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ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

ЛАБОРАТОРИЯ ЯДЕРНЫХ ПРОБЛЕМ

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MEASUREMENT OF THE TOTAL MUON CAPTURE RATE IN HELIUM-3

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Besides the measurements of partial transition rates $\mu^- + C^{12} \to B^{12} + \nu$ /1/, $\mu^- + He^3 \to H^3 + \nu$ /2/, which provided important information on the muon capture by nucleons, a considerable number of measurements of the total rate of muon capture in various complex nuclei ($A > 12$) has been performed in order to check the validity of the universal weak interaction theory/3/. However, a critical revision of the theoretical evaluations of Primakoff/4/ on heavy nuclei shows that his estimates are not sufficiently reliable, for the purpose of drawing conclusions on the validity of the universal theory/5,6,7/ Considerably less approximations are made in the calculations of the total muon capture rate in the lightest nuclei (D,He^3, He^4)/4/. Owing to this, one may expect that theoretical results in the above cases are more reliable than for heavier nuclei. In the case of the D nuclei (just as for muon capture in hydrogen/8,9/) there are complications due to mesomolecular processes. Thus, data on capture in He^3 are of great interest. The present investigation is aimed to measure the total rate of muon capture in He^3, i.e., the overall rate of the processes:

$$\mu^- + He^3 \to H^3 + \nu \tag{1}$$

$$\mu^- + He^3 \to d + n + \nu \tag{2}$$

$$\mu^- + He^3 \to p + 2n + \nu \tag{3}$$

In all these reactions one charged particle is emitted and corresponding events look like one-prong stars. Such stars were observed in the high pressure diffusion chamber with which we previously measured the rate of reaction(1)/2/. The description of the apparatus, the experimental procedure and a detailed account of experimental data treatment are to be found in these papers.

In order to separate muon stars from pion ones (see below) use was made of the range spectra of charged secondaries. The solid line in Fig. 1 shows a histogram of secondary particle ranges in the 'muon exposure' (in which 98-99% of stopped particles are muons, and 1-2% are pions). This histogram is based on stars with ranges of charged particle definitely stopping in the sensitive layer of the chamber. The histogram includes 424 stars produced by mesons having range $\geq$ 20 mm (a stopped particle is reliably identified as a meson only if its range is greater than 20 mm) .

In the spectrum obtained in the 'muon exposure' there is a considerable number of stars, produced by pion impurities, since each pion stopping, unlike a muon stopping, is accompanied by a star. In order to obtain the pure spectrum of charged particles from reactions (1,2,3) by subtraction, we made use of the range spectrum of charged particles emitted in pion capture in helium-3. We obtained this previously in a 'pion exposure'/10/, (here 70% of stoppings are due to pions, and 30% - to muons), in which the number of stars due to muons does not exceed 2%. This spectrum is shown as dashed in Fig. 1. It contains 292 stars with secondary ranges in the interval 0.5-12 mg/cm^2. The normalization of the pion spectrum was made by using the yield of the reaction $\pi^- + He^3 \to H^3 + \gamma$, the peak of which at R= 5.6mg/cm^2 is clearly seen in the spectra of both the 'muon' and 'pion' exposures. Fig. 2 shows the charged particle spectrum of one-prong stars obtained by subtracting the normalized 'pion' spectrum from the 'muon exposure' spectrum. There was excluded the 0. –0.5 mg/cm^2 region where the contribution of both exposures from the reaction

$\pi^- + He^3 \to H^3 + \pi^\circ$ is very large. More reliable data for this range interval can be obtained by extrapolating the spectrum from a neighbouring interval. As for large ranges, we confined ourselves to $R \leq 12 mg/cm^2$, i.e., to the spectrum region, where it was possible to obtain reliable data on the star detection efficiency. In plotting the spectrum (Fig. 2) the dependency of the detection efficiency upon the prong length was taken into account. This efficiency for each exposure was calculated by the Monte-Carlo method by making use of the known distribution of stops in the chamber volume. One of the calculated curves (for the 'muon' exposure) is shown in Fig. 2. A correction was made taking into account 'false' stars, which were imitated by muon stops without visible electrons accompanied by scattering near the track end. The magnitude of this correction was largest in the soft spectrum region (0.5-1.5 mg/cm^2) where it did not exceed, however, 25%. In the muon capture range spectrum the maximum at $R \cong 2 mg/cm^2$ corresponding to the reaction $\mu^- + He^3 \to H^3 + \nu$ can be clearly seen. This spectrum goes practically to zero at $R \approx 6$ mg/cm^2 apparently charged particles emitted in He^3 muon capture have rather a soft spectrum.

