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# Production of Negative μ-Mesons and Their Behavior in Nuclear Research Emulsions

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A beam of negative $\mu$-mesons produced inside the tank of the 184-inch cyclotron has been studied. 2.7±1 percent formed one-prong stars when stopped in Ilford C2 emulsion. Two two-prong stars with prong ranges of 2 or 3 microns were observed which appear to be fission-like disintegrations induced by $\mu^-$ capture. 32 percent of the $\mu^-$-mesons have clusters of grains about 1 micron in diameter or two pronglets about one micron long at their termini. These are interpreted as Auger electrons accompanying capture by a heavy nucleus, or in some cases as fission of the capturing nucleus. An upper limit on the cross section for direct production of negative $\mu$-mesons, $d\sigma/d\Omega dp$, in the forward direction at $pc=129$ Mev, has been evaluated to be 0.015 times the cross section for production of negative $\pi$-mesons in the same interval.

## INTRODUCTION

EARLY studies[1] of the mesons coming from a cyclotron target bombarded by alpha-particles revealed that some positive mesons coming from the target were muons. They also revealed that negative muons did not seem to come from the target but from regions where pions decayed in flight. The positive muons from the target were presumed to arise from decay of positive pions stopped in the target, and the observed muon spectrum was consistent with this assumption. The question whether muons are also produced in a primary process in the target can be answered in the affirmative if such mesons can be detected in the presence of a background of muons arising from decay of pions in the vicinity of the target.

This paper[2] reports an experiment to study the production of negative muons using nuclear track emulsion detectors in the vicinity of a target inside the cyclotron. The bombarding proton beam had an energy of 340 Mev, which exceeds the threshold for single production of muons by more than 200 Mev if such a process is possible. It also exceeds the threshold for production of muons in pairs, one member of which has an energy of 60 Mev—high enough to be detected in this experiment.

## EXPERIMENTAL APPARATUS

The target used was a rod of beryllium of cross section $\frac{1}{4}$ in.$\times\frac{1}{4}$ in. Adjacent to this a channel was constructed which, when placed in the magnetic field of the cyclotron, would admit particles from the target only if they emerged in the forward direction, i.e., parallel to the bombarding beam, in the momentum interval 129±4 Mev/$c$. Particles originating from points other than the target would be admitted in other momentum intervals. Pions originating from the target and traversing the channel lie in the range interval 1.5 to 1.7 cm of copper. In addition to these, a few higher energy pions will scatter into the channel and appear with longer ranges. Muons from the target, traversing the channel, would appear in the range interval 2.0 to 2.85 cm of copper. Muons which arise from decay of pions in flight will emerge from the channel distributed over a wider range interval. Since the density of pions rapidly decreases with distance from the target, the target region acts as a diffuse source of muons, even if all muons originate from decay of pions in flight.

Figure 1 is a diagram of the experimental arrangement, showing the target, lead shielding, the channel, and the absorbers in which the photographic emulsion was embedded.

At the end of the channel, in the position marked $A$ in Fig. 1, was placed a rectangular copper absorber, 2.0 cm thick, which stops $\pi$-mesons of momenta up to 142 Mev/$c$. However, $\mu$-mesons of momenta greater than 120 Mev/$c$ penetrate this barrier because of their smaller mass. The $\mu$-mesons are then slowed down in a wedge shaped copper absorber and detected in a 200-micron Ilford C2 emulsion placed behind the wedge. Immediately behind the emulsion an absorber of aluminum (chosen to reduce back scattering) was bolted, so that the three absorbers formed a solid plate holder. Figure 2 shows the position of the emulsion in the absorbers.

This method of stopping the $\pi$-mesons was employed only after the experiment had been tried without using the rectangular absorber. Originally it was hoped to observe the $\pi$-mesons and $\mu$-mesons on the same plate

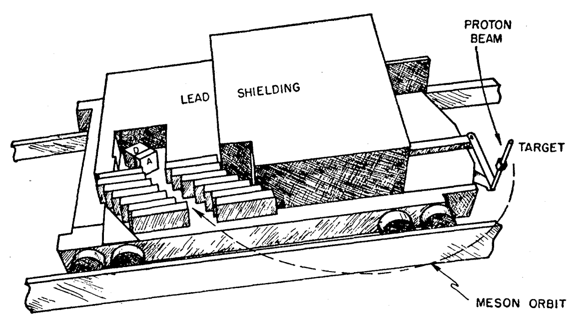


FIG. 1. Apparatus for producing a negative muon beam, showing the positions of the target, shielding, channel, and plate holder. During the bombardment, the channel and chamber containing the plate holder were covered with additional shielding.

