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ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

Лаборатория ядерных проблем

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Among the weak interaction processes of non-strange particles the least studied is the muon capture by nucleons. The investigation of the muon capture by free protons, a process which until now has not yet been observed, is of greatest interest, but future experiments on the subject will clearly encounter difficulties of interpretation because of various mesomolecular effects/1/. Experiments on muon capture by nuclei, in the main, have a global character, i.e. they yield total rates of capture, summed over many transition channels/2/. The only definite transition, which has been studied in detail, is the muon capture process in C^{12} with the formation of B^{12} /3,4/. Even in this case the interpretation of the results is made difficult by various nuclear structure effects. In addition there is no agreement among various transition rate measurements which have been performed.

The experimental investigation of the muon capture reaction in He^3 with production of H^3 and neutrino in the final state

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

is of great interest because the theoretical calculations/5,6/ of the transition rate, based on the knowledge of the ft value in the β -decay of H^3, are quite accurate. The measurement of the probability of (1) allows to determine the effective muon-nucleon coupling constant and to check the universal weak interaction theory/7/.

In addition the determination of the H^3 recoil energy in the process (1) directly gives the upper limit of the mass of the neutral particle emitted in muon capture. In this way it is possible to demonstrate the existence of the process/8/

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

which is generally assumed to take place but, in fact, had never been observed either on free protons or on nuclei*.

Below there are described the first results obtained in the investigation of reaction (1).

Since He^3 is a rare isotope at first we were planning to study muon capture in He^3 by using a mixture of helium and hydrogen; we were hoping that muons would effectively jump over from meso-hydrogen to mesohelium by analogy with the well-known process of muon jumping over from hydrogen to deuterium and other nuclei. However experiments which we performed with a diffusion chamber filled up

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* The most direct measurements of the energy carried away by the neutral particle in muon capture by nuclei was performed by Fry/9/. Nevertheless his data do not permit to get a sufficiently low estimate of the mass upper limit.

with a mixture of helium and hydrogen, as well as theoretical arguments of Gerstein, demonstrated that an efficient muon jumping over from hydrogen to helium does not take place even at helium concentration of 15 %. Consequently we had to use pure He^3 in subsequent experiments.

In the experiments use was made of a diffusion chamber, filled up with helium 3 at a pressure of 20 atmospheres. The purity of the gas was better than 99,999%. The H^3 contamination was about 10^{-15}. The vapour pressure of methyl alcohol in the sensitive layer of the chamber was less than 50 mm Hg. The magnetic chamber (H = 6000 oersted) was placed in the 217 Mev/c meson beam of the Joint Institute for Nuclear Research synchrocyclotron. Slowing down of mesons and separation of muons from pions were accomplished by means of a copper filter, placed near the chamber. Special care was taken in ahielding the chamber from thermal neutrons, which through the high cross section reaction

$$n + He^3 \longrightarrow H^3 + p \qquad (3)$$

might have given a serious background and an intolerable large density of ions in the chamber.

Until now about 6000 photographs of mesons stopping in helium 3 were obtained in the course of the 'muon exposition', that is an exposition in which the copper filter thickness was selected to give the maximum number of muons stopping in the chamber. The identification of reaction (1) was based on the circumstance that the tritium recoil in (1) must have a definite energy (1.897 MeV), and consequently a well defined range. There were analysed one-prong stars produced by stopping mesons. In Fig. 1 there is presented the distribution in range of those charged particles from stars, which stop within the sensitive layer of the chamber ('muon histogram'). In this histogram there have been included 6 cases (dotted in the figure), the identification of which was doubtful either on account of bad visibility or because the track of the stopping meson was too short. In order to clear up the question as to whether there is present a background, simulating events of type (1), which might have been produced by pions present in small amount in the course of the 'muon exposition', there were analysed 1200 pion stars, obtained in a separate experiment ('pion exposition'), characterized by a copper filter thickness chosen to obtain the maximum number of pions stopping in the chamber. The range histogram of the pion star products which stop in the chamber sensitive layer is shown in the same figure in form of shaded rectangles ('pion histogram'). The last histogram was 'normalized' to the area of the 'muon histogram' in the range region 5.00 6.00 mgr/cm^2 where in both expositions should be mainly represented events of radiative pion capture in helium 3: $\pi^- + He^3 \longrightarrow H^3 + \gamma$. From the number of stars in this region it follows that the contamination of pions stopping in the chamber in the course of the 'muon exposition' is about 2%. Such a value of the pion contamination was confirmed by independent measurements in which the total number of stars was determined when the diffusion chamber was filled up with helium 4.

