# THE PANOFSKY RATIO FOR $He^3$ AND THE ROOT-MEAN-SQUARE RADIUS OF THE TRANSITION $He^3 \rightarrow H^3$

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The capture of stopped negative pions in $He^3$ has been considered theoretically [1, 2]. The following processes are allowed by the conservation laws:

| | | |
|---|---|---|
| 1. $\pi^- + He^3 \rightarrow p + n + n$ | $(55.5\%)^{(*)}$ | absorption |
| 2. $\pi^- + He^3 \rightarrow n + d$ | $(27.8\%)$ | absorption |
| 3. $\pi^- + He^3 \rightarrow H^3 + \pi^0$ | $(9.4\%)$ | charge exchange |
| 4. $\pi^- + He^3 \rightarrow H^3 + \gamma$ | $(4.8\%)$ | radiative capture |
| 5. $\pi^- + He^3 \rightarrow d + n + \gamma$ | $(2.0\%)$ | radiative capture |
| 6. $\pi^- + He^3 \rightarrow p + n + n + \gamma$ | $(0.5\%)$ | radiative capture |

The relative rates of these processes have been calculated in ref.[1] in terms of impulse approximation, the known data on meson capture in hydrogen and deuterium being used. The capture was also considered to take place from the S-state of the mesic atom. It has been shown [2] that the ratio of the rates of reactions (3) and (4) which we shall call the Panofsky ratio in $He^3$ and denoted by $P$, may be directly related to the value of the root-mean-square radius of the transition from $He^3$ nucleus to $H^3$ in radiative processes. The following equation takes place:

$$P = \frac{P_0}{1 - {}^1/_3 k^2 r^2 + {}^1/_{18} k^4 r^4} \frac{\omega + M}{\omega_H + m} \frac{\omega_H}{\omega} \left[ \frac{E}{E_H} \frac{M}{m} \left( \frac{\mu + m}{\mu + M} \right)^3 \right]^{\frac{1}{2}}, \quad (1)$$

where $P_0$ is the Panofsky ratio, $r$ is the root-mean-square radius, cm, $k$ is the photon wave number in process (3), $cm^{-1}$, $\omega$ is the photon energy in process (4), $\omega_H$ is the photon energy in $\pi^-$-meson capture in hydrogen, $m$ is the neutron mass, $\mu$ is the $\pi^0$-meson mass, $M$ is the tritium mass, $E$ is the energy released in process (3), $E_H$ is the energy released in the process $\pi^- + p \rightarrow n + \pi^0$. The particle masses and the energies are given in MeV.

The experimental determination of the root-mean-square radius is of great interest at present, for instance, for the interpretation of the results on muon capture in $He^3$.

In the present investigation the experimental study of $\pi^-$-meson capture in $He^3$ was undertaken for the first time.

Pions were stopped in the diffusion chamber, filled with helium-3 at 20 atm pressure [4]. The chamber was in the magnetic field of 6000 gauss. One meson stop on average occurred per 4 pictures. The contamination of muon stops was 32% of the total number of stops. During two runs 8,500 photographs were obtained. The whole material was scanned three times. The results of scanning are given in Table I where the number of events of each type is indicated.

$\pi^-$-mesons captured in $He^3$ provide only one-prong stars. Due to this the registered many-prong stars should be related to the capture in carbon or oxygen nuclei belonging to the vapour of methyl alcohol.

In reactions (2), (3) and (4) the energy of secondary particles is strictly fixed. Therefore, they can be easily identified by measuring the ranges or momenta of secondary particles. In all other processes energy is distributed between three or more particles. In this

(*) The values quoted in ref.[1] have been corrected according to the latest, most accurate measurements of the Panofsky ratio, $P_0 = 1.533 \pm 0.021$ [3].

TABLE I

| One-prong stars | | | $\mu-e$ decay | | Many-prong stars | $\pi-\mu$ decay or pion scattering | Events not identified | |
|---|---|---|---|---|---|---|---|---|
| Prong end visible | Prong end not visible | Total number stars | Electron visible | Electron not visible | | | $\mu-e$ decay or a star | $\pi-\mu$ decay or a star |
| 805 | 1567 | 2372 | 700 | 353 | 21 | 1423 | 61 | 33 |

investigation the main attention was paid to reactions (3) and (4). As seen from Table I, the number of stars satisfying the selection criteria and related in the overwhelming majority to $\pi^-$-meson capture in $He^3$ amounted to 2372. It was established that on scanning three times the observation efficiency for meson stops in the chamber was independent of the event type at the end of the meson track and was close to 100%.

