SOVIET PHYSICS JETP VOLUME 15, NUMBER 2 AUGUST, 1962

EXPERIMENTAL INVESTIGATION OF μ^- MESIC ATOM PROCESSES IN GASEOUS HYDROGEN

V. P. DZHELEPOV, P. F. ERMOLOV, E. A. KUSHNIRENKO, V. I. MOSKALEV, and S. S. GERSHTEĬN

Joint Institute for Nuclear Research

Submitted to JETP editor October 26, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 439-449 (February, 1962)

A diffusion cloud chamber in a magnetic field was employed to study a number of μ mesic atom processes in hydrogen. The following quantitative data have been obtained: the cross section for elastic scattering of pμ mesic atoms on protons, $\sigma_{pp}(1.7^{+0.4}_{-0.5}) \times 10^{-19}$ cm^2; the rates of the μ-meson transfer from protons to deuterons and complex nuclei (C and O), recalculated for the density of liquid hydrogen, $\lambda_d = (0.95^{+0.34}_{-0.21}) \times 10^{10}$ sec^{-1} and $\lambda_Z = (1.2^{+0.8}_{-0.5}) \times 10^{10}$ sec^{-1}; the rate of formation of ppμ mesic molecules in liquid hydrogen, $\lambda_{pp\mu} = (0.6^{+0.8}_{-0.5}) \times 10^6$ sec^{-1}.

The experimental values of λ_d, $\lambda_{pp\mu}$, and λ_Z satisfactorily agree with the theoretical ones. This confirms the mechanism of the processes proposed in the theory. The cross section σ_{pp} was found to be close to the theoretical value computed without taking the hyperfine structure of the pμ mesic atom into account. However, it is not excluded that fast transitions to the lower state with a total mesic-atom spin F = 0 may occur.

The absolute value of λ_d determined in the present work opens the possibility of finding the absolute probabilities of a large number of μ mesic molecular processes by employing it as a scale.

1. INTRODUCTION

THE experimental study of the capture reaction of negative μ mesons by protons

$$\mu^- + p \to n + \bar{\nu} \tag{1}$$

may yield important information concerning the weak interactions. Until recently, however, reaction (1) was among the practically unknown processes involving the weak interaction of ordinary particles. The difficulties in its study were due not only to the small probability of occurrence, but also to a very large extent to the complications in the interpretation of the direct experimental data as the result of various mesic-atom and mesic-molecular effects which precede the reaction.[1-3]

As has been shown in theoretical investigations,[1,4] the probability of reaction (1) depends on the spin state of the hyperfine structure of the μ mesic hydrogen atom (F = 0 or F = 1), and for hydrogen densities greater than 10^{19} nuclei/cm^3 the capture of μ mesons should mainly occur from the lower state of the mesic atom with F = 0. (F is the total spin of the mesic atom.)

The probability of μ-meson capture in hydrogen also depends substantially on the probability $\lambda_{pp\mu}$ of the production of ppμ mesic molecules,[5-7] since the spin state of such mesic molecules is analogous to a mixture of the states F = 1 and F = 0. The experimental determination of $\lambda_{pp\mu}$ and of the transition probability of the pμ from the state F = 1 to the state F = 0 becomes therefore especially important.

The μ mesic molecular processes also determine the catalysis of nuclear reactions by μ mesons in the mixture of hydrogen isotopes,[8-10] and although the basic experimental facts are in qualitative agreement with the theory, further experiments on the determination of such quantities as the transition probability of the μ meson from the proton to the deuteron, the production probability of pdμ mesic molecules, and the probabilities of nuclear reactions in such mesic molecules, are also of interest.

Because of the urgency of these problems, several experiments devoted to the study of mesic atom processes in hydrogen and deuterium were undertaken, using the synchrocyclotron of the Joint Institute for Nuclear Research. A high-pressure diffusion cloud chamber in a magnetic field was used in this experiment. In the present article we report the results of the first series of experiments on the scattering of the pμ mesic atoms on protons, on the determination of the transition probability of the μ meson from the proton to the deuteron, on the production of the $pp\mu$ mesic molecules, and on the transfer of the μ meson from the proton to complex nuclei.

2. SCATTERING CROSS SECTION OF $p\mu$ MESIC ATOMS ON PROTONS AND THE TRANSFER OF THE μ MESONS TO COMPLEX NUCLEI

The scattering cross section of $p\mu$ mesic atoms on protons was calculated theoretically.[2,6] It can be expressed through the scattering lengths a_g and a_u of the $p\mu + p$ system in the symmetrical (a_g) and antisymmetrical (a_u) states with respect to the permutation of the spatial proton coordinates. When the c.m.s. energies ϵ of the $p\mu$ mesic atom are much greater than the energy of the hyperfine structure of the hydrogen mesic atom, $\epsilon \gg \epsilon_0$ ($\epsilon_0 \approx 0.2$ eV), the scattering

$$p\mu + p \rightarrow p\mu + p \tag{2}$$

has a cross section

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

where $k^2 = 2M_1\epsilon/\hbar^2$.

However, as was shown in [4], the $p\mu$ mesic atom should, as a result of collisions with protons and because of the "jump" mechanism, pass from the hyperfine structure state $F = 1$ to the state $F = 0$ within 2×10^{-9} sec, amounting to ~ 0.001 of the μ-meson lifetime. The measured depolarization of μ mesons in liquid hydrogen[11] evidently does not contradict such a transition.