[1] Burfening, Gardner, and Lattes, Phys. Rev. 75, 382 (1949).
[2] Preliminary results of this experiment were reported to the Berkeley meeting of the Physical Society in December, 1951. The abstract is published in Phys. Rev. 85, 771 (1952).

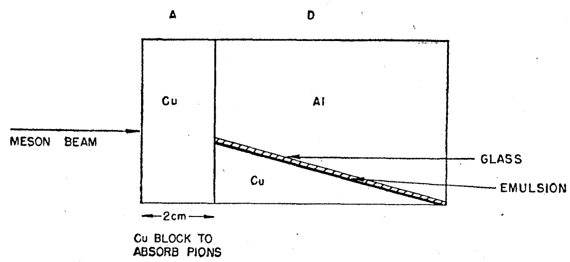


FIG. 2. Plate holder and emulsion for detecting the negative muons. Lead shielding was also placed under this plate holder to prevent mesons scattering into the emulsion from below.

separated by range into two groups. One plate containing both the pions and muons admitted by the channel was scanned to obtain the muon-pion ratio used in estimating the upper limit on the cross section for direct production. However, without the rectangular block, some $\pi$-mesons were able to reach the $\mu$-range portion of the plate by scattering into the glass backing the emulsion, or the cracks between the absorber and the emulsion, in which ranges are greater than in copper, so that when these mesons again scattered into the emulsion, they ended in the section of the plate containing the muon distribution. To eliminate this $\pi$-contamination, the rectangular absorber was placed in front of the detecting plate to stop the $\pi$-mesons before there was any chance for them to enter media in the detecting system less dense than copper.

The entire apparatus was mounted on a cart which was moved through an air lock into the cyclotron tank, where the experiment was performed.

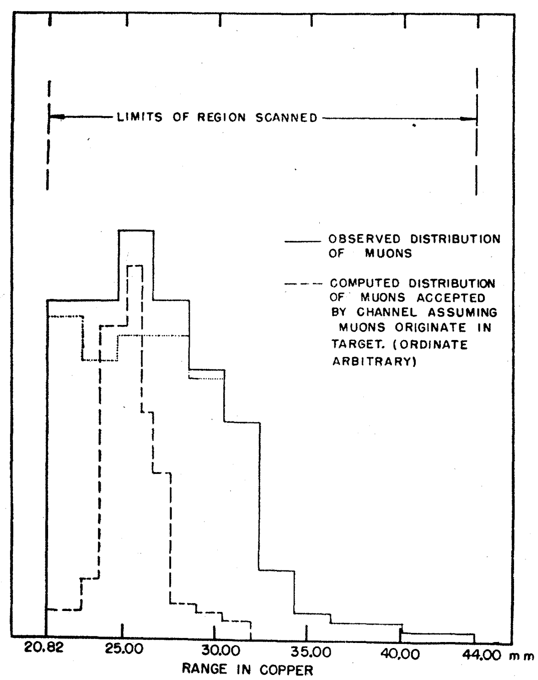


FIG. 3. Range histogram of $\rho$-mesons. The solid line histogram is the observed distribution. The dashed line shows the computed distribution expected if all of the $\mu$-mesons are produced in the target. The dotted line histogram, obtained by subtracting the dashed line distribution from the solid line distribution, is the least possible number of $\mu$-mesons which could originate from decay in flight. The area between the dotted and the solid histograms represents the maximum number of $\mu$-mesons observed which could have been produced in a primary process in the target.

## RESULTS

Following a 10-minute exposure, 369 $\rho$-meson endings were observed. Their distribution in range is shown by the solid line histogram in Fig. 3. In addition to these a number of mesons were observed, which formed stars. In line 1 of Table I, these mesons are classified by the number of prongs in the stars they produce. In order to compare our star prong spectra with those of Adelman and Jones,[3] Menon,[4] and Adelman,[5] the definition of a star prong used by these experimenters has been adopted for this study. According to their definition, any track of length greater than one micron, and having a well-defined direction of emergence from the star center, is a prong.

