Stars Produced by π^- Capture in a Hydrogen Bubble Chamber Containing Dissolved Helium*

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One-pronged stars produced by π^- capture in a hydrogen bubble chamber containing dissolved helium have been investigated. The distribution of prong lengths in the interval 0.029 to 0.64 g/cm² is presented. About one-third of the prongs in this interval are found to have a unique range corresponding to tritons from the reaction $\pi^- + He^4 \rightarrow H^3 + n$. Some prongs lying beyond the triton peak are identified as protons from the reaction $\pi^- + He^4 \rightarrow H' + 3n$. The fraction of pions producing stars is found to be approximately equal to the helium concentration.

In a study of negative mesons stopping in the Chicago hydrogen bubble chamber we have observed over one hundred one-pronged stars of which about one-third have a unique range. Mass spectrometric analysis of the hydrogen showed a small contamination of helium. In later parts of the experiment helium was deliberately added.

From the observations which follow, we conclude that the reactions involved are

$$\pi^- + He^4 \rightarrow t + n, \quad (1)$$

$$\pi^- + He^4 \rightarrow p + 3n, \quad (2)$$

and possibly

$$\pi^- + He^4 \rightarrow d + 2n, \quad (3)$$

where t, p, and d are tritons, protons, and deuterons.

The number of stars observed in each of four samples of hydrogen is shown in Table I. The figures for the fourth sample were obtained by Derrick, Pewitt, and Yodh[1] in an experiment to check the results of the Chicago work. The distribution of prong lengths for the first three samples is shown in Fig. 1. The scanners recorded all prongs of projected length greater than 2 mm which originated and ended in the chamber. In Table I and Fig. 1 we list only events of true length greater than 5 mm. The upper limit to the track lengths is set by the dimensions of the illuminated portion of the bubble chamber (Chicago Chamber—145 mm deep ×230 mm diam; Carnegie Tech. Chamber—76 mm deep ×152 mm diam). Most of the pions stop near the center of the chamber.

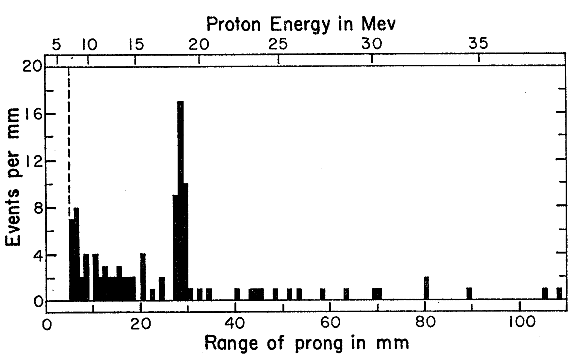

FIG. 1. Range distribution of prongs. The upper scale shows the energy the prongs would have if they were protons.

TABLE I. Number of stars and π^- stops observed in four samples of hydrogen. All stars are single-pronged. Only prongs longer than 5 mm are recorded.

Hydrogen sample	Helium concentration[a]	Total number of stars	Stars with 27–30 mm prongs	π^- stops	Stars per π^- stop ÷helium concentration
Purified[b]	9×10^{-5}	1	0	15 300	$\sim$1
Normal[c]	$\geq2.1\times10^{-4}$	75	27	72 000	$\leq$5
Contaminated[d]	$\geq1.8\times10^{-3}$	29	9	12 000	$\lesssim$1.3
Carnegie Tech[e]	$(1.0\pm0.3)\times10^{-2}$	22	11	1875	$\sim$1.2
Totals for all samples		127	47		

[a] Helium atoms per hydrogen atom from mass spectrometric analysis.
[b] The "purified" sample, obtained from the U. S. Bureau of Standards, contained about two-thirds of the normal concentration of deuterium. Special precautions were taken to clean and flush the chamber and charcoal traps before filling.
[c] The "normal" sample was commercial hydrogen. Analysis of gas from the same source showed 210 parts per million of helium. Additional helium may have entered the chamber while introducing the gas.
[d] The "contaminated" sample contained 800 parts per million of deuterium and 1600 parts per million of helium in addition to that in the "normal" sample.
[e] See reference 1.