Since about 100 MeV are released in the process of muon capture, charged particles might, in principle, be rather energetic. Strictly speaking, in order to obtain the total capture rate, it would appear necessary to measure the range spectrum in a very wide region. However, the sharp falling off in the spectrum we observed shows that use can be made of a limited range interval (up to $R \leq 6.5$ mg/cm^2). Below arguments are given in favour of the assumption that the total rate λ of muon capture in helium-3 practically does not differ from the value $\lambda_{6.5}$ – the rate of muon capture in helium-3 with emission of charged particles having ranges $R \leq 6.5$ mg/cm^2. Indeed, a range of 6.5 mg/cm^2 corresponds to protons and deuterons of ≈ 2 and ≈ 3 MeV, respectively. This is in agreement with the 'maximum' energies of these particles, evaluated under the assumption that muon capture occurs, mainly, via the direct process $\mu^- + p \to n + \nu$, and that the emitted charged particles are 'observers'. This point of view is confirmed by comparing our spectrum with the spectrum of charged particles obtained recently in studying muon capture in helium-4. (Bizzari et al./11/). The considerable difference in the maximum energies of particles observed in helium -4 and helium-3 agrees qualitatively with what should be expected for particles - 'observers', when the difference in the binding energies of helium-3 and helium-4 is taken into account.

Integrating over the interval 0.5-6.5 mg/cm^2 gives 287.6 $\pm$ 25 events. For the range interval 0–0.5 mg/cm^2 a correction of 9$\pm$ 5 stars is obtained by linear extrapolation to zero of the event number from the neighbouring interval. Thus, in calculating the total muon capture rate in He^3 there were taken into account 296.6$\pm$25 stars. If the peak from the reaction $\mu^- + He^3 \to H^3 + \nu$ is excluded, the number of stars counted in the interval 0.5-6.5 mg/cm^2 is 91.3$\pm$ 22.3. Using these values, the number of registered muon stops with the initial path length $\geq$ 20mm (67 463 $\pm$ 1093), and also the known muon lifetime (2.21×10^{-6} sec), one may obtain $\lambda_{exp.} = \lambda_{6.5}$ and the total rate of the reactions (2,3) $W_{exp} = W_{6.5}$:

$$\lambda_{exp} = (2.14 \pm 0.18) \cdot 10^3 \ sec^{-1},$$

$$W_{exp} = (0.66 \pm 0.16) \cdot 10^3 sec^{-1}.$$

In calculating these rates a correction of (7$\pm$1)% was introduced which took into consideration the fraction of stars lost in selecting events only with clearly seen prong ends.

It should be mentioned that experimental data including stars with charged particles having $R > 6.5 mg/cm^2$ do not contradict our statement that $\lambda = \lambda_{6.5}$. Indeed, one may evaluate the capture rate taking into consideration also charged particles with ranges > 6.5 mg/cm^2. As is seen from Table 1, where the values λ are given in the units of 10^3 sec^{-1}, the figures obtained in this way are compatible within statistical errors with $\lambda_{6.5}$. Note that when > 12mg/cm^2 the errors considerably exceed the statistical errors quoted in the table, since the detection efficiency in this region is very small ($\approx$ 20%) and consequently is known only roughly.

Table 1

—	$\lambda_{6.5}$	$\lambda_{12.0}$	$\lambda_{25.0}$
—	2.14 ± 0.20	2.0 ± 0.2	2.3 ± 0.3

An evaluation of λ taking into account all the events (including one prong stars with ranges of secondaries non-stopping in the sensitive layer) also gives figures compatible with $\lambda_{6.5}$. However, this estimate involves serious uncertainties not only of statistical but also of systematic character (unreliable star indentification).

The obtained value $\lambda_{exp} = (2.14 \pm 0.20)\ 10^3$ sec^{-1} is consistent with Primakoff's/4/ value λ_{theor} of the total capture rate, based on the universal theory ($\lambda_{theor} = 2.5 \times 10^3$ sec^{-1} with $\approx$ 10% uncertainty).

The rate λ is the sum of the value w, and of Λ -the partial transition rate $\mu^- + He^3 \to H^3 + \nu$ we measured earlier/2/. Thus, the whole new information is contained in the value W_{exp}. From the calculations of Primakoff and Fujii/4,12/ one may obtain the value $\lambda_{theor} - \Lambda_{theor} = W_{theor}$ which turns out to be 1.1×10^3 sec^{-1} with a 20% uncertainty.

Agreement with Primakoff's calculations was also found in measurements of the total muon capture rate in He^4/11/ ($\lambda^{He^4}_{theor} = 470$ sec^{-1}, uncertainty 10÷15%; $\lambda^{He^4}_{exp} = 450 \pm 90$ sec^{-1}). Thus, investigations of the muon capture in He^3 and He^4 yielded three independent values (W, Λ, λ^{He^4}) which turn out to be in agreement with the universal theory predictions.

