FORMATION OF HELIUM MESIC ATOMS IN A HYDROGEN-HELIUM GAS MIXTURE

O. A. ZAĬMIDOROGA, M. M. KULYUKIN, R. M. SULYAEV, A. I. FILIPPOV, V. M. TSUPKO-SITNIKOV, and Yu. A. SHCHERBAKOV

Joint Institute for Nuclear Research

Submitted to JETP editor January 23, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **44**, 1852-1858 (June, 1963).

The formation of helium mesic atoms in a mixture of helium and hydrogen was studied in a diffusion cloud chamber at 19 atmospheres pressure. It was shown that the probability of the capture of muons by helium from a hydrogen mesic atom in the ground state is at least three orders of magnitude smaller than the probability of capture by carbon or oxygen nuclei and cannot appreciably exceed 10^6/sec, in agreement with theoretical estimates.[9] Agreement with the Fermi-Teller "Z-law" was indicated for direct attachment of mesons to nuclei of the gas mixture.

NEGATIVE mesons, which are stopped relatively rapidly by matter (after $\sim 10^{-12}$ sec[1]) join nuclei to form bound mesic-atom systems. The mesons subsequently decay or are captured by other nuclei; the relative probabilities of these competing processes depend on the meson lifetime, the intensity of meson interactions with nuclei, and the transition rate to the ground state of mesic atoms. The probabilities of the direct attachment of mesons to different nuclei comprising the stopping matter have been calculated theoretically[2] to be proportional to Z; this is the Fermi-Teller law. There has been no general experimental confirmation of this law; some solids are notable exceptions, the probability of direct capture being in several instances proportional simply to the nuclear concentration.[3]

In the presence of hydrogen isotopes another secondary mechanism of mesic-atom formation comes into play, because electrically neutral mesic hydrogen can easily transfer mesons to other atoms. This effect has been observed clearly both with muons in the mixtures H_2-D_2,[4] and H_2–CH_3OH,[5] and with pions in LiH,[6] C_2H_4[7] etc. The probability of mesic atom formation through muon transfer is very appreciable, amounting to $\sim 10^{10}$/sec[5] for example, for C and O nuclei at the density of liquid hydrogen. Unlike μ-mesic atoms of hydrogen, whose lifetime depends on the muon lifetime, π-mesic atoms of hydrogen disappear rapidly because of the strong pion-proton interaction. Therefore pions can be transferred only from high orbits ($n \gtrsim 4$); the probability of such transfer in gases should be considerably lower than the probability of muon transfer.

Because of the great interest in the $\mu^- + He^3 \rightarrow H^3 + \nu$ reaction and the attractive prospect that relatively small quantities of He^3 can be used for this purpose, we performed an experiment to clarify the roles of the two mechanisms of helium mesic atom formation in a H–He mixture. During the course of the experiment in 1960 S. S. Gershteĭn pointed out the possible smallness of the cross section for the transfer of muons to helium nuclei.

EXPERIMENT

We used a diffusion cloud chamber 300 mm in diameter, and a magnetic field of 6000 Oe; the chamber was filled with a mixture of natural hydrogen and helium at 19 atm; methyl alcohol was used as the working liquid.

It follows from the experimental results[5-8] that in a diffusion cloud chamber filled with hydrogen at 20 atm about 10% of all stopping μ^- mesons do not emit decay electrons; in these cases we have stars or unpronged stoppings (muon stars) which attest to the nuclear capture of the stopping meson. At a low concentration of methyl alcohol ($\sim 0.1\%$) the given number of muon stars can probably result only from the effective realization of a secondary mechanism by which mesic atoms of carbon and oxygen are formed. The rate of muon transfer to O and C nuclei is found to be $\sim 10^9$/sec.[5] When helium is added to the hydrogen a new channel must be opened, competing with the transfer of muons to O and C. In this case the relative number of muon stars will depend on the probability λ_{He} of muon transfer to helium and on the helium concentration ϵ_{He}.