Two sources of pion contamination are known. A few high energy pions scatter into the channel. Also, there appear to be pions produced in the shielding, probably by neutrons. This is indicated by the fact that of the six negative mesons which entered the emulsion at angles greater than 90° to the muon beam direction, only two were $\rho$-mesons, while four formed stars. Also, one meson was found entering the emulsion at greater than 90° which underwent $\pi-\mu$ decay.

An attempt was made to distinguish between star-forming muons and the pion contamination, by grain-counting all of the mesons which formed stars, and a sample of the non-star-forming mesons. Although groups of predominantly $\pi$-mesons could be separated from groups of $\mu$-mesons by this method, the resolution was not sufficient to determine whether an individual meson was a pion or a muon.

Correction for the pion contamination was carried out in the following manner: all stars of three or more prongs were assumed to be due to pion capture, since their distribution is consistent with the known prong spectrum of pions and because the excitation imparted to the nucleus by muon capture is expected to be small. Normalizing to the total number of three and more prong stars, the numbers of two, one, and zero prong stars, which would most nearly fit an Adelman distribution,[5] were computed. These numbers (shown in line 3 of Table I) are subtracted from the observed distribution to deduce the number of muons ending in the plate. The results are shown in line 4 of Table I. The probable errors which have been assigned to these numbers have been computed from the formula for the probable error of the difference between a Poisson variable (the ob-

[3] F. L. Adelman and S. Jones, Science **111**, 226 (1950).
[4] Menon, Muirhead, and Rochat, Phil. Mag. **41**, 583 (1950).
[5] F. L. Adelman, Phys. Rev. **85**, 249 (1952); see also line 2 of Table I.

