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Direct measurement of the rates of formation of the molecules $pp\mu$ and $pd\mu$ in gaseous hydrogen

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A gas target filled with H_2, H_2+Xe, and H_2+Xe+D_2 (xenon concentration 3×10^{-5}, deuterium $\approx7\%$) at a pressure of 40 atm in the muon beam of the JINR synchrocyclotron has been used to measure the rate of formation of the mesic molecules $pp\mu$ and $pd\mu$, and also the ratio of the rates of transfer of the muon from the proton and deuteron to xenon. The following results were obtained:
$\lambda_{pp\mu}=(2.34\pm0.17)\cdot10^6\ \text{sec}^{-1}$,
$\lambda_{pd\mu}=(5.53\pm0.16)\cdot10^6\ \text{sec}^{-1}$,
$B=1.62\pm0.05$.

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With the coming into operation of high-current accelerators—meson factories—we have a real possibility of accomplishing such fundamentally important experiments as precision measurements of the rate of μ capture in gaseous hydrogen and deuterium. For choice of the optimal conditions and correct interpretation of the data of these experiments, it is necessary to know the parameters of the mesic-atom processes occurring in hydrogen—formation of $pp\mu$ and $pd\mu$ molecules. It is important to emphasize that the determination of these parameters must be carried out specifically in gaseous hydrogen, in view of the possible nontrivial dependence on the density of hydrogen.

The experimental and theoretical values of the rates of formation of the mesic molecules $pp\mu$ ($\lambda_{pp\mu}$) and $pd\mu$ ($\lambda_{pd\mu}$) are given in Table 1. Until recently no direct measurements of $\lambda_{pd\mu}$ had been made in a gas. In earlier work by some of the present authors[10] an attempt was made to evaluate $\lambda_{pd\mu}$ on the basis of the measured yield of muons from the catalysis reaction (1a) in the $pd\mu$ molecule

$$pd\mu \nearrow \mathrm{He}^3+\mu^-+5.3\ \mathrm{MeV} \qquad (1a)$$
$$pd\mu \searrow \mathrm{He}^3\mu+\gamma+5.5\ \mathrm{MeV}, \qquad (1b)$$

it being necessary for this purpose to utilize various data on reactions (1a) and (1b) obtained in experiments with liquid hydrogen. In our recent work[6] the value of $\lambda_{pd\mu}$ in a gas was found by analysis of the time distribution of the γ rays from reaction (1b) with use of the value obtained by Bleser *et al.*[1] for the rate of reaction (1b) and with the assumption of a statistical nature of the population of the spin states of the $d\mu$ system. The purpose of the present work was direct measurement of $\lambda_{pp\mu}$ and $\lambda_{pd\mu}$ in gaseous hydrogen. In the course of the work we also obtained the ratio B of the muon transfer rates from the proton and deuteron to xenon.

METHOD OF MEASUREMENT

The work utilized a method similar to that described elsewhere[2,4] and based on use of a mixture of hydro-

TABLE 1. Experimental and theoretical values of the rates of production* of hydrogen mesic molecules and values of B.**

Source	$\lambda_{pp\mu}$	$\lambda_{pd\mu}$	B
	Experiment		
Columbia University,[1] liquid H_2	1.89 ± 0.20	5.8 ± 0.3	...
CERN,[2] liquid H_2	2.55 ± 0.18	6.82 ± 0.25	...
JINR,[3] diffusion chamber	1.5 ± 0.6	...	...
JINR,[4] gaseous H_2 (60 atm)	2.74 ± 0.25	...	...
CERN,[5] gaseous hydrogen (6 atm)	...	...	1.98 ± 0.12
JINR,[6] gaseous H_2+D_2 (40 atm)	...	5.45 ± 0.65	...
Present work, gaseous H_2 (40 atm)	2.34 ± 0.17	5.53 ± 0.16	1.62 ± 0.05
	Theory		
[7]	2.6	1.3	...
[8]	3.9	3.0	...
[9]	...	...	1.77 ± 0.02

