Copy 2

UCRL- 486 2nd ed.

UNCLASSIFIED

UNIVERSITY OF CALIFORNIA — BERKELEY

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

RADIATION LABORATORY

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

UCRL-486
Second Edition

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

Contract No. W-7405-eng-48

REVIEW OF WORK ON ARTIFICIALLY PRODUCED MESONS

Hugh Bradner

October 19, 1949

Second Printing May 15, 1950

Berkeley, California

OUTLINE

1. Introduction

2. General Background

3. Experimental Arrangements

3.11 Negative Mesons from α-Particle Bombardment

3.12 Positive Mesons from α-Particle Bombardment

3.2 Meson Production in the Proton Beam

3.3 Meson Production by Neutrons

4. Meson Production

4.11 Excitation Curve for the α-Particle Beam

4.12 Cross Section for Production of π^- Mesons by α-Particle Beam

4.13 Energy Spectrum for Mesons Produced by the α-Particle Beam

4.14 Excitation Function for the Mesons Produced by the Proton Beam

4.15 Cross Section for Production of Negative π Mesons by Proton Beam

4.16 Neutron Beam

4.21 Ratio of Cross Sections for Production of Low Energy Positive and Negative π Mesons

4.22 Ratio of Cross Sections for Production of High Energy Positive and Negative π Mesons

4.3 Neutral Mesons

5. Production of μ Mesons

5.1 Source of μ^- Mesons

5.2 Production of μ^+ Mesons

6. Properties of Mesons

6.111 General Discussion - Mass of π^- Mesons

6.112 Mass Measurements by Radius of Curvature and Range

6.113 Mass Measurements by Grain Counting

6.12 Stars Produced by π^- Mesons

6.13 Decay of π^- Mesons

6.14 Half-life of Negative π Mesons

6.15 Charge on the π Meson

6.21 Star Production by μ^- Mesons

6.311 Mass of Positive Mesons by Radius of Curvature and Range

6.312 Mass Measurements by Comparison with Proton Range

6.32 Decay of Positive π Mesons

6.33 Half-life of Positive π Mesons

6.41 Masses of the μ^+ and μ^- Mesons

6.42 $\pi^+ - \mu^+$ Decay and the Mass of the Neutretto

6.43 Decay of the μ^+ Meson

7. Production of Mesons by X-rays from the Synchrotron

7.1 Introduction

7.2 Experimental Arrangements

7.3 Experimental Results - Calculation of Positive and Negative π Yields

7.4 Ratio of Positive and Negative π Meson Yields

7.5 Energy and Angular Distribution and Cross Section

8. Summary of Meson Properties

8.1 Notes on Table 8(1)

9. Auxiliary Data

9.11 Energy Available in the Laboratory System for Meson Production

9.12 Absolute Threshold

9.2 Range-energy Relations in Nuclear Emulsions

10. Acknowledgments

11. Bibliography

REVIEW OF WORK ON ARTIFICIALLY PRODUCED MESONS

Hugh Bradner

October 19, 1949

1. Introduction

Artificially produced mesons were detected for the first time at the University of California Radiation Laboratory in February 1948.[1] The mesons were created by bombarding a carbon target with the 390 Mev alpha-particle beam of the 184-inch synchrocyclotron[2] and were detected by the characteristic tracks which they made in going through the emulsions of special photographic plates.

Shortly before Gardner and Lattes announced the production of mesons by the cyclotron, Sakata[3], Tanikawa[4] and Bethe and Marshak[5] had predicted the existence of light and heavy mesons on the basis of cosmic ray evidence and Powell and co-workers[6] had established the existence of mesons of two masses by studies of nuclear plates exposed to cosmic rays and had deduced some properties of the particles. They concluded that the light, or μ, meson had a mass of approximately 200 electron masses; while the heavy meson, which they termed π or σ had approximately 300 to 400 electron masses. They did not know how many of the heavy nonstar forming mesons were positive; though they inferred that most or all of the star forming, or σ, mesons were negative. It was deduced that π and σ mesons had strong interaction with nuclei and that the heavy mesons had a mean lifetime between 10^{-6} and 10^{-11} seconds. The decay in flight of π and σ mesons formed at high altitudes was presumed to give μ mesons, the particles ordinarily seen at sea-level. σ mesons produced nuclear explosions upon coming to rest in light or heavy elements, while positive π mesons were thought always to produce positive μ mesons upon coming to rest in matter. From the fact that the positive μ meson always was produced with the same kinetic energy of approximately 4 Mev, Lattes et al. concluded that a single neutral particle

was also produced during the decay. The preliminary estimates of π^- meson and μ^+ meson masses, however, led to the erroneous conclusion that the neutral particle had about the same mass as the μ^+ meson.

The production of mesons in the Berkeley cyclotron opened the possibility of studying the mesons under conditions of 10^8 times higher intensity, with magnetic sorting to separate the particles of different charges. Two immediate results were the recognition that approximately one-third of the heavy negative (π^-) mesons do not produce stars, and the assignment of a mass value of 313 ± 16 electron masses to the π^- meson. (Both of these observations were further refined in later experiments.)

The present review is concerned with the investigation of properties of heavy and light mesons, performed with the α-particle beam of the Berkeley cyclotron during the period from February, 1948 to February, 1949, and with the proton beam of the machine from February to July, 1949. A short account of the results thus far obtained with the 335 Mev Berkeley synchrotron(7) will be given near the end of the paper.

It is the purpose of this paper to assemble the best values available at the present time on meson production and meson properties. The material is arranged for easy reference and future additions, rather than coherent reading. It appears difficult to present a detailed account of the investigations, and at the same time to show clearly the development of current views concerning mesons. Therefore, the main body of the text will treat the individual experiments in considerable detail, while a summary of present concepts of meson properties will be given in the last section of the paper.*

Work that has been reported only in American Physical Society meetings will

---

*The table has been revised to April, 1950.

be treated in greater detail than those researches which have been published. The experimental work presented here is the result of the joint effort of a number of people most of whom have comprised the Film Program Group* of the University of California Radiation Laboratory. This summary report was begun by C.M.G. Lattes during his stay in Berkeley, and many of the sections on experiments with π^- mesons were drafted by him. Sections 4.11, 4.14 and 6.12 were written by S. Jones and part of Section 4.12 was written by H. Wilcox. V.Z. Peterson and H. Wilcox made the cross section calculations. D. Sherman has compiled an extensive bibliography to accompany this paper, but because of its length it has been assigned a separate report number, UCRL 487. The rest of the text was assembled by H. Bradner, and he assumes responsibility for opinions not attributed to other experimenters. The sequence of topics follows closely the outline submitted by W.H. Barkas to the Echo Lake Cosmic Ray Symposium in June, 1949. There are a number of topics for which detailed information has been obtained directly from the experimenter, and in these cases, credit for the contributions will be given in the text.

All the work except that described in Section 4.3 was done with Eastman Kodak "NTB" or Ilford "Nuclear Research" plates, since the meson intensity and ratio of mesons to background was so low that other methods of detection such as cloud chambers and scintillation counters failed to show the presence of mesons. A very few cloud chamber photographs have been obtained which show mesons produced by neutrons and x-rays, and some success has just recently been achieved by L.W. Alvarez

---

*The group working with mesons produced by the cyclotron has included Mr. F. Adelman, Dr. W.H. Barkas, Mr. A.S. Bishop, Mr. K. Bowker, Dr. H. Bradner, Mr. J. Burfening, Mr. P. Carnaham, Mr. W. Conover, Dr. E. Gardner, Miss E. Grunwald, Mr. S. Jones, Dr. C.M.G. Lattes, Dr. E. Martinelli, Mr. E.O. Meals, Mr. D. O'Connell, Mr. A. Oliver, Mr. V.C. Peterson, Dr. R. Richardson, Miss F. Smith, Mr. S. White, Dr. C. Richman, Dr. H. Wilcox, Mr. M. Weissbluth, and others.

in using counters to detect positrons from the decay of positive μ mesons.*

A brief report on pair spectrometer investigations by York and Moyer on high energy photons is contained in Section 4.3 since their work implies the possible existence of neutral mesons.

2. General Background

Before describing the experimental arrangement used for the production and the detection of mesons in the cyclotron it is worthwhile to point out a few observations which served to guide the search for artificially produced mesons.

a. At the beginning of 1948 two types[1][2] of mesons with masses of the order of 200 and 300 e.m. were known to exist. It was assumed that such mesons did not exist inside nuclei, so that if they were to be produced under nuclear bombardment, their mass would have to be provided at the expense of the kinetic energy of the incident particles. Furthermore, it was believed that if mesons were created at all, they would be produced in single nucleon-nucleon collisions. If this assumption is correct, it would appear at first sight that alpha-particles of approximately 400 Mev would not have enough energy to produce either μ or π mesons;** at least 100 Mev would be needed in the center of mass system to make a μ meson and 150 Mev for a π meson, while each neutron or proton in the alpha particle beam would carry only 100 Mev and therefore have only 50 Mev available in the nucleon-nucleon center of mass system for meson production.

The situation is not so discouraging, as was pointed out by McMillan and Teller[3] and substantiated by Horning and Weinstein,[4] when one takes into

---

*Note added in proof: Preliminary data suggest that J. Steinberger is also successful in detecting positive mesons by delayed coincidences, and there are indications that H. Bradner and M. Dazey have detected π^- meson stars in transtilbine.

**For the remainder of this paper the symbol π will refer to either positive or negative heavy meson unless a superscript designates a specific sign.

account the internal kinetic energy of the nucleons in the α-particles and in the target nucleus. The nucleons are assumed to oscillate within the nucleus, with a Fermi energy of approximately 25 Mev. Under favorable conditions the impinging nucleon can be moving within its nucleus in the direction of the beam, while the nucleon in the target can be moving in the opposite direction. The momentum at impact is thus increased by the factor

$$\frac{2\sqrt{E_f} + \sqrt{E_\alpha/4}}{\sqrt{E_\alpha/4}}$$

where E_f is the Fermi energy, and E_α is the α-particle energy. The calculations of these writers implied that π mesons could be produced by the α-particle beam, but that π meson production in the 190 Mev deuteron beam would be negligible.

b. The experiments of Conversi et al.[5] on the absorption of cosmic ray mesons in heavy and light materials clearly indicated that μ mesons do not interact strongly with nucleons, as would be expected if they were responsible for nuclear forces.[6] An estimate of the cross section for μ meson production in the cyclotron, based on these results, shows that it is too small to detect. On the other hand, the direct production of π mesons in cosmic ray stars[7] and the frequent occurrence of stars at the end of their range, indicated that these heavier mesons participate in a strong nuclear interaction and consequently might have a reasonably high cross section for production in the cyclotron. It was, therefore, clear that in looking for artificially produced mesons one should try to arrange the experiment in a way most favorable for the detection of π rather than μ mesons.

c. The most obvious way to look for artificially produced mesons was to expose the plates to the full-energy α-particle beam and search for stars produced in the emulsion. It was known from plates exposed to cosmic rays that occasionally

mesons are ejected in addition to the usual heavy particles from the center of the star. An experiment of this type was tried. The exposure was arranged as shown in Fig. 2(1) and about 5000 α-particle induced stars were observed under 500 diameters magnification. No mesons were found, but this negative result was expected from a theoretical estimate of the probability of the process and the fact that only mesons of energy up to a few Mev would be registered in the insensitive plates which were used. It was, therefore, clear that an arrangement must be devised to separate the mesons from the much larger number of heavy particles which were also produced under α-particle bombardment.

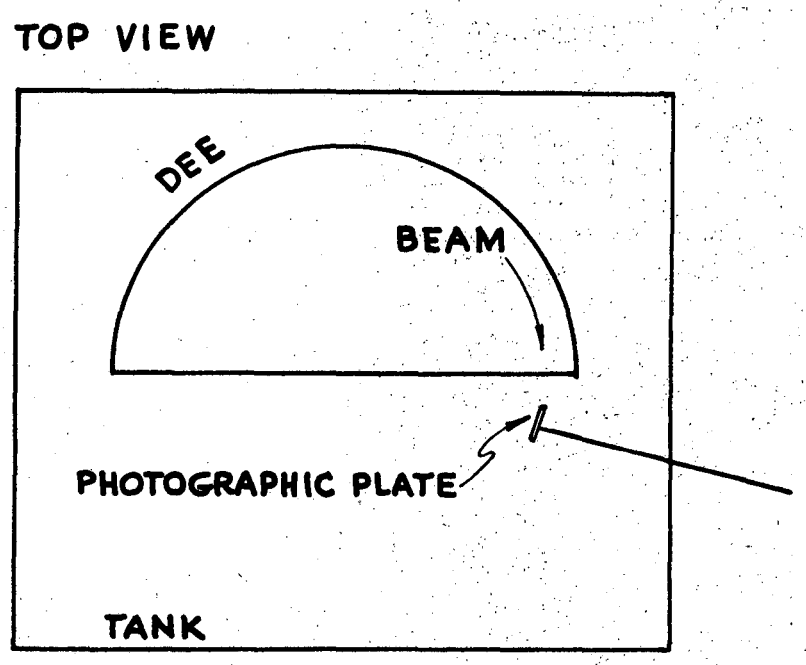
It seemed that an arrangement most suitable for detecting mesons would be one allowing the separation of negative from positive particles, since mesons were the only negative particles expected to be recorded in B1 and C2 plates. E. McMillan suggested the simple and convenient method described in the next section.

3. Experimental Arrangement

3.11 Negative mesons from alpha-particle bombardment

The experimental arrangment that has been used repeatedly for producing and detecting negative mesons produced by α-particles in the cyclotron is shown in Figs. 3.11(1) and 3.11(2). The exposures were made inside the machine in order to make use of the full beam intensity and at the same time to take advantage of the cyclotron magnetic field to separate the negative mesons from the main bulk of heavy positive particles produced during the bombardment.

