OBSERVATION OF THE REACTION $\mu^- + He^3 \rightarrow H^3 + \nu$

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Submitted to JETP editor July 25, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1804-1808 (December, 1961)

A diffusion chamber filled with He^3 was used to observe the $\mu^- + He^3 \rightarrow H^3 + \nu$ reaction. The upper limit of the mass of the neutral particle emitted in muon capture by nucleons ($m_\nu < 6$ Mev) was determined by measuring the recoil energy of H^3. According to preliminary data, the probability of this reaction is $(1.30 \pm 0.40) \times 10^3\ sec^{-1}$ and agrees with the theoretical value predicted by the universal theory of weak interactions.

ONE of the most studied among the weak interactions of nonstrange particles is the capture of a muon by a nucleon. The study of the not yet observed capture of a μ^- meson by a free proton is of great interest. However, the interpretation of the experimental results will be complicated by various molecular effects.[1] In experiments on the capture of muons in complex nuclei, it is the total probability of the various processes which has generally been measured.[2] The only definite process studied in detail is the process of the absorption of a muon by the C^{12} nucleus with the formation of B^{12}.[3,4] But even in this case, the interpretation of the experimental results is made more difficult by insufficiently accurate knowledge of the nuclear wave functions and by a number of other factors. Also, the results of the measurements made by different authors do not agree with each other at the present time.

Interest in the experimental study of the capture reaction of slow μ^- mesons in He^3 with formation of tritium and a neutrino in the final state

$$\mu^- + He^3 \rightarrow H^3 + \nu \qquad (1)$$

is due to the fact that the theoretical calculations [5,6] of the probability of this reaction, based on the known value of ft for the β decay of tritium, have high accuracy. Measurement of the probability of the process (1) makes it possible to determine the effective muon-nucleon interaction constant and thus to confirm the validity of the universal theory of weak interactions.[7]

In addition, determination of the energy of the tritium formed in process (1) makes it possible to estimate by a direct method the upper limit of the mass of the neutral particle emitted in the muon capture, and to prove, by the same method, the existence of the process [8]

$$\mu^- + p \rightarrow n + \nu, \qquad (2)$$

which, although it is generally accepted, has not yet been observed with complete reliability either for free protons or in complex nuclei.*

The first results of a study of the reaction (1) are described below.

Because He^3 is a rare isotope, we first contemplated using a mixture of hydrogen and helium for the study of muon capture in He^3, relying on an effective interception of the muons from the state of meso-hydrogen, similar to the well-known interception of muons by deuterium and other nuclei. However, as experiments carried out by us with a diffusion chamber filled with a mixture of hydrogen and helium have shown (as well as the theoretical estimates of S. S. Gershteĭn) an effective interception of muons by the helium does not occur, even at a helium concentration of 15 per cent. Therefore, we used pure He^3 in the subsequent experiments.

In the experiments, a diffusion chamber was used which was filled with He^3 at a pressure of 20 atm. The purity of the gas used was better than 99.999 per cent. The impurity of tritium amounted to about 10^{-15}. The vapor pressure of the methyl alcohol in the sensitive layer of the chamber was less than 50 mm Hg. The chamber was placed in a magnetic field of 6000 oe and was also inserted in the extracted 217-Mev/c meson beam of the synchrocyclotron of the Joint Institute for Nuclear Research. The slowing of the mesons and the separation of the mesons from pions was accomplished by a copper filter located near the chamber. Spe-

*The most direct measurement of the energy carried by the neutral particle in the process of muon capture by the nucleus, was made by Fry;[9] nevertheless, his data do not permit a reliable estimate of the mass of the neutral particle.