K_Z will denote the formation probability of mesic atoms μZ (μHe, μO, μC) when muons are transferred from hydrogen mesic atoms. We then have[1)]

$$K_Z = \lambda_Z \varepsilon_Z \Big/ \left[\lambda_e + \sum \lambda_Z \varepsilon_Z\right], \tag{1}$$

where λ_Z is the probability of muon transfer from a hydrogen mesic atom to a nucleus of charge Z, and λ_e is the probability of muon decay. The relative probability X of muon star formation in the given mixture will be

$$X = P_{\mathrm{He}}\gamma_{\mathrm{He}} + P_{\mathrm{C}}\gamma_{\mathrm{C}} + P_{\mathrm{O}}\gamma_{\mathrm{O}} + P_{\mathrm{H}}\left(1 - \sum K_Z\right)\gamma_{\mathrm{H}} + P_{\mathrm{H}} K_{\mathrm{He}}\gamma_{\mathrm{He}} + P_{\mathrm{H}}(K_{\mathrm{C}}\gamma_{\mathrm{C}} + K_{\mathrm{O}}\gamma_{\mathrm{O}}), \tag{2}$$

where $\gamma_Z = \Lambda_Z/(\lambda_e + \Lambda_Z)$ is the relative probability of μ^- capture, P_Z is the probability of direct attachment, and Λ_Z is the rate of μ^- capture. The subscript Z denotes the nucleus. The first five terms in (2) can be neglected because γ_{H}, γ_{He}, ϵ_{O} and ϵ_{C} are small. Substituting K_Z from (1), we obtain

$$X = P_{\mathrm{H}} \frac{(\lambda_{\mathrm{C}}\gamma_{\mathrm{C}} + \lambda_{\mathrm{O}}\gamma_{\mathrm{O}})\varepsilon}{\lambda_e + (\lambda_{\mathrm{C}} + \lambda_{\mathrm{O}})\varepsilon + \lambda_{\mathrm{He}}\varepsilon_{\mathrm{He}}}. \tag{3}$$

Besides the desired quantity λ_{He} the quantities λ_{O}, λ_{C}, and $\epsilon = \epsilon_{\mathrm{O}} = \epsilon_{\mathrm{C}}$ in (3) are not well known. A theoretical calculation indicates that λ_{C} is of the order of λ_{O}.[9] By using data from two experiments with different helium concentrations ϵ'_{He} and ϵ''_{He} we can then obtain from (3) and from the analogous expression for the other helium concentration the equation

$$\lambda_{\mathrm{He}} = \lambda_e(\gamma_{\mathrm{O}} + \gamma_{\mathrm{C}})\left[\frac{X''}{P''_{\mathrm{H}}} - \frac{X'}{P'_{\mathrm{H}}}\right] \times \left\{(\gamma_{\mathrm{O}} + \gamma_{\mathrm{C}})\left[\frac{X'}{P'_{\mathrm{H}}}\varepsilon'_{\mathrm{He}} - \frac{X''}{P''_{\mathrm{H}}}\varepsilon''_{\mathrm{He}}\right] + 2\frac{X'}{P'_{\mathrm{H}}}\frac{X''}{P''_{\mathrm{H}}}(\varepsilon''_{\mathrm{He}} - \varepsilon'_{\mathrm{He}})\right\}^{-1}, \tag{4}$$

where X', P'_{H} and X'', P''_{H} are the values of X and P_{H} corresponding to the two helium concentrations ϵ'_{He} and ϵ''_{He}. The product of the unknown quantities λ_{O}, λ_{C}, and ϵ is excluded. We do not know the probabilities P'_{H} and P''_{H} from a rigorous point of view. However, if we neglect the contribution to λ_{He} from capture originating in high orbits, P'_{H} and P''_{H} can be determined by observing pion stars when π^- mesons are stopped in the same mixtures. Thus, by measuring the number of muon and pion stars in two helium concentrations, we can determine the transfer probability λ_{He}.