Fig. 3.11(1) gives a general view of the exposure set-up. The plate holder is supported by a probe which can be moved in and out radially by remote control in order to obtain the desired energy of the bombarding α-particles. The incident ions follow the orbit shown. Negative mesons produced at the target are deflected by the magnetic field and focused roughly at the position of the plates, as


TOP VIEW
DEE
BEAM
PHOTOGRAPHIC PLATE
TANK

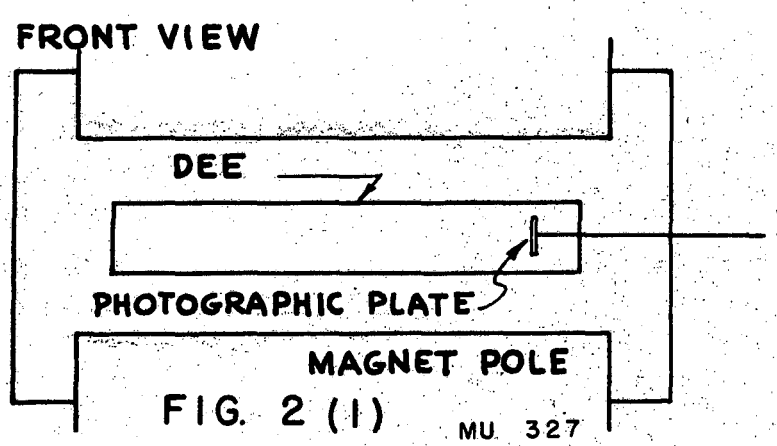
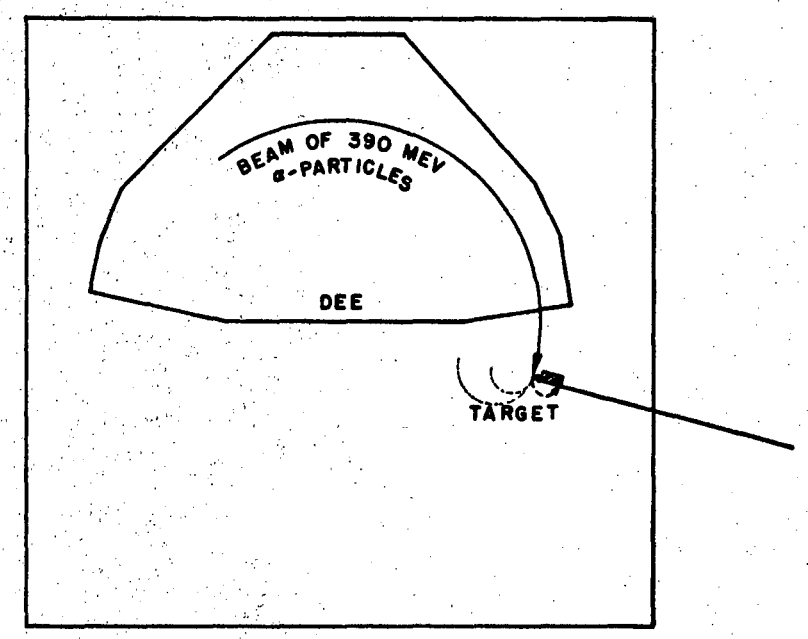

FRONT VIEW
DEE
PHOTOGRAPHIC PLATE
MAGNET POLE

FIG. 2 (I)

MU 327

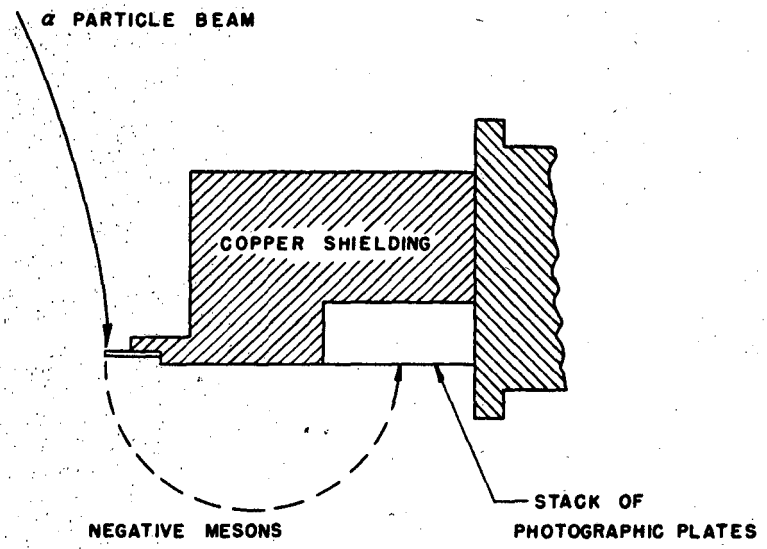


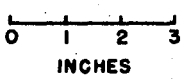
PLAN VIEW OF CYCLOTRON

0 1 2 3
FEET

FIG. 3.11 (1)

MU 344





MU 345

FIG. 3.11(2)

14134-1

shown by the orbits drawn in broken lines. Positive mesons and heavy particles are deflected in the direction away from the plates, as indicated by the orbits drawn in dotted lines.

Fig. 3.11(2) gives a larger view of the actual plate holder. The target was usually a solid piece of graphite or beryllium with dimensions 1 in. x 1 in. x 1/16 in., the smallest dimension being parallel to the α-particle beam. The main body of the plate holder was made of copper with sufficient thickness in all directions to stop ions originating in the target or scattering toward the plates from various places in the interior of the cyclotron.

The distance between the tip of the target and the photographic plates was 4 in. to 7 in., so that mesons of mass 300, describing semicircular orbits as indicated, had an energy from 2 to 4 Mev, depending upon the point of entrance in the plate. Mesons of such energy have a range of approximately 150 to 500 microns in the plates of the type used and their complete path through the emulsion can easily be followed. The dimensions of the plate holder may be inferred from the scale provided in Fig. 3.11(2). Fig. 3.11(3) is an actual photograph of the standard plate holder used in most of the exposures.

For most of the exposures the plates were stacked with emulsion side up and the mesons allowed to enter the emulsions through their "leading" edge. This arrangement is convenient mainly for getting a large concentration of meson tracks near the leading edge of the plate.

The plates were generally wrapped in ordinary photographic black paper 1/10 mm thick to permit handling in daylight. Unwrapped plates were used when it was important to have an accurate measurement of the range or of the initial direction of the mesons in the emulsion. The plates were then exposed singly and tilted 3 to 5 degrees, so that the mesons entered through the upper surface of the emulsion. Measurements on meson tracks near the edge of a plate are not reliable because the

emulsion suffers a considerable distortion during processing. Furthermore the emulsion often peels from the glass for the first 100 to 200 microns.

Most of the exposures were made with Ilford type C2 Nuclear Research plates. When a greater grain density in the tracks was desired, as in the study of π-μ decay or in following the tracks of mesons of energy greater than 5 Mev, more sensitive plates, such as Eastman Kodak "NTB" or Ilford C3, were found more suitable. For work in which a high discrimination between meson and protons tracks was necessary, less sensitive plates, such as Ilford E1 and F3, were employed. Very sensitive plates, such as Eastman Kodak NTB3, Ilford G5, and Kodak Ltd. NT4, have been used recently, but a large background of low energy electron tracks limits their usefulness. The usual thickness of the plates has been 50 to 200 microns and a standard processing technique(1) has been used for most experiments.

Ordinarily, observation and measurement of the meson tracks is made using microscopes with 6X to 10X eyepieces and 90X oil immersion or 40X apochromatic objective. Under these conditions an experienced observer can easily recognize the characteristic tracks left by mesons in the photographic emulsions. Only in a few instances has grain counting been used as a means of identification of the mesons. The appearance of a plate under the microscope is much like Fig. 3.11(4), which is a simple photomicrograph* of a meson amidst a background of random grains and heavy particle tracks. Meson tracks ordinarily scatter too much to permit this type of recording, so ordinary events are sketched, and particularly interesting tracks are photographed stepwise to bring successive short sections of the tracks into focus. Completed mosaics of typical π^--meson tracks photographed with 90X oil immersion objective are shown in Figs. 3.11(5) and 3.11(6).

The plates exposed in the cyclotron during the early stages of the work,

---

*The photomicrographs used in this paper are the work of Mr. A.J. Oliver.

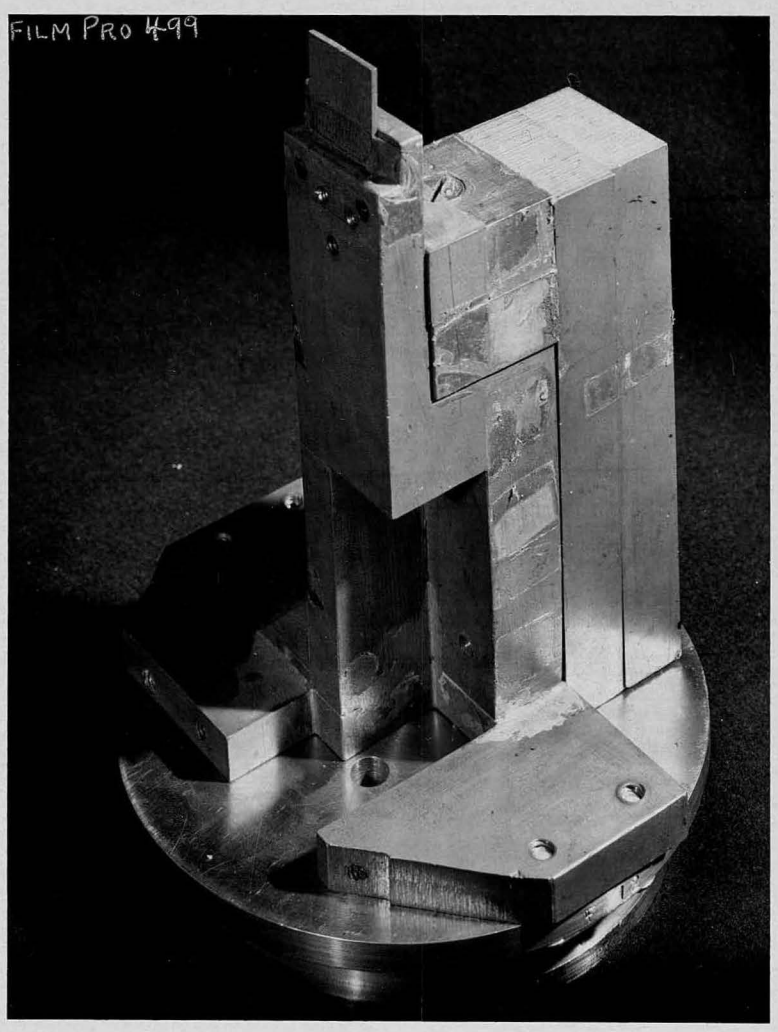


FIG. 3.11 (3)

OZ 722

FIG. 3.11 (4)

OZ 733

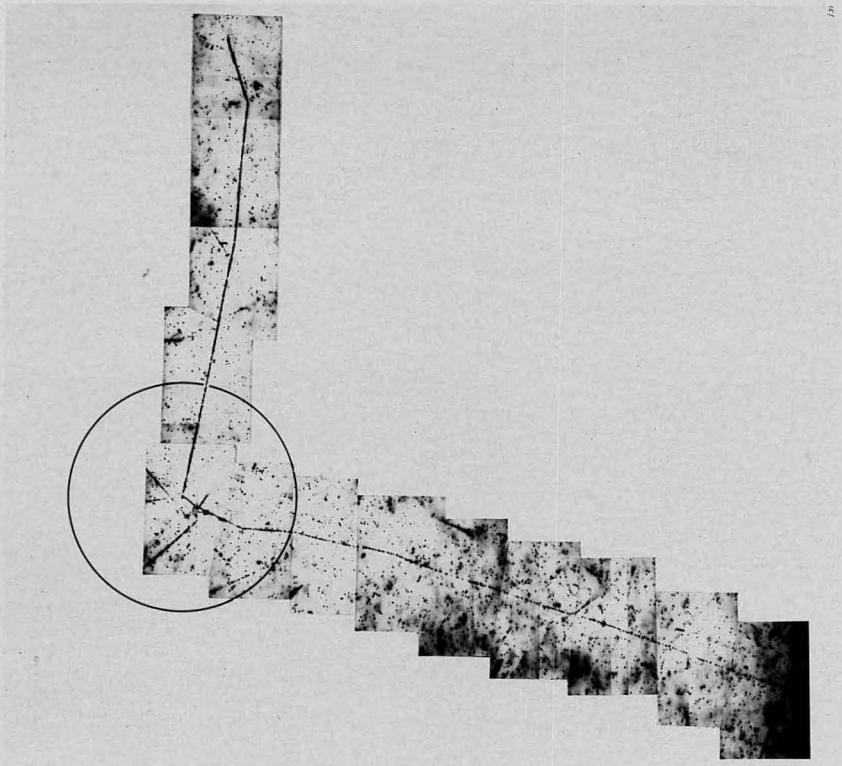


FIG. 3.11 (5)

OZ 729

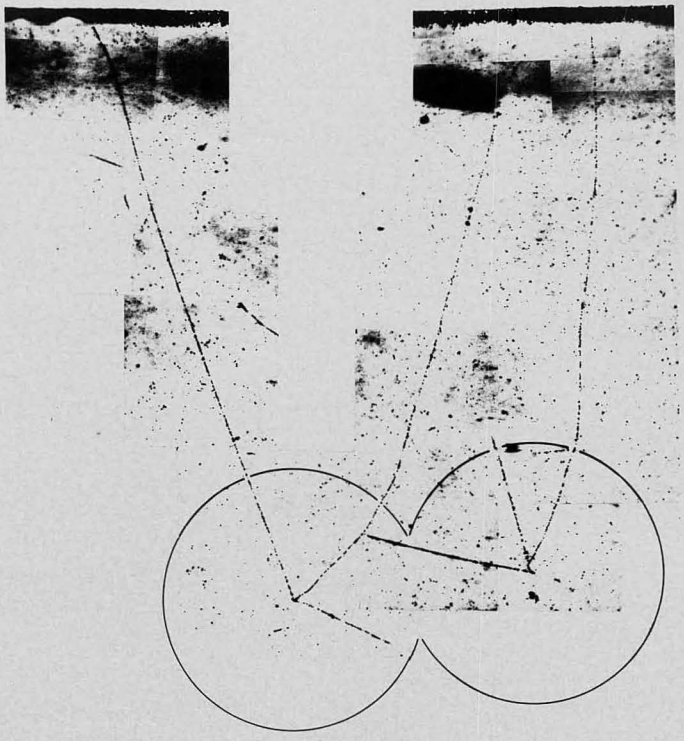


FIG. 3.11(6)

OZ 731

when examined under the microscope, showed a very great number of tracks of protons, deuterons, alpha-particles, etc., stemming presumably from nuclear explosions produced by fast neutrons in the shielding, in the glass, and in the emulsion itself. The orientation of the background tracks was random, and it was clear that most of the neutrons did not originate in the target. A few mesons were found, but the ratio of meson tracks to background was of the order of 1:10,000.

During the first few months after the mesons were detected, a great deal of effort was spent in reducing the neutron background. In the final arrangement it was possible to show that about half of the neutron background originated directly in the target. In the very best exposures the number of background tracks decreased nearly as the square of the distance from the target.