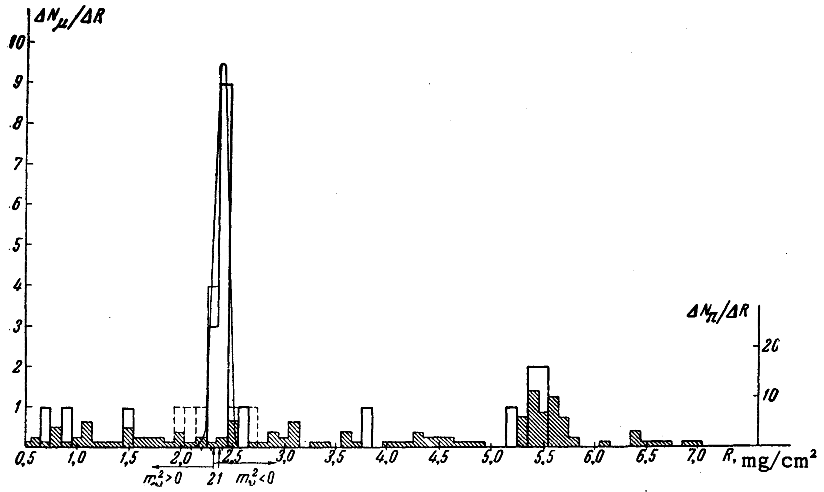

FIG. 1. Spectrum of the range of particles stopped in the sensitive layer of the chamber; the spectrum is connected with the stopping of mesons. $\Delta N_\mu/\Delta R$ is the number of cases per range interval obtained in a "muon exposure;" $\Delta N_\pi/\Delta R$ is the same factor, obtained in "pion exposure." The arrow 1 marks the experimental range of tritium in reaction (1); the arrow 2 – the expected range of tritium in reaction (1), computed from the range-energy relation[10] under the assumption that the mass of the neutrino is equal to zero.

cial precautions were taken to shield the chamber from thermal neutrons which produce the reaction

$$n + \mathrm{He}^3 \to p + \mathrm{H}^3, \qquad (3)$$

with a large cross section, creating a large background and a large ion content in the chamber.

To date, about 6000 photographs of the stopping of mesons in He^3 have been obtained in "muon exposure," i.e., in exposures in which the thickness of the filter corresponds to a maximum number of muons present in the chamber. The identification of the reaction (1) was based on the fact that the nucleus of tritium emerges with a sharply defined energy (1.897 Mev) and consequently has a definite range. Single-pronged stars produced by the stopped mesons were analyzed. Figure 1 shows the spectrum of path lengths of the secondary charged particles stopped in the sensitive layer of the chamber ("muon histogram"). The six cases shown with dashed lines in this drawing were identified with less reliability because of poor visibility condition or because the track of the stopped meson was short. To clear up the problem of the background which can be produced by the stopped pions present as an impurity in the "muon exposure," some 1200 pion stars were analyzed. These were obtained in a separate experiment ("pion exposure"), in which the thickness of the filter was chosen so as to obtain a maximum of pion stops in the chamber. The histogram of the paths of products of the pion stars which stop in the sensitive layer of the chamber is shown in the same drawing by shaded rectangles ("pion histogram"). The latter histogram is "normalized" to the area of the "muon histogram" in the region of paths from 5.00 to 6.00 mg/cm^2, where events of radiative capture of π^- mesons in He^3 should generally occur:

$$\pi^- + \mathrm{He}^3 \to \mathrm{H}^3 + \gamma.$$

From the number of stars obtained in the observed range interval it follows that the impurity of pions stopped in the chamber in the "muon exposure" amounted to ~2 per cent. This estimate agrees with the independent determination of the pion impurity made from the total number of stars in a chamber filled with He^4.

The results obtained indicate that the stars recorded in the "muon exposure," in the entire range interval considered, were chiefly produced by pions, with the exception of the region around 2.40 mg/cm^2, where a monoenergetic group of particles formed by stopped muons is apparently observed. An estimate of the absolute scatter of the values of the range was carried out on the basis of the measurement of a large number of total ranges of the proton and tritium formed in He^3 by thermal neutrons in the reaction (3). The number of such events on each frame was about 20. The mean square error of the range in these measurements was found to be equal to 0.06 mg/cm^2. The error curve with this half-width is also plotted in Fig. 1 for illustration of the scale of the range spread of the monoenergetic particles measured.

It is seen that the group of particles with range of about 2.40 mg/cm^2 can actually be regarded as monoenergetic. The energy of these particles agrees with the expected value of the energy of H^3 in process (1). This means that in the capture of the muon in He^3 there is a transition in which only one neutral particle should be emitted. In this case, its mass is very small and is compatible with a value equal to zero (see below), while its spin must be half integral. It can be assumed that 14 cases of μ^- meson capture in He^3 with formation of tritium and a neutrino in the final state were observed by us. A typical photograph of process (1) is shown in Fig. 2. The mean value of the range of the tritium, determined from the 14 cases, amounts to 2.37 ± 0.02 mg/cm^2.

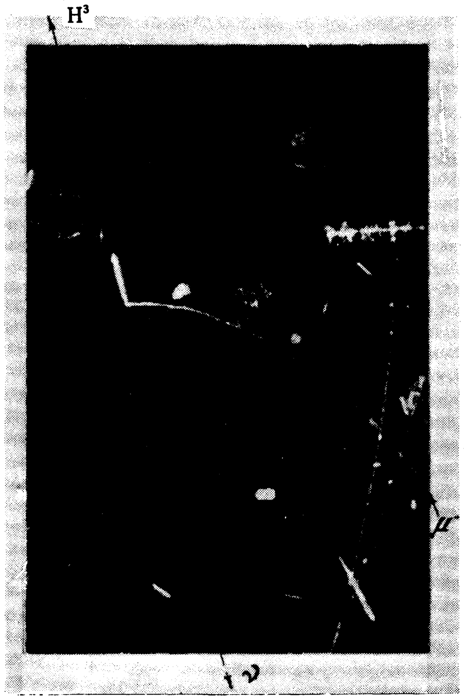

FIG. 2. Typical photograph of the reaction $\mu^- + He^3 \rightarrow H^3 + \nu$. The short traces visible on the photograph are generated by thermal neutrons in the reaction $n + He^3 \rightarrow H^3 + p$ ($R_{H^3} + R_p = 0.86\ mg/cm^2$).

