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V.P. Dzhelepov, P.F. Yermolov, Ye.A. Kushnirenko, V.I. Moskalev

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AN EXPERIMENTAL INVESTIGATION OF μ^- MESONIC ATOMIC PROCESSES IN GASEOUS HYDROGEN

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Abstract

A number of mesonic atom processes in hydrogen has been studied experimentally by means of a diffusion cloud chamber in the magnetic field. The following quantitative data have been obtained: the cross section for elastic scattering of $p\mu$ *- mesonic atoms on protons* $\sigma_{pp} = (1.7^{+0.4}_{-0.5}) \cdot 10^{-19}\ cm^2$*; the rates of the meson transfer from a proton to deuterons and complex nuclei (C and O) recalculated to the liquid hydrogen density* $\lambda_d = (0.95^{+0.34}_{-0.21})\ 10^{10}\ sec^{-1}$ *and* $\lambda_z = (1.2^{+0.8}_{-0.5}) \cdot 10^{10}\ sec^{-1}$*, the rate of the formation of mesonic molecular ions* $pp\mu$ *in liquid hydrogen*

$$\lambda_{pp\mu} = (0.6^{+0.8}_{-0.5}) \cdot 10^{6}\ sec^{-1}.$$

The experimental values of λ_d, $\lambda_{pp\mu}$ *and* λ_z *are in good agreement with the theoretical ones what confirms the validity of the mechanisms of the processes suggested theoretically. The cross section* σ_{pp} *turned out to be close to the theoretical value calculated without the hyperfine structure of the* $p\mu$ *mesonic atom being taken into account. However, the possibility of the fast transitions to the lower state with the total spin of a mesonic atom* $F = 0$ *is not excluded.*

The determination of the absolute value λ_d *of carried out in this investigation allows to find the absolute probabilities of a number of* μ *- mesonic molecular processes by using it as a scale.*

I. Introduction

An experimental study of the reaction in which negative muons are captured by protons

$$\mu^- + p \to n + \tilde{\nu} \qquad (1)$$

may present important information for the theory of weak interactions. However, until recently reaction (1) was referred to the processes practically not studied among the phenomena concerned with the weak interactions of ordinary particles. The difficulty in solving this problem is due not only to a small probability of the above-mentioned reaction but, for the most part, to the complications which different mesonic atom and mulecular effects preceding this reaction introduce into the interpretation of the results which can be obtained experimentally[1-3]. As has been shown in theoretical papers[1,4], the probability of reaction (1) depends upon the hyperfine structure spin state of the $p\mu$-mesonic atom (F = 0 or F = 1), and for the densities of hydrogen larger than 10^{19} nuclei/cm^3, the muon capture occurs mainly from the lower state of a mesonic atom with F = 0 (F is the total mesonic atom spin).

The probability of muon capture in hydrogen depends also essentially on that of the formation of $pp\mu$ mesonic ions ($\lambda_{pp\mu}$)[5-7], since the spin state of such ions turns out to be analogous to the mixture of states F = 1 and F = 0.

Therefore, to determine experimentally the magnitude of $\lambda_{pp\mu}$ and to obtain the information about the probability of transitions of $p\mu$ from the state F = 1 into F = 0 becomes of great importance.

μ - mesonic molecular processes are essential also for the catalysis of nuclear reactions by muons in the mixture of hydrogen isotopes,[8-10] and though the main experimental facts are in qualitative agreement with the theory, further experiments on the determination of the rates of the muon transfer from a proton to a deuteron, of the $pd\mu$ mesonic molecular-ion formation, and of the nuclear fusion reaction in this mesonic ion are also of interest. As far as these problems are very acute, a number of experiments were arranged at the Joint Institute for Nuclear Research synchrocyclotron which were aimed at investigating the mesonic atomic and molecular processes occurring in hydrogen and deuterium. In these experiments a high pressure diffusion cloud chamber placed in the magnetic field was used.

This paper presents the results which were obtained in the first series of experiments pertaining to the study of $p\mu$ -mesonic atom scattering on protons, to the determination of the rates of the muon transfer from a proton to a deuteron, of the formation of the $pp\mu$ mesonic ions and of the muon transfer from a proton to complex nuclei.

2. The Cross Section for $p\mu$ -Mesonic Atom Scattering on Protons and Muon Transfer to the Complex Nuclei

The cross section for $p\mu$ -mesonic atom scattering on protons has been theoretically calculated in[2,6]. It may be expressed in terms of the scattering lengths a_g and a_u of the $p\mu + p$ system in the symmetrical (a_g) and antisymmetrical (a_u) state with respect to the interchange of the space proton coordinates. At energies of the ϵ mesonic atom in the c.m.s. which are much greater than the energy of the hyperfine structure of the hydrogen mesonic atom $\epsilon >> \epsilon_o$ ($\epsilon_o \approx 0.2$ eV), the cross-section of scattering

$$p\mu + p \rightarrow p\mu + p \qquad (2)$$

is of the form

$$\sigma_{pp} = 4\pi \left(\frac{1}{4} \frac{a_g^2}{1 + a_g^2 k^2} + \frac{3}{4} a_u^2 \right), \qquad (3)$$

where $k^2 = \frac{2 M_1 \epsilon}{\hbar^2}$.

However, as was shown in the theoretical paper[4], the $p\mu$ mesonic atom is expected to transfer from the hyperfine structure state $F = 1$ to the state $F = 0$ for 2.10^{-9} sec what is 0.001 of the muon lifetime as a result of collisions with protons and because of the ' jump ' mechanism. The results of the measurements of the muon depolarization in liquid hydrogen[11] are likely not to be in contrast with such a transition.

For $p\mu$ mesoatoms in the state $F = 0$ at the thermal energies ($\epsilon << \epsilon_o$), this cross section is given by the formula:

$$\sigma^{(0)}_{pp} = 4\pi \left(\frac{a_g + 3a_u}{4} \right)^2 . \qquad (4)$$

The scattering lengths a_g and a_u have been calculated in[2,6].