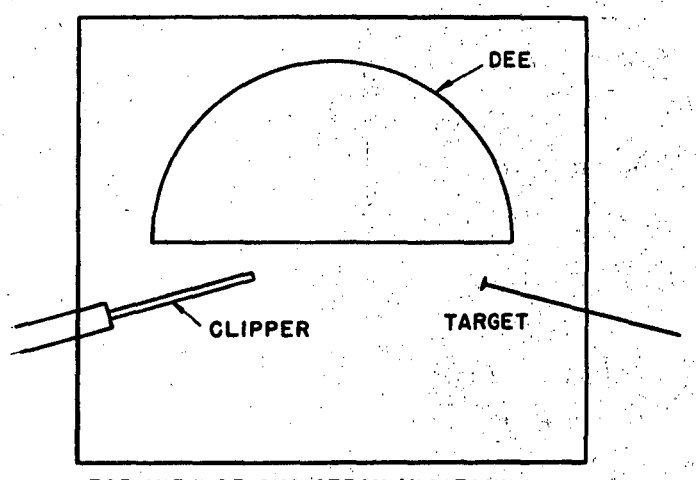
The exact origin of the neutrons coming from places other than the target is not yet completely understood. Of the various devices tried for reducing the neutron background the only ones found definitely to be effective were:

a) Reducing the deuteron contamination of the α-beam. It was found that, as expected, deuterons of 190 Mev did not produce a detectable number of mesons. As it is not possible to obtain an alpha-particle beam free from deuteron contamination, even by first letting the vacuum tank down to atmospheric pressure before running the cyclotron for α-particles, and as these deuterons served only to increase the background to meson ratio, a device suggested by W.K.H. Panofsky was designed by Robert Watt for minimizing the deuteron contamination. Such a mechanism is made possible by the fact that the α-particles begin their accelerations at a different time in the frequency modulation cycle than do the deuterons. Pulsing the ion source arc on at precisely the correct time gave a 98 percent pure beam of alpha-particles. The pulsing time was determined experimentally on each group of exposures by reading a special double probe which measured the α-particle current and the deuteron current simultaneously.

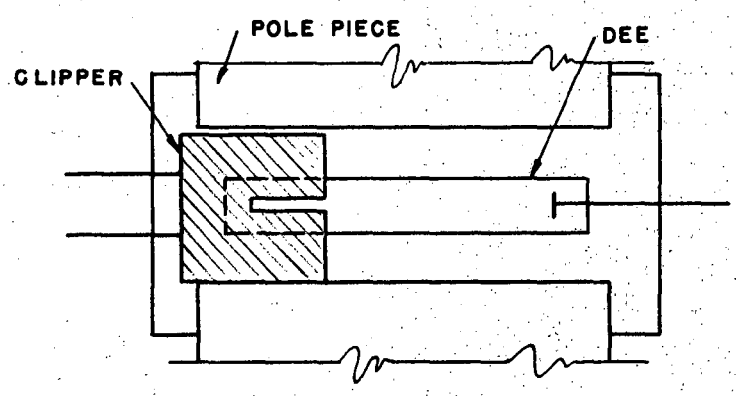
b) Beam "clipper." Originally most of the background due to alpha-particles came from ions which scattered from the target. These could subsequently strike the dee near the plate holder and produce neutrons, or could spiral outward in the reduced magnetic field beyond the beam radius and actually strike the plate holder. A "clipper" shaped as shown in Fig. 3.11(7) was placed on the opposite side of the cyclotron from the target in order to stop the beam which had been scattered from the target at small angles upward, downward, or radially outward. The back of the clipper ordinarily was set at 1/2 inch larger radius than the target.

When the two devices were used, it was possible to obtain occasional α-beam exposures with a ratio of meson tracks to background tracks of approximately 1/50. Usually the ratio was nearer to 1/100. With the normal beam intensity of 1/10 of microampere, a ten minute exposure provided a convenient density of tracks for study. In exposures of stacks of plates there were about 300 mesons entering the emulsion of each plate through the "leading" edge. (100 microns thick, 3 inches long.) Single plates exposed at a grazing angle of about 5 degrees showed about 4000 mesons distributed over the 3 inch by 1 inch area.

It is possible to eliminate practically all the background except that coming directly from the target, by making the bombardment outside the cyclotron with the deflected beam. C. Richman is using the deflected proton beam to study the energy distribution of mesons up to 150 Mev from a carbon target. By using an auxiliary magnet of a few kilogauss to sort out the negative mesons, it is possible in principle to reduce the background still further, since mesons of a given energy could be focused to a position farther away from the target than is possible with the cyclotron magnetic field. As the number of mesons would decrease linearly with the distance between target and plate in the best arrangement while the background would decrease as the square of the distance, the advantages are obvious. This type of exposure requires long bombardments since at present the intensity per unit



TOP VIEW OF CYCLOTRON VAC. TANK



SIDE VIEW OF CYCLOTRON VAC. TANK

CLIPPER FOR α BEAM

MU-338

FIG. 3.11 (7)

area in the deflected beam is only about 10^{-6} of the available current in the internal beam.

3.12 Positive mesons from α-particle bombardment

An important difference between exposures for negative mesons and for positive mesons is that, in the latter case, ions leaving the target curve in the same direction as the mesons and, therefore, cannot be eliminated by shielding. Tracks of mesons are approximately 100 times as long as tracks of protons with the same momentum, and hence the latter will not be confused with meson tracks if a good channel is employed. However, they do contribute seriously to the background on the plates. Exposures suffer further because of the small yields of low energy positive mesons as indicated in the Section 4.21.

The most common type of plate holder for the detection of positive mesons is shown in Fig. 3.12(1).* Note that it differs from the holders described in Section 3.11 in that it accepts only mesons ejected from the target in a backward direction in order that the plates may be placed at a radius larger than the beam.

For experiments such as comparison of positive π to negative π yields, in which positive mesons ejected in the forward direction were desired, it was possible to use plate holder such as shown in Fig. 3.12(2). Background was very severe in this type of holder because stray particles from the cyclotron beam struck the rear of the holder and the thickness of the holder is limited by the size of the airlock opening into the cyclotron. (Since the range of the proton beam is greater than that of the alpha-particle beam, this type of holder cannot be used in connection with the 345 Mev proton beam. A larger airlock now being designed should improve the situation.)

---

*E. Gardner has kindly permitted the use of this and other figures from a forthcoming paper on meson mass measurements.

3.2 Meson production in the proton beam

The main difficulty in using the 345 Mev proton beam comes from the increased range of stray protons and the increased energy of neutrons from the target. This makes it desirable to increase the shielding around the plates, and, in particular, to place as much shielding as possible between the plates and the target. It has not been possible to use a plate holder of the type of Fig. 3.12(2) with the proton beam. However, holders shown in Figs. 3.2(1) and 3.12(1) are satisfactory.

New types of holders shown in Figs. 3.2(2), (3), and (4) are being used to study mesons of energies from 20 Mev to their upper limit of approximately 150 Mev. Mesons leaving the target with high energy at approximately 90° to the beam are slowed down to about 10 Mev by an absorber of copper or another material before entering the plates.

The channel of the holder in Fig. 3.2(2) is designed to pass mesons of a nominal energy of 50 Mev, but because of its small total length will pass mesons with energies from 40 Mev to 80 Mev emitted at $90^{\circ} \pm 3^{\circ}$ to the proton beam direction. A copper absorber placed at the exit end of the channel immediately in front of the plates reduces the 50 Mev meson energy to approximately 14.5 Mev. Mesons with initial energy between 46 and 66 Mev stop in the plate. This arrangement thus has good angular resolution, and moderately good energy resolution.

The holder shown in Fig. 3.2(3) is designed to slow the mesons down before they enter the channel. The distance between target and plates is smaller than in the holder of Fig. 3.2(2), and improved meson yield is achieved at the expense of angular resolution. Different energy regions are selected for study by using different absorbers at the entrance to the channel.

The type of holder that is shown in Fig. 3.2(4) was originally proposed by C. Richman for use with the deflected cyclotron beam. It does not take advantage of magnetic separation of ions, but simply interposes a copper absorber between

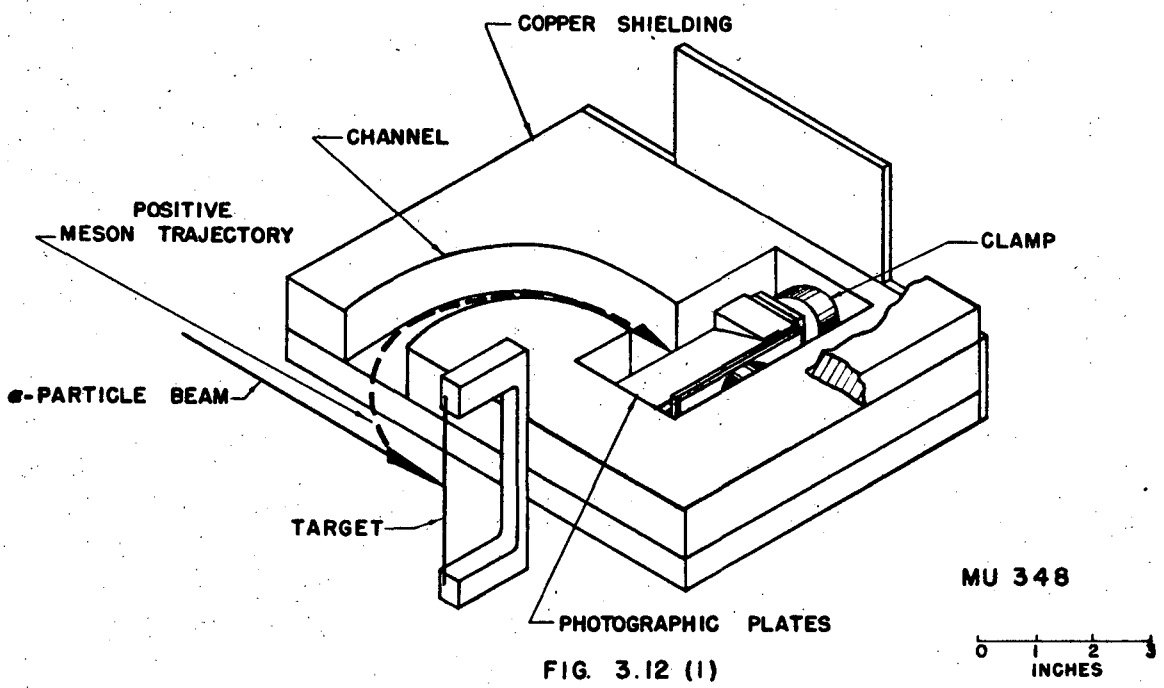

COPPER SHIELDING
CHANNEL
POSITIVE
MESON TRAJECTORY
CLAMP
α-PARTICLE BEAM
TARGET
PHOTOGRAPHIC PLATES
MU 348
0 1 2 3
INCHES

FIG. 3.12 (1)

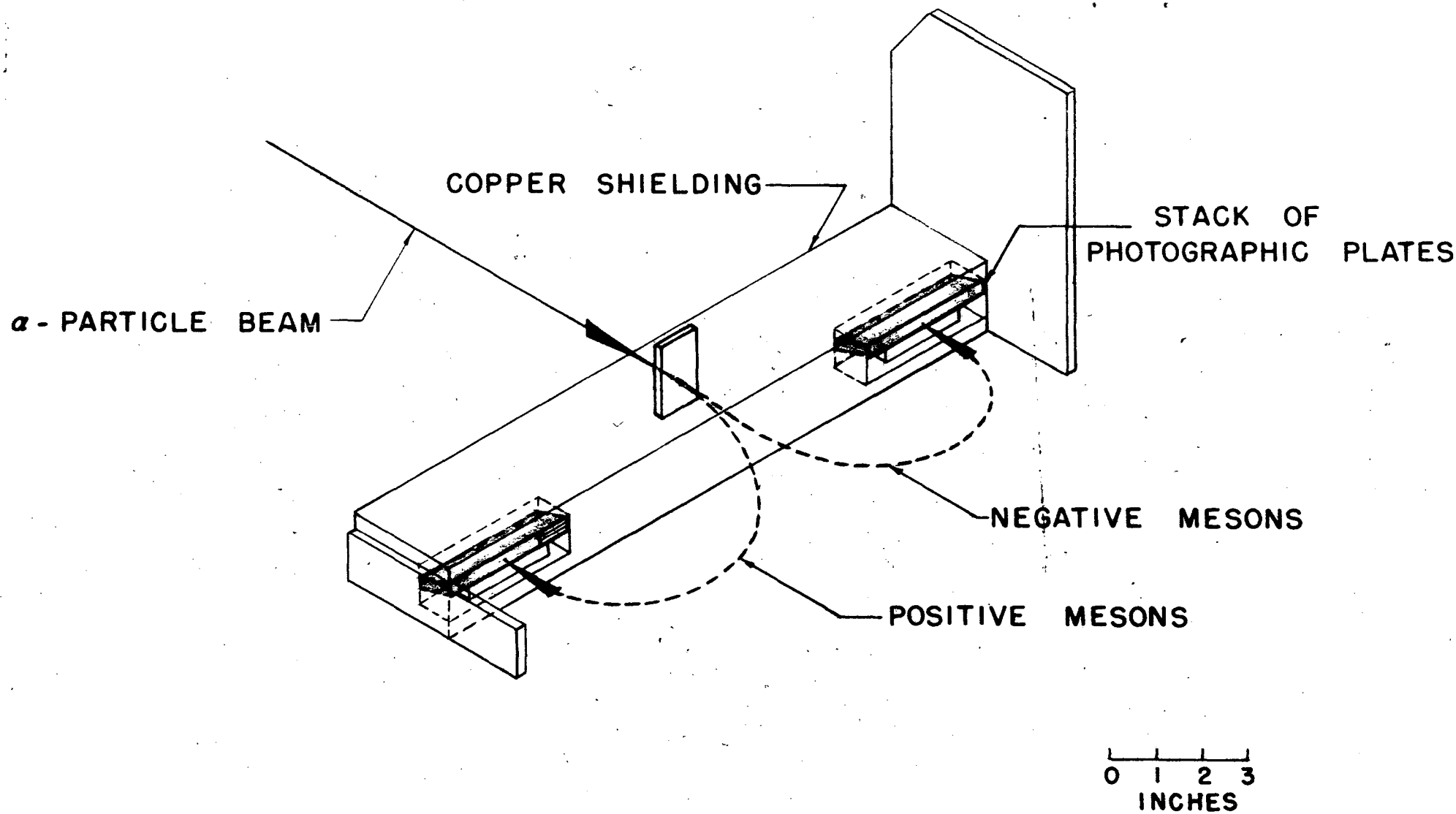


FIG. 3.12 (2)