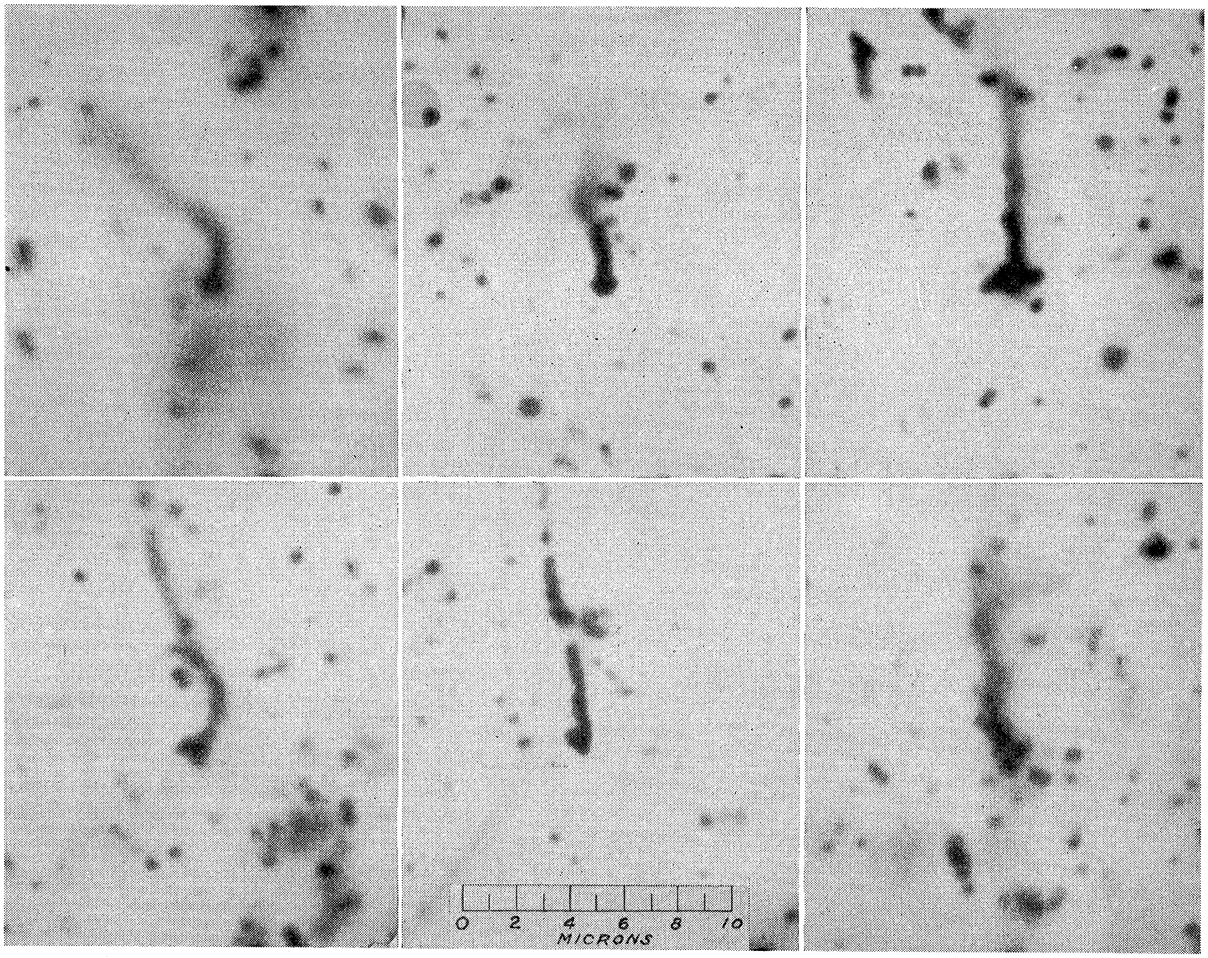


FIG. 4. Examples of muons ending in spherical clusters of grains or in pronglets, one micron long.

served number of stars of given prong number), and a constant (the Adelman percentage) times another Poisson variable (the total number of stars of more than two prongs). Of the mesons observed, 367 are calculated to be $\mu$-mesons; 10 or $2.7\pm1$ percent of these formed one-prong stars. Morinaga and Fry,[6] studying negative muons from the Chicago cyclotron, find 3.1 percent forming stars, 2.6 percent forming one prong stars. The similarity between the prong distributions obtained in this experiment, and the experiment of Morinaga and Fry, confirmed that the mesons which were studied were actually negative $\mu$-mesons.

A study of the endings of these mesons under a magnification of 1375× showed that 32 percent of the non-star-forming mesons ended in roughly spherical clusters of grains about one micron in diameter, or in two short pronglets each about one micron long (see Fig. 4).* Short pronglets were observed by Franzinetti[7] and were interpreted by Cosyns *et al.*,[8] as due to internal conversion electrons resulting from capture of muons in

TABLE I. Star prong spectra.

| Number of prongs | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Observed distribution | 369 | 20 | 8 | 5 | 3 | 2 | 1 |
| Adelman distribution (%) | 27 | 24 | 24 | 16 | 8 | 1 (5 and 6 combined) | |
| Probable $\pi$ contamination | 12 | 10 | 10 | 5 | 3 | 2 | 1 |
| Deduced muon prong spectrum | $357\pm13$ | $10\pm4$ | $0+3$ | | | | |

[6] H. Morinaga and W. F. Fry, Phys. Rev. **87**, 182 (1952).

[7] C. Franzinetti, Phil. Mag. **41**, 86 (1950).

* *Note added in proof:*—Recent work by Fry (private communication) supports belief in the Wheeler-Tiomno mechanism for capture of $\mu^-$ mesons, $\mu^-+P\rightarrow n+\nu$, with a neutrino energy of about 75 Mev and a resulting nuclear excitation of about 25 Mev. The range of a light nucleus in the emulsion recoiling from the emission of a 75 Mev neutrino or from a neutron or neutrons emitted with most of the nuclear excitation energy will be of the order of one micron (James F. Miller, University of California Radiation Laboratory Report 1902). Such recoils might explain a few of the heavy clusters of grains at the meson endings.

[8] Cosyns, Dilworth, Occhialini, Schoenberg, and Page, Proc. Phys. Soc. (London) **A62**, 801 (1949).