The selected events were measured with a stereo-projector. The range spectrum of secondary particles from one-prong stars is shown in Fig. 1. Two peaks with $R \sim 0.2$ mg/cm$^2$ and $R \sim 5.5$ mg/cm$^2$ corresponding to the two mono-energetic particle groups are well seen in this spectrum. The tritium energy in the reactions $\pi^- + He^3 \rightarrow H^3 + \pi^0$ and $\pi^- + He^3 \rightarrow H^3 + \gamma$ is 0.19 MeV and 3.27 MeV. The expected values of tritium ranges with such energies correspond to the range values of the peaks in the spectrum. This indicates that the peak in the region of 0.2 mg/cm$^2$ refers to charge exchange process (3), while in the region of 5.5 mg/cm$^2$—to process of radiative capture (4). Fig. 2 presents two photographs showing

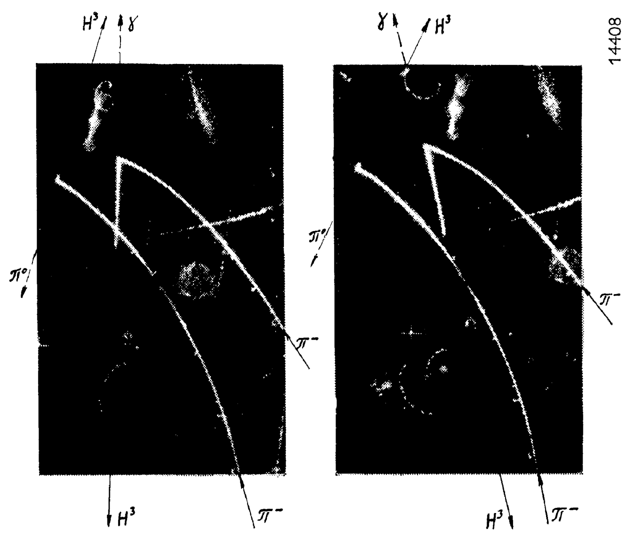


**Fig. 2** The stars from the processes $\pi^- + He^3 \rightarrow H^3 + \pi^0$ and $\pi^- + He^3 \rightarrow H^3 + \gamma$.

stars related to these processes. The deuteron range length from reaction (2) is too great to be registered as a star with a track ending in the chamber. The approximately smoothly distributed background which is present in the spectrum is formed by a part of events from reactions (1), (5), (6).

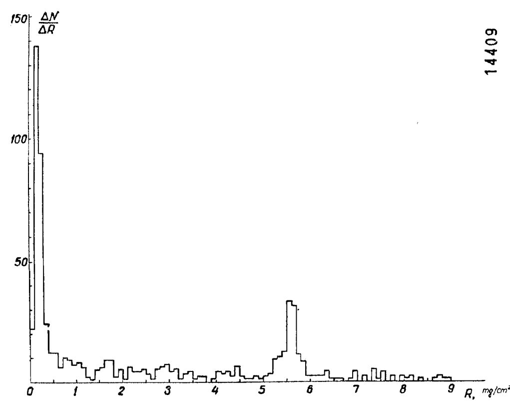


**Fig. 1** The spectrum of secondary particle ranges from one-prong stars in $\pi^-$-meson capture in $He^3$.

In separating the events, due to charge exchange and radiative capture, it was supposed that the behaviour of the background in the region of peaks is monotonous. In the left side of Table II there are data on reaction (3).

As seen from the quoted spectrum, secondary particles from reaction (3) have very short track lengths. Therefore, to assure a high selection efficiency in scanning, not only obvious short prong events were considered to be stars but also all the cases when the meson track end had any peculiarity (distortion, inhomogeneity). The background of false stars in this

TABLE II

| Reaction (3) | | | | | Reaction (4) | | | |
|---|---|---|---|---|---|---|---|---|
| Range interval $mg/cm^2$ | Number of events | Back-ground of muon events | Back-ground due to other reactions | Number of events $H^3\pi^0$ | Range interval $mg/cm^2$ | Number of events | Back-ground due to other reactions | Number of events $H^3\gamma$ corrected for efficiency |
| 0−0.5 | 382±19.5 | 23.3±4.2 | 43±6.5 | 315.7±21 | 5.2−5.9 | 114±10.7 | 14.2±2.7 | 146.6±16.5 |

case is determined by the muon background (muon scattering, etc.). In order to evaluate this background the results of scanning the material obtained during the $\mu$-exposure were used [5]. Due to a small pion contamination (<2%) and an inconsiderable yield of stars from muon capture in $He^3$, practically all the events with a peculiarity at the end are false imitations of short track length stars.