OZ 572

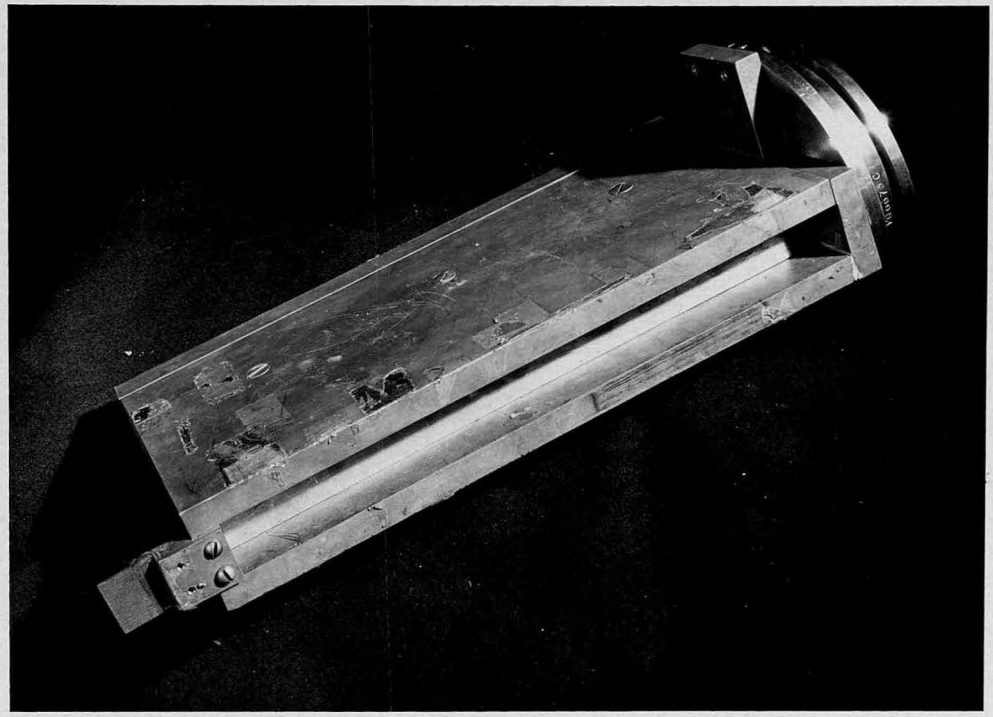


FIG. 3. 2 (1)

OZ 723

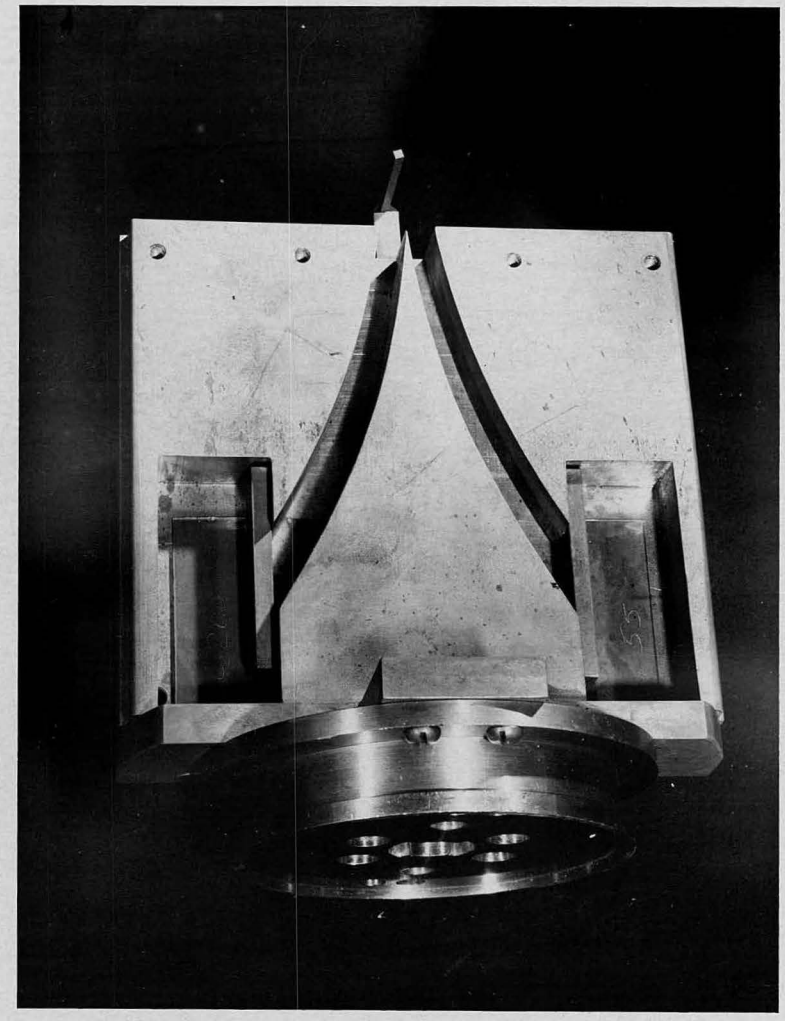


FIG. 3.2(2)

OZ724

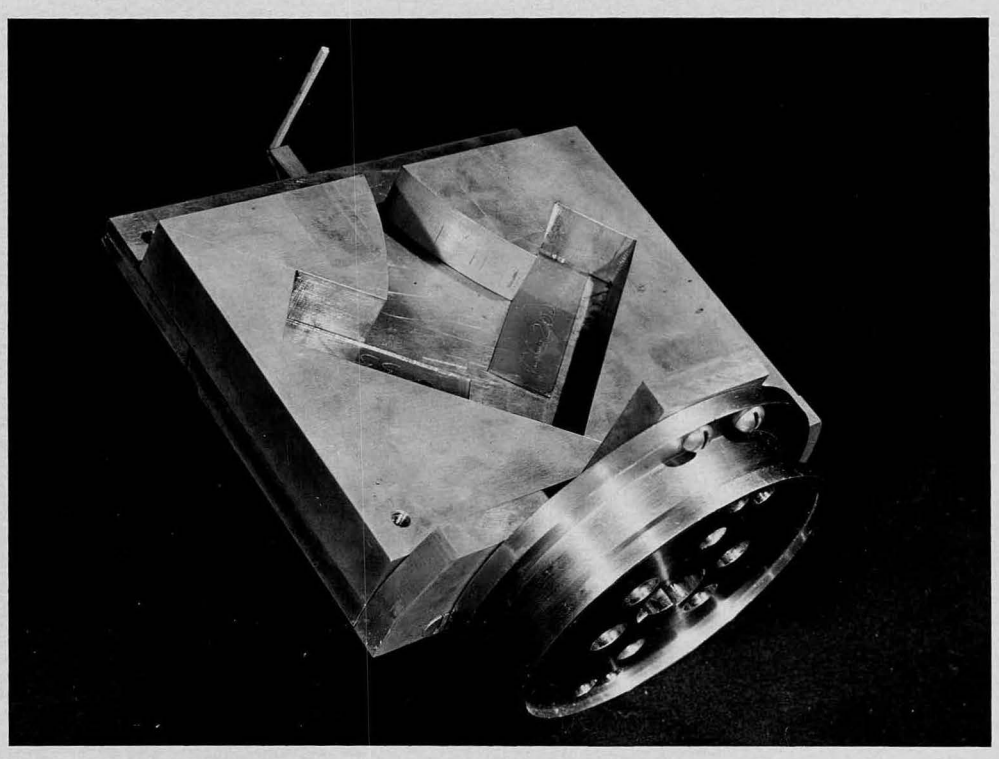


FIG. 3. 2 (3)

OZ 726

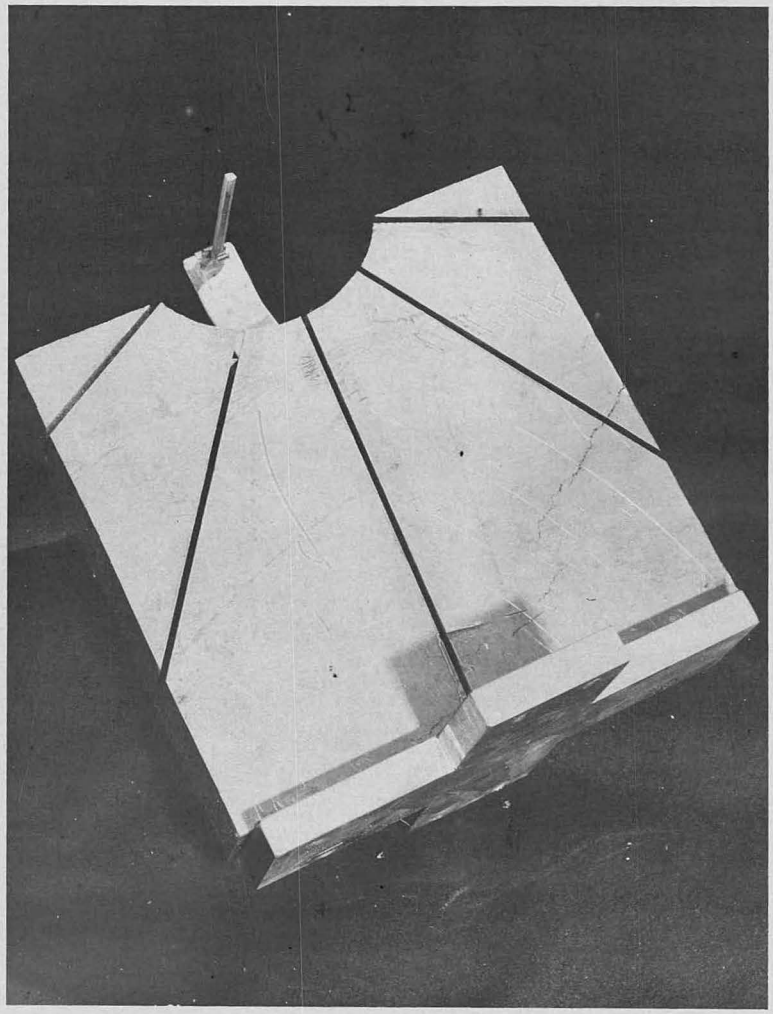
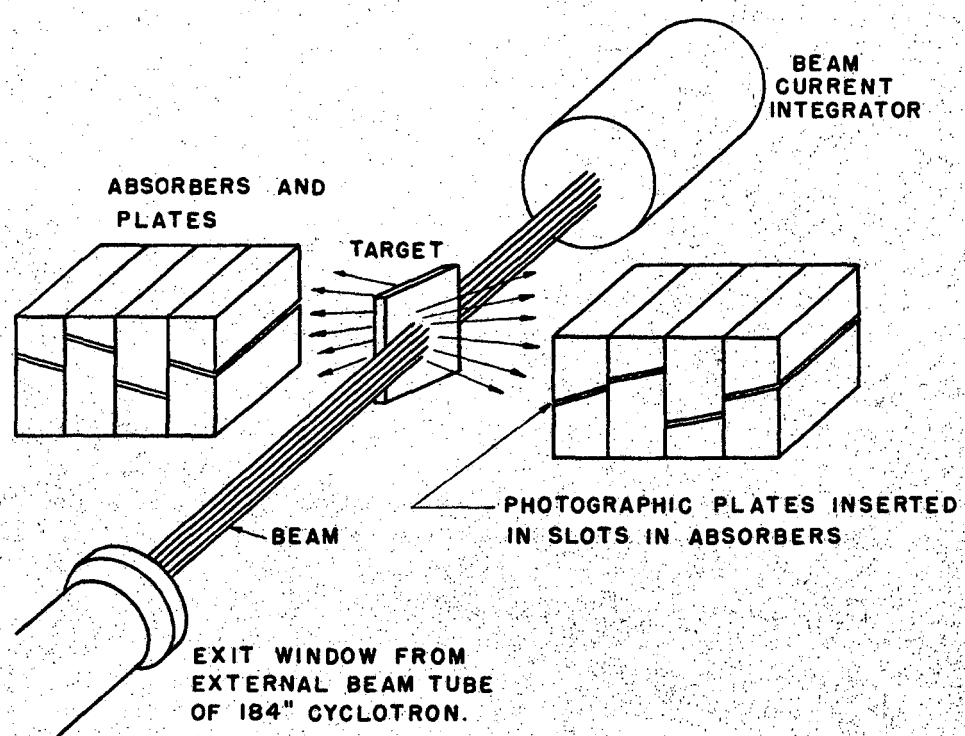


FIG. 3.2 (4)

OZ 725



MU 337

Fig. 3.2 (5)

the target and the plates. Plates are placed in slots in the copper block and meson energies are estimated from the thickness of copper between the target and the terminus of the meson. Exposures made with this type of holder show prohibitively high background for mesons of less than 20 Mev at 90° to the proton beam, but are very satisfactory for meson energies above 50 Mev. Plates exposed in the forward quadrant show progressively more background while those in the backward quadrant give better exposures than those in the 90° position. Positive and negative mesons drift in opposite directions under the influence of the magnetic field, so that π^+ and π^- mesons ending in the same region of a plate did not leave the target in the same direction. V. Peterson[1] has calculated the drift of mesons, and finds that they end approximately 7 1/2° away from their initial direction, regardless of their initial energy.

Richman and Wilcox's present arrangement for obtaining mesons from the 345 Mev external proton beam is shown schematically in Fig. 3.2(5), which they have kindly given permission to use. In their method, the external beam from the cyclotron goes through a target and is subsequently collected and integrated. The positive and negative mesons produced in the target enter the essentially infinite blocks of absorber material, where they come to rest after traversing a distance assumed to be appropriate to the initial energy, according to the ordinary nuclear stopping law. During this process the mesons scatter somewhat, but in the absorber the volume density of stopped mesons at a given depth of penetration is unchanged and measures the number produced in the target with the corresponding energy. Nuclear emulsions are buried in these absorbers in order to sample the meson population, and in this way the energy dependence of the differential meson cross section at a given angle of observation in the laboratory is measured. No magnetic separation technique is used; positive and negative mesons can, however, be distinguished by the fact that the π^+ mesons decay into observable μ^+ mesons,

whereas the π^- mesons are captured and in 73 percent of the cases give rise to an observable star in the emulsion.