In both papers close values $a_u \approx 5$(in the units of $a_\mu = \frac{\hbar^2}{m_\mu e^2} = 2{,}55.10^{-11}$ cm) have been obtained for a_u , while in the magnitude of a_g a great difference is observed (according to[6] $a_g \approx -11$; according to[2] $a_g \approx -17$). This difference may be due to the fact that the $pp\mu$ mesonic ion has a virtual level with an energy close to zero, and under the resonance conditions a_g turns out to be rather sensitive to the approximations assumed in these papers. It is essential that in (4) the scattering lengths having opposite signs are added. As a result, $\sigma^{(0)}_{pp}$ may be far less than the corresponding value of σ_{pp} at $K = 0$*. Therefore, the comparison of the experimentally measured cross section with the calculating one enables us to estimate whether the corresponding theoretical approximations are correct and, thus, to get information about the $p\mu$ mesonic atom distribution over the spin states just before the muon decay or its capture by a nucleon.

Method. To determine this cross section experimentally the following method may be used. As far as the $p\mu$ mesonic atom travelling in hydrogen with a thermal velocity is electrically neutral, it will cover appreciable distances (diffuse) from the point of its generation to that of muon decay. Therefore, the process of $\mu - e$ -decay on the pictures in the diffusion chamber must look like so as the beginning of the decay electron tracks should be somewhat displaced with respect to the ends of the tracks of the muons coming to rest. The length of the gaps thus appearing between the muon and electron tracks depends on a number of factors, including the scattering cross section. As is seen from what will follow, it is the investigations of the length distribution for the gaps detected on the pictures that allow to determine this cross section.

As soon as the hydrogen density in the diffusion cloud chamber is some dozens lower than that in the bubble chamber, it creates very favourable conditions for good observation and measurements of such gaps. The main difficulty encounted in similar experiments is that owing to the presence in the chamber of carbon and oxigen nuclei which are the components of methyl alcohol the scattering process (2) is overlapped by another process-the muon transfer from protons to these nuclei which will lead to some decrease in the length of these gaps. The first experiment we have performed was devoted to the determination of the scattering cross sections (2) by the $\mu - e$ -decays with the gaps and to the obtaining of the rate of the muon transfer to complex nuclei.

Experimental Arrangement

The diffusion cloud chamber/13/ with the working diameter of 380 mm was placed into the magnetic field of 7200 oersted and exposed to the π^- and μ^--meson beam with the momentum of 260 MeV/c. The muons were slowed down and pions were absorbed by means of a copper filter 11.5 cm thick and of the 0.8 cm steel wall of the chamber. The admixture of π-mesons coming to rest in the chamber was determined by the relative number of one-prong stars due to π-mesons when the chamber was filled with helium, or by distinguishing π and μ mesons stoppings in hydrogen by measuring the mean radius of the curvature along a certain length of the track. This admixture in different runs was 1–5%. The cham-

*For the values of the parameter $a_g = -17.8$ and $a_u = 5.25$ accepted in /12/, the cross section $\sigma^{(0)}_{pp}$ is obtained to be anomalously small, because of the 'accidental' coincidence $|a_g| \simeq 3a_u$. However, in view of the above-mentioned uncertaity in the magnitude of a_g, this cannot be considered important.

ber was filled with hydrogen which was purified from the contaminations of N_2, O_2, H_2O etc by letting it through the trap with silica-gel and activated carbon cooled down to the temperature of liquid nitrogen. The exposure was made for two values of the hydrogen pressure. The analysis of the technical hydrogen we have used has shown that the atomic concentration of the deuterium admixture is 0.007% in it.

The first two runs have been performed under the pressure of 22.7 atm., but with different concentration of C and 0 nuclei which was estimated by the temperature of the vapour source or by the temperature and critical super saturation of the upper part of the sensitive region. The temperature of the vapour source was in the first run + 2° C, in the second - 15°C. The two latter runs were made under the hydrogen pressure of 5.0 atm., and the surface of the vapour source with the temperature of 0° C was decreased. Besides, in the fourth run the concentration of complex nuclei was increased by adding 22 mm Hg of air.

The Results of the Experiments

The main results and conditions of experiments are listed in the Table.

In all the runs along with usual $\mu - e$ -decays there were observed the events in which the beginning of the decay electron track is vividly displaced from the end of the stopped μ -meson at a distance ranging from a half-width of the track ($\sim$0.25 mm) up to 3.5 mm. In Fig. 1a is given an example of such an event observed in the first run. The length of the gap is 2 mm. Both the lengths of the gaps and the frequency of their appearance given in Column 7 depend on the concentration of complex nuclei and especially on the hydrogen pressure. When the hydrogen contains a very small contamination of deuterium (technical hydrogen) these gaps are due to the diffusion of $p\mu$ mesonic atom for a time before the decay or transfer of a μ -meson to a complex nucleus. The muon transfer to the complex nuclei occurs comparatively quickly, what the effects we have observed point to:

1) The appearance of the muon stoppings not accompanied by the decay electron, and the appearance of the stars with one or more heavy charged particles (Column 6) which are due to the nuclear muon capture by the complex nucleus.

2) The emission of Auger electrons. In the cases with gaps the beginning of the decay electron track is very frequently accompanied by a distinct 'point', i.e., a gathering of drops with the dimension 0.3 – 0.6 mm (Fig. 1b). The frequency of the appearance of these 'points' depends upon the concentration of complex nuclei (Column 8), and these 'points' are accounted, very likely, for the short-range Auger electrons arising in the cascade muon transition from the excited levels of the C or 0 mesonic atoms after the muon transfer from the $p\mu$ -mesonic atom to these atoms.

To clear up the latter circumstance (the smallness of Auger electron energy) another run was performed without the magnetic field under the same conditions as run 3. There were identified 43 $\mu - e$ -decays, n 10 of which the beginning of the electron track was accompanied by a visible 'point'. Out of all the 43 $\mu - e$ -decays, only in 3-4 events one could not exclude the presence of the second electron whose range or multiple scattering would point out that its energy is considerably greater than 10 KeV (the range in the chamber is more than 2 mm). This fact implies that after the muon transfer to the C or O nuclei most of the emitted Auger electrons have the energy of less than 10 KeV.

The observation of these effects allow to determine the rate of the muon transfer to complex nuclei. This problem turns out to be difficult enough due to the smallness of the effect and to the complications connected with the identification of the transfer events. Therefore, several methods of determining this rate have been used.