Using this value of the range and experimental data on the ionization losses of the energy of protons in helium,[10] one can determine the upper limit of the mass of the neutral particle emitted in the process of muon capture by the nucleons. In this case it is shown that its mass is less than 6 Mev, with a probability of 99 per cent. The masses of the charged particles taking part in the process (1) were taken to be the following: $m_{He^3} = 2808.22$ Mev, $m_{H^3} = 2808.75$ Mev, $m_\mu = 105.65$ Mev. It should be remarked that the estimate carried out includes only the statistical errors in the determination of the range of tritium and does not take into account possible systematic errors which can undoubtedly take place, in particular, in the transition from range to energy. Therefore, a more definite conclusion would be that it was not possible for us to observe the finite mass of the muon neutrino emitted in the reaction (1); the scale of uncertainty in the mass of the neutrino, as analysis of the various inaccuracies shows, amounts to ~8 Mev.

The probability of reaction (1), Λ, can be determined in practice as the ratio of the number of cases of this reaction to the total number of muon stoppings in He^3, multiplied by the known probability of μ-e decay. The observed number of cases of (1) and the number of muon stoppings satisfying the accepted sampling criteria (5196) were corrected with account of the effectiveness of the scanning. The effectiveness of the recording of the tritium was determined from analysis of the spectrum of visible lengths of tracks of charged particles in pion stars, and amounted to (88 ± 4) per cent. The effectiveness of the scanning was determined from the results of independent repetition of scanning of part of the material, and was shown to be equal to 94 per cent.

Taking the value 2.21×10^{-6} sec for the lifetime of the muon, we obtain a value of Λ equal to $(1.30 \pm 0.40) \times 10^3\ sec^{-1}$. This result should be compared with the theoretical value of $(1.54 \pm 0.08) \times 10^3\ sec^{-1}$, obtained by Wolfenstein[6] on the basis of the universal theory of weak interactions, and is clearly the most accurate of the theoretical values of Λ.

The reliability of the agreement of the result that was obtained with the theory is small because of its large statistical error; therefore, at the present time, work is being carried on by us on the improvement of the statistical accuracy of the results. It can be noted, however, that the accuracy with which the universal interaction theory is tested in the experiment described above (~30 percent) is comparable with the accuracy of the test of this theory[6] by experiments on the study of a pure Gamow-Teller transition in the reaction $\mu^- + C^{12} \rightarrow B^{12} + \nu$. The result obtained by us gives the first rough information on the value of the vector constant of μ-nucleon interaction, the sign of which, as is well known,[11] is opposite to the sign of the axial-vector constant.

If we assume that the hyperfine states of the He^3 mesoatoms are statistically populated (there are strong theoretical arguments in favor of this [12]), then the probability of the reaction (1) determines the value of $3G_G^2 + G_F^2$, where G_G and G_F are the Gamow-Teller and Fermi effective coupling constants. For our purpose, one can express them approximately in terms of the axial-vector $g_A^{(\mu)}$ and the vector $g_V^{(\mu)}$ constants:

$$G_F = g_V^{(\mu)}, \qquad G_G \approx g_A^{(\mu)}.$$

Combining the most accurate value of the probability of the reaction $\mu^- + C^{12} \rightarrow B^{12} + \nu$, equal to $(6.31 \pm 0.24) \times 10^3\ sec^{-1}$[4] with the value of the probability of the process $\mu^- + He^3 \rightarrow H^3 + \nu$, we get the result that $|g_V^\mu| < 2\,|g_A^\mu|$, with a probability of 90 per cent.

The authors express their deep gratitude to P. L. Kapitza, V. P. Peshkov, V. M. Kuznetsov and A. I. Filimonov for invaluable help in carrying out purification of He^3 from tritium at the Institute for Physical Problems of the U.S.S.R. Academy of Sciences, and S. S. Gershteĭn for numerous useful discussions. We are grateful to V. P. Dzhelepov and L. I. Lapidus for interest in the work, and also to G. M. Aleksandrov, V. V. Kuznetsov, V. I. Orekhov, V. F. Poenko, A. G. Potekhin, D. B. Pontecorvo and I. V. Falomkin for help in the preparation of the apparatus and participation in the measurements.

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Translated by R. T. Beyer
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