3.3 Meson production by neutrons

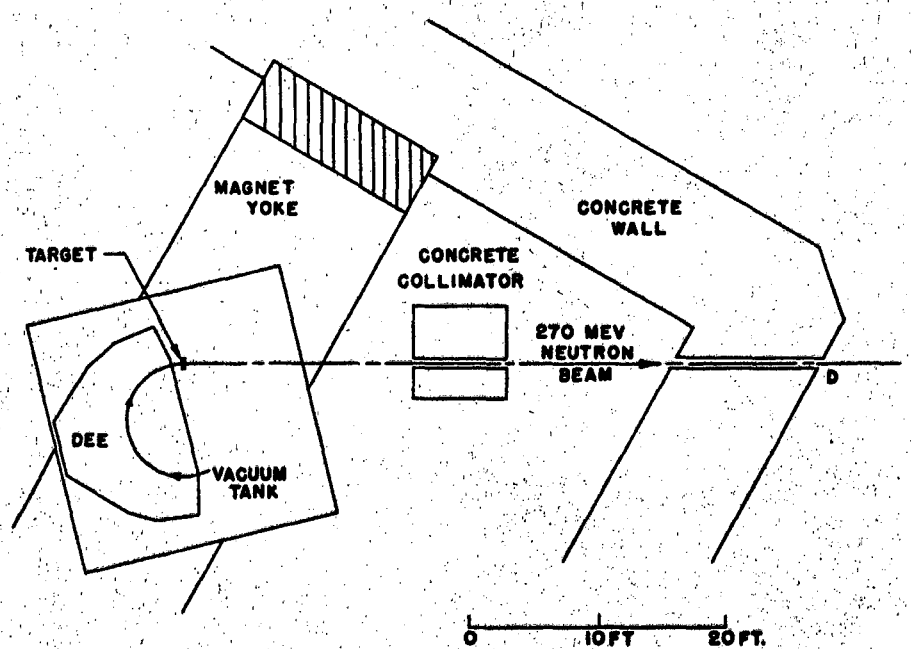
When 345 Mev protons strike a target, charge exchange takes place, producing high energy neutrons in the forward direction as shown in Fig. 3.3(1). The energy spectrum of the neutrons has been shown by Crandall and Hadley (1) to have an average value of approximately 270 Mev with a half-width at half maximum of approximately 50 Mev. The yield of neutrons 40 ft. from a 1 μa beam of 345 Mev protons striking a 2 inch thick Be target is approximately 10^4 neutrons cm^{-2} sec^{-1}. Nuclear track plates placed in this beam show recoil tracks and nuclear stars with with occasional, directly produced meson tracks.

Plates have also been exposed by Richman and by Bradner to obtain tracks of mesons produced in a carbon target by neutrons. The arrangement was somewhat similar to the one described above for use with the deflected proton beam. Twenty hour exposures were required to obtain a few mesons per cm^2 of emulsion, and longer exposures could not be used because of background.

4. Meson Production

4.11 Excitation curve for α-particle beam

Since the possibility of producing π mesons in the cyclotron depended upon the available internal energy of nuclei, and since calculations using this quantity were open to question, the early experiments were designed to gather only easily obtainable information that would be most useful later for making bombardments to observe mesons in restricted regions of meson energy and angle of emission from the target. The excitation curve and the energy spectrum for the production of negative mesons in carbon were measured by Jones and White(1), and the cross section was measured by V. Peterson.(2)



EXPERIMENTAL ARRANGEMENT

MU 336

FIG. 3.3 (1)

14169-1

For the excitation curve, the standard plate holder described in Section 3.11 was put at different radii inside the cyclotron. Exposures were made with a carbon target 1/16 inch in thickness. Those mesons were counted which stopped in a strip 2mm deep along the leading edge of the emulsion. This region contained mesons which had left the target at angles up to about 45 degrees from the forward direction of the α-beam and which had energies from about 2 to 10 Mev.

The number of σ mesons observed versus the bombarding beam energy is given in Table 4.11(1).* Column 1 contains the energy of the bombarding α-particles; column 2, the number of star-forming mesons actually counted; column 3, the relative area scanned; and column 4, the number of mesons relative to the number at 390 Mev, corrected for beam current, relative emulsion thickness, and area scanned. The cross section for the reaction $C^{12}(\alpha,\alpha n)C^{11}$ is constant within the statistical error throughout the range of α-particle energies used.(4)

It is evident from the excitation function, as well as from energy considerations, that π mesons are not normally made in pairs by the 390 Mev α-particle beam.

4.12 Cross section for production of π^- mesons by the α-particle beam

A differential cross section measurement for meson production by the full energy α-beam was made by V. Peterson(1) for mesons of energy 2 to 5 Mev emitted within 45 degrees of the forward direction. A standard plate holder was used with a one-quarter inch thick carbon target, and the intensity of the beam was monitored by means of a thin polystryrene foil fixed to the front of the target. One-quarter inch thickness of target was chosen in order that the α-beam would scatter enough in a single passage through the target to hit the clipper and thus fail to make a second pass through the polystyrene. The total beam current was calculated by

---

*The data and curves for this section and for Section 4.13 have been taken from an article by S.B. Jones and R.S. White, submitted for publication in the Physical Review.

Table 4.11(1)

α-particle Energy(Mev)	Number of σ Mesons Observed	Relative Area Scanned	Relative Yield (Corrected)
390	241	1.42	100
342	109	1.00	34.0
304	24	1.00	6.7
266	4	1.00	0.5

These data have been plotted in Fig. 4.11(1), which also includes data of Section 4.14 for the proton beam. In addition, the absolute minimum thresholds calculated in Section 9.12 by the method of Barkas[3] have been indicated.

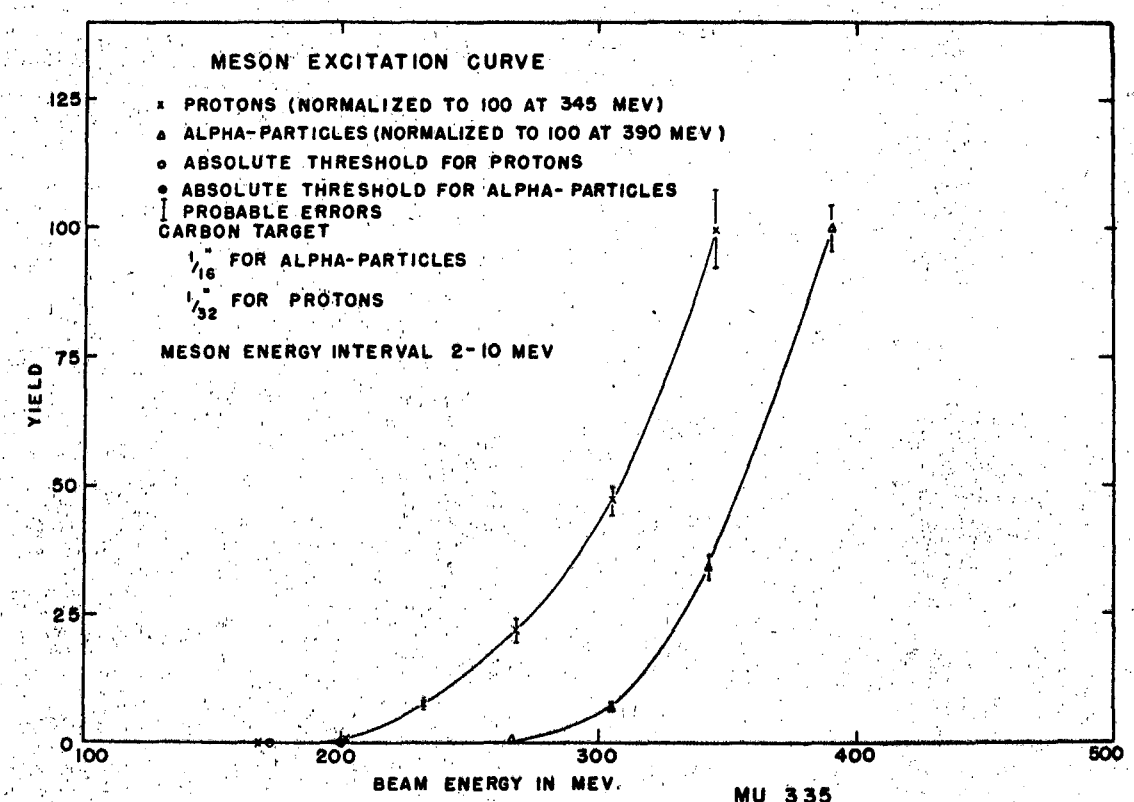

MESON EXCITATION CURVE
× PROTONS (NORMALIZED TO 100 AT 345 MEV)
▲ ALPHA-PARTICLES (NORMALIZED TO 100 AT 390 MEV)
○ ABSOLUTE THRESHOLD FOR PROTONS
● ABSOLUTE THRESHOLD FOR ALPHA-PARTICLES
I PROBABLE ERRORS
CARBON TARGET
1/16" FOR ALPHA-PARTICLES
1/32" FOR PROTONS
MESON ENERGY INTERVAL 2-10 MEV
YIELD
125
100
75
50
25
0
100
200
300
400
500
BEAM ENERGY IN MEV.
MU 335

FIG. 4.11 (1)

measuring the 20-minute positron activity in the polystryrene due to the $C^{12}(\alpha,\alpha n)C^{11}$ reaction whose cross section is known[1] for 390 Mev α-particles. Correction was made for the differences in solid angle subtended by the plate for the various trajectories. No correction was made for target thickness. The differential cross section was based upon the measurement of 71 mesons which ended in the emulsion. Peterson has kindly recalculated his results, using 1.37×10^{-8} sec. for the half life of the π^- meson (cf. Section 6.33). The calculated differential cross section under these conditions is $3.0 \pm 0.8 \times 10^{-32}$ cm^2 Mev^{-1} $ster^{-1}$ per carbon nucleus. The value is expressed in terms of the carbon nucleus rather than the nucleon since the relative contribution of proton and neutron is not known. The accuracy of the cross section calculation is impaired by the small number of mesons observed, and by the fact that the 1/4 inch carbon target is thick for the energy of the observed mesons. In fact, the half-thickness of the target would indicate that the observed mesons were produced with a mean energy of 10 Mev.

4.13 Energy spectrum for mesons produced by the α-particle beam

The energy spectrum of π^- mesons produced by 390 Mev α-particles on a carbon target was measured by Jones and White.[1] The plate holder, shown in Fig. 4.13(1), was designed to allow the simultaneous exposure of four stacks of plates to mesons at distances of from 1 to 13 inches from the target. The mesons originate from the extreme left side of the 1 in. x 1 in. x 1/16 in. carbon target attached to the plate holder as pictured in Fig. 4.13(1).

Fig. 4.13(2) is a composite map of all the plates, showing the point at which each meson stopped in the emulsion. The blocked-in areas designate the areas scanned. Star-forming mesons are indicated by a cross and non-star-forming ones by a circle. Only star-forming mesons were considered in this experiment. There is a unique relationship between position of a meson terminus and the angle and energy with which it left the target, provided that straggling and scattering are

neglected.

The energy spectrum is defined by $\frac{dN}{dE\, d\Omega}$, where dN is the number of mesons which leave the target in the energy interval dE and in the solid angle $d\Omega$. Since the plates were located in the horizontal plane the element of solid angle was taken as $d\phi d\theta$ where $d\phi$ is the vertical angle subtended by the elements of emulsion in question at the target and $d\theta$ is the corresponding horizontal angle. $d\theta$ is measured from the forward direction of the α-beam.

The number of mesons that end in a particular energy and angle interval may be found by a direct count of the numbers in the corresponding areas. The sets of curves for the analysis were found by constructing graphically the approximately semicircular orbits of mesons of various energies and angles. Graphical plotting was necessary because of the rapid rate of change of the magnetic field of the cyclotron with increasing radius at the position of the plates.

The solid curve in Fig. 4.13(2) represents the calculated positions on the plates of mesons which leave the target in the direction of the α-beam.

The non-star forming mesons found nearer to the emulsion edge than the solid curve are probably μ^- mesons formed by the decay of π^- mesons in the immediate vicinity of the plate, the decay being in a direction which favors a low μ^- meson energy. Calculations show that the region of 8-10 inches from the target is especially favorable to this situation.

The data obtained by counting the number N of σ mesons observed in the various areas are plotted in Fig. 4.13(3). N is plotted versus E for mesons entering the plate at angles up to 30° from the perpendicular.

The data were corrected for the relative plate thickness, relative areas scanned and solid angle subtended. Correction was also made for vertical focusing due to the radial decrease of the magnetic field, and for decay in flight. From Fig. 4.13(3) it appears that the peak of the energy distribution has not yet been

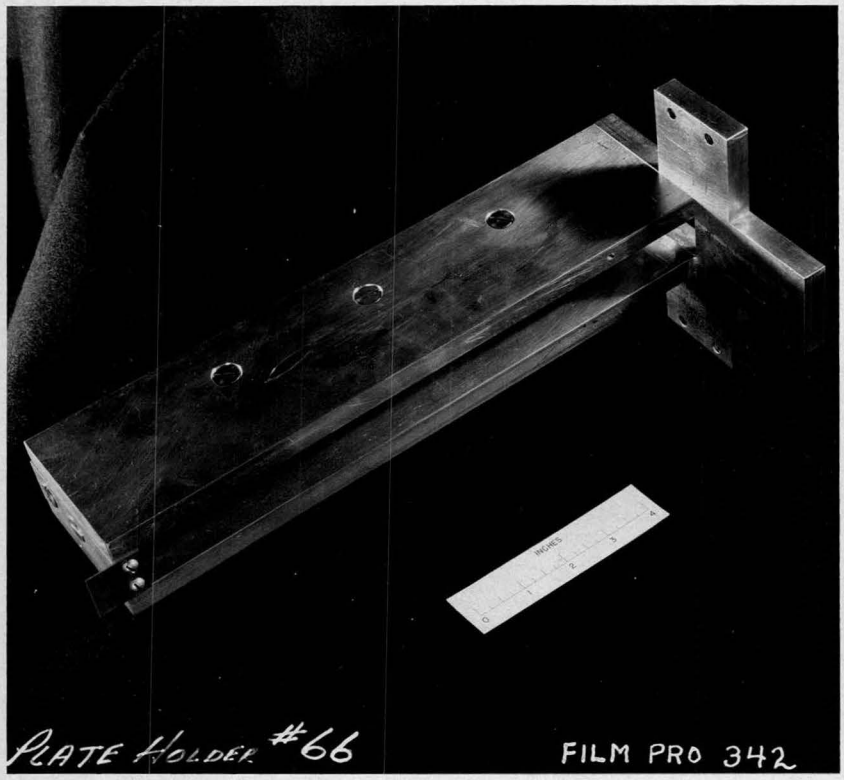


FIG. 4.13 (1)