The diffusion chamber was exposed to a beam of negative mesons having the initial momentum 170 MeV/c from the synchrocyclotron of the Joint Institute for Nuclear Research. The mesons were slowed down by a copper filter (absorber) placed in front of the chamber. In two runs the nuclear concentrations of helium were $\epsilon'_{\mathrm{He}} = 4.9\%$ and $\epsilon''_{\mathrm{He}} = 14.3\%$. The isotope was He^4 in the first case and He^3 in the second case. In each run the chamber was exposed along with two different thicknesses of the filter, thus ensuring a maximum number of muon stoppings in the chamber (experiments I and II) or of pion stoppings (experiments III and IV).

EXPERIMENTAL RESULTS

A. Results of experiments I and II. We have determined the relative probabilities X' and X'' of muon capture by nuclei. All the experimental data and the identifications of events in the scanned photographs are included in the following table:

	Experiment I	Experiment II
ϵ_{He}	0.049	0.143
No. of photographs	6950	30600
Total number of meson stoppings	1075	5045
No. of stoppings in groups		
μ–e decays	639	3521
stars	24	82
unpronged stoppings	104	194
unpronged stoppings or μ–e decays	254	1248

Muon captures by nuclei are not always accompanied by the emission of charged particles visible in the chamber. Therefore the identification of muon stars requires that unpronged stoppings be analyzed along with the visible stars. This analysis involved first, the discrimination of muon and pion stoppings by their masses, and secondly, the sifting out of μ-e decay events which resembled unpronged stoppings when the observation conditions did not permit us to exclude the possibility of electron emission. These simulated unpronged stoppings were concentrated mainly near the boundary of the sensitive layer of the chamber. To reduce the background of simulated unpronged stoppings and to permit mass measurements we used the following selection criteria:

1) The meson stopping point must lie within the sensitive layer in a zone of 100-mm radius, 30 mm high, and 20 mm from the bottom of the chamber, with additional further limitation in the region where the beam enters the chamber.

1)In (1) and elsewhere we shall not consider the formation of deuterium mesic atoms or hydrogen mesic molecules, which are unimportant under our conditions.

2) The visible track length of the stopping particle must be not less than 50 mm.

Moreover, only about one-half of the data from experiment II were considered.

Masses were measured according to momenta and residual ranges in the reprojections. Track radii of curvature were determined using a template of variable curvature; a suitable curve for this purpose was found to be an involute with parameter a = 42.5 mm. The mass measurements are given in Fig. 1, where the smooth lines are

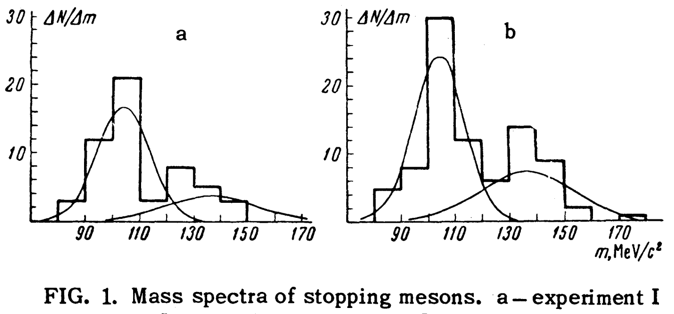

FIG. 1. Mass spectra of stopping mesons. a – experiment I [$\epsilon(He^4)$ = 4.9%], b – II [$\epsilon(He^3)$ = 14.3%]. The smooth lines are resolving power curves.

the resolving power curves obtained from independent mass measurements of reliable muons and pions. The resolving power curves enabled us to distinguish pion and muon stoppings according to the measured masses:

	Experiment I	Experiment II
No. of muon stoppings		
μ–e decays	319	512
stars	6	6
unpronged stoppings	27	45
unpronged stoppings or μ–e decays	8	6
No. of pion stoppings		
stars	2	10
unpronged stoppings	12	20

The small fraction of events called "unpronged stoppings or μ-e decays" included among muon stoppings resulted from the existence of dead spots near the stopping points. In order to divide these events into true unpronged stoppings and μ-e decays we determined the solid angle within which an emitted electron would not be visible, and then took into account the relative probability of μ-e decays in the given experiment.

