code converters TC1 and TC2 were used to measure the time interval between the opening of the gates and the instant a signal appeared from detectors $E1$, $E2$, and 5. The channel scale value of each of these converters was 20 nsec. A logic register (LR) coded the number of the electron detector. If a secon-

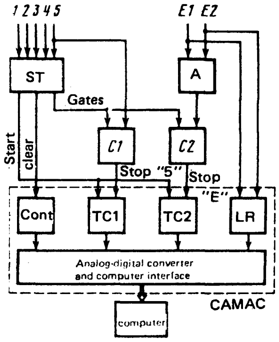

FIG. 2. Simplified block diagram of the electronics: ST) block for generating the muon stopping signal, A) adder C1 and C2) coincidence circuits, Cont) control block, TC1 and TC2) time to code converters, LR) logic register.

dary muon was registered while the gates were open (a signal from detector 1), a "clear" signal was generated in the ST block and the control block (Cont) was used to clear the information from the converters TAC1 and TAC2 and from the block LR.

The measuring part of the electronics was constructed to the CAMAC standard and was connected to a computer.

In Table II we give the data characterizing the measurement conditions. The main exposures were exposures 1 and 3, carried out with protium and deuterium, respectively, at $H=140$ Oe. Exposures 2 and 4 ($H=0$) were made to obtain independent information on the shape of the initial part of the electron temporal spectrum and exposure 8 was made to determine the background of random coincidences. In exposures 5–7 a graphite disk (100 diam × 10 mm) was placed in the center of the working volume of the target. The purpose of these control measurements, with the precession amplitude and frequency known beforehand, was to check for possible sources of systematic error in the time measurements. In addition, the parameters of the apparatus were also monitored during the course of periodically repeated measurements of the random coincidence spectra, when the TC converters were triggered from a generator and the detectors $E1$ and $E2$ were irradiated by a radioactive Po and Be compound.

The counting rate of the 23 coincidences (the intensity of the muon beam) was $N_{23}\approx 10^4$ sec^{-1} throughout all the measurements. For the exposures with hydrogen, the triggering rate was $N_{234\bar{5}}\approx 50$ sec^{-1} and the electron counting rate was $N_e\approx 10$ sec^{-1}. The integrated con-

TABLE II. Data characterizing the measurement conditions.

Exposure number	Target	H, Oe	Number of electrons registered, 10^6
1	Protium, 40 atm	140	1.0
2	»	0	0.1
3	Deuterium, 40 atm	140	1.3
4	»	0	0.3
5	Graphite	140	3.0
6	»	70	1.0
7	»	0	2.8
8	Vacuum	0	0.01

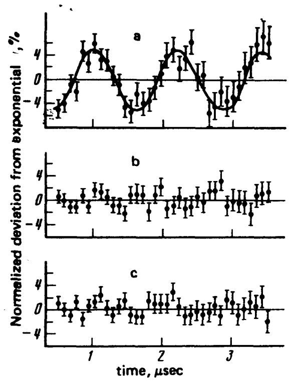

FIG. 3. Temporal distributions obtained with one of the electron detectors in exposures with graphite for $H = 70$ Oe (a) and for protium (b) and deuterium (c) for $H = 140$ Oe. Each distribution is normalized to the exponential $e^{-t/\tau}$, where τ is the muon lifetime in carbon or hydrogen. The line in Fig. 3a is a dependence of the type (1) with the optimal values of the parameters found by computer.

tribution of the random coincidence background divided by that for the initial interval of duration 2 μsec was 10% for the exposures with hydrogen when the coincidences $(5, E)$ were excluded and was several times smaller when they were included. The rate of event accumulation was roughly an order of magnitude higher for the exposures with graphite than for the exposures with hydrogen, and the background level was correspondingly lower.

The measurement data in exposures 1–8 were obtained in the form of temporal spectra for each electron detector. For the rest of the analysis we summed the numbers of events over the four channels in each of these spectra. In this manner we obtained 90-channel distributions with a scale value of 80 nsec/channel, the start of which corresponded to a time 0.5 μsec from the instant of muon stopping, and the end corresponded to 7.7 μsec. Several of these distributions constructed for half of the measurement interval (0.5–3.5 μsec) are given in Fig. 3.

4. ANALYSIS OF THE EXPERIMENTAL DATA

In the first stage of the analysis the experimental electron temporal distributions were compared to the approximating expression

$$y = Be^{-\lambda t} + C, \tag{15}$$

that is, neglecting oscillations. As expected, the distributions obtained in the exposures with graphite for $H = 70$ and 140 Oe are in poor agreement with this approximation ($\chi^2 > 200$), while the distributions measured with graphite at $H = 0$ are in good agreement with it. It also turned out that the electron temporal spectra for the exposures with hydrogen are described fairly well by (15), which contains a single exponential without an oscillating part, indicating that the polarization in hydrogen is relatively small (compared to the case of graphite).