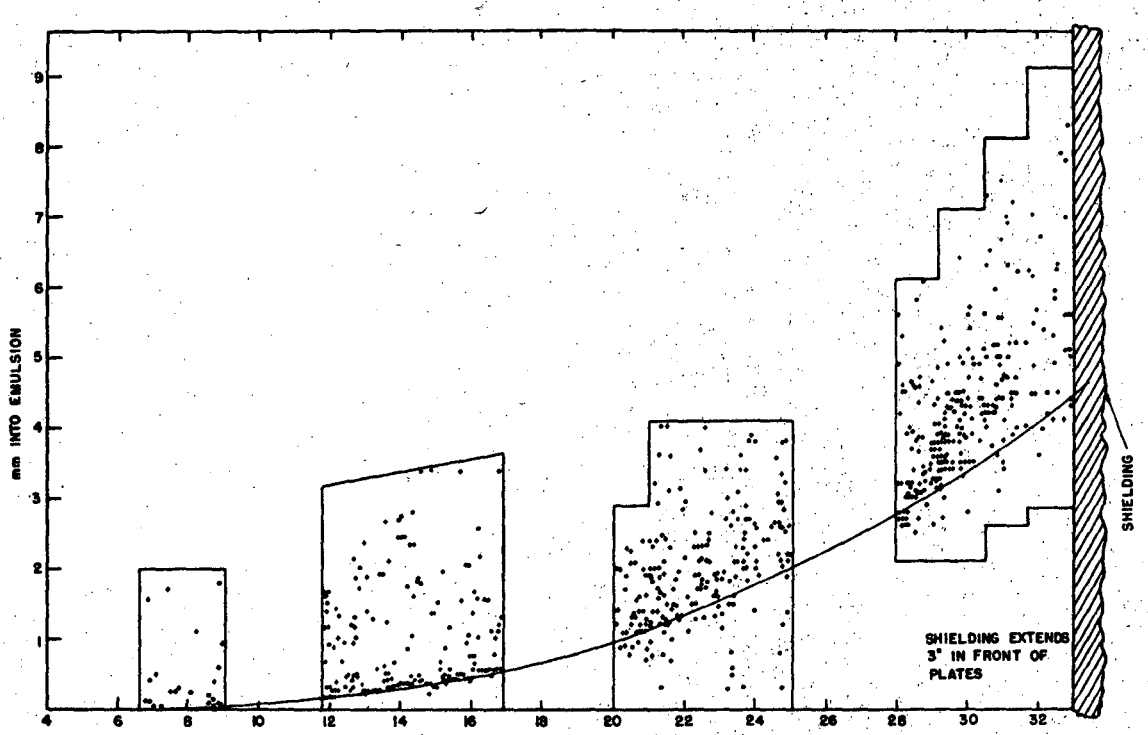


FIG. 4.13(2) MU 352

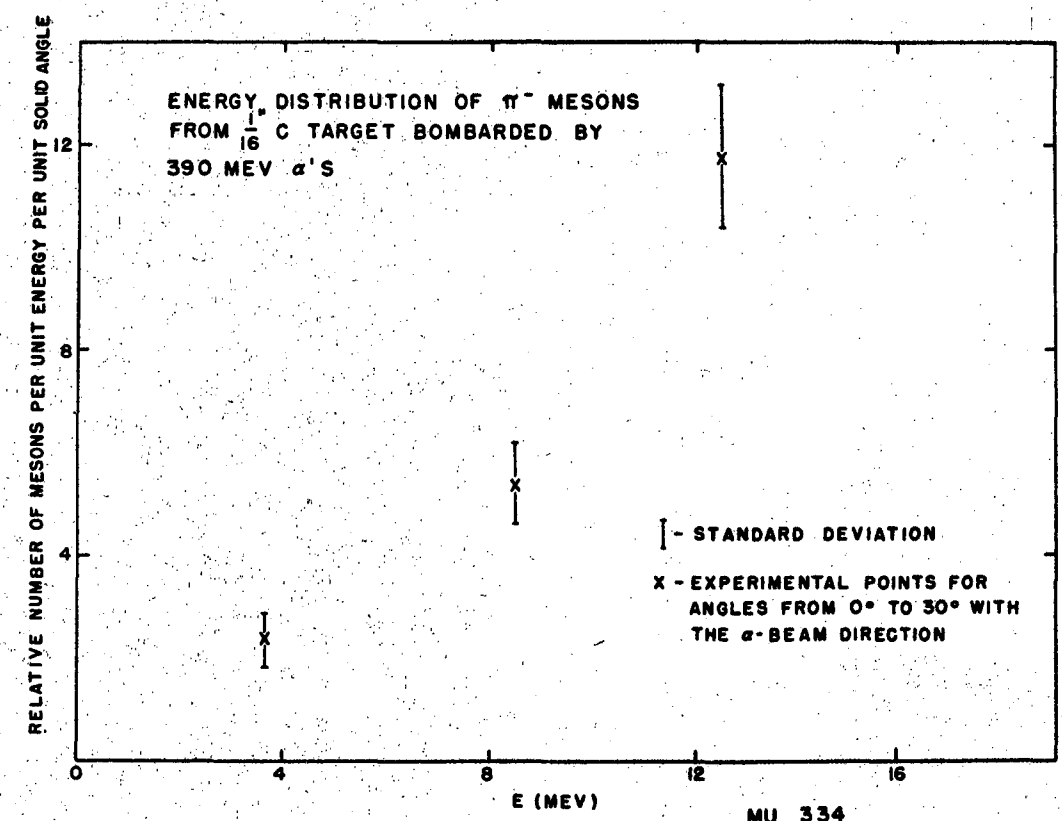

ENERGY DISTRIBUTION OF π^- MESONS
FROM $\frac{1}{16}$ C TARGET BOMBARDED BY
390 MEV α'S
RELATIVE NUMBER OF MESONS PER UNIT ENERGY PER UNIT SOLID ANGLE
12
8
4
0
4
8
12
16
E (MEV)
I - STANDARD DEVIATION
X - EXPERIMENTAL POINTS FOR
ANGLES FROM 0° TO 30° WITH
THE α-BEAM DIRECTION
MU 334

FIG. 4.13 (3)

reached at 12.5 Mev.

4.14 Excitation function for mesons produced by the proton beam

Jones and White[1] have made a study of the variation of π^- meson yield with proton energy, using a technique similar to that described in Section 4.11 for excitation by α-particles. The proton study was limited to σ mesons with energies from 3-10 Mev emitted between 0° - 45° of the beam direction from a 1/32 inch thick carbon target. Eastman type NTB plates with 100 μ emulsion were used to record the mesons. The results are presented in Table 4.14(1). The last column gives the relative yield, corrected for integrated beam current, area scanned, and thickness of plate. The ralative integrated beam current was found by measuring the relative target activities at a fixed time after bombardment, and using the cross section for the $C^{12}(p,pn)C^{11}$ reaction for protons of 170 to 340 Mev measured by Aamodt et al.[2] The data are plotted in Figure 4.11(1).

4.15 Cross section for the production of π^- mesons by protons

An experiment similar to the one described in Section 4.12 has been performed by Peterson[1] in order to determine the differential cross section for the production of π^- mesons by a beam of 345 Mev protons on carbon. The differential cross section for the production of mesons with energies ranging from 11-13 Mev and emitted at angles between 0° -30° with the direction of the proton beam from a 1/16 in. carbon target was found to be 1.0×10^{-30} cm^2 Mev^{-1} $steradian^{-1}$ per carbon nucleus. The results cannot be compared directly with the cross section measurements on mesons produced by α-particles except by means of the energy distribution, discussed in Section 4.13. This indicates that the differential cross section for the production of 11-13 Mev mesons by 345 Mev protons is approximately 12 times as large as the differential cross section for the production of similar mesons by 390 Mev α-particles.

A more comprehensive experiment on cross section and energy spectrum is being

Table 4.14(1)

Proton Energy	Number of Mesons Observed	Relative Area Scanned	Relative Yield (Corrected)
345	75	.86	100
306	126	.69	47
269	46	.63	22
233	19	.80	8
201	3	.86	1
167	0	1.00	0

carried out by C. Richman and H.A. Wilcox who have extended the observations to meson energies above 100 Mev. They have kindly permitted the use of their preliminary data, and a schematic view of their apparatus, shown in Fig. 3.2(5). Thus far, their arrangement has been used only to observe mesons emitted at 90° to the beam direction (in the laboratory system) from a carbon target bombarded by the deflected proton beam. The preliminary data on the differential cross section for meson production versus meson energy are exhibited in the graph of Fig. 4.15(1). It should be emphasized that in addition to statistical uncertainties, the value of the cross section suffers an uncertainty arising from the possibility that fast mesons have a large cross section for interaction with nuclei of the absorber.

4.16 Production of mesons by neutrons

E. Gardner, F.M. Smith, H. Bradner, and C.M.G. Lattes have made brief examinations of plates exposed directly to the 270 Mev neutron beam. Gardner[1] has found a total of 5 mesons originating in stars, compared with approximately 50,000 ordinary nuclear stars in the same area scanned. One of the meson events is pictured in Fig. 4.16(1), which shows a negative meson coming from a star, and terminating in a star. Many such events have been reported in studies of plates exposed to cosmic rays.[2] No accurate cross section for meson production by neutrons can yet be estimated.

H. Bradner and B. Rankin[4] have placed plates near a carbon target bombarded by the 270 Mev neutron beam. A very rough preliminary cross section for production of 50-70 Mev mesons at 90° to the neutron beam has been calculated by Bradner and Wilcox[3] to be between 0.2 and 0.5 x 10^{-30} cm^2 $ster^{-1}$ Mev^{-1} carbon $nucleus^{-1}$. The yield of π^- mesons is 12.6 ± 1.5 times as large as the yield of π^+ mesons.

4.21 Ratio of cross sections for production of low energy positive and negative π mesons

Mesons produced in the nucleus must traverse the electric field of the nucleus

in escaping to the point at which they are detected. Thus, a positive meson formed with energy less than the Coulomb barrier height would have a reduced probability of escaping from the nucleus. If the spectra of positive and negative mesons were identical when created, the observed spectra should be different, particularly in the low energy region. This effect should be more profound the higher the atomic number of the nucleus from which they are produced. The result, on this hypothesis, would be to reduce more and more the number of low energy positive mesons relative to the low energy negative mesons as the atomic number of the target is increased.

To study the anticipated effect Barkas(1) counted the number of positive and the negative π mesons produced by 390 Mev α-particles in identical (2-5 Mev) energy intervals. Targets of Be, C, Al, Cu, In and Pb 1/64 inch thick were used. Ilford C2 and C3 nuclear emulsion plates were employed to observe the mesons. The detecting plates were placed symmetrically on opposite sides of the target in the 184-inch cyclotron as shown in Fig. 3.12(2). Both the positive and negative mesons were emitted in the forward direction.

Fig. 4.21(1) shows the ratio of positive to negative mesons found as a function of atomic number. The ratio falls steeply with nuclear charge; indeed, no positive mesons were observed from In or Pb, although the yield of negative mesons was observed not to change rapidly with atomic number.

4.22 Ratio of cross sections for production of high energy positive and negative π mesons

If mesons of energy as high as 50 Mev are studied, the effect of the Coulomb barrier should be small, and it would be expected that the ratio of π^+ to π^- mesons would be approximately $\frac{A+Z}{A-Z}$, where A is the atomic weight and Z the atomic number of the target. This formula is derived by the following simplified argument: If the incoming proton interacts with a proton, then either one of them may change into a neutron and a positive meson. If the incoming proton interacts with a neutron,

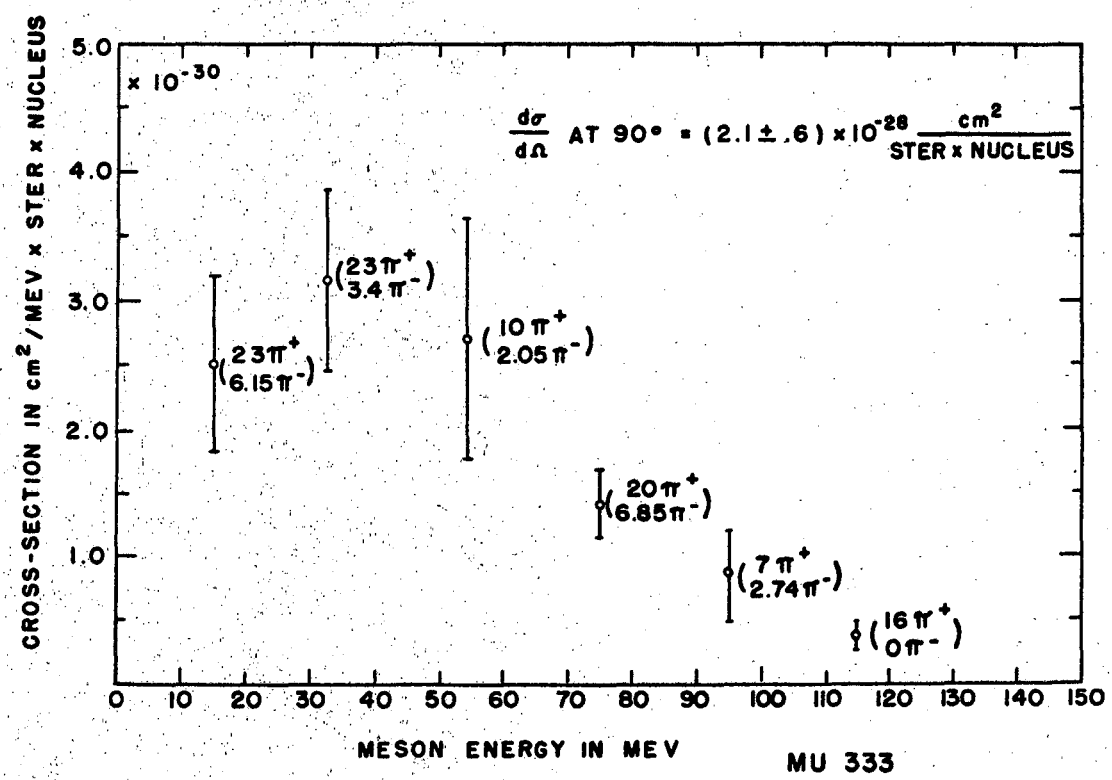

CROSS-SECTION IN cm²/MEV x STER x NUCLEUS
5.0
4.0
3.0
2.0
1.0
x 10⁻³⁰
dσ/dΩ AT 90° = (2.1 ± .6) x 10⁻²⁸ cm²/STER x NUCLEUS
(23π⁺ 6.15π⁻)
(23π⁺ 3.4π⁻)
(10π⁺ 2.05π⁻)
(20π⁺ 6.85π⁻)
(7π⁺ 2.74π⁻)
(16π⁺ 0π⁻)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
MESON ENERGY IN MEV
MU 333