*The rates $\lambda_{pp\mu}$ for the process $p\mu+p\to pp\mu$ and $\lambda_{pd\mu}$ for the process $d\mu+p\to pd\mu$ are given in units of 10^6 sec^{-1}.
**The quantity $B=C_{Xe}\varphi\lambda^p_{Xe}/C_{Xe}\varphi\lambda^d_{Xe}$ is the ratio of the rates of the processes $p\mu+\mathrm{Xe}\to \mathrm{Xe}\mu+p$ and $d\mu+\mathrm{Xe}\to\mathrm{Xe}\mu+d$.

gen with a small impurity of a gas with $Z>1$ (in our case we used xenon with an atomic concentration 10^{-5}). The sequence of processes occurring after stopping of a muon and formation of the $p\mu$ atom in mixtures of H_2 + Xe and H_2 + Xe + D_2 is shown schematically in Fig. 1. Direct landing of muons on Xe atoms can be neglected under our conditions.

The rate $\lambda_{p\mu}$ of disappearance of $p\mu$ atoms is determined by the processes of $pp\mu$ molecule formation, muon transfer to Xe and D atoms, and also muon decay:

$$\lambda_{p\mu}=\lambda_0+\varphi\lambda_{pp\mu}(1-C_D)+\varphi C_{Xe}\lambda_{Xe}{}^p+\varphi C_D\lambda_{pd}. \quad (2)$$

For the $d\mu$ atom the corresponding quantity is

$$\lambda_{d\mu}=\lambda_0+\varphi(1-C_D)\lambda_{pd\mu}+\varphi C_D\lambda_{dd\mu}+\varphi C_{Xe}\lambda_{Xe}{}^d. \quad (3)$$

In these expressions $\lambda_0=0.455\times10^6$ sec^{-1} is the free-muon decay rate, λ_{pd} is the muon transfer rate from a proton to a deuteron, λ^p_{Xe} and λ^d_{Xe} are the muon transfer rates from a proton and deuteron to Xe atoms, C_{Xe} and C_D are the atomic concentrations of xenon and deuterium, and φ is the ratio of the gas density to the density of liquid hydrogen. The rates of the mesic-molecular processes have been reduced to conditions of liquid hydrogen (atomic density of hydrogen 4.22×10^{22} cm^{-3}).

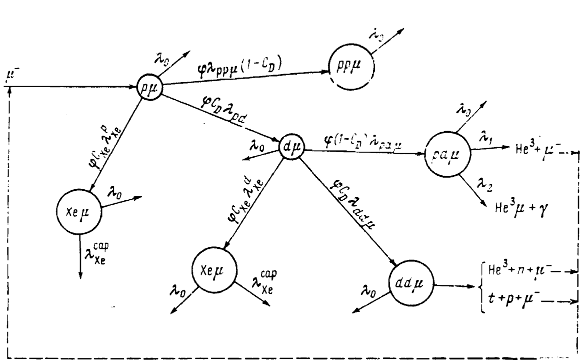

FIG. 1. Schematic diagram of processes occurring on stopping of μ^- mesons in a gas mixture H_2 + Xe + D_2.

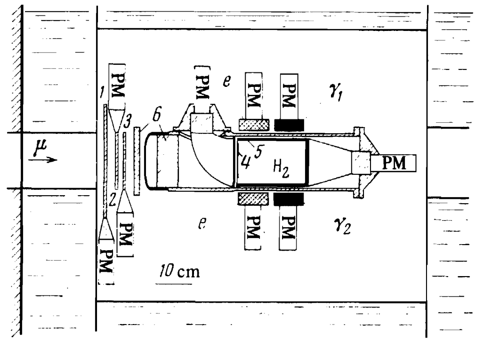

FIG. 2. Diagram of experimental apparatus (gas target and detectors).