In the first run the rate of the transfer was determined by the formula

$$\lambda'_z cq = \frac{\lambda_o \, n_{stop.} a}{n_{\mu e} - n_{stop.} a} , \qquad (5)$$

where λ'_z is the rate of the muon transfer from a proton to the complex nuclei in the gaseous hydrogen; C is the concentration of complex nuclei (Column 3); q = 1 for experiments 1 and 2 and q = (5.02/22.7) = 0.22 for experiments 2,3 and 4; $\lambda_o = 0.452 \cdot 10^6 sec^{-1}$ is the probability of the muon decay, $n_{stop.}$ is the number of the muon stoppings without electrons; $n_{\mu e}$ is the number of decays; $a = \frac{2\lambda_o}{\lambda^c_{cap} + \lambda^o_{cap}}$; λ^c_{cap} and λ^o_{cap} are the rates of nuclear muon capture by carbon and oxigen found experimentally /14/. This method of the determination suggests that the probabilities of the muon transfer to the C and O nuclei should be the same.

In the remaining three runs $\lambda'_z cq$ was determined by the following methods.

1) By the frequency of appearing the Auger electrons at the beginning of the decay electron track under the assumption that the visible 'point' can be seen always by the muon transfer to a complex nucleus. To clear up the validity of this assumption an experiment was arranged in which 3% of C and O nuclei (CO_2) were added to the hydrogen at the pressure of 21 atm. In order to increase the dimensions of the gaps 5% of deuterium were also let into the chamber (see Sec. 4). In this experiment about 95% of muons which are on the $d\mu$ -mesonic atom orbit will transfer to carbon and oxigen nuclei before their decay. Out of the 40 events in which the gaps were longer than 1 mm, in 37 at least, the beginning of the decay electron track was accompanied by a visible 'point'. This points out that in not less than 90% of all the events the transfer to the complex nucleus is accompanied by the Auger electron.

2) By the magnitude of $\lambda'_z cq$ from run 1 and by the ratio of the number of stars with visible prongs in runs 2,3,4.

3) By the magnitude of $\lambda'_z cq$ from run 1 and by the ratio of the concentration of complex nuclei in runs 2,3,4.

It turned out that tne values of the rates of the transfer to the complex nuclei obtained by various methods are in good agreement with each other. This confirms, to some extent, the validity of the assumptions and estimates of the relative concentrations of complex nuclei. In Column 9 of the Table are presented the obtained values of the transfer rates. For runs 2,3 and 4 are given the values averaged over all the methods. The errors take into account both the statistical errors and the uncertainties in identifying the events and in determining the concentration of complex nuclei.

The measurements were made of the lengths of the gaps directly on the film by means of a UIM–22 microscope with 50 X magnification (the photographing scale is 1 : 15). The projection lengths l' of the distance from the beginning of the decay electron track to the end of the muon track were measured, a half width of the muon track being taken into account. At the same time those events were rejected in which the length of the projection of the electron track is less than 5 mm, the electron track itself is not clearly seen, or the point at which the muon comes to rest is covered with a gathering of drops, the grid, background tracks etc. We also rejected the events in which the gap was due to a local insensitive region in the vicinity of the muon stopping (in these cases the muon track becomes thinner at the end of the range, and the electron 'looks' at the stopping point). The distributions over the true gap lengths were constructed by those described above, with the corrections taking into account the events with the gaps not observed because of the finite track width. For runs 2 and 3, these distributions are shown in Fig. 2. Some background events the number of which was estimated in special measurements were excluded from these distributions. The numerical values of the mean squares of the gap lengths are given in Column II. The errors in these values take into account the uncertainty due to the inclusion of a small number of doubtful events into the distributions.

The Determination of the Cross Section σ_{pp} for Elastic Scattering of $p\mu$ Mesonic Atoms on Hydrogen

The magnitudes of $\lambda'_z cq$ and $\overline{r^2}$ found experimentally allow to determine the cross section σ_{pp}. Indeed, if $p\mu$ -mesonic atoms have thermal energies, then the mean square of the gap length is connected with the diffusion coefficient D of $p\mu$ mesonic atoms in hydrogen by the relation

$$\overline{r^2} = 6 D \tau \quad , \qquad (6)$$

where $\frac{1}{\tau} = \lambda_0 + \lambda'_z cq.$

In its turn

$$D = \frac{3\pi}{32} \frac{\bar{v}}{N \bar{Q}_d} \quad , \qquad (7)$$

where $\bar{v}$ -is the mean velocity of the relative motion of $p\mu$ and H_2. N is the number of protons in cm^3, while $\bar{Q}_d$ is the value of the migration cross section averaged over the Maxwell distribution

$$\bar{Q}d = \frac{\int_0^\infty v^5 \exp\left(-\frac{m v^2}{2\kappa T}\right) Q\, dv}{\left(\frac{m}{2\kappa T}\right)^5} . \qquad (8)$$

The quantity Q entering (8) is equal to $Q = 2\pi \int (1 - \cos\theta)\, \sigma(\theta) \sin\theta\, d\theta$; $\sigma(\theta)\, d\theta$ is the differential cross section for $p\mu$ -mesonic atom scattering on hydrogen; $m = \frac{M_1 M_2}{M_1 + M_2}$ is the reduced mass of $p\mu$ and of the H_2 molecule, T is the mean temperature of gas.

Since in the real hydrogen the scattering of $p\mu$ -mesonic atoms takes place not on free protons, but on the H_2 molecules, then it is necessary here to take for $\sigma(\theta)$ the differential cross section for the $p\mu$ -mesonic atom scattering on the H_2 molecules. This magnitude is not difficult to be calculated if the cross section for $p\mu$ scattering on free protons is known. This may be made by the method of the pseudo-potential used in computing slow neutron scattering on molecules.

The calculation of the magnitudes $\bar{Q}_d$ for $p\mu$ mesonic atom scattering, the $p\mu$ -mesonic atoms are in the F =0 state, on the ortho- and parahydrogen molecules for $\bar{v} = 2.7 \cdot 10^5 cm/sec$ and at the temperature $T = 242^\circ K$ (our experimental conditions) leads to the result

$$(\bar{Q}d)_{para} \simeq 0,6\, \sigma_{pp} \quad , \qquad (\bar{Q}d)_{ortho} \simeq 2\sigma_{pp} \quad , \qquad (9)$$

while for the statistical mixture of ortho- and parahydrogen (3/4 ; 1/4):

$$\bar{Q}d \simeq 1,6\, \sigma_{pp} . \qquad (10)$$

Making use of (6), (7), and (10) we find the expression for determining the cross section

$$\sigma_{pp} = \frac{1,1\, \bar{v}}{r^2 N (\lambda_0 + \lambda'_z cq)} . \qquad (11)$$

In the last Column of the Table are presented the cross sections σ_{pp}-calculated by this formula according to the values $\lambda'_z cq$ and r^2 indicated in Column 9 and 11.