Because of possible unfavourable space orientation of star prongs their length (if $R<0.3$ mg/cm$^2$) was not measurable in all the cases, therefore a fraction of events was included in the range interval (0 to 0.5 mg/cm$^2$) indicated in Table II without measuring (93 events). The performed measurements of secondary particle track lengths from the capture of thermal neutrons $n+He^3 \rightarrow H^3+p$, and also from the reaction $\pi^-+He^3 \rightarrow H^3+\gamma$ show that in measurements the deviation from the mean path length does not exceed 0.3 mg/cm$^2$. Therefore, it can be considered that the overwhelming majority of events from reaction (3) will be included in the region of track lengths from 0 to 0.5 mg/cm$^2$. The detection efficiency in the chamber for the prongs of such a length (i.e., the probability that a prong is not cut off by the edges of the sensitive layer) was taken to be equal to 100%. It was assumed that in the track length interval from 0 to 0.5 mg/cm$^2$ the background due to other reactions remained the same as in the neighbouring interval from 0.5 to 1 mg/cm$^2$.

The results of detecting the reaction $\pi^-+He^3 \rightarrow H^3+\gamma$ are shown in the right side of Table II. The detection efficiency of a prong 5.5 mg/cm$^2$ long was derived by analysing the prong distribution of all the stars. The mean value of the efficiency (for both the exposures) turned out to be (68.2±2%). The background due to other reactions was determined from the nearest zones to the right and to the left of the peak $H^3\gamma$. The mean range of tritium in this reaction was (5.55±0.05) mg/cm$^2$.

Using the data of Table II, we find the Panofsky ratio in $He^3$ to be:

$$P = 2.16 \pm 0.28$$

The relative rates of reactions (3) and (4) prove to be the following:

$$W_3 = (13.5 \pm 0.9)\%. \quad W_4 = (6.2 \pm 0.7)\%.$$

The evaluation of the root-mean-square radius of the transition from $He^3$ to $H^3$, made on the basis of relation (1) and the experimentally obtained value $P$, gives

$$r = (1.24^{+0.30}_{-0.46}) \times 10^{-13} \text{ cm} .$$

This value of the root-mean-square radius is in better agreement with the value $1.56 \times 10^{-12}$ cm calculated in ref. [6] on the basis of the known magnitude of $He^3$ binding energy and on taking into account a hard core potential for nucleon-nucleon interaction, than with $1.78 \times 10^{-13}$ cm quoted by Fujii and Primakoff [7].

The yield of the processes $\pi^-+He^3 \rightarrow H^3+\pi^0$ and $\pi^-+He^3 \rightarrow H^3+\gamma$ turns out to be somewhat larger than it was predicted in ref. [1].

Finally, it should be noted that further augmentation of experimental material will make sufficiently accurate (~10%) determination of the transition radius $He^3 \rightarrow H^3$ possible.

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# DETERMINATION OF THE ROOT-MEAN-SQUARE RADIUS OF TRANSITION $He^3-H^3$

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The experimental investigations of $\mu$-meson capture in $He^3$ is of great importance for checking the universal weak interaction theory. However, the muon-nucleon interaction constant can be determined exactly only in the case when the mean-square radius of transition $He^3 \to H^3$, $\langle H^3|r^2|He^3\rangle$ is known. The theoretical calculations of this value depend on the choice of the nucleon-nucleon interaction potential and of the nuclear model. Calculations carried out by Werntz [1] and Fujii and Primakoff [2] yield different results. Following Werntz $r = 1.56\times10^{-13}$ cm; Fujii and Primakoff have obtained $r = 1.78\times10^{-13}$ cm. The aim of the present note is to show that $r$ can be calculated if we know the Panofsky ratio for He, $P_{\mathrm{He}}$, i.e. the ratio of the probabilities of the processes

$$\pi^- + He^3 \to H^3 + \pi^0 \quad \text{and} \quad \pi^- + He^3 \to H^3 + \gamma\,.$$

The calculation is based on the following assumptions: (a) the $\pi$-meson capture is considered in terms of the impulse approximation; (b) in the nuclear wave function only the $S$-wave is taken into account.

Following Pomeranchuk [3] the $\pi$-meson capture in hydrogen will be described by phenomenological potentials:

$$a\delta(\bar{r}_p - \bar{r}_n) \text{ for the process } \pi^- + p \to n + \pi^0\,,$$

$$\frac{b}{\sqrt{\omega}}(\bar{\sigma}\bar{e})\delta(\bar{r}_p - \bar{r}_n) \text{ for the process } \pi^- + p \to n + \gamma,$$

where $\bar{r}_n$ is the $\pi$-meson coordinate, $\bar{r}_p$ is the proton coordinate, $\omega$ is the $\gamma$-quantum energy, $\bar{e}$ is the unit vector of the $\gamma$-quantum polarization, $a$ and $b$ are constants. The ratio $|a|^2/|b|^2$ is easily expressed in terms of the Panofsky ratio for hydrogen, which is measured with great accuracy. The Panofsky ratio for hydrogen according to Cocconi *et al.* [4] is $P_{\mathrm{H}} = 1.53 \pm 0.02$.

The nuclear wave functions $He^3$, $H^3$ are

$$\Psi = \frac{1}{\sqrt{2}}(\chi'\xi'' - \chi''\xi')\,\psi(r_1, r_2, r_3)$$