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[1] K. Derrick, E. G. Pewitt, and G. B. Yodh (private communication).

When the prong lengths in the peak between 27 and 30 mm are averaged using appropriate values for the liquid hydrogen density for each run, we find a range of 0.162 ± 0.003 g/cm^2 corresponding to energies of 18.4, 25.3, 30.5, and 73.3 Mev for protons, deuterons, tritons, and alpha particles. The small curvature of the prongs in the 25 000-gauss field of the chamber shows that they are certainly heavier than protons and probably heavier than deuterons. If we assume that the peak is due to a two-body process we may analyze the possible combinations of prongs and recoils. Since the prong is heavier than a proton, the recoil, if charged, must be at least as heavy as Li^6 in order to leave no visible track. If the recoil is neutral it cannot be a photon or neutrino since a massless recoil would need an energy much greater than the rest energy of a pion in order to balance momentum with prongs of the observed range. Of the remaining prong-recoil combinations, (d-n), (t-n), (α-n), the only one involving a plausible initial system is the one corresponding to reaction (1). Further evidence against the combination α-n or any other combination involving a nucleus of $Z>1$ is the complete absence of multiple-pronged stars.

If the prong is a triton its energy as determined from the range is 30.5 ± 0.5 Mev. The recoiling neutron would have an energy of 91.2 ± 1.5 Mev to balance momentum. The total kinetic energy of the product particles would be 121.7 ± 2.0 Mev. This is to be compared with the energy calculated from the masses of the assumed particles:

$$\{M_\pi-[(M_t+M_n)-M_\alpha]\}c^2=119.1 \text{ Mev}.$$

We note that the two figures for the total kinetic energy are in good agreement.

No complete analysis was possible for the stars lying outside the peak. However, range vs curvature measurements were made of eight prongs longer than 30 mm. Six were identified as protons by comparison with tracks which were known to be stopping protons. Two appeared to be deuterons though they were not positively identified.

From the data presented we conclude:

(a) Reactions (1) and (2) occur when negative pions are captured by He^4. No conclusive test was made for reaction (3).

(b) Reaction (1) occurs in about $\frac{1}{3}$ of all the events with prong ranges between 5 and 110 mm (i.e., 0.029 and 0.64 g/cm^2). These limits correspond to 7.2- to 38-Mev protons or 9.9- to 53-Mev deuterons.

(c) The total number of 5- to 110-mm stars per stopping pion is approximately equal to the fraction of helium atoms in the solution. (See last column of Table I.)

Our conclusion that reaction (1) occurs in about $\frac{1}{3}$ of the pion captures contradicts the results of work by Ammiraju and Lederman[2] who captured negative pions in a diffusion cloud chamber. They found that tritons were produced on the order of or less than one time in 60 captures. Somewhat over half of their events lay outside the range covered by our experiment. The difference in prong ranges included in the two experiments reduces but does not remove the difference in the conclusions concerning triton production. We do not understand the discrepancy. As indicated in Table I, the measurements of the Carnegie Institute group are in good agreement with the Chicago-Argonne experiment.

Our result is in rough agreement with the theoretical work of Petschek[3] who finds that 22% of π^- from the K shell in helium should lead to triton emission. In an earlier work Clark and Ruddlesden[4] predicted a ratio of 3%. The important difference between these calculations was that Petschek used a helium wave function which favored higher energy components.

The emphasis in this work has been to establish the existence and approximate frequency of triton emission. A detailed study of the proton and deuteron spectrum would be required for a further test of the helium wave function or other features of the theoretical work. The appearance of the tritons provides a convenient test for helium in the bubble chamber.

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[2] P. Ammiraju and L. M. Lederman, Nuovo cimento 4, 283–306 (1956).
[3] A. G. Petschek, Phys. Rev. **90**, 959 (1953).
[4] A. C. Clark and S. N. Ruddlesden, Proc. Phys. Soc. (London) **A64**, 1060 (1950).