For $p\mu$ mesic atoms in the state $F = 0$ and for thermal energies ($\epsilon \ll \epsilon_0$), this cross section is given by the formula

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

The scattering lengths a_g and a_u were calculated in two articles[2,6] in which close values for a_u were obtained, namely $a_u \approx 5$ (in units of $a_\mu = \hbar^2/m_\mu e^2 = 2.55 \times 10^{-11}$ cm) while a large discrepancy resulted in the value of a_g (according to [6] $a_g \approx -11$, and according to [2] $a_g \approx -17$). This difference may be due to the fact that the $pp\mu$ mesic molecule has a virtual state with energy close to 0, and, at resonance conditions, the value of a_g is very sensitive to the approximations underlying the calculations. The fact that scattering lengths of opposite sign enter into expression (4) is significant. As a result, the value of $\sigma_{pp}^{(0)}$ may be markedly less than the corresponding value of σ_{pp} for $k = 0$.* Under these conditions, a comparison of the measured and calculated cross sections enables us to test the theoretical approximations, and thus obtain information on the distribution of $p\mu$ mesic atoms with respect to the spin states just before the decay of the meson or its capture by the nucleon.

Method. The following method can be used for the determination of the scattering cross section. The $p\mu$ mesic atom, moving in hydrogen with thermal velocity and being electrically neutral, will traverse a large distance from the place of its production before the μ meson decays. Therefore, the μ-e decay process should appear in the photographs of the diffusion chamber as if the origin of the decay electron track were slightly shifted away from the end of the stopping μ-meson track. The magnitude of the gap thus produced between the μ-meson and electron tracks depends on a number of factors, among them the scattering cross section. As will be shown below, a study of the length distribution of the gaps recorded on photographs can indeed be used to find the cross section.

The conditions in the diffusion chamber, where the hydrogen density is tens of times lower than the density in the bubble chamber, are very convenient for good observation and measurement of the gaps. The main difficulty in the experiment is that the presence in the chamber of carbon and oxygen nuclei, contained in the methyl alcohol, superimposes another process on the scattering process (2), viz., the transfer of μ mesons from protons to these nuclei, which leads to a decrease in the gap length. The first part of the experiments was devoted to the determination of the cross section (2) from μ-e decay events with gaps and, simultaneously, to finding the probability of the μ-meson transfer to complex nuclei.

Experimental setup. The diffusion chamber[13] with a working volume diameter of 380 mm was placed in a magnetic field of 7200 Oe and irradiated by a beam of π^- and μ^- mesons of 260 MeV/c. The μ mesons were slowed down and the π mesons absorbed in a 11.5 cm copper absorber and in the chamber wall (8 mm steel). The admixture of π mesons stopping in the chamber was determined either from the relative number of single-prong stars produced by π mesons when the cham-

*For the values of parameters assumed in[12], $a_g = -17.3$ and $a_u = 5.25$, the cross section $\sigma_{pp}^{(0)}$ due to the "chance" coincidence $|a_g| \approx 3a_u$ was found to be anomalously small. However, because of the above-mentioned uncertainty in the value of a_g, this result cannot be gi ven serious consideration.

ber was filled with He, or by the identification of the π and μ mesons stopping in hydrogen by measuring the mean radius of curvature for a given track length. This admixture amounted to 1—5% in different experiments. The chamber was filled with hydrogen purified from admixtures of nitrogen, oxygen, water vapor, etc., by passing it through traps with silica-gel and activated carbon cooled to the temperature of liquid nitrogen. Exposures were made at two values of the hydrogen pressure. The analysis of a sample of the technical hydrogen used showed that the atomic concentration of deuterium in it amounted to 0.007%.

The first two experiments were carried out at a pressure of 22.7 atm but at different concentrations of the C and O nuclei, estimated from the temperature of the vapor source or from the temperature and the critical supersaturation of the upper part of the sensitive layer. The temperature of the vapor source in the first experiment was +2°C and in the second −15°C. The two last experiments were carried out at a hydrogen pressure of 5.0 atm, with a decreased evaporation surface of the vapor source, whose temperature was 0°C. In addition, the concentration of complex nuclei was increased by the addition of air at 22 mm Hg in the last experiment.

Results of the experiments. The main results of the experiments and the experimental conditions are shown in the table.

In all experiments, in addition to normal μ-e decays, events were observed in which there was a marked gap between the origin of the decay electron track and the end of the stopping μ meson track, having a size between the half-width of the μ-meson track (~ 0.25 mm) and 3.5 mm. An example of such an event obtained in Experiment 1, is shown in Fig. 1a. The gap length is 2 mm. Both the lengths of the gaps and the frequency of their appearance, given in row 6, depend on the concentration of the complex nuclei and especially strongly on their pressure. In the experiments using hydrogen with a small admixture of deuterium (technical hydrogen), these gaps were due to the diffusion of the pμ mesic atom up to the time of its decay or up to transfer of the μ meson to a complex nucleus. The μ meson transfer to complex nuclei was relatively fast, as shown by the following observed effects:

1) Stopped μ mesons unaccompanied by decay electrons, and stars with one or more heavy charged particles (row 5) due to the nuclear capture of μ mesons by complex nuclei.

2) The emission of Auger electrons. The origin of a decay electron track (in events with gaps) is often accompanied by a well-defined "dot," i.e., a cluster of drops 0.3—0.6 mm in diameter (Fig. 1b). The frequency of such dots depends on the concentration of complex nuclei (row 7) and can clearly be attributed to the short-range Auger electrons originating in the cascade transitions of the μ mesons from the excited states of the C and O mesic atoms after the capture of the μ mesons from the pμ mesic atoms.

An experiment was carried out under the same conditions as Experiment 3, but without the magnetic field, in order to explain the low energy of the Auger electrons. Altogether, 43 μ-e decay events were identified, in 10 of which the origin of the decay electron track was accompanied by a visible "dot." Only in three or four out of the 43 μ-e decays was it possible to exclude the existence of a second electron, whose range or multiple scattering would indicate that its energy was considerably greater than 10 keV (range in the chamber > 2 mm). This means that after the transfer of the μ mesons to a C or O nucleus the majority of emitted Auger electrons had an energy < 10 keV.

