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ESTIMATE OF THE MUON NEUTRINO MASS

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For an accurate evaluation of the mass of the neutral particle emitted in the reaction $\mu^- + \mathrm{He}^3 \rightarrow \mathrm{H}^3 + \nu$, the range-energy relation for 0.2—3.0 MeV tritons moving through helium has been obtained experimentally. For this purpose tritium ranges were measured at different energies for several reactions in a diffusion cloud chamber. Experimental data on the energy loss of protons passing through helium were also used. The total number of observed events of the reaction in question was about 200. This permitted us to obtain the range and hence the triton energy with good accuracy. The measured value of triton energy and the known masses of all charged particles in the above reaction permitted us to derive the neutral particle mass. It turned out to be $m_\nu = 6^{+2}_{-6}$ MeV/c^2.

1. In an earlier communication[1] regarding the observation of the reaction

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

we discussed the question of the mass of the neutral particle emitted during the muon capture process. To estimate the mass we used the measured value of the range of the recoil nucleus (tritium) and the experimental data on the energy losses following passage of protons in helium, losses which are known in the energy region from 20 to 600 keV[2]. The conclusion was that we were unable to observe a finite mass, and the uncertainty in the value of the mass was ~ 8 MeV/c^2. The latter estimate did not take into account the difficult-to-analyze uncertainty in the absolutization of the ratio of the range to the energy. The absolutization difficulties are connected, first, with the extrapolation to zero of the energy lost when the particle passes through matter, and second, with allowance for the different systematic errors occurring during the measurement of the range.

The present note is devoted to a refinement of the range-energy ratio for tritium in helium. To this end we measured the ranges of tritium for different energies in the following reactions, which were investigated with the aid of a diffusion chamber:

$$\pi^- + \mathrm{He}^3 \rightarrow \mathrm{H}^3 + \pi^0, \qquad (2)$$

$$\pi^- + \mathrm{He}^3 \rightarrow \mathrm{H}^3 + \gamma, \qquad (3)$$

$$n + \mathrm{He}^3 \rightarrow \mathrm{H}^3 + p. \qquad (4)$$

The reactions (2) and (3) represent the capture of stopping negative pions by the He^3 nuclei, while reaction (4) represents the capture of thermal neutrons. In reaction (4) we measured the total range of the tritium and the proton. The obtained results, together with the new more exact experimental values of the range of tritium from the reaction (1), were used to estimate the mass of the neutral particle emitted following muon capture. To determine the average value of the tritium range in reaction (1) we used the total available material, which amounted to ~ 200 events[3].

According to the latest notions, the neutral particle emitted following the capture of the muon is a muon neutrino, and its mass is exactly equal to zero. The better experimental estimates of the upper limit of the mass of the muon neutrino, obtained from an analysis of $\pi-\mu$ and $\mu-e$ decays, amount to ~ 3 MeV/c^2 [4]. The muon capture process, by virtue of the large energy release, is less convenient for the estimate of the neutrino mass. However, the favorable possibilities of an absolute measurement of the tritium energy in the reaction (1) give grounds for hoping to obtain a result which is not much inferior in accuracy to the available estimates. We note also that an estimate of the mass of the neutral particle emitted following muon capture remains of phenomenological interest, since there are no pertinent direct experimental data.

2. The range of the charged particle was determined as the distance between the point of interaction and the point where the particle ceases

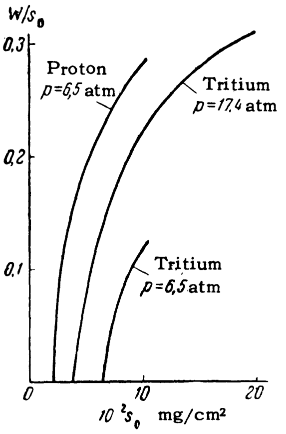

FIG. 1. Correction, defined as part of the maximum width of the track which must be subtracted from the measured value of the range in order to obtain its correct value, as a function of the maximum track width.

to ionize the atoms of the medium. Both points are masked by the track itself, which on the average is 0.5 mm wide. Whereas the initial point is determined relatively easily, to find a method for determining the end point of the range additional research was necessary. It was first necessary to determine the connection between the track width s and the propagation of the blackening x in the ion column along the direction of motion of the particle. It was found that the blackening propagates less along than transverse to the track, namely $x = 0.4s$. This result was obtained by measuring cases of elastic scattering of relativistic particles by helium nuclei, with distinctly visible tracks of the recoil nuclei. It was then necessary to establish the dependence of the track width on the ionization produced by the particle, since the last segment of the tritium range, on which the ionization decreased from a value corresponding to the maximum track width to zero, is commensurate with the track width. To solve this problem we used tracks of mesons stopped in the chamber, for which the change in width is well noticeable in the ionization-loss region of interest to us, for in the case of mesons this region corresponds to a large segment of the range from a certain point on the meson track to the stopping point. The ranges and the widths of the tracks were measured with a reprojector and a UIM-21 microscope. The summary results for the correction that must be subtracted from the total length of the track in order to obtain the correct value of the range are shown in Fig. 1. The correction is expressed in units of the width s_0 corresponding to maximum ionization. As can be seen from the figure, the correction depends on the mass of the particle and on the working pressure in the chamber.