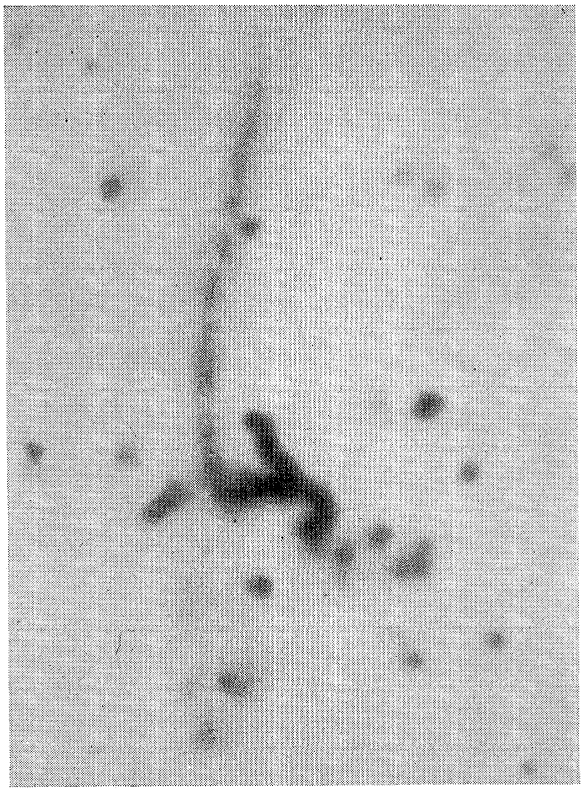

FIG. 5. One of the small two-prong stars, in which each prong is only 3 microns long.

silver and bromine. Several experimenters[9] (including the author) believe that some of these pronglets are too heavily ionizing to be electrons, which suggests as an alternate interpretation that some of these events are fission type disintegrations. In addition to these, two two-prong stars were found in which the prongs were only two or three microns long (see Fig. 5). These prongs are too heavily ionizing to be electrons, and of too short range to be protons escaping the barrier of a still intact nucleus. They appear to be fission of a light nucleus. Although such stars are not a frequent consequence of $\pi$-meson capture, the possibility that these may have been caused by $\pi$-mesons cannot be excluded. George and Evans,[10] exposing plates underground to cosmic rays, found 0.6 percent of the stopped negative muons forming small two prong stars.

The energies of the mesons detected in the plate were measured by their ranges in the copper absorbers. The solid line histogram in Fig. 3 shows the observed range distribution of $\rho$-mesons in the plate. The dashed line histogram in the same figure is the range distribution of $\mu$-mesons which would be expected if the $\mu$-mesons were produced in the target. This curve was obtained from an observed range distribution of $\pi$-mesons selected by the channel from a target of the same dimensions as the one used in this experiment. The ranges of $\mu$-mesons having the same momenta as the $\pi$-mesons observed were computed and the relative abundances in each momentum interval of the spectrum plotted for these ranges.

An upper limit on the number of directly produced muons may be estimated by considering the observed distribution as the sum of the muons produced directly in the target, and the muons arising from decay in flight of pions near the target. The spectrum of these latter muons should be as if they originated from a wide, diffuse target centered at the real target. In particular, the distribution should not be double peaked, nor should its peak, if it has one, be displaced from the peak of a distribution from the real target. Keeping the decay-in-flight spectrum subject to these conditions, the maximum number of muons which could have come directly from the target was determined.

The resulting decay-in-flight spectrum is shown by the dotted line histogram in Fig. 3. The number of mesons between the dotted line and the solid line is the maximum number which can have been directly produced. This number may be compared with the number of $\pi$-mesons produced in the same solid angle and momentum interval to obtain an upper limit on the ratio of the cross sections $d\sigma/d\Omega dp$ for muon and pion production. For this, a plate which had been exposed without the absorber $A$ of Fig. 2 was scanned and the ratio of muons to pions admitted by the channel was found to be 0.13. Of the muons, 12 percent is the maximum fraction which could have been directly produced in the target. Therefore, the maximum value of $d\sigma/d\Omega dp$ at $pc=129$ Mev in the forward direction is 0.015 times the cross section for negative pion production in the same interval.

Grateful thanks are due Harry Heckman for construction of the channel and for data on the $\pi$-meson spectrum in the channel, Mr. A. J. Oliver for the photographs of Figs. 4 and 5, Dr. Walter Barkas for conceiving and proposing the experiment, and Dr. Barkas and Dr. Frank Adelman for many helpful discussions throughout the course of the experiment.