These effects made it possible to determine the probability of transfer of μ mesons to complex nuclei. The problem is quite a difficult one because of the small effect, and because of the difficulty in identifying transfer events. Several methods were therefore used to determine the transfer probability.

In the first experiment, the transfer probability was determined from the formula

$$\lambda'_Z cq = \frac{\lambda_0 n_{\mathrm{stop}} a}{n_{\mu e} - n_{\mathrm{stop}}}, \qquad (5)$$

where λ'_Z is the transfer probability of a μ meson from a proton to a complex nucleus in gaseous hydrogen; c is the concentration of complex nuclei (column 2 of the table); q = 1 for Experiments 1 and 2 and q = 5.02/22.7 = 0.22 for Experiments 3 and 4; $\lambda_0 = 0.452 \times 10^6\ \mathrm{sec}^{-1}$ is the decay probability of the μ meson; n_{stop} is the number of stopped μ mesons unaccompanied by electron tracks; $n_{\mu e}$ is the number of μ-e decays; $a = 2\lambda_0/(\lambda^{C}_{\mathrm{cap}} + \lambda^{O}_{\mathrm{cap}})$, where $\lambda^{C}_{\mathrm{cap}}$ and $\lambda^{O}_{\mathrm{cap}}$ are the probabilities of nuclear capture of the μ mesons by carbon and oxygen respectively, found experimentally by Sens.[14] In this method, it is assumed that the probability of μ-meson transfer is the same for C and O nuclei.

In the remaining three experiments, the value of $\lambda'_Z cq$ was determined by the following methods:

1. From the frequency of Auger electrons accompanying the decay electron track, and assuming that a visible dot is observed in each transfer

	Number of experiment			
	1	2	3	4
Hydrogen pressure, atm	22.7	22.7	5.02	5.02
Concentration of complex nuclei (C,O, or N) in hydrogen, %	0.2	0.07	0.7	1.3
Number of photographs	4000	8000	16000	7000
Number of stopping μ mesons*	718	550	202	98
Number of stars with visible prongs originating in the capture of μ mesons by complex nuclei**	21	6	5	5
Ratio of the number of events with visible gaps to total numbers of events, %	9	15	50	40
Ratio of the number of events with gaps accompanied by Auger electrons to the number of events without Auger electrons	>60%	10/26	21/10	13/4
$(\lambda'_Z cq) \times 10^{-6}$, sec^{-1}	$0.8^{+0.4}_{-0.2}$***	$0.21^{+0.11}_{-0.07}$	$0.7^{+0.4}_{-0.2}$	$1.1^{+1.0}_{-0.5}$
$(\lambda_0 + \lambda'_Z cq) \times 10^{-6}$ sec^{-1}	$1.3^{+0.4}_{-0.2}$	$0.66^{+0.11}_{-0.07}$	$1.2^{+0.4}_{-0.2}$	$1.6^{+1.0}_{-0.5}$
$\overline{r^2}$, mm^2	0.10 ± 0.014	0.22 ± 0.04	1.4 ± 0.3	1.1 ± 0.4
$\sigma_{pp} \times 10^{19}$, cm^2	$1.9^{+0.4}_{-0.6}$	$1.7^{+0.4}_{-0.5}$	$0.7^{+0.2}_{-0.3}$	$0.6^{+0.3}_{-0.4}$

*The numbers shown in this row are found after substracting the number of stopping π mesons and of false stoppings.

**The number of stars shown in this row includes the single-prong stars for Experiments 1 and 2 with $l' > 2$ mm, and with $l' > 7$ mm for Experiments 3 and 4. (l' is the length of the projection of the track on the horizontal plane.)

***In the determination of $\lambda_Z cq$ in this experiment, using a number of selection criteria, it was found that the ratio $n_{stop}/n_{\mu e} = 34/267$.

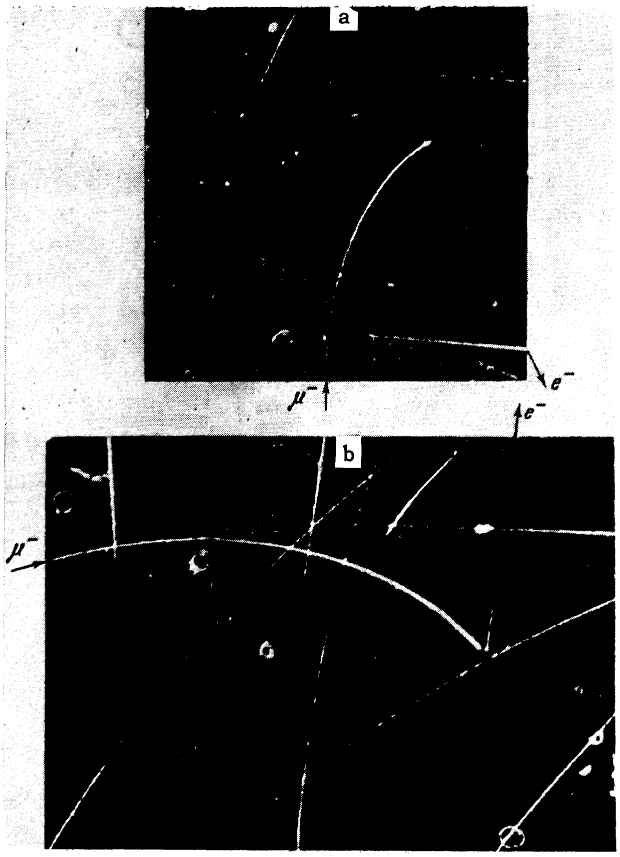

FIG. 1. Photographs of $\mu \to e$ decays in hydrogen (under the condition of Experiments 1 and 2). The gap between the beginning of the decay electron track and the end of the stopping μ meson track is due to the diffusion of the $p\mu$ mesic atom; a – at the beginning of the electron track there is no visible dot; b – a dot (an Auger electron) is visible at the beginning of the decay electron track.

of a μ meson to a complex nucleus. To find out whether this assumption is correct, an experiment was carried out in which 3% of C and O nuclei (CO_2) were added to hydrogen at 21 atm. In order to increase the gap size, 5% of deuterium was also added (see Sec. 4). In this experiment, about 95% of the μ mesons in the orbit of a $d\mu$ mesic atom were transferred before decaying to C and O nuclei. In 37 out of the 40 cases found with gap length greater than at least 1 mm, the decay electron track was accompanied by a visible dot. This fact indicates that, in not less than 90% of all cases, the transfer to a complex nucleus is accompanied by an Auger electron emission.