The time distributions of electrons from decay of muons and of the γ rays of mesic x radiation of the Xeμ atom can be written in a unified form for the mixtures H_2 + Xe and H_2 + Xe + D_2:

$$dn_\gamma/dt=\lambda_{Xe}\exp(-\lambda_s t), \quad (4)$$

$$\frac{dn_e}{dt}=\left(\lambda_0-\frac{\lambda_0'\lambda_{Xe}}{\lambda_s-\lambda_0'-\lambda^{cap}_{Xe}}-\frac{\lambda_0\lambda_x}{\lambda_s-\lambda_0}\right)\exp(-\lambda_s t)+\frac{\lambda_0\lambda_x}{\lambda_s-\lambda_0}\exp(-\lambda_0 t), \quad (5)$$

where for the H_2 + Xe mixture we have $\lambda_s=\lambda_{p\mu}$ (Eq. (2)), $\lambda_x=\varphi(1-C_D)\lambda_{pp\mu}$, $\lambda_{Xe}=\varphi C_{Xe}\lambda^p_{Xe}$, and for the mixture H_2 + Xe + D_2 we have $\lambda_s=\lambda_{d\mu}$, $\lambda_x=\varphi(1-C_D)\lambda_{pd\mu}$, $\lambda_{Xe}=\varphi C_{Xe}\lambda^d_{Xe}$; λ_x is the rate of formation of $pp\mu$ or $pd\mu$ molecules, which competes with transfer of a muon to xenon, λ^{cap}_{Xe} is the rate of capture of a muon by the Xe nucleus, and λ_0' is the muon decay rate in the orbit of an Xeμ atom.

We can see from Eq. (5) that it is the sum of two exponentials with arguments $-\lambda_s t$ and $-\lambda_0 t$, the contribution of the exponential with argument $-\lambda_0 t$ being determined by the desired quantity λ_x, the rate of mesic-molecule formation. Analysis of the experimental time distributions by means of expressions similar to Eqs. (4) and (5) in order to determine the parameters of the indicated exponentials provides the possibility of finding the desired quantities λ_x and λ_{Xe}. We note that this method in principle does not require separation of electrons and γ rays in their detection.

EXPERIMENTAL ARRANGEMENT

The experiment was carried out in the low-background laboratory of the JINR synchrocyclotron in a muon beam with momentum 130 MeV/c and intensity 2×10^4 sec^{-1}. The location of the apparatus is shown in Fig. 2. After passing through monitor counters 2 and 3 and a large-aperture counter 1, the muons were slowed down in an absorber 6 and entered the gas target. The design of the target and the method of detecting muon stoppings in the gas by means of CsI(Tl) scintillators have been described elsewhere.[11,12] Purification of the hydrogen was accomplished by means of a system with a palladium filter,[12,13] which assured absence of impurities with $Z>1$ in the hydrogen at the level of 10^{-8} parts by volume. Detection of γ rays and electrons was accomplished with two detectors (γ_1, γ_2) with NaI(Tl) crystals of diameter 150 mm and length

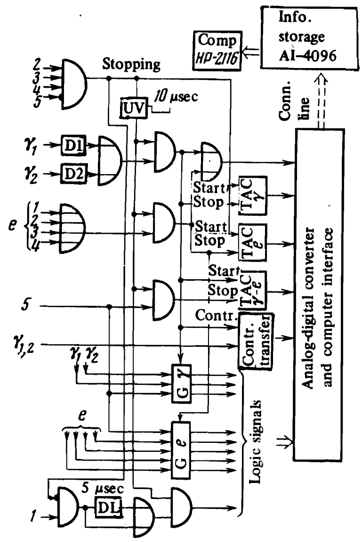

FIG. 3. Block diagram of electronics.

100 mm and by four counters (e_1–e_4) with stilbene crystals of diameter 70 mm and length 30 mm.

It may be noted that the technique chosen by us was in many ways similar to that used by Budyashov *et al.*[4] except for one important feature. In counters 4 and 5 in our experiments we used not a plastic scintillator but one of cesium iodide (the thickness in counter 4 was 250 μ, and counter 5 was made in the form of a hollow vessel of diameter 130 mm, length 200 mm, and wall thickness 5 mm). This permitted us to avoid difficulties associated with providing the necessary purity of hydrogen, and enabled us to reduce the background due to muon stoppings in the material of counter 4.