Table

Nº of the run	H_2 pressure in atm.	Concentration of complex nuclei of C, O or N in hydrogen in %	The number of pictures	The total number of muon stoppings *	The number of stars with visible prongs from the muon capture by complex nuclei **	The percentage of the number of events with visible gaps	The ratio of the number of events with gaps and with Auger electrons to that without Auger electrons	$(\lambda_z^1 cq) \cdot 10^{-6}$ sec^{-1}	$(\lambda_0 + \lambda_z^1 cq) \cdot 10^{-6}$ sec^{-1}	$\bar{r}^2$ mm^2	$\sigma_{pp} \cdot 10^{19}$ cm^2 $(p\mu + p \to p\mu + p)$
1	2	3	4	5	6	7	8	9	10	11	12
1	22,7	0,2	4000	718	21	9%	>60%	$0{,}8^{+0{,}4}_{-0{,}2}$ xxx)	$1{,}3^{+0{,}4}_{-0{,}2}$	$0{,}10 \pm 0{,}014$	$1{,}9^{+0{,}4}_{-0{,}6}$
2	22,7	0,07	8000	550	6	15%	10/26	$0{,}21^{+0{,}11}_{-0{,}07}$	$0{,}66^{+0{,}11}_{-0{,}07}$	$0{,}22 \pm 0{,}04$	$1{,}7^{+0{,}4}_{-0{,}5}$
3	5,02	0,7	16000	202	5	50%	21/10	$0{,}7^{+0{,}4}_{-0{,}2}$	$1{,}2^{+0{,}4}_{-0{,}2}$	$1{,}4 \pm 0{,}3$	$0{,}7^{+0{,}2}_{-0{,}3}$
4	5,02	1,3	7000	98	5	40%	13 /4	$1{,}1^{+1{,}0}_{-0{,}5}$	$1{,}6^{+1{,}0}_{-0{,}5}$	$1{,}1 \pm 0{,}4$	$0{,}6^{+0{,}3}_{-0{,}4}$

* The numbers indicated in this Column are given without pion and false stoppings.

** The number of stars indicated in Column 6 includes one-prong stars for runs 1 and 2 with $l' > 2$mm, for runs 3 and 4 – with 7 mm (ℓ' is the length of the track projection along the horizontal plane).

*** When $\lambda'_{z}cq$ was determined in this run, it has been found that $\frac{n_{stop.}}{n_{\mu e}} = \frac{34}{267}$, a number of selection criteria have been applied.

3. Discussion of the Experimental Results on the Determination of the Cross Sections σ_{pp} and on the Muon Transfer to Complex Nuclei

1. The comparison of the cross section σ_{pp} calculated by the found values of $\overline{r^2}$ and λ'_{zcq} shows that the effect of $p\mu$ -mesonic atom scattering on complex nuclei is small since it is not demonstrated in changing the concentration of complex nuclei or the hydrogen pressure. Along with this, it should be noted that $\overline{r^2}$ changes more strongly in varying the hydrogen density than it follows from the diffusion formula (11) (for instance, in rum 3 we have to expect by (11) that $\overline{r^2}$ increases five times as large in comparison with run 1, but not 13 times as large what was obtained experimentally). In view of this, a difference has been obtained in the calculated values of cross sections for high and low hydrogen pressures.

Apparently, this cannot be fully accounted for possible neglected experimental inaccuracy. If this discrepancy is real , then it may be due to the following reasons:

a) $p\mu$ -mesonic atom has the initial energy of order of 1 eV* which exceeds essentially the thermal one (0.02 eV), and the scattering cross section is increasing with decreasing velocity. In this case the application of the diffusion approximation for $p\mu$ -mesonic atom scattering at low densities H_2 (5 atm) may turn out not quite justified since the time before the decay or transfer can be compared with the time before the slowing down to the thermal velocity (for the energy of 1 eV, the number of $p\mu + p$ collisions before the slowing down is about 6, while for $\sigma_{pp} \approx 1.10^{-19} cm^2$ and $v_{therm} = 2.10^5 cm/sec$, the number of collisions before the decay or transfer is equal to 5).

b) $p\mu$ -mesonic atoms may be in the two states F = 0 or F = 1, whose cross sections for elastic scattering differ from each other 5–10 times. In this case it is possible to satisfy the values of $\overline{r^2}$ obtained experimentally by an appropriate choice of the statistical weights of these states. These qualitative reasons for a possible difference in the magnitudes of the cross sections for the two pressures may be checked by further increasing the accuracy of the magnitudes obtained experimentally and in a more accurate analysis of the range distribution.

In order to compare the experimental absolute value of the cross section σ_{pp} with the theoretical one we make use of the magnitude $1.7.10^{-19} cm^2$ experimentally obtained with high hydrogen pressure and low concentration of complex nuclei (run 2) since the application of the diffusion formula in this case is more justified (the number of collisions $p\mu + p$ is about 40), whereas the effects from complex nuclei are very small. This value is in agreement with the magnitude $3.10^{-19} cm^2$ obtained by Cohen et al/6/.

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* If the transition of a muon from high orbits to the K-orbit of a mesonic atom occurs as a result of the collisions with H_2 molecules, as it was pointed out by Weightman/15/, then a part of the coupling energy of a H_2 molecule (about 1 eV) will be transferred to a $p\mu$ - mesonic atom.

However, the magnitude $3.10^{-19} cm^2$ is calculated without taking into account the hyperfine structure of a $p\mu$ -mesonic atom. If the scattering lengths $a_u = +5$ and $a_y = -11$ found by Cohen et al are used, then the cross section in the state F = 0 calculated by (4) is equal to $1.10^{-20}\ cm^2$ and differs from an experimental one about 20 times (for $a_u = +5$ and $a_g = -17$ given in /2/, the magnitude $\sigma^{(0)}_{pp} < 10^{-20} cm^2$).In order to bring into agreement the theoretical scattering cross section in the state F = 0 with the experimental one for the given scattering length $a_u = +5$ (in which there are no noticeable discrepancies between /2/ and /6/), it is necessary to put a_g either equal to + 3 , or to − 30. The magnitude of $a_g = +3$ suggests the presence of the bound level in the $pp\mu$ system and seems, therefore, unlikely (although it yields a small value of the cross section with the transition to the lower state of the hyperfine structure). The magnitude of $a_g = -30$ is not impossible theoretically, but seems too large.