2. From the value of $\lambda'_Z cq$ of Experiment 1, and the ratio of the number of stars with visible prongs in Experiments 2, 3, and 4.

3. From the value of $\lambda'_Z cq$ of Experiment 1, and the ratio of concentration of complex nuclei in Experiments 2, 3, and 4.

It was found that the probabilities of transfer to complex nuclei obtained by the various methods are in satisfactory agreement. This confirms the correctness of the assumptions made and the estimates of the relative concentration of complex nuclei. The values of the transfer probabilities are shown in row 8 of the table where, for Experiments 2, 3, and 4, the values given are averaged over all methods of determination. The errors indicated take into account both statistical errors in the identification of events and the errors in the determination of the concentration of complex nuclei.

The gap length was measured directly on the film using a UIM-22 microscope with 50x magnification (the ratio of reduction in photography was 1:15). The projections l' of the distances from the beginning of the decay electron tracks to the end of the meson tracks on the horizontal plane were measured taking the half-width of the μ-meson track into account. Events in which the length of the electron track projection was less than 5 mm, in which the electron was not clearly visible, or in which the point where the μ meson stopped was obscured by a concentration of drops, the grid, background tracks, etc., were excluded. Cases in which the gap was due to a local insensitivity near the point at which the μ meson stopped were also excluded. In those cases, the μ meson track usually becomes thinner towards its end, and the electron "looks" towards the point at which the meson stopped.

The distributions of the projections were transformed into distributions of the real gap length, and corrections were introduced which took into account the number of events in which a gap was not observed because of finite track width. For Experiments 2 and 3, these distributions are shown in Fig. 2. Some background events were excluded from these distributions; their number was estimated by special measurements. Values of the mean squares of the gap lengths are shown in row 10 of the table. The indicated errors of these values take the inclusion of a small number of doubtful cases into account.

Determination of the elastic scattering cross section σ_{pp} of $p\mu$ mesic atoms on hydrogen. The values of $\lambda'_Z cq$ and $\overline{r^2}$ found in the experiment enabled us to determine the cross section σ_{pp}. In fact, if the $p\mu$ mesic atoms have thermal energies, then the mean square gap length is connected with the diffusion coefficient D of the $p\mu$ mesic atoms in hydrogen by the relation

$$\overline{r^2} = 6D\tau, \tag{6}$$

where $1/\tau = \lambda_0 + \lambda'_Z cq$. In turn,

$$D = \frac{3\pi}{32}\frac{\bar{v}}{N\overline{Q}_d}, \tag{7}$$

where $\bar{v}$ is the mean velocity of the relative motion of $p\mu$ and H_2, N is the number of protons per cm^3, and $\overline{Q}_d$ is the transfer cross section averaged over the Maxwellian distribution:

$$\overline{Q}_d = \left(\frac{m}{2\varkappa T}\right)^{-5}\int_0^\infty v^5 \exp\left(-\frac{mv^2}{2\varkappa T}\right) Q dv. \tag{8}$$

The quantity Q in Eq. (8) is

$$Q = 2\pi\int (1 - \cos\theta)\,\sigma(\theta)\,\sin\theta\, d\theta,$$

where $\sigma(\theta)d\theta$ is the differential cross section of the $p\mu$ mesic atoms in hydrogen, $m = M_1M_2/(M_1+M_2)$ is the reduced mass of the $p\mu$ and of the H_2 molecule, and T is the mean gas temperature.

Since the scattering of $p\mu$ mesic atoms in actual hydrogen occurs not on free protons but on H_2 molecules in actual hydrogen, we have to use the differential scattering cross sections of $p\mu$ mesic atoms on H_2 molecules instead of $\sigma(\theta)$. This quantity can easily be calculated if the scattering cross section of $p\mu$ mesic atoms on free protons is known. The calculations can be carried out by the pseudopotential method used in calculating the scattering of slow neutrons on molecules.

The calculation of $\overline{Q}_d$ for scattering of $p\mu$ mesic atoms in a state F = 0 on molecules of ortho- and parahydrogen lead, for $\bar{v} = 2.7 \times 10^5$ cm/sec and T = 242°K (conditions of our experiment), to the result

$$(\overline{Q}_d)_{\text{para}} \approx 0.6\sigma_{pp}, \qquad (\overline{Q}_d)_{\text{ortho}} \approx 2\sigma_{pp}, \tag{9}$$

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

$$\overline{Q}_d \approx 1.6\,\sigma_{pp}. \tag{10}$$

Using the relations (6), (7), and (10), we find the expression for the cross section

$$\sigma_{pp} = \frac{1.1\bar{v}}{\overline{r^2}N(\lambda_0 + \lambda'_Z cq)}. \tag{11}$$

The values of the cross section σ_{pp}, calculated according to this formula using the values of $\lambda'_Z cq$ and $\overline{r^2}$ given in row 8 and 10 of the table, are shown in the last row of the table.