A block diagram of the electronics is shown in Fig. 3. The signal from stopping of muons in the gas ($234\bar{5}$) was used to trigger a time gate of duration 10 μsec (the univibrator UV). During this time interval we detected the γ rays from mesic x radiation and electrons from decay of muons stopped in the target.

By means of time-to-amplitude converters (TACγ and TACe) we measured the time of appearance of the signals from the γ and e detectors with respect to the moment of stopping of the muon. In the γ_1 and γ_2 channels we placed pulse-height discriminators with a lower threshold corresponding to an energy 1.5 MeV. The type and number of detectors which recorded an event were determined by means of logic signals produced by the gates Gγ and Ge. To reduce the background due to stopping of muons in the detectors themselves, we provided anticoincidences ($23\bar{\gamma}$) and ($23\bar{e}$) with a resolving time ≈ 0.15 μsec.

The complete information on an event included:

1) the time of appearance of the signals from the γ and e detectors with respect to the muon stoppings;

2) the pulse height of the signal from the γ detector;

3) the logic signals indicating the type and number of detectors which received signals;

4) the logic signal corresponding to the presence of a second muon recorded by detector 1 in a period of 5 μsec prior to the time of stopping of the muon and 10 μsec afterwards;

5) the monitor count (23), the stopped-muon count ($234\bar{5}$), and the count of events recorded by the γ and e detectors;

6) identifying information.

The amplitude and time information, converted to a digital code, together with the content of the logic-signal register,[14,15] were transmitted to an HP-2116 computer.

PERFORMANCE OF THE EXPERIMENT. SELECTION OF EVENTS

In the muon beam we made four runs of total duration 40 hours. The experimental conditions are listed in Table 2. In all four experiments we made measurements of the time spectra of events recorded by the γ and e detectors in coincidence and anticoincidence with detector 5 (the spectra $e+5$, $e-5$, $\gamma+5$, $\gamma-5$). In addition, we also measured the pulse-height distributions from the NaI(Tl) detectors.

It should be noted that our method does not permit discrimination between electrons and γ rays. This is due to the fact that counter 5 detects with appreciable efficiency the cascade of mesic x rays from the Xeμ atom. Therefore the distributions recorded by the detectors of each type actually are the sum of the spectra of γ rays and electrons and are described by superposition of expressions (4) and (5). By using the coincidences and anticoincidences with detector 5, we were able to vary the ratio between the electron component and the γ-ray component in the total spectrum of events, and this permitted more accurate determination of the parameters of each of these components.

The characteristic time distributions are given in Figs. 4–9 (the abscissa is the time from the moment of muon stopping, and the ordinate is the number of events per 0.378-μsec interval), and Fig. 10 shows the pulse-height spectrum of events obtained by means of the γ detectors. During the experiment we made a calibration of the time and energy scales every 5–6 hours by means of a quartz-crystal oscillator and standard γ-ray sources (Co^{60}, Po–Be).

ANALYSIS OF DATA AND EXPERIMENTAL RESULTS

To find the quantities $\lambda_{pp\mu}$, $\lambda_{pd\mu}$, and $B = \lambda^{p}_{\mathrm{Xe}}/\lambda^{d}_{\mathrm{Xe}}$ we used the method of least squares to analyze the time distributions of events recorded by the γ and e detectors in runs I, II, and III. The background distribu-

TABLE 2. Conditions of the various runs.