The temperature correction was introduced on the basis of the measured temperature distribution in the sensitive layer of the chamber. The temperature distribution was measured with thermocouples with the chamber filled with hydrogen, which is close in its thermodynamic properties of He^3. The latter circumstance, as well as many other factors, for example the difficulty of measuring the pressure very accurately, leaves some uncertainty in the estimate of the absolute accuracy of the range measurement. For our purposes it would be very important to eliminate the systematic errors which can occur when the experimental material obtained under different conditions is used. These include shrinkage of the film, incomplete identity of the measuring instruments, etc.

The range of tritium in the reaction (2) and the total range of the proton and tritium in the reaction (4) were measured at a chamber pressure of 6.5 atm. The range of tritium in reaction (1) was measured at 17.4 atm, while that of reaction (3) at two pressures: 6.5 and 17.4 atm. Typical photographs of the processes are shown in Fig. 2. The photograph of the event due to reaction (3) at low pressure shows clearly the scattering of the tritium prior to stopping. Bends of this type were straightened in the measurements, in order to make the measurement results at low and high pressures equivalent, since no such "hooks" are seen at high pressure. There were several hundred events of each type. This made it possible to obtain from the measurements the average values of the ranges with the statistical accuracy indicated in the table. The table lists the values of the energy

Reaction	E, MeV	R, mg/cm²	l, mm ($p = 6.5$ atm)	l, mm ($p = 17.4$ atm)
$\mu^- + He^3 \rightarrow H^3 + \nu$	1,8965*	$2,34 \pm 0,01$	—	9.0
$\pi^- + He^3 \rightarrow H^3 + \pi^0$	0.1887	$0,247 \pm 0.003$	2.5	—
$\pi^- + He^3 \rightarrow H^3 + \gamma$	3.281	$5.56 \pm 0,01$	—	21,5
		$5,57 \pm 0.01$	56,0	—
$n + He^3 \rightarrow H^3 + p$	0.1915 (E_p=0,5732)	$0.940 \pm 0,010$	9,5	—

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*The energy is calculated for a zero neutrino mass.