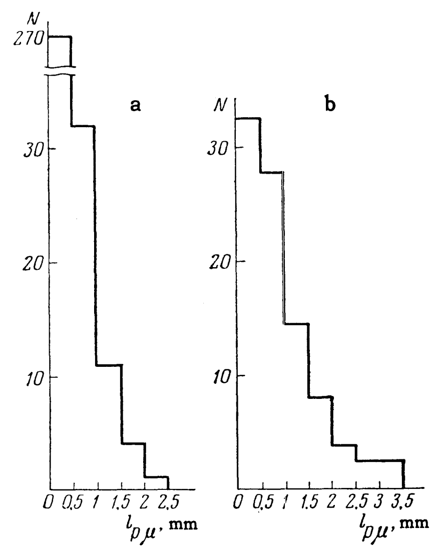

FIG. 2. Distribution of the number of $\mu \to e$ decay events in hydrogen with respect to gap length: a – hydrogen pressure of 22.7 atm (Experiment 2), b – hydrogen pressure of 5 atm (Experiment 3).

3. RESULTS OF THE MEASUREMENTS OF THE σ_{pp} CROSS SECTION AND OF THE TRANSFER OF μ MESONS TO COMPLEX NUCLEI

1. A comparison of the cross sections σ_{pp} calculated using the measured values of $\overline{r^2}$ and $\lambda'_Z cq$, shows that the effect of scattering of $p\mu$ mesic atoms on complex nuclei is small, since it does not reveal itself when the concentration of complex nuclei or the pressure of the hydrogen is varied. It can furthermore be said that the value of $\overline{r^2}$ varies more sharply with the hydrogen density than should follow from the diffusion equation (11) [e.g., in Experiment 3 we should expect from Eq. (11) an increase of $\overline{r^2}$ by a factor of five as compared with Experiment 1, and not by a factor of 13 as was found experimentally]. As a result, we obtain a difference in the calculated cross sections for high and low hydrogen densities. This difference clearly cannot be explained wholly by possibly overlooked experimental errors. If such a difference really exists, it might, for example, be due to the following reasons:

a) The $p\mu$ mesic atoms have initial energies of the order of 1 eV,* which is considerably greater than the thermal energy (0.02 eV), and the scattering cross section increases with increasing velocity. In that case, the use of the diffusion approximation for the scattering of $p\mu$ mesic atoms at a low hydrogen density (5 atm pressure) may turn out not to be quite correct, since the time before decay or transfer will be comparable to the slowing-down time until thermal velocity is reached. (For a mesic-atom energy of 1 eV, the required number of collisions $p\mu + p$ is ~ 6, while for $\sigma_{pp} \approx 1 \times 10^{-19}$ cm^2 and $v_{thermal} = 2 \times 10^5$ cm/sec, the number of collisions before decay or transfer occurs is five.)

b) $p\mu$ mesic atoms can occur in two states: $F = 0$ or $F = 1$, for which the cross sections of the elastic scattering differ by a factor of five to ten. In that case, we can satisfy the values of $\overline{r^2}$ obtained in the experiment by a suitable choice of statistical weights of the states. This qualitative explanation of the possible difference in the magnitude of the cross sections for two pressures can be tested only by increasing the accuracy of the measurements and of the analysis of the range distribution of the $p\mu$ mesic atoms.

To compare the experimental absolute cross sections σ_{pp} with the theoretical ones, we shall use the value of absolute cross section 1.7×10^{-19} cm^2, obtained in the experiments at a high hydrogen pressure and low concentration of complex nuclei (Experiment 2), since the use of the diffusion formula is, in that case, more justified (the number of $p\mu + p$ collisions is about 40), and the effects of complex nuclei are small. This value is in sufficiently good agreement with the value of 3×10^{-19} cm^2 obtained by Cohen et al.[6] However, the latter value is obtained without taking the hyperfine structure of the $p\mu$ mesic atom into account. If we use the scattering lengths $a_u = +5$ and $a_g = -11$ found by Cohen et al,[6] then the cross section in the state $F = 0$ calculated according to Eq. (4) is $\sigma_{pp}^{(0)} \approx 1 \times 10^{-20}$ cm^2 and differs from the experimental value by a factor of about 20. (For $a_u = +5$ and $a_g = -17$ mentioned in [2], we have $\sigma_{pp}^{(0)} < 10^{-20}$.) To make the theoretical scattering cross section in the state $F = 0$ of the $p\mu$ mesic atom agree with the experimental value for the given scattering length $a_u = +5$ (in whose calculation there is no great difference between [2] and [6]), it is necessary to set a_g equal either to $+3$ or -30. The value $a_g = +3$ requires the existence in the $pp\mu$ system of a bound state, and is therefore not very probable, although it gives a small value of the cross section with a transition to a lower state of the hyperfine structure. The value $a_g = -30$ cannot be theoretically excluded, but seems to be rather high.

Thus, the experimental value of σ_{pp} does not contradict the cross section calculated neglecting the hyperfine splitting. This does not exclude the possibility of fast transitions $F = 1 \rightarrow F = 0$. More definite conclusions will probably be reached after a recalculation of possible values of the scattering lengths a_u and a_g will have been made, and when the accuracy in the observed range distributions of the $p\mu$ mesic atoms will have been increased.