Thus, the experimental value does not contradict the magnitude of the cross section calculated without taking into account the hyperfine structure. But this does not exclude the possibility of fast transitions F = 1 → F = 0. More definite conclusions can be, probably, drawn in a further theoretical estimation of the possible values of the scattering lengths and in increasing the accuracy of the experimental range distributions of the $p\mu$ -mesonic atom.

2. The mechanism of the muon transfer from the hydrogen nuclei to complex nuclei has been treated by one of the authors (S. Gerstein). It was found that a great rate of the transfer to the C and 0 nuclei depends upon the presence of the intersections of the mesonic molecular terms in the $p\mu Z$ system (if the nuclear charge $Z \geq 3$). This mechanism accounts also for a small experimentally observed magnitude of the cross section for the muon transfer to He /16,17/, (as far as in the $p\mu\ He$ system the above-mentioned intersection of the terms is absent). A detailed consideration shows that a muon is transferred from protons mainly to the mesonic atom levels with the quantum number n = 4 for carbon and n = 5 for oxigen. Therefore, subsequent cascade transitions of mesonic atoms to the ground state with the probability close to 100 % must be followed by the emission of one or some Auger electrons with an energy of some KeV. The frequency of appearance of the 'points' visible at the beginning of the electron track and their dimensions are in agreement with the transition mechanism suggested.

The calculation shows also that the cross sections for the muon transfer to C and 0 nuclei are approximately the same: $\sigma v = 1.3 \cdot 10^{-12}\ cm^3/sec$ for carbon and $\sigma v = 2.10^{-12} cm^3/sec$ for oxigen, while the rate of the muon transfer to C and 0 nuclei (for the liquid hydrogen density) is equal to $\lambda_z = 5 \cdot 10^{10}\ sec^{-1}$.The experimental value of λ_z for liquid hydrogen calculated by $\lambda'_{z cq}$ found in the first run from

$$\lambda_z = \lambda'_{z}cq \frac{N_{liq.}}{N_{gas.}} \frac{1}{C_1} , \qquad (12)$$

is equal to $\lambda_z = (1.2 ^{+0.8}_{-0.5}) \cdot 10^{10} sec^{-1}$. In (12), N_{liq} and N_{gas} are the number of protons in cm^3 for liquid and geseous hydrogen, respectively; $C_1 = (0.002 ^{+0.0013}_{-0.0005})$ is the concentration of C and 0 nuclei in the first run. If one takes into account both the approximate character of the calculation and the errors in the experimental data, then one can think that this value of λ_z is in reasonable agreement with the theoretical one. The account of the results of the recently performed experiments on the muon transfer to Ne nuclei/17/ allows, very likely, to draw even more general conclusion that the rate of the muon transfer from hydrogen to light nuclei do not change strongly from a nucleus to a nucleus. Indeed, it was found in/17/, that the ratio $\lambda_{Ne}/(\lambda_o + \lambda_{pp\mu}) = (9.5 \pm 3) \cdot 10^3$. Hence, by making use of the magnitude $\lambda_{pp\mu}$ we have determined (see Sec. 4) we get $\lambda_{Ne} = (1.0 ^{+1.4}_{-0.6}) \cdot 10^{10} sec^{-1}$.

4. The Determination of the Rate of the Muon Transfer from a Proton to a Deuteron and of the $pp\mu$ Mesonic Ion Formation

In the muon transfer from a hydrogen mesonic atom to a deuteron in the reaction

$$p\mu + d \rightarrow d\mu + p \qquad (13)$$

the produced mesonic atom $d\mu$ receives the energy of 45 eV because of the difference in the reduced masses of $p\mu$ and $d\mu$. As is known, Alvaretz et al./8/ found that the mesonic atom with such an energy has a range in liquid hydrogen of about 1 mm. This fact has led one to hope that at the pressure of the gaseous hydrogen in the diffusion cloud chamber of about 20 atm., the range of a mesonic atom will be essentially longer and, thus, a comparatively easy means for determining the rate of transfer (13) appears.

The experimental procedure with a deuterium was analogous to that in run 1 (see Sec. 2). The deuterium concentration in hydrogen was tested in special experiments and was found to be 0.44%. Measures were taken to avoid a large background from the particles passing through the chamber which would make the identification of the events with the transfer to deuterium difficult. The gaseous deuterium used in the experiment was carefully purified from tritium (the tritium contamination in it was less than $5 \cdot 10^{-14}$ atomic parts).

About 800 events were found on 10000 pictures. A half of these events were usual $\mu - e$–decays, while the remaining ones reached 10 – 15 mm between the end of the stopped muon and the electron. In Fig. 3 are given two examples of such events with the gaps of 7 and 11 mm.

The distribution of 341 events by the lengths of the gap projections along the horizontal plane with

$l > 1$ mm is shown in Fig. 4 (except the background events with the gaps from the $p\mu$-atom diffusion). In the same figure the smooth curve shows the calculation distribution of the projections of the gap lengths. It has been obtained on the basis of the distribution of the real gap lengths which can be put as

$$\frac{dn}{dl} = A \exp\{ bl - \frac{\lambda}{v_o b} [\exp(bl)] \} , \qquad (14)$$

where $b = \frac{1}{2} N\sigma\eta$, N is the number of protons in cm^3, σ is the cross section for elastic scattering of $d\mu$ mesonic atoms on protons, deuterons and complex nuclei (it was taken to be $7.10^{-21} cm^2$/2/); η is a part of $d\mu$-mesonic atom energy lost per collision, $\eta = 0.45$; v_o is the initial velocity of a $d\mu$-mesonic atom equal to $6.6.10^6$ cm/sec ; λ is the sum of the rates of the muon transfer from a deuteron to the C and O nuclei and of the muon decay taken to be $\lambda = 1.5.10^6 sec^{-1}$. In the calculation of distribution (14) it was assumed that a $d\mu$-mesonic atom loses its energy only in the collision with protons and since in such scattering a possible deviation from its original direction does not exceed 30^o in the lab. system, it was assumed to move along the straight line. Besides, it was taken into account that the way covered by a $d\mu$-mesonic atom is determined not only by the slowing down time but also by the time before the decay or the muon transfer to complex nucleus. One can see from Fig. 4, that a qualitative agreement is observed between the calculation and measured distributions. In determining the rates of the muon transfer from a proton to a deuteron the most essential corrections were introduced into the total number of such events: the correction for the inefficiency of observing the events with the gaps (+17%), the background from false events (–8%) and the contribution from the region with $l' < 1$ mm (+ 4%). As a result, it was found out that the ratio of the number of the muons transferring to deuterium to that not transferring is equal to 1.12 ± 0.18. Hence, the rate of the transter $p\mu + d \rightarrow d\mu + p$ is $(1.45 ^{+0.51}_{-0.32}) . 10^6 sec^{-1}$. By dividing this value into the deuterium concentration and multiplying it by the ratio of the densities of the liquid and gaseous hydrogen, we get the folliwing value for the rate of the muon transfer from a proton to a deuteron in the liquid hydrogen:

$$\lambda_d = (0.95 ^{+0.34}_{-0.21}) . 10^{10} sec^{-1} .$$

The obtained experimental value of λ_d is in good agreement with the magnitude calculated by using the method of the refined adiabatic approximation what was done by Belyaev et al/18/, as well as Cohen et al/6/.

The knowledge of the absolute value of λ_d playing a great role, e.g., in the catalysis phenomena is especially important since it allows to determine another quantity essential for the mesonic molecular physics, i.e., the rate of the $pp\mu$-mesonic molecular ion formation in liquid hydrogen. Indeed, in some papers[8,17] the yield of the reaction $d\mu + p \rightarrow He^3 + \mu$ has been determined and the ratio $\lambda_d/(\lambda_o + \lambda_{pp\mu})$ has been found . The most reliable data for this ratio have been recently obtained by Schiff[17]. He found that

$$\frac{\lambda_d}{\lambda_o + \lambda_{pp\mu}} = (8{,}9 {}^{+6,2}_{-3,6})\ 10^{3}\ .$$

By substituting here our magnitude of λ_d, we get the absolute rate of the $pp\mu$ mesonic ion formation in liquid hydrogen to be

$$\lambda_{pp\mu} = (0{,}6 {}^{+0,8}_{-0,5})\ 10^{6}\ \mathrm{sec.}^{-1}$$

This value agrees within the error with that calculated by Zeldovich and Gerstein[5]* which is $1.3 . 10^6$ sec^{-1}, but it is much less than $6.5 . 10^6$ sec^{-1} and $9 . 10^6$ sec^{-1} calculated by Cohen et al[6] and Wu et al[7].

Then, using the results of[17] and taking into account the upper limit of our experimental value of $\lambda_{pp\mu}$, one can estimate the upper limit of the absolute rate of $pd\mu$ mesonic ion formation in liquid hydrogen.

If it is assumed that the rates of the muon transfer from a proton and a deuteron to a neon are the same, we get $\lambda_{pd\mu} < 0.6 . 10^6 sec^{-1}$. It should be emphasized that this value does not contradict the estimate resulting from Ashmore et al experiments[9] $\lambda_{pd\mu} > 0.2 . 10^6 sec^{-1}$, but is in sharp discrepancy with the estimate $\lambda_{pd\mu} > 10^7 sec^{-1}$ obtained in investigating the catalysis of the nuclear reactions in the liquid deuterium bubble chamber[10].

5. Conclusion

In this paper some quantitative characteristics of a number of mesonic atomic processes in hydrogen have been determined experimentally. Although the magnitude of the cross section for $p\mu$-mesonic atom scattering on protons is close to the expected theoretical value of the cross section calculated without taking into account the hyperfine structure, the problem about the probability of the transitions $F = 1 \rightarrow F = 0$ is still open. More definite conclusions can be, probably, drawn by studying further the mesonic atom distributions over the range lengths and by specifying theoretically the scattering lengths a_g and a_u. The found values of λ_d, $\lambda_{pp\mu}$, and λ_z are in good agreement with the calculation ones and confirm the validity of the mechanisms of the processes suggested in the theory. However, a higher accu-

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* In[5], the value of $\lambda_{pp\mu}$ has been found to be $1.5 . 10^6$ sec^{-1} for the number of hydrogen nuclei $N = 4.2 . 10^{22} cm^{-3}$; the value $\lambda_{pp\mu} = 1.3 . 10^6 sec^{-1}$ has been calculated for $N = 3.5 . 10^{22} cm^{-3}$, what is more real under the condition of the liquid hydrogen bubble chamber.

racy of these experimental values and, especially, of the rate of the $pp\mu$ mesonic ions formation in liquid hydrogen is necessary as far as the problem of the muon capture by protons is concerned.

The contradiction in the estimates of $\lambda_{pd\mu}$ obtained from experiments in which hydrogen contaminated with a small amount of deuterium and liquid deuterium contaminated with a small amount of hydrogen[10] were used could point out a possibility of a new mechanism of the catalysis. Therefore, the experiments on a direct determination $\lambda_{pd\mu}$ are at present especially interesting.

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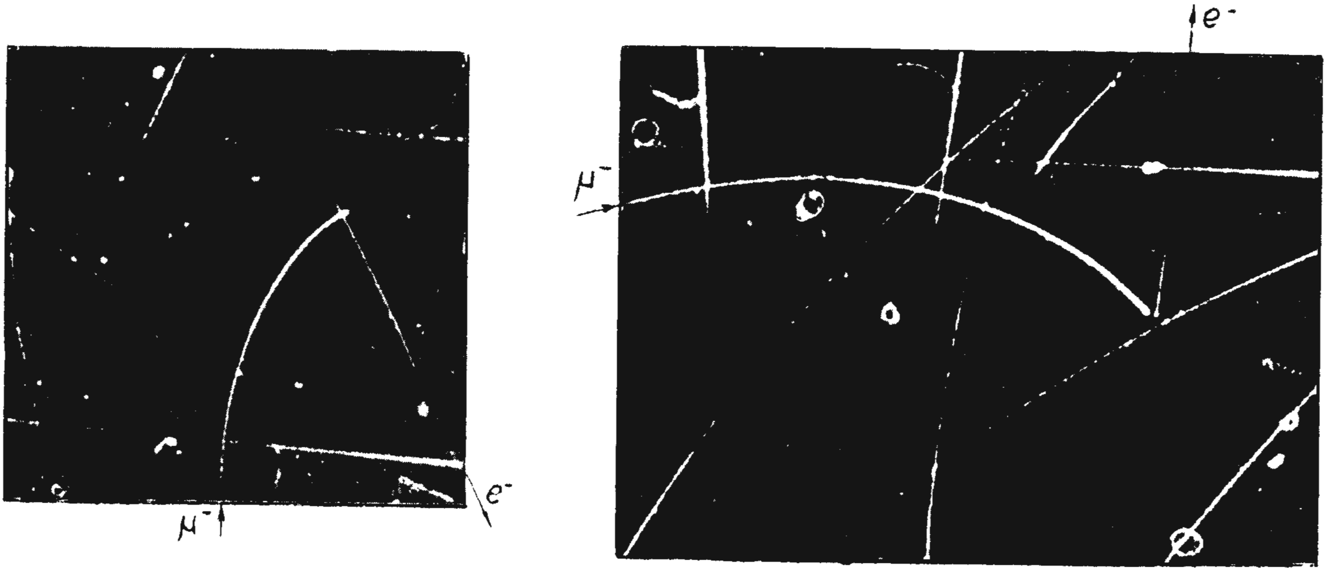