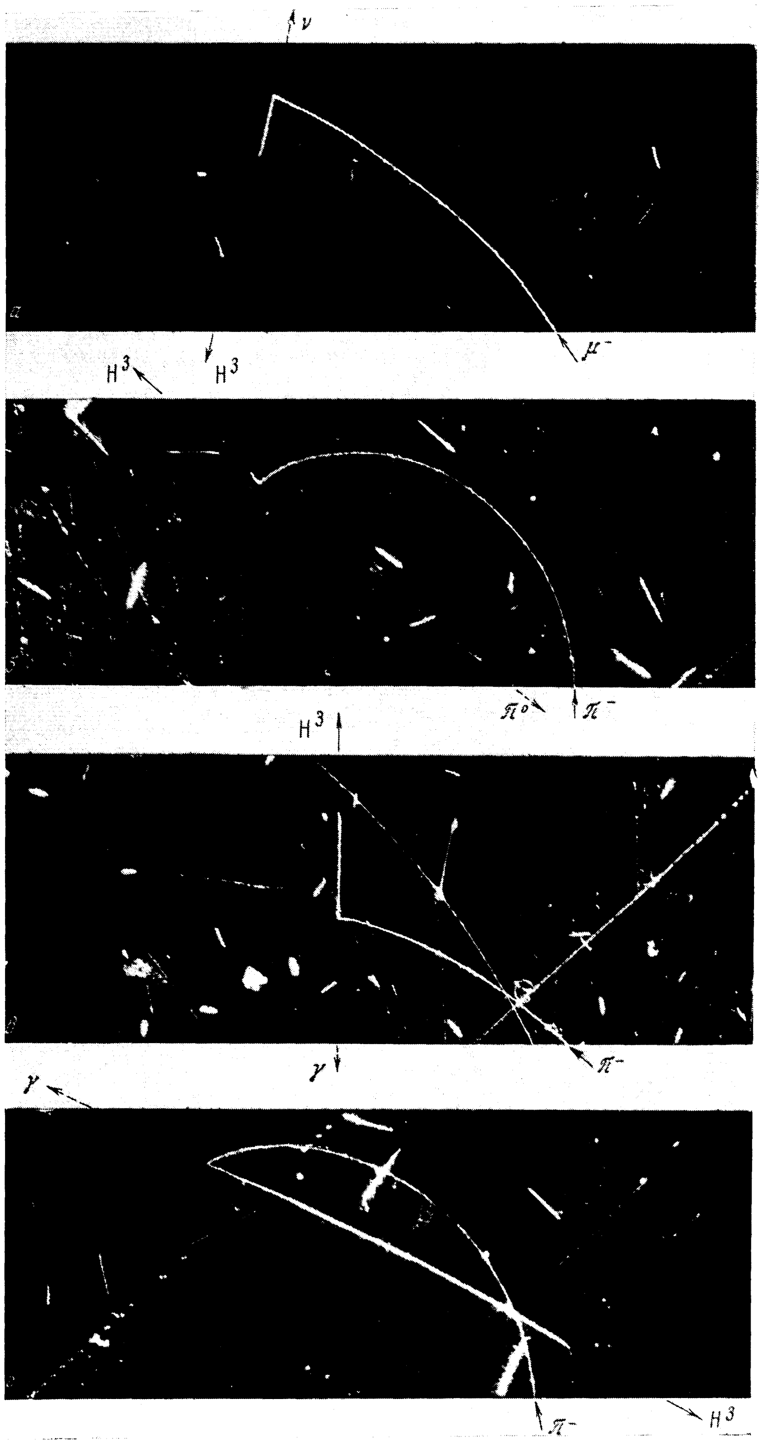

FIG. 2. Photographs a and b show the events due to reactions (1) and (3) at high chamber pressure, 17.4 atm, while photographs c and d show events from reactions (2) and (3) at low pressure, 6.5 atm. Each photograph contains a case of reaction (4); at high pressure these are the short strokes, and at low pressure these are longer.

in the measured range of tritium in the indicated reactions, with the exception of the last reaction, where the summary range of the tritium and the proton is shown. However, the range of the proton from the last reaction can be obtained, since the range of the tritium in this reaction is very close to the range of the tritium in reaction (2). The last two columns of the table show for illustrative purposes the tentative values of the ranges.

The good agreement between the values of the ranges of tritium in reaction (3) at two different pressures confirms the correctness of the measurement procedure and offers evidence that there are no noticeable systematic errors in the temperature corrections at the different pressures.

The range-energy curve obtained on the basis of the experimental data concerning the proton energy loss in the helium, was calibrated against a point corresponding to a tritium energy 0.1887 MeV. A possible control point is the range of the

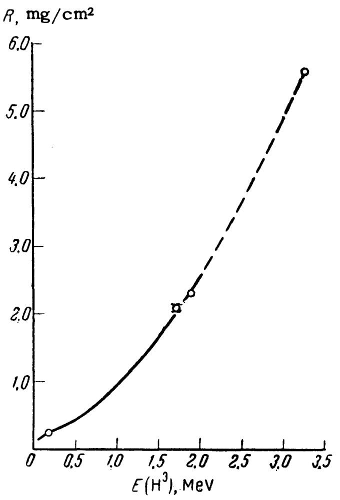

FIG. 3. Range-energy relation for tritium in He^3. The continuous part of the curve is drawn through the extreme left experimental point in accordance with the data on the energy loss accompanying the passage of protons through helium[2]; the dashed part of the curve, which joins the experimental points, is a continuation of the continuous part.

proton in reaction (4). After recalculating to tritium, we obtain the following results: R = 2.07 ± 0.03 mg/cm^2 at E = 1.716 MeV. This point, however, was measured with lower accuracy and in addition, the range may be slightly overestimated here, since this result has been obtained from the range of the proton in reaction (4), for which the scattering before stopping plays a lesser role than for tritium. The calibrated range-energy curve in the energy region 0.1887—2 MeV, together with the experimental points, is shown in Fig. 3. It must be noted that the value of the range at E = 3.281 MeV corresponds in a certain sense to an energy limit. Below this energy theoretical calculation of the energy losses due to passage of tritium through helium cannot give the required accuracy, so that to calculate the ranges at high energies it is necessary to know the range of the tritium at the limiting energy. Consequently, the value obtained for the range can be used to make more precise the theoretical values of the tritium and proton ranges in helium.

3. The obtained dependence of the range on the energy was used to determine the energy of the tritium during the muon capture process. It was found to be E = 1.8908 ± 0.0057 MeV. An estimate of the neutrino mass can be made by means of the formula

$$m_\nu = \sqrt{(\Delta E - E)^2 - 2Mc^2E}, \qquad (5)$$

where ΔE is the energy released in reaction (1), E is the kinetic energy of the tritium in reaction (1), and M is the mass of the tritium nucleus, with

$$\Delta E = [M(\mu^-) + M(\mathrm{He}^{3++}) - M(\mathrm{H}^{3+})]\,c^2 - E_\mathrm{b},$$

where E_b—binding energy of the muon on the Bohr orbit of the He^3 nucleus. The following values were assumed in the calculations for the masses of the particles participating in the reaction:

$M(\mu^-) = 105.654 \pm 0.002\ \mathrm{MeV}/c^2,$
$M(\mathrm{He}^{3++}) = 2808.217 \pm 0.017\ \mathrm{MeV}/c^2,$
$M(\mathrm{H}^{3+}) = 2808.746 \pm 0.017\ \mathrm{MeV}/c^2,$
$E_\mathrm{b} = 0.0113\ \mathrm{MeV}.$

In addition, there is a well-known value for the mass difference $M(H^{3+}) - M(He^{3++}) = 0.5293 \pm 0.0003$ MeV/c^2. After substituting the numerical values in (5) we get $m_\nu = 6^{+2}_{-6}$ MeV/c^2, that is, a zero value for the muon neutrino mass is not excluded, and for the upper limit we can visualize a value 8 MeV/c^2.

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178