2. The mechanism of the μ meson transfer from the hydrogen to the complex nuclei was considered by one of the authors (S.G.). It was found that the high probability of transfer to the C and O nuclei is due to the crossing of mesic molecular terms in the $p\mu Z$ system (if the nuclear charge $Z \geq 3$). This mechanism also explains the experimentally observed small value of the cross section for the transfer of the μ mesons to the He nuclei,[16,17] since the cross terms mentioned above do not exist in the $p\mu$He system. A detailed consideration shows that the μ meson is transferred from the protons to the oxygen mainly at the mesic atom levels with principal quantum numbers $n = 4$ for carbon and $n = 5$ for oxygen. The consecutive

*If the transition of the μ mesons from a high orbit to the K orbit of the mesic atom occurs as a result of collisions with H_2 molecules, as was mentioned by Weightman,[15] then a part of the molecular binding energy H_2 ($\sim$1 eV) will be transferred to to the $p\mu$ mesic atom.

cascade transitions of the mesic atoms to the ground state with probability close to 100% should therefore be accompanied by the emission of one or several Auger electrons with energies of several keV. The frequency of the dots visible near the beginning of the electron track, and also their size, are consistent with the assumed transfer mechanism.

The calculation also shows that the transfer cross sections of μ mesons to C and O nuclei are roughly the same ($\sigma v = 1.3 \times 10^{-12}$ cm^3/sec for carbon and $\sigma v = 2 \times 10^{-12}$ cm^3 for oxygen), and that the transfer probability of μ mesons to the C and O nuclei (for the density of liquid hydrogen) is $\lambda_Z = 5 \times 10^{10}$ sec^{-1}. The experimentally obtained value of λ_Z for the liquid hydrogen, calculated from the value of $\lambda'_Z cq$ found in Experiment 1 from the relation

$$\lambda_Z = \lambda'_Z cq \,(N_{\text{liquid}} / N_{\text{gas}})\, c^{-1}, \tag{12}$$

is $\lambda_Z = (1.2^{+0.8}_{-0.5}) \times 10^{10}$ sec^{-1}. The values N_{liquid} and N_{gas} in (12) denote the number of protons per cm^3 for liquid and gaseous hydrogen respectively; $c_1 = 0.002^{+0.0013}_{-0.0005}$ is the concentration of C and O nuclei in Experiment 1. If we take the approximate character of the calculation and the errors of the experimental data into consideration, we can regard this value of λ_Z to be in reasonable agreement with the theory. Results of recent experiments on the transfer of μ mesons to Ne nuclei [17] allow us to draw the more general conclusion that the probability of μ-meson transfer from hydrogen to light nuclei varies little from nucleus to nucleus. In fact, Shiff [17] found that the ratio $\lambda_{\text{Ne}}/(\lambda_0 + \lambda_{pp\mu}) = (9.5 \pm 3) \times 10^3$. Hence, using the value $\lambda_{pp\mu}$ found by us (see Sec. 4), we obtain $\lambda_{\text{Ne}} = (1.0^{+1.4}_{-0.6}) \times 10^{10}$ sec^{-1}.

4. DETERMINATION OF THE PROBABILITY OF μ MESON TRANSFER FROM A PROTON TO A DEUTERON AND OF THE PRODUCTION OF $pp\mu$ MESIC MOLECULES

The $d\mu$ mesic atom produced upon transfer of a μ meson from a hydrogen mesic atom to a deuteron in the reaction

$$p\mu + d \rightarrow d\mu + p \tag{13}$$

gains an energy of 45 eV, because of the difference in the $p\mu$ and $d\mu$ reduced masses. As is well known, Alvarez et al [8] found that a $d\mu$ mesic atom with such energy has a range of ~ 1 mm in liquid hydrogen.

This has led to the hope that, at a hydrogen gas pressure of ~ 20 atm in the diffusion chamber, the range of the $d\mu$ mesic atoms will be considerably larger so that it would be relatively easy to determine the probability of the transition (13).

The experiment with deuterium was similar to Experiment 1 (see Sec. 2). The concentration of deuterium in hydrogen was chosen in special preliminary experiments and amounted to 0.44%. Measures were taken to exclude a large background of particles crossing the chamber, which would make it difficult to identify the events involving a transfer to deuterium. The gaseous deuterium used in the experiments was carefully rid of tritium, the remaining tritium admixture being less than 5×10^{-14} atomic parts.

About 800 events were found in 10 000 pictures, about half of which were the usual $\mu \rightarrow e$ decays, while the rest had gaps amounting to 10 to 15 mm between the end of the track of the stopped μ mesons and the electron track. Two examples of such events with gaps of 7 and 11 mm are shown in Fig. 3.

The distribution of 341 events with respect to the gap length projections on a horizontal plane for $l' > 1$ mm is shown in Fig. 4 (corrected for the background of events with gaps due to the diffusion of the $p\mu$ mesic atoms). In the same figure, the smooth curves show the calculated distribution of the gap-length projections. This was obtained from the distribution of the real gap lengths, which is given by the equation

$$\frac{dn}{dl} = A \exp\left\{bl - \frac{\lambda}{v_0 b} e^{bl}\right\}, \tag{14}$$

where $b = N\sigma\eta/2$, N is the number of protons per cm^3, σ is the cross section of elastic scattering of $d\mu$ mesic atoms on protons, deuterons, and complex nuclei, taken as 7×10^{-21} cm^2 [2]; $\eta = 0.45$ is the energy fraction of the $d\mu$ mesic atoms lost in one collision, $v_0 = 6.6 \times 10^6$ cm/sec is the initial velocity of the $d\mu$ mesic atoms, and λ is the sum of the probabilities of μ-meson transfer from the deuteron to the complex C and O nuclei. The probability of free decay of the μ meson was taken as $\lambda = 1.5 \times 10^6$ sec^{-1}. In calculating the distribution (14), it was assumed that the $d\mu$ mesic atoms lose energy only in collisions with protons, and since, for such scattering, the possible l.s. deflection from the original direction is less than 30°, it was assumed that the atoms move in a straight line. Also taken into account was the fact that the path traversed by the $d\mu$ mesic atoms is determined not only by the slowing down, but also by the time before the decay or transfer of the μ meson to a complex nucleus.