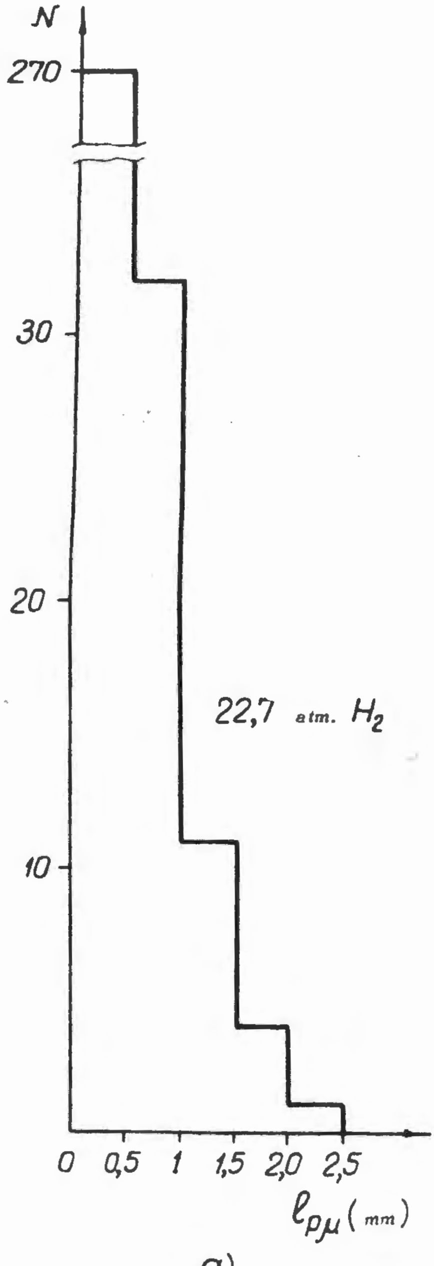
a)　　　　　　　　b)

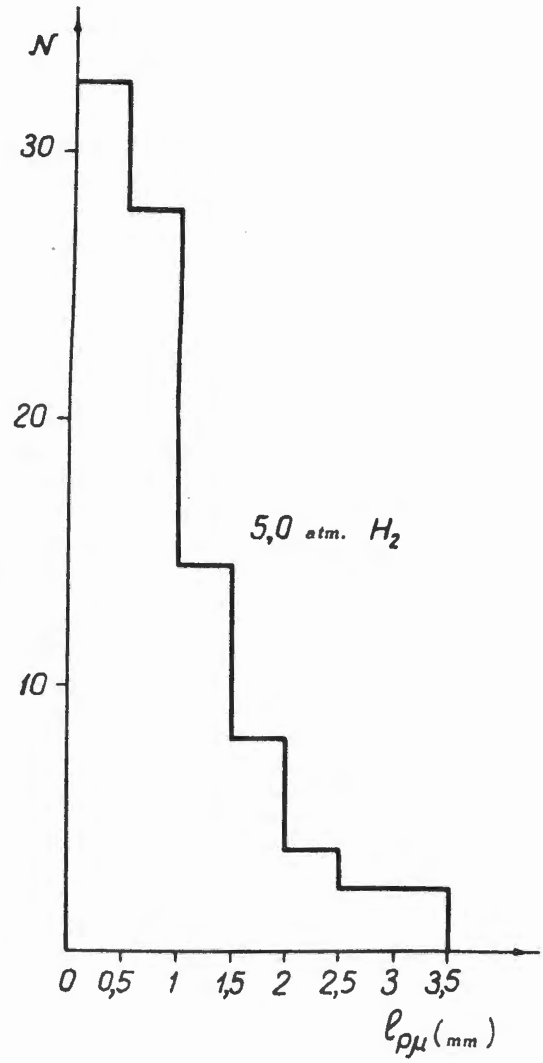
Fig. 1.

Pictures of $\mu - e$ -decays in hydrogen (runs 1,2). The displacements between the beginning of the electron track and the end of the stopped muon are due to the diffusion of a $p\mu$ -mesonic atom.

a) at the beginning of the decay electron track there is no visible 'point';

b) at the beginning of the decay electron track there is observed a visible 'point' (Auger electron)