The experimental relative probabilities of muon star formation were

$$X' = 0.110 \pm 0.018, \qquad X'' = 0.098 \pm 0.013.$$

B. Results of experiments III and IV. In these experiments we measured the relative probabilities P'_H and P''_H of the formation of π-mesic hydrogen atoms according to the ratio between the registered unpronged stoppings and one-prong stars. This was based on the fact that pion capture by helium is always accompanied by the emission of a visible charged particle. As previously, in order to reduce the background of simulated unpronged stoppings all registered events were subjected to selection criterion 1. The results were:

	Experiment III	Experiment IV
ϵ_{He}	0.049	0.143
Total No. of registered stoppings	101	432
Stoppings satisfying selection criterion:		
μ–e decays	15	52
stars	5	29
unpronged stoppings	32	71
unpronged stoppings or μ–e decays	4	11

In the calculation of P_H these results were combined with data on pion stoppings in experiments I and II, with a correction for unpronged muon stoppings. The results were

$$P'_H = 0.87 \pm 0.05, \qquad P''_H = 0.71 \pm 0.04.$$

The production probabilities of π-mesic atoms of helium are correspondingly

$$P'_{He} = 0.13 \pm 0.05, \qquad P''_{He} = 0.29 \pm 0.04.$$

C. Yield of the reaction $\mu^- + He^3 \rightarrow H^3 + \nu$. In experiment II, when the chamber was filled with a mixture of hydrogen and the light helium isotope He^3, it was possible to calculate directly the total probability $P''_{He} + P''_H K''_{He}$ of the formation of μ-mesic atoms of helium from the yield of the reaction $\mu^- + He^3 \rightarrow H^3 + \nu$ and from the rate of this reaction as predicted by the universal weak interaction theory.[10] The events in which muons are captured by He^3 from H^3 in its final state can be identified from the completely determined tritium range. The measured spectrum of secondary-particle ranges is shown in Fig. 2; about 4 events out of 5×10^3 muon stoppings are attributable to the given reaction, and $P''_{He} + P''_H K''_{He} = 0.28 \pm 0.14$.

FIG. 2. Measured spectrum of secondary particle ranges in experiment II [$\epsilon(He^3)$ = 14.3%]. The arrow indicates the predicted tritium range in the reaction $\mu^- + He^3 \rightarrow He^3 + \nu$.

DISCUSSION OF RESULTS

Let us first consider the experimental ratios $X'/P'_H = 0.13 \pm 0.02$ and $X''/P''_H = 0.14 \pm 0.02$. We recall that the ratio X/P_H represents approximately the relative probability of muon capture by C and O nuclei, reduced to an identical number of hydrogen mesic atoms in the ground state. The fact that the experimental values of X/P_H for two helium concentrations are practically identical shows the unimportance of the mechanism whereby helium mesic atoms are formed through the transfer of muons from states of hydrogen mesic atoms. This conclusion is consistent with direct data on the formation probability of helium μ-mesic atoms if we compare the experimental values $P''_{He} = 0.29 \pm 0.04$ and $P''_{He} + P''_H K''_{He} = 0.28 \pm 0.14$. The absolute rate of muon transfer to helium from the ground state of mesic hydrogen is obtained by substituting the values obtained for X'/P'_H and X''/P''_H in (4):

$$\lambda_{He} = -(1.4 \pm 3.8)\cdot 10^6 \text{ sec}^{-1},$$

so that the transfer rate to helium at 19 atm cannot appreciably exceed 10^6/sec.

It is useful to compare the last result with the rate of muon transfer to carbon and oxygen. Letting $\lambda_O = \lambda_C$ and $\lambda_{He} = 0$ and taking the oxygen and carbon concentrations $\epsilon_O = \epsilon_C = 0.0006 \pm 0.0002$, from our experimental data and (3) we obtain

$$\lambda_C = \lambda_O = (0.9 \pm 0.4)\cdot 10^9 \text{ sec}^{-1}$$

or

$$\lambda_C = \lambda_O = (2.6 \pm 1.2)\cdot 10^{10} \text{ sec}^{-1}$$

converted to the density of liquid hydrogen ($N = 3.5 \times 10^{22}/\text{cm}^3$). The transfer rate is seen to differ by at least three orders of magnitude. Schiff[11] has also found evidence that the transfer of muons to helium in liquid hydrogen is much smaller than to other nuclei.