The results demonstrate that the stars obtained in the 'muon exposition' are mainly produced by pions all over the range interval of Fig. 1 with the exception of the region close to $2.40\ \mathrm{mg/cm^2}$ where, as it seems, there appears a monoenergetic group of particles produced by stopping muons. An estimate of the spread in the range determination was made on the basis of measurements of the 'total' range (H^3 range plus proton range) of a large number of events in which a thermal neutron was captured by He^3 according to reaction (3). The number of such events was about 20 per picture. The width (standard deviation) of the range distribution in these measurements was $0.06\ \mathrm{mg/cm^2}$. A Gauss curve with such a width is drawn in Fig. 1 in order to illustrate the magnitude of the spread affecting measurements of the range of monoenergetic particles in our conditions. It can be seen that the particle group with range near $2.40\ \mathrm{mg/cm^2}$ may really be considered as monoenergetic. The energy of these particles is in agreement with the expected value of the tritium energy in reaction (1). This means that in the muon capture by helium 3 there must be present a transition in which only one neutral particle is emitted, the mass of this particle being compatible with a zero value (see below) and its spin being half-integer. It is possible to conclude that we have observed 14 events of muon capture in He^3 with emission of tritium and neutrino in the final state. Fig. 2 shows a typical photograph of process (1). The mean range of tritium determined on the basis of 14 cases is $(2.37 \pm 0.02)\ \mathrm{mg/cm^2}$.

Using this value and experimental data on ionization losses by protons in helium /10/ one can estimate the upper limit of the mass of the neutral particle emitted in the process of muon capture by nucleons. This mass turns out to be less than 6 MeV with a probability of 99%. The masses of charged particles participating in this reaction were taken to be $m_{\mathrm{He}^3} = 2808{,}22$ MeV, $m_{\mathrm{H}^3} = 2808{,}75$ MeV, $m_{\mu} = 105{,}65$ MeV. It should be noted that the estimate given above does not take into account systematical errors which certainly can be present, in particular, in the energy range relation, and includes only statistical errors in the tritium range measurements. Because of this, a more conservative conclusion is that a finite value for the mass of the muon neutrino emitted in reaction (1) could not be observed, the uncertainty in the neutrino mass being about 8 MeV (as this is brought about by an analysis of different errors).

The probability Λ of reaction (1) may practically be written as the product of the known rate of (μe) decay times the ratio of the number of events of type (1) to the total number of muon stops in helium 3 . Corrections, taking into account the detecting efficiency of tritium nuclei with the proper range in the chamber and the scanning efficiency, were applied to the number of observed events of type (1) and to the number of stopping muons (5196). The detecting efficiency of tritium was determined by analysing the spectrum of visible track lengths of charged particles emitted in pion stars and was (88 ± 4)%. The scanning efficiency was determined by repeating the scanning of a part of the data and turned out to be 94 %.

If the muon mean life is taken to be $2.21 . 10^{-6}$sec., the value of Λ is $(1.30 \pm 0.40) . 10^{3}$ sec.$^{-1}$. This result should be compared with the theoretical value $(1.54 \pm 0.08) . 10^{3}$ sec^{-1} of Wolfenstein/6/ (apparently the most accurate one) based on the universal weak interaction theory.

The confidence in the agreement of the experimental result with the theory is not high because of the large statistical error; consequently we are at present aiming to improve very significantly the statistical accuracy of the data. It may be noted, however, that the 30% accuracy with which the universal interaction theory has already been checked in the experiment described above is comparable with the accuracy with which this theory was tested/6/ in the investigations of the pure Gamow-Teller transition in the reaction $\mu^- + C^{12} \longrightarrow B^{12} + \nu$. Our result gives the first rough information on the magnitude of the vector muon-nucleon interaction constant, the sign of which, as it is well known/11/, is opposite to the sign of the axial-vector constant.