FIG. 4.15 (1)

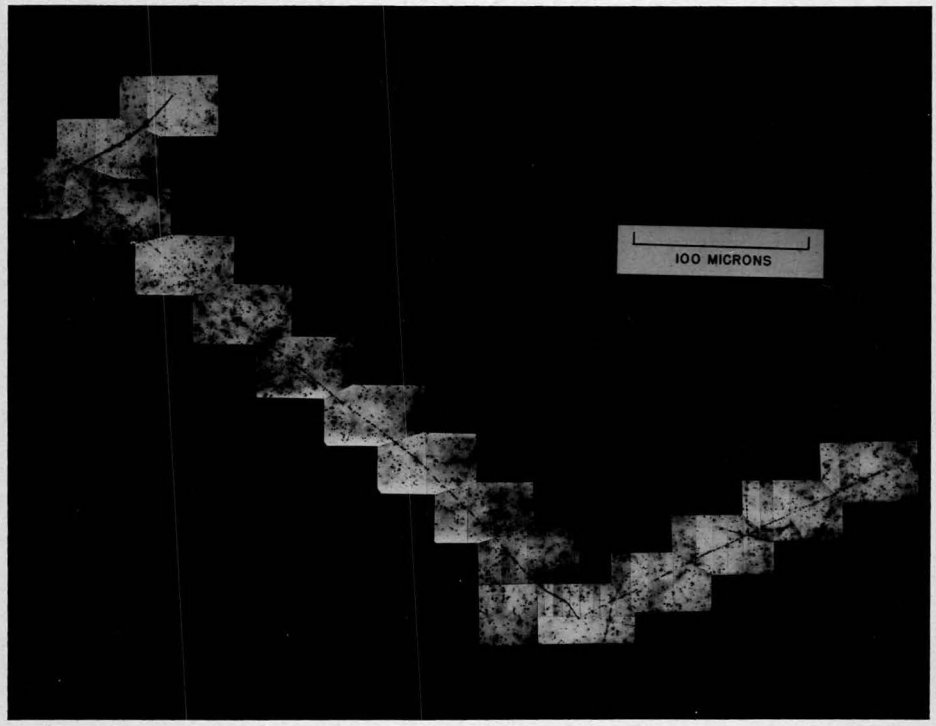


FIG. 4.16 (I)

OZ 728

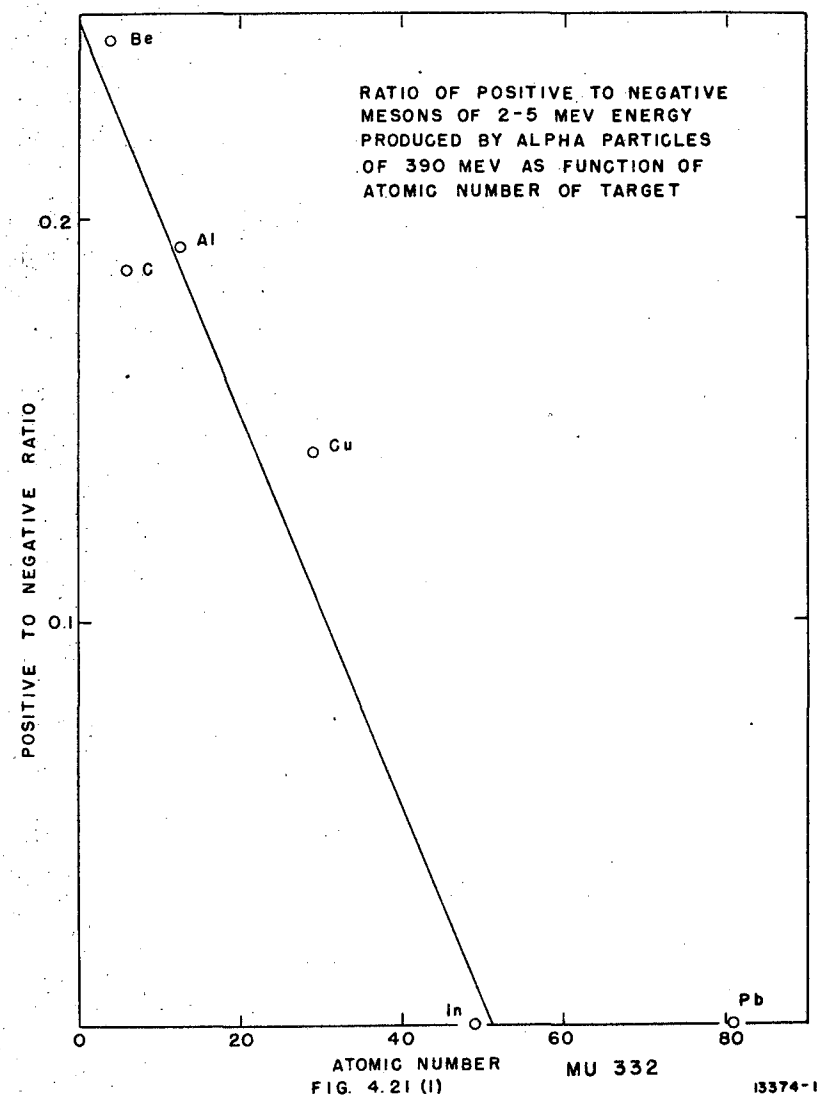

RATIO OF POSITIVE TO NEGATIVE
MESONS OF 2-5 MEV ENERGY
PRODUCED BY ALPHA PARTICLES
OF 390 MEV AS FUNCTION OF
ATOMIC NUMBER OF TARGET
Be
Al
C
Cu
In
Pb
0.2
0.1
POSITIVE TO NEGATIVE RATIO
0
20
40
60
80
ATOMIC NUMBER
MU 332
13374-1

FIG. 4.21 (1)

then the proton may change to a neutron plus a positive meson, or the neutron may change to a proton plus a negative meson. Thus if the target nucleus contains N neutrons and P protons and if p-p and p-n interactions are considered roughly equal, one would expect a positive π to negative π ratio of $(2P + N)/N$. Since $A = P + N$ and $Z = P$, it follows that the ratio of positive to negative mesons should be as $\frac{A + Z}{A - Z}$, as stated above. For carbon the ratio should be 3:1.

H. Bradner is investigating the positive and negative π ratio, using the arrangements shown in Figs. 3.2(2), (3), and (4). C. Richman and H. Wilcox are obtaining data in plates exposed outside the cyclotron shielding. Preliminary results indicate a ratio of approximately 5:1 for 50-70 Mev mesons emitted at $90^\circ \pm 5^\circ$ from the 345 Mev proton beam striking a carbon target.

4.3 Neutral Mesons

Experiments have been conducted by H. York et al.[1] [2] using a pair production spectrometer to investigate the high energy photons produced when nuclei are bombarded with 345 Mev protons. Their findings are consistent with the assumption that a short-lived neutral meson π° is produced in a manner similar to the positive and negative π mesons and that the decay of the neutral meson into two photons gives rise to the observed photons.

They have observed:

1) A peak at approximately 125 Mev in the energy distribution of the photons emitted in the forward direction, while the energy distribution in the backward direction shows a maximum at about 70 Mev. The positions of these two maxima correspond to the Doppler shift which would occur if photons were emitted spherically symmetrically by the decay of a π° meson in a system moving with $v = 0.32c$ in the forward direction;

2) A value of approximately 0.5×10^{-27} for the absolute cross section for producing a pair of high energy photons. This is in rough agreement with estimates

of the total cross section for producing charged mesons by the proton beam;

3) The following relative yield of the quanta as a function of proton energy:

E_p (Mev)	Rel. Yield
345	1.0
290	0.35
230	0.07
180	0.01

The yield at 180 Mev is consistent with bremsstrahlung yield.

The extremely close agreement between these yields and the excitation function for π^-mesons (Section 4.14) must be taken as fortuitous, since the experiments on π^-meson yields were made in a very restricted energy and angle interval, and are not necessarily representative of the absolute cross section for π^-meson production.

4) That the yields of the photons increase more slowly with atomic number of the target than do the inelastic cross sections, as shown in the following table:

	Be	Cu	Ta
Relative yield of high energy photons	1.0	2.8	4.0
Relative inelastic cross sections for 270 Mev neutrons	1.0	4.0	11.0

5) That the yield of photons by bombardment with 190 Mev deuterons does not show a high energy gamma peak and that it is less than 1 percent of the yield from 345 Mev protons. The yield and energy distribution of photons from deuteron bombardment appear to be heavy particle bremsstrahlung.

6) That the photons originate within 10 mils of the target. This fact, coupled with an estimate of the velocity based upon the Doppler shift, permits an upper limit of 3×10^{-13} sec. to be calculated for the half-life of the particle

producing the radiation.

The possibility that the photons result from an excited nucleon has not been ruled out.

5. Production of μ Mesons

5.1 Source of μ^- mesons

The experiments with the channel plate holder to be described in Section 6.112 showed that very few if any μ^- mesons come directly from the target. Less than 1/2 percent of the meson tracks seen in such an exposure are μ^- mesons, and those which are observed usually do not have the correct range to have passed through the channel. It is therefore concluded that μ^- mesons are not produced directly by the proton beam striking a target and arise only from decay in flight of π^- mesons. This is confirmed by the very rare occurrence of $\pi^- = \mu$ meson decay tracks in the emulsion (Section 6.13) and is in agreement with the view that the π meson is the strongly interacting particle involved in nuclear forces, while the μ meson interacts only slightly and hence has a small cross section for production in fast nucleon-nucleon collision.

5.2 Production of μ^+ mesons

The work of Burfening, Gardner, and Lattes[1] with positive mesons in an open plate holder showed that μ^+ mesons with a maximum energy of approximately 4 Mev do come from the target. Since this maximum energy of the μ^+ meson is equal to the kinetic energy given to it in π^+ decay, μ^+ mesons are assumed to come from decays of π^+ mesons which have stopped in the target. The large yield is accounted for by the fact that low energy π^+ mesons stop in the target and decay. A few higher energy π^+ mesons are returned to the target by 360° focusing, and both emit μ^+ mesons after coming to rest there.

6. Properties of Mesons

6.111 General discussion - Mass of π^- mesons

When mesons were first observed in the cyclotron,[1] it was found that most of them gave rise to stars at the end of their range in the emulsion. As it was known from cosmic ray experiments that light mesons very rarely if ever give rise to stars, while heavy negative mesons generally do, it was concluded that most of the mesons observed were heavy. A preliminary study of the mass of the mesons was made by estimating their radius of curvature in the magnetic field and measuring their range in the emulsion. The results indicated that most of the mesons had a mass of 313 $\pm$ 16 e.m. The mass measurements described later in this section give a more accurate value for the mass of the heavy meson. The experiments are described rather fully, since no account of the mass measuring methods has yet been published, and also because it is hoped that some of the confusion from widespread quotation of different mass values can be eliminated by this presentation of old and new mass values.

If the charge of the mesons observed in the photographic emulsions is known, the mass may be obtained by any one of three independent methods: a) measuring the radius of curvature of the orbit in a magnetic field and the range in emulsion; b) measuring the ralative grain density of meson and proton tracks; c) measuring the small angle scattering due to Coulomb interactions.

Only the first two methods have been used in Berkeley. By comparing the results obtained it will be shown in Section 6.15 that the charge of the meson is equal within three percent to the electron charge.

6.112 Mass measurement by radius of curvature and range

Sections 6.112 and 6.311 contain information and drawings which Barkas, Bishop, Gardner and Lattes have kindly furnished from the draft of their forthcoming paper[1] on mass measurements. The discussion of this section will cover their experimental

method, but the mass values have been recalculated by Frances Smith, using the latest values of the range-energy relation and of the cyclotron magnetic field.

The plate holder used in the exposure for the mass measurement of negative mesons is shown in Fig. 6.112(1). The mesons originate from a "ribbon" target of dimensions 3 1/2 in. x 1/32 x 1/16 in. and are collected in the plates, which are exposed without wrapping and inclined at an angle of 5° relative to the plane of the beam.

In order to obtain an accurate result the following procedure was used:

a) The dimension in the plane of the beam of a slender target defined the radius of the point of origin of the mesons to within 1/64 in. If a solid target of the type described in Section 3.11 had been used, the origin of the mesons would not have been known since the beam undergoes multiple passages through this target and in doing so may strike it in regions other than the very edge.

b) The distance from the target to a reference point in the emulsion was measured to a high degree of accuracy by placing a fiducial mark on the plates at the time of exposure. The fiducial mark is put on by means of a "marker" as shown in Fig. 6.112(2). When the point (C) contacts the target, the globe behind the slit lights, leaving a developable fine line in the plate. The distance from the target to this fiducial mark is known to .001 inch. The position of the meson track with respect to this line is found with the microscope by measuring the coordinates of both within limits of error of 100 microns.

c) The channel was used in order to obtain mesons with a small energy spread, and to eliminate some mesons produced in places other than the target, such as π mesons produced by stray beam and μ mesons arising from π mesons that decay in flight. The channel was designed to admit into the plate only those mesons ejected within an angle of 14° relative to the incident beam, since the error in the calculated value of the mass increases for higher angles, as will be shown by Eq. 6.112(5).