S. S. Gershteĭn predicted this seemingly unexpected result. The low rate of muon transfer to helium is accounted for by the fact that the helium mesic atom is evidently a unique mesic atom in that the lowest molecular terms of μHe and μH do not intersect. The transfer can therefore only be a tunnel transition and must be strongly inhibited. Theoretical estimates of the muon transfer rate to helium ($\lambda_{He} \sim 10^5$/sec) for liquid-hydrogen density[9] agree with our results.

We note also that the experimental relative probabilities of the formation of hydrogen and helium π-mesic atoms are in better agreement, as can be seen from the table, with the law of proportionality to Z. This can be interpreted as indicating the correctness of the Z-law for the direct capture of mesons and the unimportant role of meson transfer to helium from high orbits. Another possible explanation would be that the probability of direct capture is independent of Z and that the observed deviation is due to transfer. We consider the first explanation more realistic since the experimental results concerning the formation of mesic atoms in a gaseous mixture without hydrogen (a mixture of helium and methyl alcohol vapor) which we obtained in investigating π^- capture in He[12] also favor the Z-law. The experimental formation probability of carbon and oxygen mesic atoms is 0.011 ± 0.002; the Z-law predicts 0.009 ± 0.003.

Formation probabilities of helium mesic atoms

ε_{He}	P_{He}	Predicted value	
		$P_{He} \sim \varepsilon_{He} Z$	$P_{He} \sim \varepsilon_{He}$
0.049	0.13±0.05	0.10	0.05
0.143	0.29±0.04	0.26	0.14

The authors are deeply indebted to S. S. Gershteĭn, P. F. Ermolov, and B. Pontecorvo for numerous valuable discussions, and to A. I. Tokarskaya and E. A. Shvaneva for assistance with the measurements.

1 A. S. Wightman, Phys. Rev. **77**, 521 (1950).

2 E. Fermi and E. Teller, Phys. Rev. **72**, 399 (1947).

3 Sens, Swanson, Telegdi, and Yovanovitch, Nuovo cimento **7**, 536 (1958).

4 Alvarez, Bradner, Crawford, Crawford, Falk-Vairant, Good, Gow, Rosenfeld, Solmitz, Stevenson, Ticho, and Tripp, Phys. Rev. **105**, 1127 (1957).

5 Dzhelepov, Ermolov, Kushnirenko, Moskalev, and Gershteĭn, JETP **42**, 439 (1962), Soviet Phys. JETP **15**, 306 (1962).

6 Panofsky, Aamodt, and Hadley, Phys. Rev. **81**, 565 (1951).

7 P. Ammiraju and L. M. Lederman, Nuovo cimento **4**, 283 (1956).

8 Sargent, Cornelius, Rinehart, Lederman, and Rogers, Phys. Rev. **98**, 1349 (1955).

9 S. S. Gershteĭn, JETP **43**, 706 (1962), Soviet Phys. JETP **16**, 501 (1963).

[10] L. Wolfenstein, Proc. of the Tenth Annual Rochester Conf. on High Energy Physics (1960), Interscience, New York, 1961, p. 529; Bull. Am. Phys. Soc. **6**, 33 (1961).

[11] M. Schiff, Nuovo cimento **22**, 66 (1961) and **23**, 661 (1962).

[12] Falomkin, Filippov, Kulyukin, Pontecorvo, Scherbakov, Sulyaev, Tsupko-Sitnikov, and Zaĭmidoroga, Proc. of the 1962 Annual International Conf. on High Energy Physics at CERN, Geneva, 1962, p. 14.

Translated by I. Emin
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