The principal data of this stage of the analysis for exposures 1, 3, and 7 are given in Table III.

TABLE III. Results of analyzing the electron temporal distributions using the expression $y = Be^{-\lambda t} + C$.

Exposure number	Measurement conditions	Electron detector	Optimal value of the parameter λ, 10^6 c^{-1}	Value of ($\chi^2 = 87$)
1	Protium, $H = 140$ Oe	$E1$	0,452±0,003	92
		$E2$	0,457±0,003	86
3	Deuterium, $H = 140$ Oe	$E1$	0,452±0,003	104
		$E2$	0,458±0,003	87
7	Graphite, $H = 0$	$E1$	0,498±0,002	77
		$E2$	0,494±0,002	98

From these data we see that the muon decay rates λ in hydrogen and carbon obtained with each electron detector are in agreement with the known values.[26,27] This means that the possible systematic errors in our measurements are sufficiently small. The optimal values of the parameter C found by comparison of the experimental distributions with expression (15) agree with the results of independent measurements of the random coincidence background in an evacuated target.

In the next stage we used the following function as the approximation for the temporal distributions:

$$y = Be^{-\lambda t}[1 + A\cos(\omega t + \varphi)] + C, \tag{16}$$

that is, expression (1) with $\lambda_d = 0$. During the analysis we either varied all the parameters of expression (16) or successively fixed the value of the parameter ω for a definite interval and then varied the remaining parameters for this value of ω (this is the so-called frequency analysis). The results of the analysis of the temporal distributions obtained in the exposures with graphite at $H = 70$ and 140 Oe when all the parameters were varied are given in Table IV. We see from these data that the values of the precession amplitude A agree with the earlier measurements,[28] while the values of the precession frequency are close to the expected values (2) for $H = 70$ and 140 Oe. The small deviation in the ratio of ω(140 Oe) and ω(70 Oe) from two is obviously due to the presence of the external magnetic field. This field, calculated from the ratio of ω(140 Oe) and ω(70 Oe), is roughly 3 Oe and is in agreement with an independent determination from the analysis of the data of exposure 7. This value of the external field was taken into account in the subsequent analysis.

From the data of Table IV we see that the phase difference $\Delta\varphi = \varphi_1 - \varphi_2$ for the first (φ_1) and the second (φ_2) electron detector agrees with the expected value $\Delta\varphi = \pi$. The accuracy of determining the precession

TABLE IV. Data from the analysis of the electron temporal distributions measured in exposures with graphite.

Exposure number	H, Oe	Electron detector	λ, 10^6 sec^{-1}	A, %	ω, rad/μsec	$\varphi_1 - \varphi_2$, rad	Value of χ^2 ($\overline{\chi^2} = 84$)
5	140	$E1$	0.492±0,002	4.9±0.2	11,8±0.03	3.36±0.12	98
		$E2$	0.493±0.002	5.0±0.2	11.8±0.03		92
6	70	$E1$	0.493±0,003	5.0±0,3	5.8±0.05	2,98±0,21	60
		$E2$	0.495±0.003	5.2±0.3	5.8±0.05		113

amplitude and frequency also agrees with that expected and indicates that significant systematic errors due to instability of the apparatus parameters are absent.

In addition to the separate processing of the temporal distributions for each electron detector we carried out a joint analysis of the two such distributions obtained in each exposure. In this case the parameters λ, A, and ω were found directly for the two distributions and the phase difference was assumed to be $\Delta\varphi=\pi$. The advantages of this procedure are obvious—here it is possible to eliminate from the temporal spectra possible systematic distortions that have the same character for the two electron detectors. The values of the parameters A, ω, and λ found from the joint analysis of the temporal spectra for the exposures with graphite at $H=140$ Oe are

$$\lambda=(0.492\pm0.0015)\cdot10^{6}\ \mathrm{sec}^{-1},\ A=(4.91\pm0.13)\cdot10^{-2},$$

$$\omega=(11.81\pm0.017)\ \mathrm{rad}/\mu\mathrm{sec}.$$

We see that they coincide with the data obtained from the separate reductions (Table IV). The results of the frequency analysis are the following: the optimal values of the parameter A for different values of ω, obtained by reducing the temporal distributions of exposures 5, 6, and 7 (graphite), are given in Fig. 4 for the separate reductions and in Fig. 5 for the joint reduction. In Fig. 4 we also give the data of the reduction of the random-coincidence spectrum measured in one of the calibration exposures.