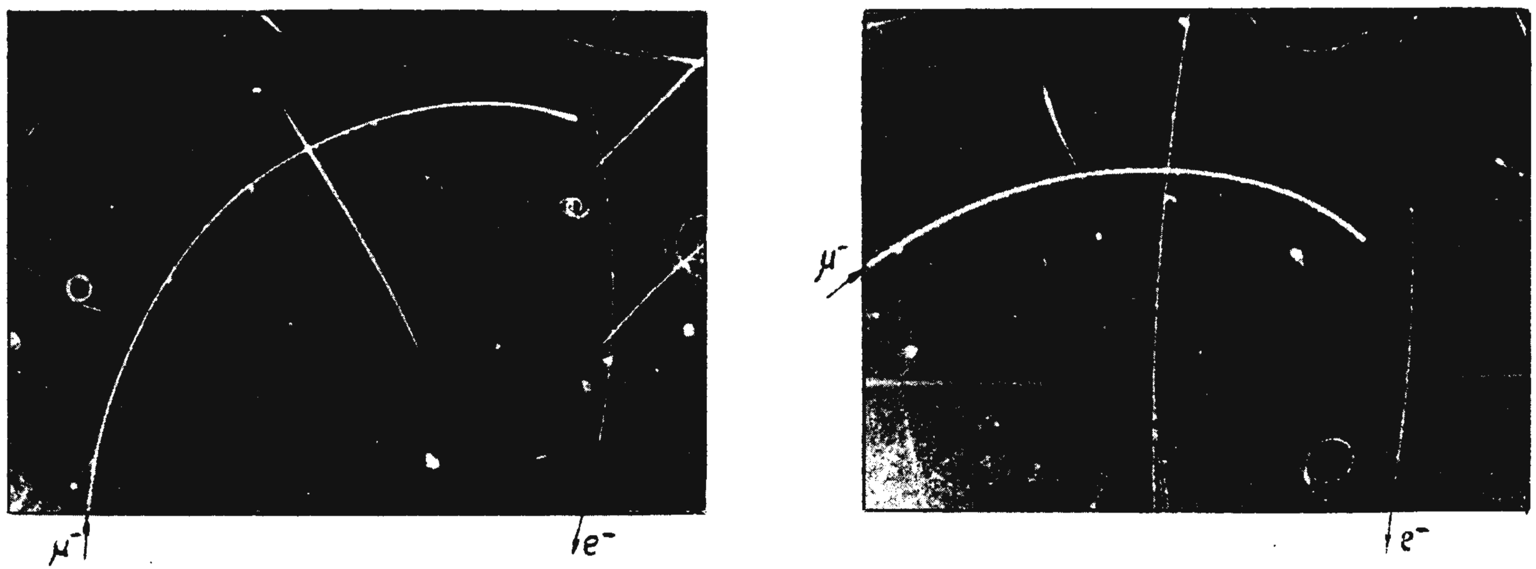
b)

F i g. 2.

Distribution of the events of $\mu - e$ -decays in hydrogen by the gap lenghts .

a) H_2 pressure of 22.7 atm (run 2).

b) H_2 pressure of 5.0 atm (run 3).



a) b)

Fig. 3.

Pictures of μe-decays in hydrogen contaminated with deuterium. The displacements between the beginning of the decay electron track and the end of the stopped muon are due to the process $p\mu + d \to d\mu + p$ and to the subsequent range of the $d\mu$-mesonic atom.

a) at the beginning of the decay electron track there is no visible 'point';

b) at the beginning of the decay electron track there is observed a visible 'point'.(Auger electron)

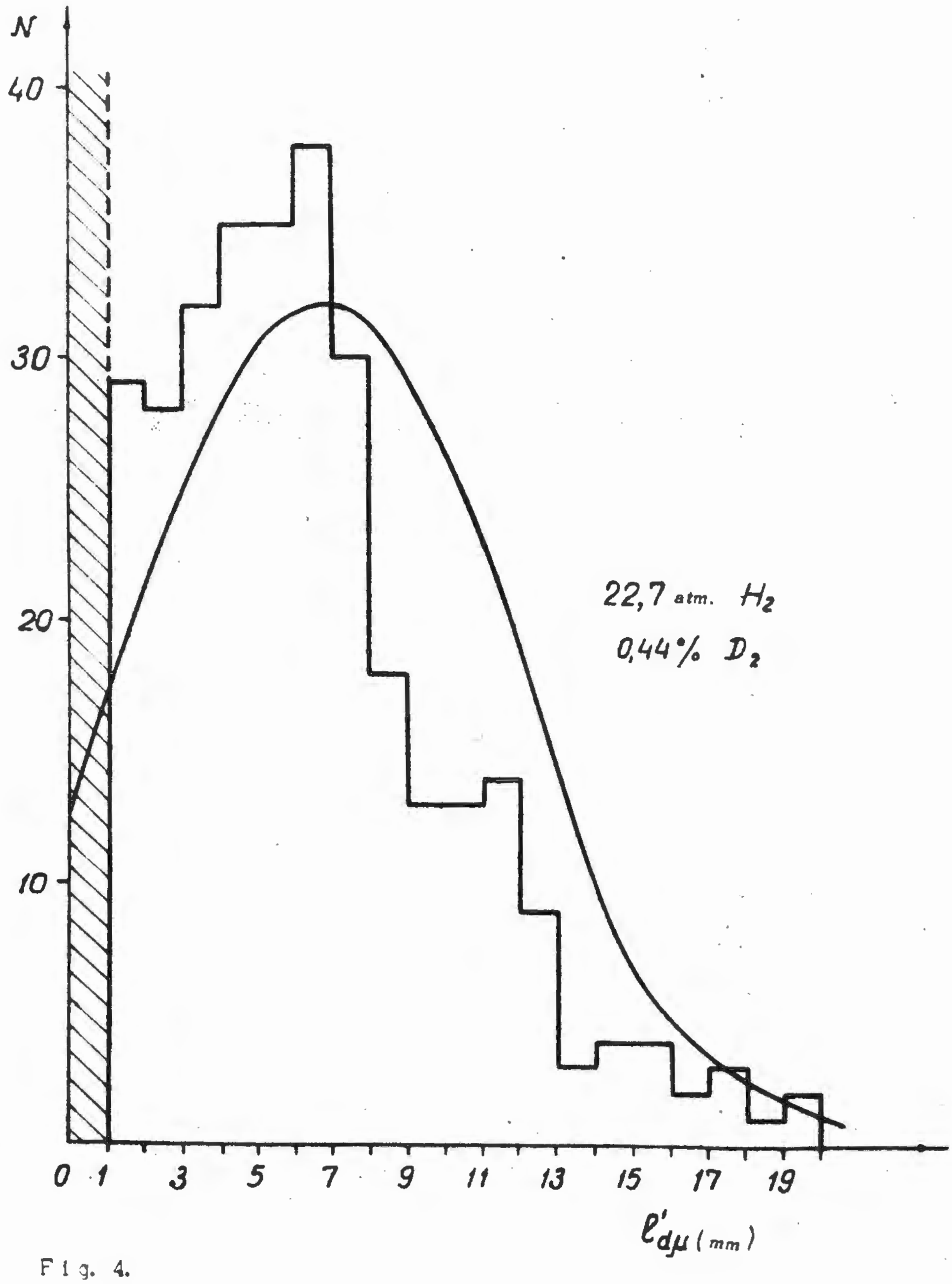


Fig. 4.

Distribution by the projections of the gap lengths of the events of $d\mu$ -mesonic atoms produced in the process $p\mu + d \to d\mu + p$. (P_{H_2} = 22.7 atm, C_{D_2} = 0.44%). The smooth curve shows the calculation distribution. (See the text).

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