Run	Target filling	Gas pressure in the target at $T = 20°$C, atm	Concentration, atomic fraction	
			Xe	D_2
I	H_2	40	–	$<10^{-6}$
II	H_2+Xe	40	$\approx 3\cdot 10^{-5}$	$<10^{-6}$
III	H_2+Xe+D_2	43	$\approx 3\cdot 10^{-5}$	0.07
IV	Vacuum	10^{-5}	–	–

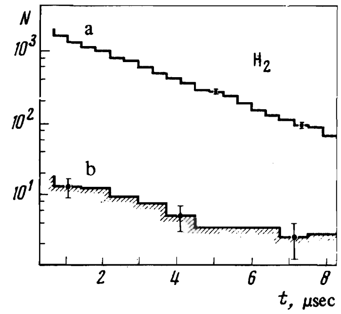

FIG. 4. Time spectra of events recorded by the detectors in coincidence with counter 5 ($e+5$): a—run I, b—data of run IV normalized to number of muon stoppings in run I (N is the number of events in a 0.378-μsec interval).

tions, obtained in experiment IV and reduced to the conditions of the appropriate run, were subtracted for each channel. The maximum contribution of the background did not exceed 3%. Analysis was carried out from time values $t \geqslant t_{\text{init}} = 0.5$ μsec. This limit was chosen from the condition of discrimination of the background due to muon stoppings in the scintillators of counters 4 and 5 (muon lifetime $\tau_\mu(\text{Cs, I}) = 0.08$ μsec). The numbers of events recorded are given in Table 3.

The time distributions of the events recorded were fitted by the following function, which was obtained with inclusion of expressions (4) and (5):

$$\frac{dN^i}{dt} = A^i\delta_1\lambda_{Xe}\exp(-\lambda_s t) + D^i[F\delta_1\exp(-\lambda_s t) + \delta_2 G\exp(-\lambda_0 t)]; \qquad (6)$$

here

$$F = \lambda_0 - \frac{\lambda_0'\lambda_{Xe}}{\lambda_s - \lambda_0' - \lambda_{Xe}^{cap}} - \frac{\lambda_0\lambda_x}{\lambda_s - \lambda_0}, \quad G = \frac{\lambda_0\lambda_x}{\lambda_s - \lambda_0}$$

(the superscript i corresponds to the type of spectrum). The factors δ_1 and δ_2 are different from unity only for the conditions of runs III ($H_2 + Xe + D_2$); they take into account the effect of processes occurring before formation of the $d\mu$ atom and are due to the difference in the transfer rates of the muon from the proton and deuteron to xenon. In analysis of the spectra of the types $\gamma + 5$ and $\gamma - 5$ obtained in run III, we took into account in the fit also the contribution of γ rays from the catalysis reaction in the $pd\mu$ system. The total magnitude of

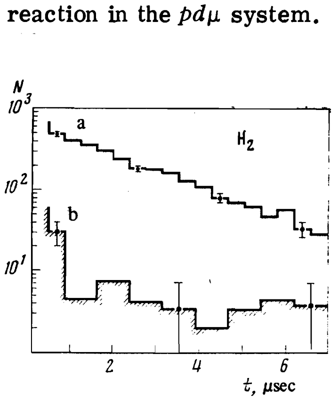

FIG. 5. Time spectra of events recorded by the γ detectors in coincidence with counter 5 ($\gamma+5$): a—run I, b—normalized data of run IV.

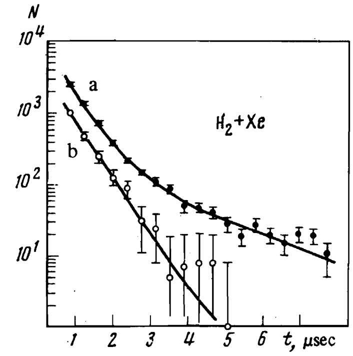

FIG. 6. Time spectra of events recorded by the e detectors in run II (the normalized background has been subtracted): a—coincidences with detector 5 ($e+5$), b—anticoincidences with detector 5 ($e-5$); the solid lines are theoretical curves.

this effect amounted in this case to about 3%. In analysis of the spectra of types $e+5$ and $e-5$ the contribution of γ rays from catalysis to the spectra was not taken into account, since it was negligible (0.1%).