The results of analyzing the temporal spectra obtained in the exposures with protium and deuterium at $H=140$ Oe are given in Fig. 5. We see that within the experimental error there is no increase of the precession amplitude from the mean value $A\approx0$. The values of the precession amplitude found by computer at the expected values of the precession frequencies for $F=1$ in protium and $F=\frac{3}{2}$ and $\frac{1}{2}$ in deuterium, and the corresponding values of the muon residual polarization, are given in Table V. The error in the precession amplitude (0.25%) was deduced from the uncertainty of A in the computer analysis and also includes the final accuracy (0.1%) with which it was verified that systematic distortions due to the apparatus were absent in the measurement of the time. The value of the

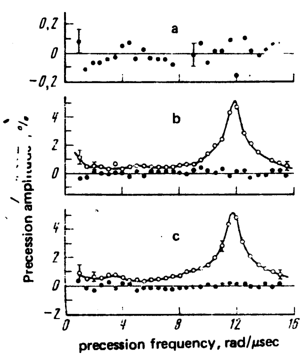

FIG. 4. Results of analyzing the temporal distributions obtained for measurements of random coincidences (a) and in exposures with graphite for the detectors E1 (b) and (E2) (c). Points. ●–$H=0$, ○–$H=140$ Oe.

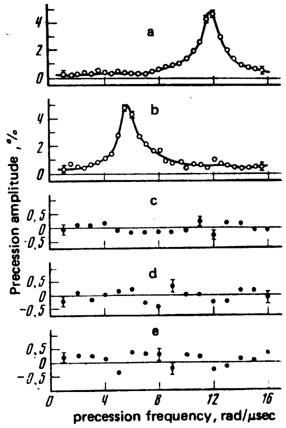

FIG. 5. Results of the joint analysis of the temporal distributions for the detectors E1 and E2 obtained in exposures with graphite for $H=140$ Oe (a), $H=70$ Oe (b), $H=0$ (c) and in exposures with protium (d) and deuterium (e) for $H=140$ Oe.

residual polarization was found taking into account the value $\beta=0.85$, found in Ref. 28 for the muon beam used in the present study. We see from the data of Table V that the experimental electron temporal distributions obtained in the exposures with protium and deuterium are in agreement with expression (1) at $A=0$ and $\lambda_d=0$.

Further analysis for the purpose of determining the possible value of the damping rate of the precession amplitude allowed us to estimate the rate of muon depolarization in exchange collisions of muonic atoms for protium and deuterium, namely, $\lambda_d'(\mathrm{H}), \lambda_d'(\mathrm{D})>2\times10^{6}\ \mathrm{sec}^{-1}$ (90% confidence level), or for the density of liquid hydrogen

$$\lambda_d(\mathrm{H})>4\cdot10^{7}\ \mathrm{sec}^{-1}, \tag{17}$$

$$\lambda_d(\mathrm{D})>4\cdot10^{7}\ \mathrm{sec}^{-1}. \tag{18}$$

The experimental estimate (17) agrees with the calculated value[6] (8) and at the same time does not contradict the assertion that the muon has practically lost its polarization even in an excited state of the $p\mu$ atom. The estimate (18) is in poor agreement with the calculations of Ref. 6 and with the experimental data of Ref. 12, indicating that exchange collisions of $d\mu$ atoms with deuterons have a relatively small effect in gaseous deuterium. At the same time our estimate (18) is close to the calculated value found in Ref. 9 and does not contradict the data of the experiment in Ref. 13, which is evidence in favor of fast $\frac{3}{2}\to\frac{1}{2}$ transitions in gaseous deuterium.

As a result, the interpretation of our data on muon depolarization in deuterium is ambiguous. In order to have our data agree with the results of Ref. 6 and 12

TABLE V. Results of the anaylsis of the electron temporal distributions obtained in exposures with hydrogen.

Measurement conditions	ω, rad/μsec	A, %	χ^2	P, %
Protium, $H=140$ Oe	4.1 ($F_{p\mu}=1$)	0.08±0.25	183	0.3±0.9
Deuterium, $H=140$ Oe	3,6 ($F_{d\mu}=3/2$)	0.16±0.25	208	0.6±0.9
	4.8 ($F_{d\mu}=1/2$)	0.28±0.25	205	1.0±0.9

it is necessary to assume that processes occurring during the deexcitation of the muonic atom play an important role in the muon polarization loss in hydrogen. On the other hand, our result (18) together with the data of Ref. 13 does not contradict the idea that there is some mechanism for a fast transition to a lower state of the hyperfine structure of the $d\mu$ atom which occurs even after the course of the cascade of the muonic atom. To arrive at a definite conclusion about this it is necessary to have both new calculations of the muonic atom cascade and new measurement data on muon polarization, on the shape of the energy spectrum of the muonic x rays and on the muon capture rate for different values of the deuterium density.

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[1)]Liquid or gaseous at a pressure $P \leqslant 10$ bar.

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