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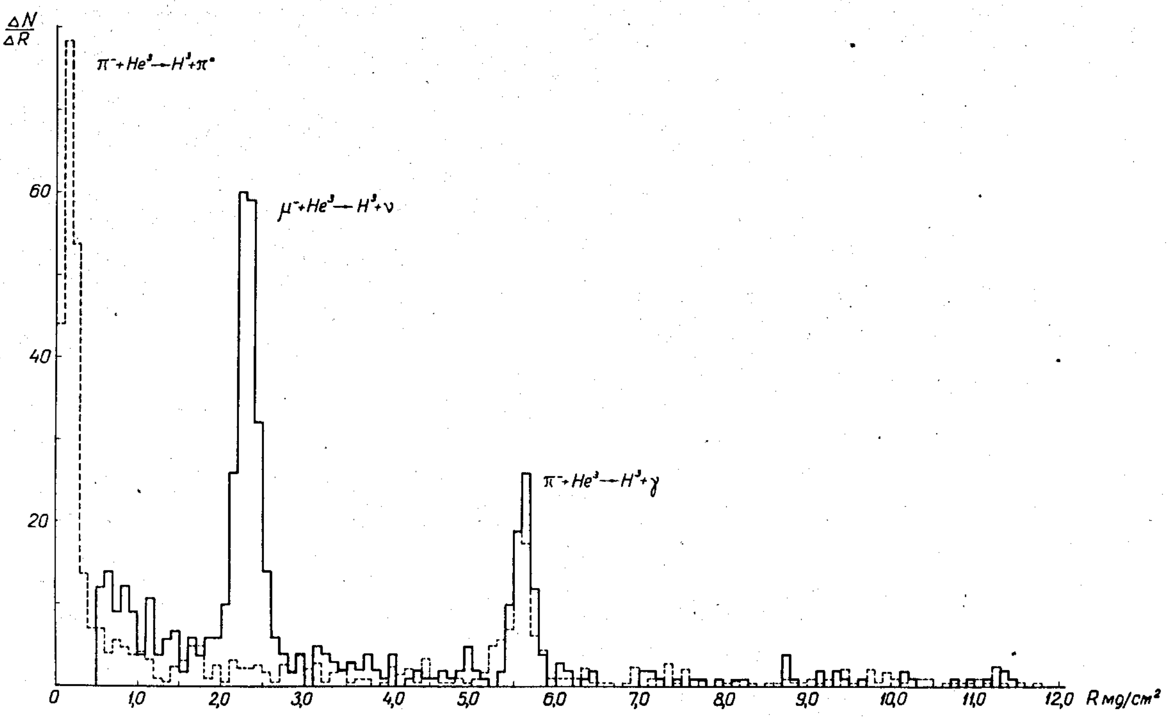

Fig. 1. Range spectra of secondaries due to stars induced by mesons stopped in He^3. A solid curve is the spectrum obtained in 'muon exposure'; A dashed curve is the normalized spectrum obtained in 'pion exposure'.

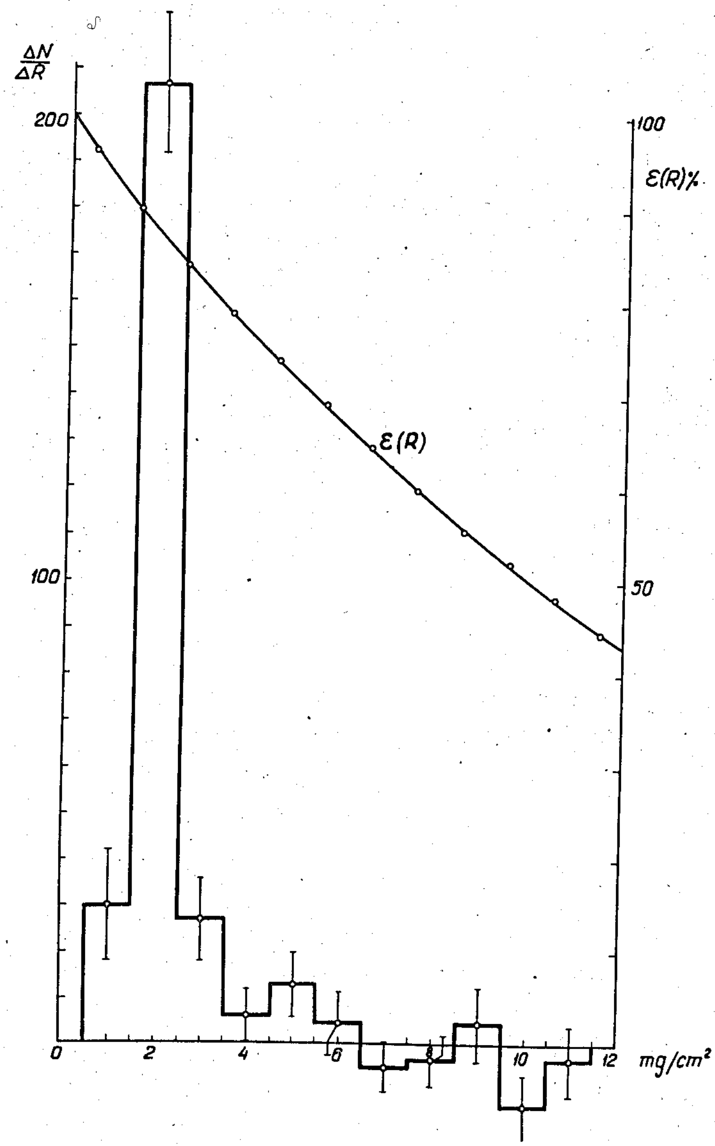

Fig. 2. The histogram is the range spectrum of secondaries obtained on subtracting the 'pion' spectrum from the 'muon' one. A smooth curve is the dependence of detection efficiency upon the range of secondaries.