The coefficients A^i and D^i in Eq. (6) are normalization parameters for the γ component and the electron component of the combined spectrum, respectively. These coefficients can be represented as follows:

$$A^i = N_\mu\varepsilon_\gamma^i, \quad D^i = N_\mu\varepsilon_e^i, \qquad (7)$$

where N_μ is the number of muon stoppings in the gas; ε_γ^i and ε_e^i are the detection efficiencies for γ rays and electrons (these coefficients obviously depend on the type of detector and whether or not coincidences with counter 5 were used).

For the optimal concentration of xenon chosen by us, the arguments λ_s and λ_0 of the exponentials in expression (6) were substantially different, which enabled us to determine the contribution of each of these components with reasonable accuracy. Since the contribution of the electron component with argument $-\lambda_0 t$ is proportional to the product $D^iG = D^i\lambda_0\lambda_x/(\lambda_s - \lambda_0)$, to find the desired parameters λ_x and λ_{Xe} it is sufficient in this case to know the value of D^i and there is no need to determine the value of A^i. Information on the nor-

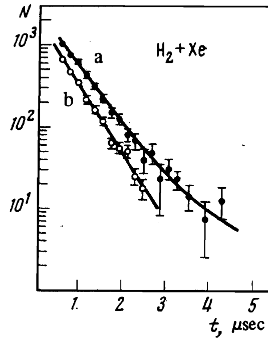

FIG. 7. Time spectra of events recorded by the γ detectors in run II (The normalized background has been subtracted): a—coincidences with detector 5 ($\gamma+5$), b—anticoincidences with detector 5 ($\gamma-5$); the solid lines are theoretical curves.

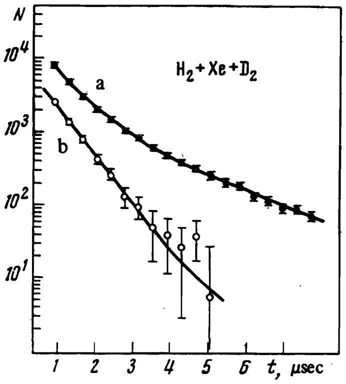

FIG. 8. Time spectra of events recorded by the e detectors in run III (the normalized background has been subtracted): a—coincidences with counter 5 ($e+5$), b—anticoincidences with counter 5 ($e-5$); the solid lines are theoretical curves.

malization factor D^i can be obtained from the total number of events recorded in run I (hydrogen):

$$D_k^i = R_k e^i, \tag{8}$$

where R_k is the ratio of the numbers of muon stoppings in the gas for run k and run I, calculated from the ratio of the monitor counts for these runs, and e^i is the total number of events in the spectrum of type i for run I.

The product $A^i \delta_1 \lambda_{Xe}$ was determined in the χ^2 minimization process.

In spectra obtained under different conditions, the ratio of the electron and γ components and consequently the contributions of the exponentials with arguments $-\lambda_s t$ and $-\lambda_0 t$ to the functions fitting these spectra were different. In particular, for the spectra $\gamma+5$ and $\gamma-5$ measured in run II, analysis was carried out only to obtain additional information on the value of λ_s, which was used in analysis of the other spectra.

The results of the analysis are given in Table 4, along with data obtained by combining the results of analysis of the different spectra (the latter data are given

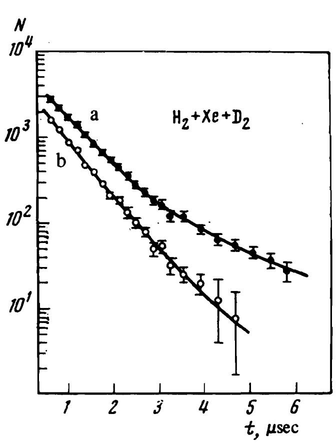

FIG. 9. Time spectra of events recorded by the γ detectors in run III (the normalized background has been subtracted): a—coincidences with counter 5 ($\gamma+5$), b—anticoincidences with counter 5 ($\gamma-5$).