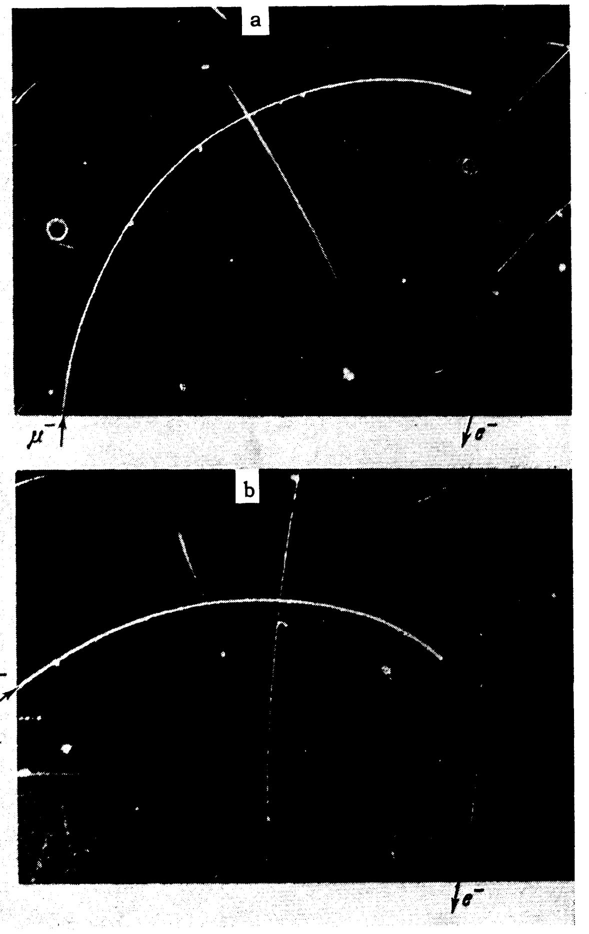

FIG. 3. Photographs of $\mu \to e$ decays in hydrogen with an admixture of deuterium. The gap between the beginning of the decay electron track and the end of the track of the stopping μ meson is due to the process $p\mu + d \to d\mu + p$ and to the range of the $d\mu$ mesic atom. a – no dot is visible at the beginning of the electron track, b – a dot (an Auger electron) is visible at the beginning of the decay electron track.

A qualitative agreement between the calculated and measured distribution can be seen in Fig. 4. In the determination of the probability of the μ meson transfer from the proton to the deuteron, the following most essential corrections were introduced into the total number of such events for the inefficiency of observation of cases with gaps (+17%), for background of false events (−8%), and for the contribution from the range with $l' < 1$ mm (+4%). As a result, it was found that the ratio of the number of μ mesons transferred to deuterium to the number of mesons not transferred equals 1.12 ± 0.18. Hence, the probability of the $p\mu + d \to d\mu + p$ transition amounts to $(1.45^{+0.51}_{-0.32}) \times 10^6\ \mathrm{sec}^{-1}$. Dividing this value by the concentration of deuterium and multiplying by the ratio of densities of the liquid and gaseous hydrogen, we obtained the following value for the transition probability of the μ meson from the proton to the

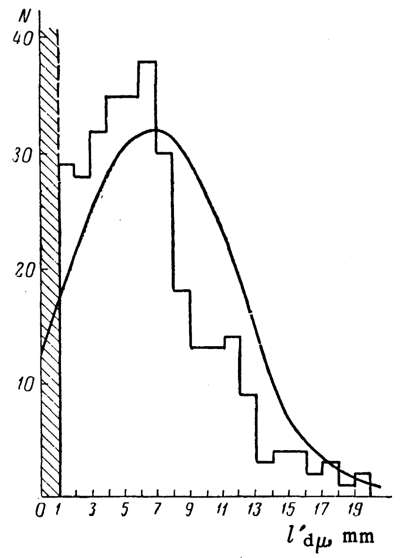

FIG. 4. Distribution of the projected gap lengths for $d\mu$ mesic atoms produced in the process $p\mu + d \to d\mu + p$ (hydrogen pressure of 22.7 atm, $c_{D_2} = 0.44\%$). The smooth curve represents the calculated distribution.

deuteron in liquid hydrogen:

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

The experimentally obtained value of λ_d is in good agreement with the value $1.14 \times 10^{10}\ \mathrm{sec}^{-1}$ calculated using the improved adiabatic approximation by Belyaev et al [18] and also by Cohen et al. [6]

The knowledge of the absolute value of λ_d, which plays an important role (e.g., in catalysis phenomena), is also especially valuable because it opens the way for the determination of another quantity important for mesic molecular physics, i.e., the probability of production of $pp\mu$ mesic molecules in liquid hydrogen. In fact, in a number of experiments, [8,17] the yield of reaction $d\mu + p \to He^3 + \mu$ as a function of the concentration of deuterium was determined, and the ratio of $\lambda_d/(\lambda_0 + \lambda_{pp\mu})$ was found. The most reliable data for this ratio were recently obtained by Shiff. [17] It was found that

$$\lambda_d / (\lambda_0 + \lambda_{pp\mu}) = (8.9^{+6.2}_{-3.6}) \cdot 10^3.$$

Substituting here the value of λ_d found by us, we obtain the absolute probability of production of mesic molecules of $pp\mu$ in liquid hydrogen

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

This value agrees within the limits of experimental error with the value* $1.3 \times 10^6\ \mathrm{sec}^{-1}$ calculated by Zel'dovich and one of the authors, [5] and is

*In[5] the value $\lambda_{pp\mu} = 1.5 \times 10^6\ \mathrm{sec}^{-1}$ was obtained for $N = 4.2 \times 10^{22}$ hydrogen nuclei per cm^3; the value of $\lambda_{pp\mu} = 1.3 \times 10^{-6}\ \mathrm{sec}^{-1}$ refers to $N = 3.5 \times 10^{22}$, which corresponds to the operating conditions of the liquid hydrogen chamber.