If it is assumed that the hyperfine structure states of meso-He^3 are populated statistically (in favour of such an assumption there are serious theoretical arguments 12/), the probability of reaction (1) defines the value $3G_G^2 + G_F^2$, where G_G and G_F are the Gamow-Teller and Fermi effective coupling constants. For our purpose these can be expressed through the axial-vector $g_A^{(\mu)}$ and the vector $g_V^{(\mu)}$

$$G_F = g_V^{(\mu)}$$

$$G_G \sim g_A^{(\mu)}$$

Combining the most precise value of the $C^{12} \longrightarrow B^{12}$ experimental transition rate, $(6.31 \pm 0.24) . 10^3$sec^{-1} (4), with our experimental rate of the process $\mu^- + He^3 \longrightarrow H^3 + \nu$ we find that $\left|g_V^{(\mu)}\right| < 2\left|g_A^{(\mu)}\right|$ with a probability of 90%.

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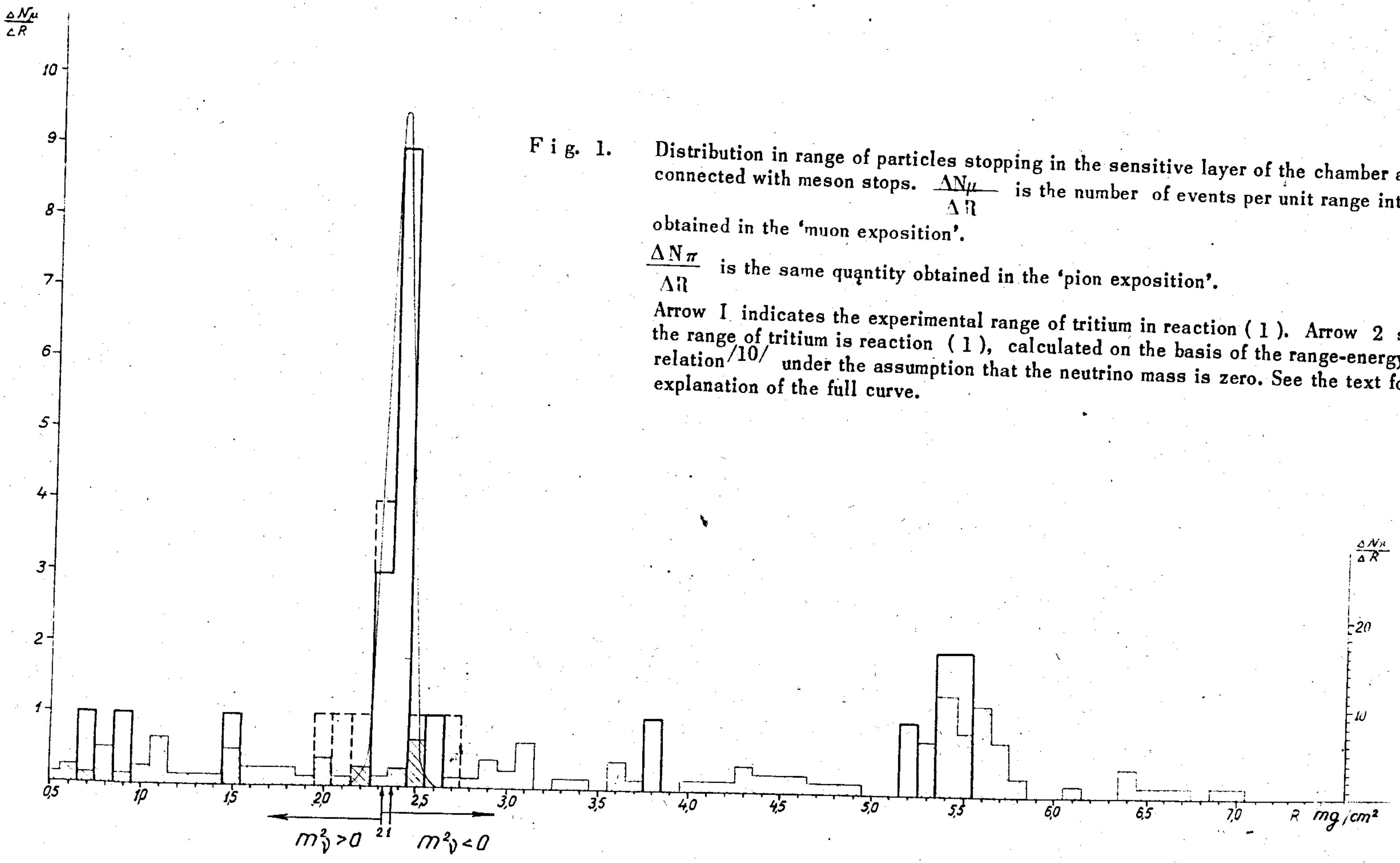