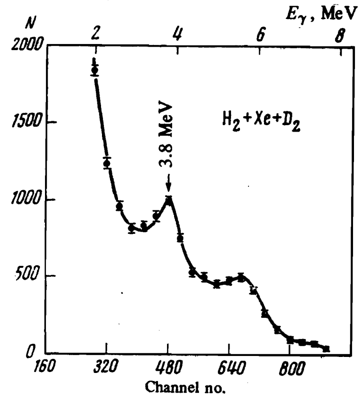

FIG. 10. Pulse-height distribution of events recorded by the γ detectors in run III in anticoincidence with detector 5 (the abscissa is the γ-ray energy and the ordinate is the number of events per 0.294-MeV interval). The energy of the K_α line of mesic x rays for xenon is 3.8 MeV (the arrow indicates the location of the corresponding photopeak).

also in Table 1).

From the experimental data given in Table 1, we can see that the value of $\lambda_{pp\mu}$ obtained by us agrees with the results of Refs. 1–4. The measured value of $\lambda_{pd\mu}$ is in agreement with our data (Ref. 6) and with the data of Bleser *et al.*[1] and differs from the value obtained by Conforto *et al.*[2]

The values of the quantity B obtained by us and at CERN[5] differ somewhat (see Table 1). The cause of this discrepancy may be the fact that the determination of B involved the value of the transfer rate λ_{pd} of the muon from the proton to tne deuteron, which is known with a large uncertainty.[1,16,17] We note that under the conditions of our work ($\varphi C_d \lambda_{pd}/\lambda_{p\mu} \approx 1$) the dependence of the value of B obtained on λ_{pd} is much weaker than under the conditions of Ref. 5.

Comparison of the measured values of $\lambda_{pp\mu}$ and $\lambda_{pd\mu}$ obtained under different experimental conditions permits us to conclude that the rates of formation of the mesic molecules $pp\mu$ and $pd\mu$ in liquid and gaseuos hydrogen do not differ. As can be seen from Table 1, the results of calculations of $\lambda_{pp\mu}$ agree with the measured values of this quantity. In regard to $\lambda_{pd\mu}$, the results of theoretical studies[7,8] do not agree with the experimental values.[1,2,6] It should, however, be noted that the theoretical calculations of the rates of formation of

TABLE 3. Experimental data of runs.

Type of event selection	Histogram number	Number of events		
		H_2 (1) *	H_2+Xe (1.464) *	H_2+Xe+D_2 (6.077) *
$e+5$	1	8439±92 (108±10) **	5889±78	33233±188
$e-5$	2	130±22 (102±15) **	2074±105	7866±200
γ_1+5	3	2001±50 (50±20) **	3037±87	10868±144
γ_1-5	4	17±20 (78±20) **	2350±50	8426±99
γ_2+5	5	2437±52 (64±25) **	4030±100	14651±162
γ_2-5	6	31±15 (88±11) **	3130±57	11485±114

*In parentheses we have given the number of muon stoppings in relative units.

**In parentheses we have given the normalized background values obtained in run IV (evacuated target).

TABLE 4. Results of analysis of experimental data.

Type of histogram	Run	Quantity in units of 10^6 sec^{-1}				
		$\lambda_{pp\mu}$	$\lambda_{pd\mu}$	$C_{Xe}\varphi\lambda^p_{Xe}$	$C_{Xe}\varphi\lambda^d_{Xe}$	B
$e+5$; $e-5$	II and III	2.34±0.17	5.53±0.21	1.281±0.026		1.59±0.05
$\gamma+5$; $\gamma-5$	III	–	5.53±0.27	–	0.785±0.019	1.63±0.05 *
Final result		2.34±0.17	5.53±0.16			1.62±0.05

*This value was calculated from the ratio of the values of λ^p_{Xe} and λ^d_{Xe} obtained in runs II and III.

mesic molecules are approximate. The most important approximation is the replacement of the molecular wave functions of the hydrogen molecule by the atomic wave functions in calculation of the coefficients of electron conversion accompanying the mesic-molecule formation process. In addition, in calculation of the wave functions of the mesic molecules formed, approximate potentials were used, and in the wave function of the incident mesic atom only the S-wave was taken into account. Thus, a final comparison of theory and experiment must be put off until more careful calculations are made.

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