[9] E. P. George, private communication, and reference 7.

[10] E. P. George and J. Evans, Proc. Phys. Soc. (London) **A64**, 193 (1951).

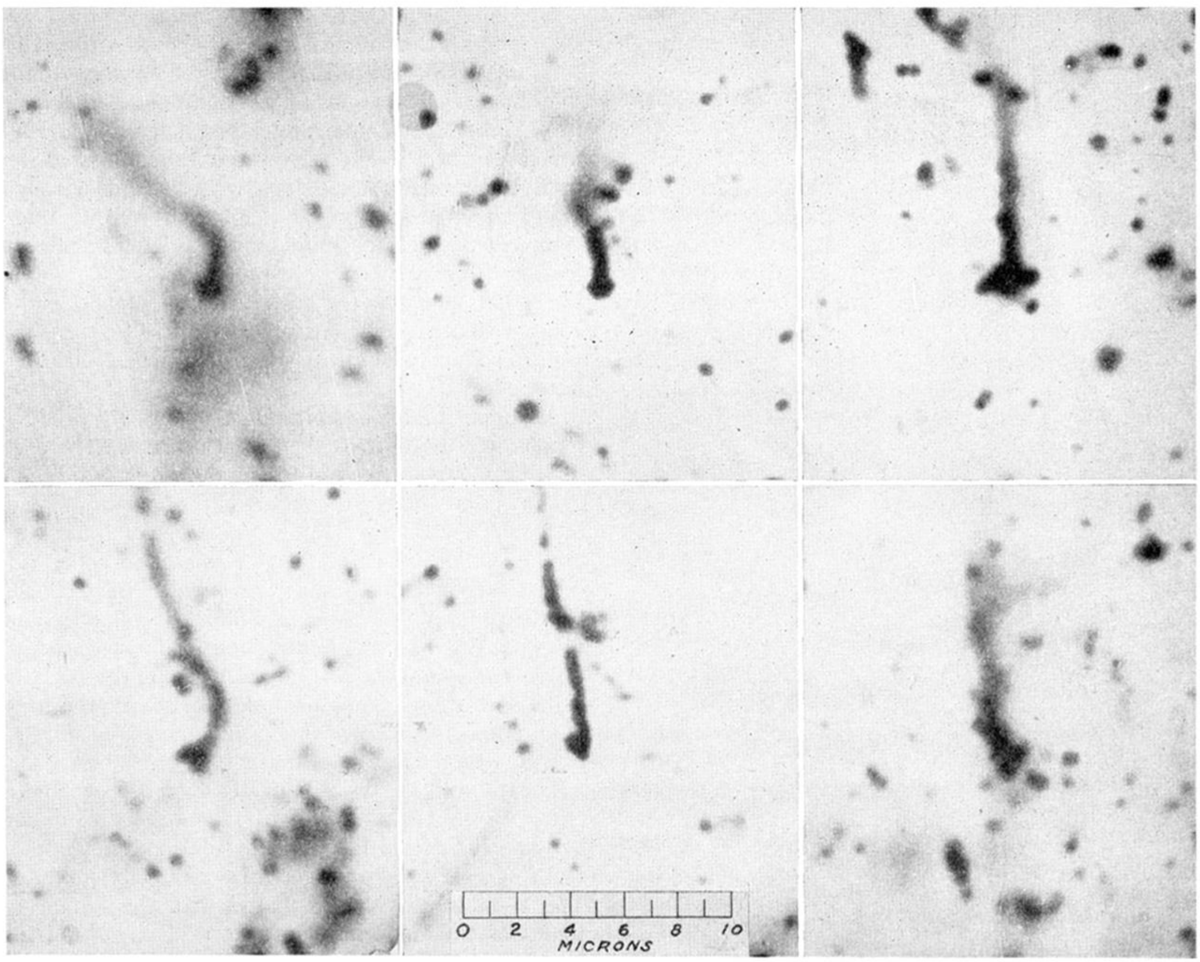


FIG. 4. Examples of muons ending in spherical clusters of grains or in pronglets, one micron long.

FIG. 5. One of the small two-prong stars, in which each prong is only 3 microns long.