considerably less than the values 6.5×10^6 sec^{-1} and 9×10^6 sec^{-1} calculated by Cohen et al [6] and Wu et al. [7]

Furthermore, from the results of Shiff, [17] assuming for $\lambda_{pp\mu}$ the upper limit of the experimental value, we can estimate the upper limit of the absolute value of the probability of $pd\mu$ mesic molecule production in liquid hydrogen. If we assume that the probability of the μ meson transfer from protons and deuterons to neon are the same, then we obtain $\lambda_{pd\mu} \leq 0.6 \times 10^6$ sec^{-1}. It should be mentioned that this value does not contradict the estimate $\lambda_{pd\mu} > 0.2 \times 10^6$ sec^{-1} following from the experiment of Ashmore et al, [9] but is greatly different from the estimate $\lambda_{pd\mu} > 10^7$ sec^{-1} obtained in the study of the catalysis of nuclear reactions in a liquid hydrogen chamber. [10]

5. CONCLUSIONS

In the present experiment, several quantitative characteristics of a number of mesic atom processes in hydrogen have been determined. Although the measured value of the cross section for the scattering of $p\mu$ mesic atoms on protons σ_{pp} is close to the expected theoretical value calculated neglecting the hyperfine structure, the problem concerning the probability of transitions $F = 1 \rightarrow F = 0$ remains open. It might be possible to draw more definite conclusions in this respect from a further study of the range distribution of the $p\mu$ mesic atoms and from a more exact calculation of the scattering lengths a_g and a_u. The values of λ_d, $\lambda_{pp\mu}$, and λ_Z obtained are in sufficiently good agreement with the calculated values, and confirm the assumed mechanism of the processes. However, in order to increase the accuracy of the measurements of these quantities, and especially of the probability of the production of $pp\mu$ mesic molecules (which is important in connection with the problem of μ^- meson capture by protons) the experiments are being continued.

The above-mentioned discrepancy in the estimate of the value $\lambda_{pd\mu}$ obtained from experiments carried out with hydrogen with a small admixture of deuterium, and with liquid deuterium with a small admixture of hydrogen [10] could indicate the possibility of a new catalysis mechanism, and therefore the experiments giving a direct determination of $\lambda_{pd\mu}$ are at this time especially interesting.

The authors express their gratitude to Ya. B. Zel'dovich for valuable discussion, to the synchrocyclotron crew and especially to T. N. Tomilina and E. I. Rozanova for ensuring good operation of the accelerator, to E. M. Kuchinskii, A. V. Brzhestovskaya, N. P. Vasilistov, and E. A. Kurchevskaya for removing the tritium from the deuterium, and to L. Krasnoslobodtseva, T. Sazhneva, and Yu. Saĭkina for help in scanning the photographs and in the measurements.

[1] Ya. B. Zel'dovich and S. S. Gershteĭn, JETP **35**, 821 (1958), Soviet Phys. JETP **8**, 570 (1959).

[2] Ya. B. Zel'dovich and S. S. Gershteĭn, UFN **71**, 581 (1960), Soviet Phys. Uspekhi **3**, 593 (1961).

[3] H. Primakoff, Revs. Modern Phys. **31**, 802 (1959); S. Weinberg, Phys. Rev. Letters **4**, 575 (1960); L. Wolfenstein and V. L. Telegdi, Proceedings of the 1960 Annual International Conference on High Energy Physics at Rochester, Publ. by the University of Rochester, 1961, p. 529, 713.

[4] S. S. Gershteĭn, JETP **34**, 463 (1958), Soviet Phys. JETP **7**, 318 (1958).

[5] Ya. B. Zel'dovich and S. S. Gershteĭn, JETP **35**, 649 (1958), Soviet Phys. JETP **8**, 451 (1959).

[6] Cohen, Yudd, and Riddel, Phys. Rev. **119**, 397 (1960).

[7] Wu, Rosenberg, and Sandstrom, Nucl. Phys. **16**, 432 (1960).

[8] Alvarez, Bradner, Crawford et al, Phys. Rev. **105**, 1127 (1957); Cresti, Gottstein, Rosenfeld, and Ticho, Report UCRL 3782, 1958, p. 8.

[9] Ashmore, Nordhagen, Strauch, and Townes, Proc. Phys. Soc. (London) **71**, 161 (1958).

[10] Fetkovich, Fields, Yodth, and Derrick, Phys. Rev. Letters **4**, 570 (1960).

[11] Ignatenko, Egorov, Khalupa, and Chultém, JETP **35**, 894 (1958), Soviet Phys. JETP **8**, 621 (1959).

[12] S. S. Gershteĭn, JETP **36**, 1309 (1959), Soviet Phys. JETP **9**, 927 (1959).

[13] Budagov, Viktor, Dzhelepov, Ermolov, and Moskalev, Proceedings of the Conference on Cloud, Diffusion, and Bubble Chambers, Dubna, 1958; JETP **38**, 734 (1960), Soviet Phys. JETP **11**, 531 (1960).

[14] J. C. Sens, Phys. Rev. **113**, 679 (1959).

[15] A. F. Weightman, Thesis, Princeton, 1949; Phys. Rev. **77**, 521 (1950).

[16] Zaĭmidoroga, Kulyukin, Pontecorvo, Sulyaev, Filippov, Tsupko-Sitnikov, and Shcherbakov, Preprint, Joint Inst. Nuc. Res. D-678, 1961.

[17] M. Shiff, Preprint EFINS—61—33, Report 351, June, 1961.

[18] Belyaev, Gershteĭn, Zakhar'ev, and Lomnev, JETP **37**, 1652 (1959), Soviet Phys. JETP **10**, 1171 (1960).

Translated by H. Kasha
70