Fig. 1. Distribution in range of particles stopping in the sensitive layer of the chamber and connected with meson stops. $\frac{\Delta N_\mu}{\Delta R}$ is the number of events per unit range interval obtained in the 'muon exposition'.

$\frac{\Delta N_\pi}{\Delta R}$ is the same quantity obtained in the 'pion exposition'.

Arrow 1 indicates the experimental range of tritium in reaction (1). Arrow 2 shows the range of tritium is reaction (1), calculated on the basis of the range-energy relation/10/ under the assumption that the neutrino mass is zero. See the text for the explanation of the full curve.

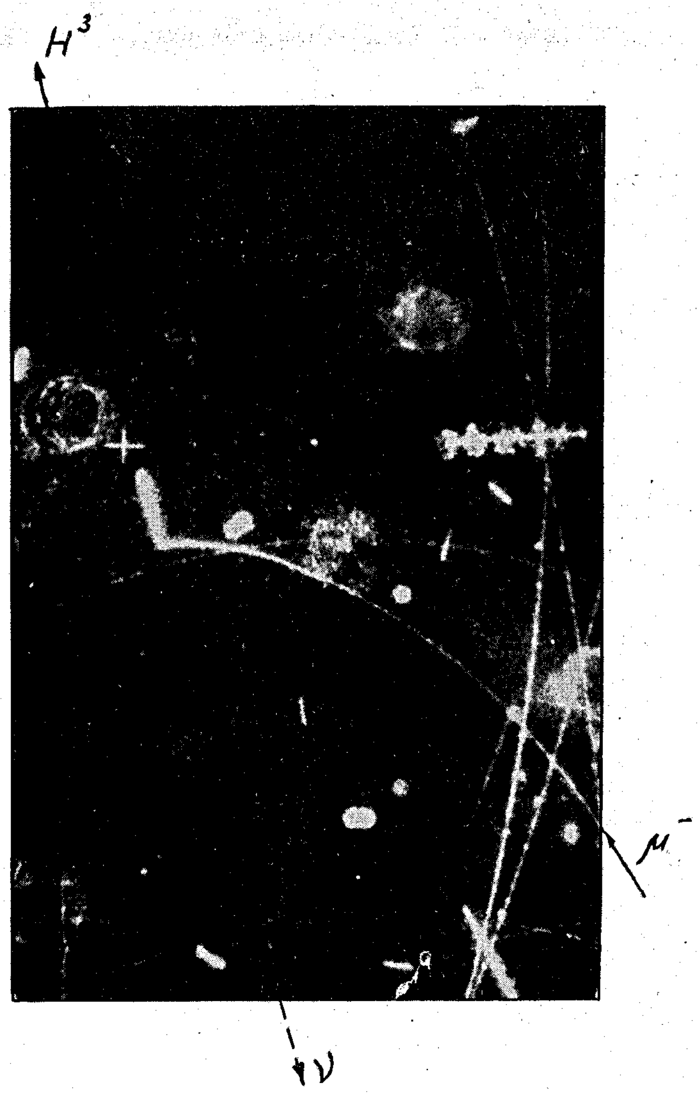

Fig. 2. Typical picture of an event $\mu^- + \mathrm{He}^3 \text{ —— } \mathrm{H}^3 + \nu$.

The short tracks which are visible on the picture are produced by thermal neutrons in the reaction $n + \mathrm{He}^3 \text{ —— } \mathrm{H}^3 + p$

$(R_{H^3} + R_p = 0.86 \text{ mg/cm}^2)$.

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