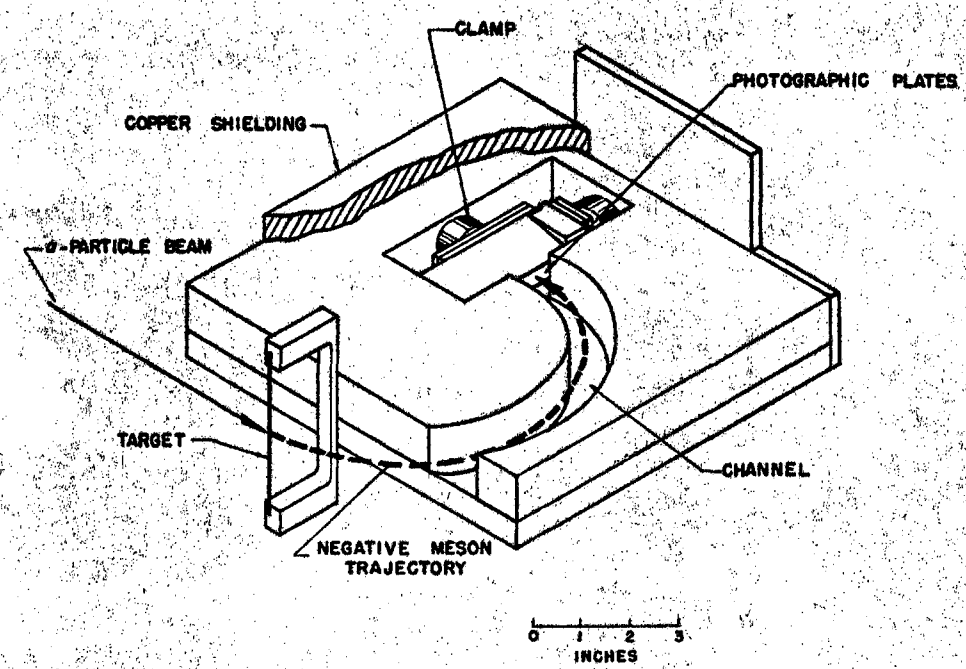
d) The angle at which mesons entered the plate was measured. Microscope eyepieces were fitted with rotary cross-hairs and protractors graduated in degrees. With these it was possible to measure the entrance angle with respect to the plate edge with an error less than 1 degree. At 14° this corresponds to maximum error in radius of curvature of $\frac{\cos 13^{\circ} - \cos 14^{\circ}}{\cos 14^{\circ}}$ or 0.4 percent.

e) The ranges of the mesons in the emulsion were measured under high magnification by comparison with a calibrated scale placed in the microscope eyepiece. The characteristic wandering of the tracks associated with the small angle scattering makes it necessary to measure the range in steps, dividing each track into relatively straight segments, and adding these lengths together. For the highest accuracy the Z or depth component of each segment was also measured and compounded with the projected length. This Z component can be measured by the focusing adjustment of the microscope and it amounts, after allowance is made for the shrinkage of the emulsion, to about 1 percent of the range in the experiment described here.

f) The intensity of the magnetic field along the line from the target to the photographic plate was measured by means of a flip coil[2] and by the method of proton moments[3] under standard conditons of the cyclotron magnetic field. The results obtained are plotted in Fig. 6.112(3) and the absolute values are believed to be correct within 0.03 percent up to 80 inches and 0.3 percent at larger radii. As the measurements to which the present mass calculations apply were made with the target at the 81 inch position (full energy beam), and as the magnetic field is not uniform over the region where the mesons travel (81 inches to 87.5 inches), the orbits are not perfect circles. In the calculations, the radius of curvature was first calculated under the assumption of a uniform magnetic field of strength

$$H = \int \frac{H \quad dR}{AB} \qquad 6.112(1)$$

and the orbit assumed to be a circle of radius $\rho = \frac{AB}{2 \cos \theta \cos \alpha}$ as illustrated



HOLDER FOR MASS MEASUREMENT STUDIES

FIG. 6.112 (1) MN 349

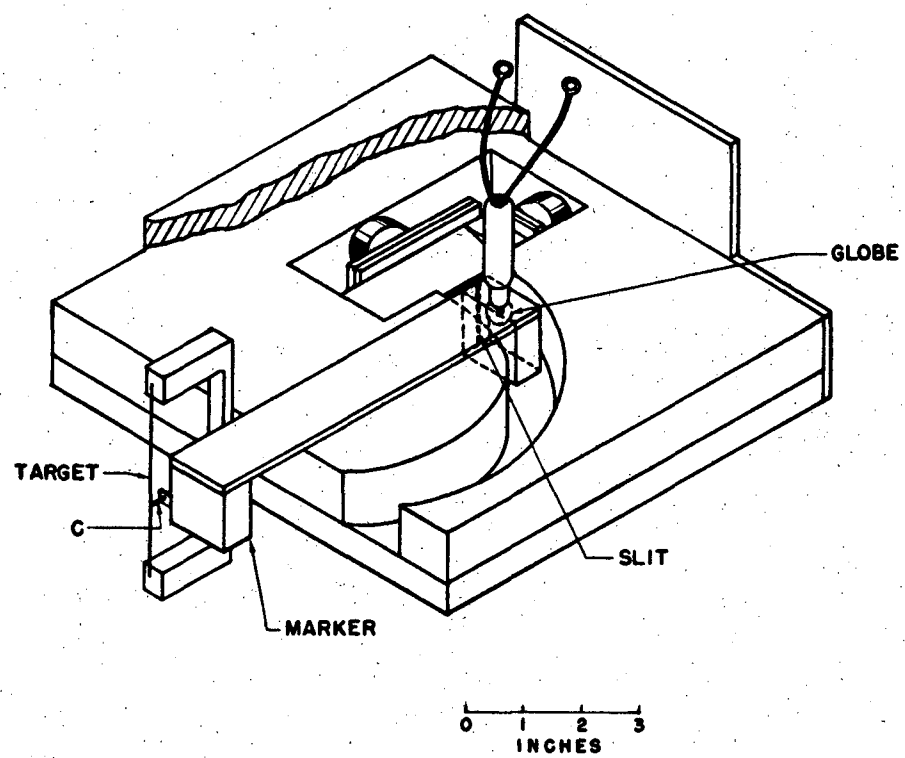


FIG. 6.112 (2)

MU 350

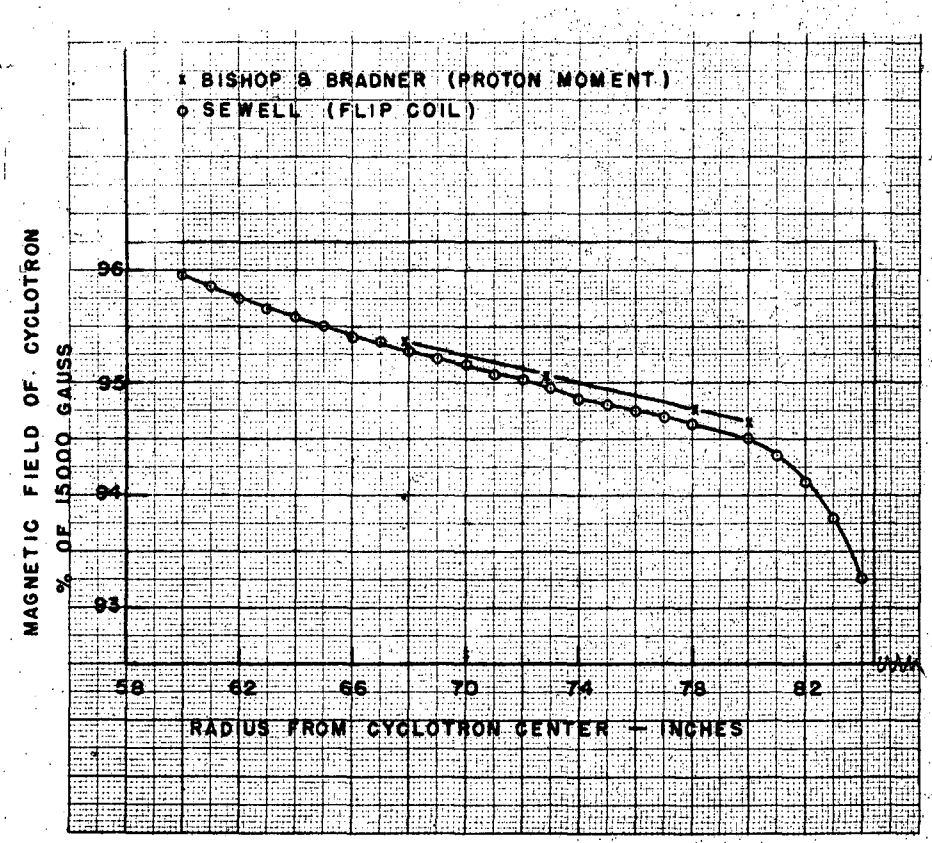
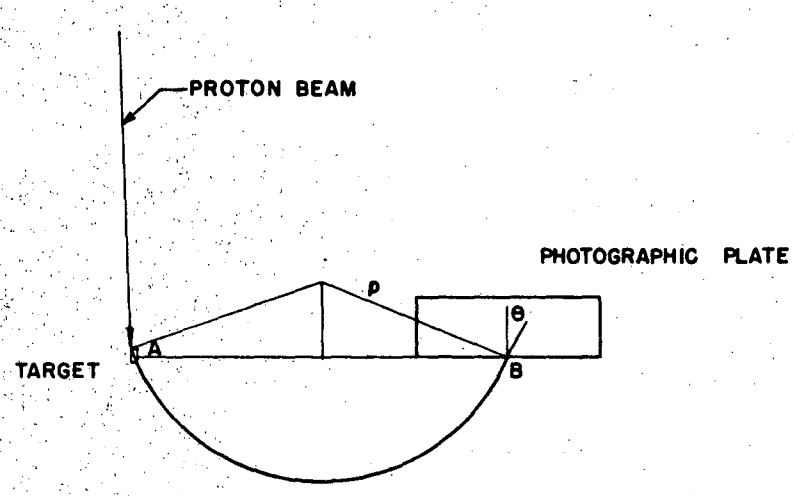


FIG. 6.112 (3) MU 331



MU 346

$$\rho = \frac{AB}{2\cos\theta}$$

FIG. 6.112 (4)

in Fig. 6.112(4). Here α is the angle between the plane of the emulsion and the plane of the beam. Henrich[4] has calculated that the error in ρ introduced by using the average field is approximately 0.3 percent.

g) The range-energy relation Eq. 9.2(6)

$$E = K\, m^{1-n}\, z^{2n}\, R^{n}, \qquad 6.112(2)$$

with $z = 1$, was combined with the classical formula for the enrgy of a charged particle in a magnetic field:

$$E = \frac{e^2}{2mc^2} \quad \overline{(H\rho)}^2, \qquad 6.112(3)$$

where

E = energy of the meson

e = charge on the meson, expressed in e.s.u.

m = mass of the meson

$\overline{H\rho}$ = magnetic rigidity of the meson

c = velocity of light

to give a first approximation to the mean mass

$$m = \left[\frac{e^2(\overline{H\rho})^2}{2c^2 K\, R^n}\right]^{\frac{1}{2-n}} \qquad 6.112(4)$$

A relativistic correction (of approximately 0.8 percent) was then applied to give the rest mass of the π meson.

Fig. 6.112(5) displays a histogram of the mass values obtained with the channel arrangement described above. After all corrections are applied, the mean value obtained for the mass of heavy negative mesons is 280.5 ± 6 e.m. The main sources of error were uncertainties in the value of the magnetic field, which is falling off rapidly, and in the range energy curve. Section 6.312 will describe a way of minimizing the error due to uncertainties in the magnetic field and the range energy curve, by measuring the mass of the protons with an arrangement similar to that used for mesons.

When Alvarez[5] plotted trajectories for the mesons, he found that the few badly scattered masses could be attributed to π mesons which had struck the walls of the channel or originated in the shielding. The histogram of Fig. 6.112(6) displays his results. This procedure of reconstructing a meson trajectory by use of the measured range and radius of curvature does not rule out the possibility of mesons with different masses, but simply discards some spurious tracks if it is assumed that only one mass of meson is present.

The importance of considering only the mesons of nearly normal incidence to the plate is indicated by the graph, 6.112(7), of meson mass values obtained with an open plate arrangement of the type described in Section 3.11 above. It will be noted that the mass values have a wider spread for large angles of incidence, as would be expected from the calculated error in the measurement of ρ as a function of incident angle:

$$\frac{d\rho}{\rho} \simeq \tan\theta \, d\theta \qquad 6.112(5)$$

The mass measurements described above were made by bombardment with full energy (390 Mev) α-particles. Measurements made with 340 Mev α-particles, with 345 Mev protons, and other arrangements with different types of target gave essentially the same results.

6.113 Mass measurements by grain counting

Measurements of the mass of mesons produced in the cyclotron have been made by Barkas, Gardner and Lattes,[1] by Van Rossum,[2] and by Bowker,[3] following the method of grain counting described by Lattes, Occhialini, and Powell.[4]

It can be easily shown (cf. 9.2) that the number of grains in the residual range R of a particle with mass m and unit electron charge is given by a relation

$$N \simeq m\,F\,(R/m) \qquad 6.113(1)$$

where F is some undetermined function. In principle, Eq. 6.113(1) coupled with the

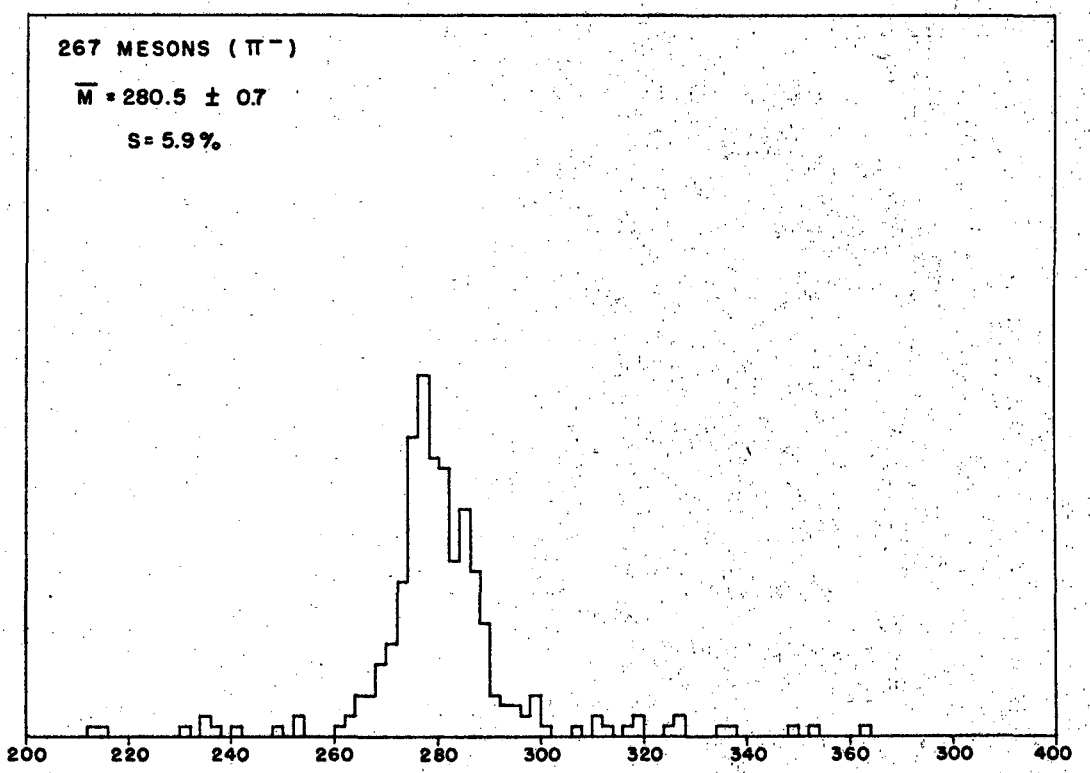


FIG. 6.112(5)

14277-1

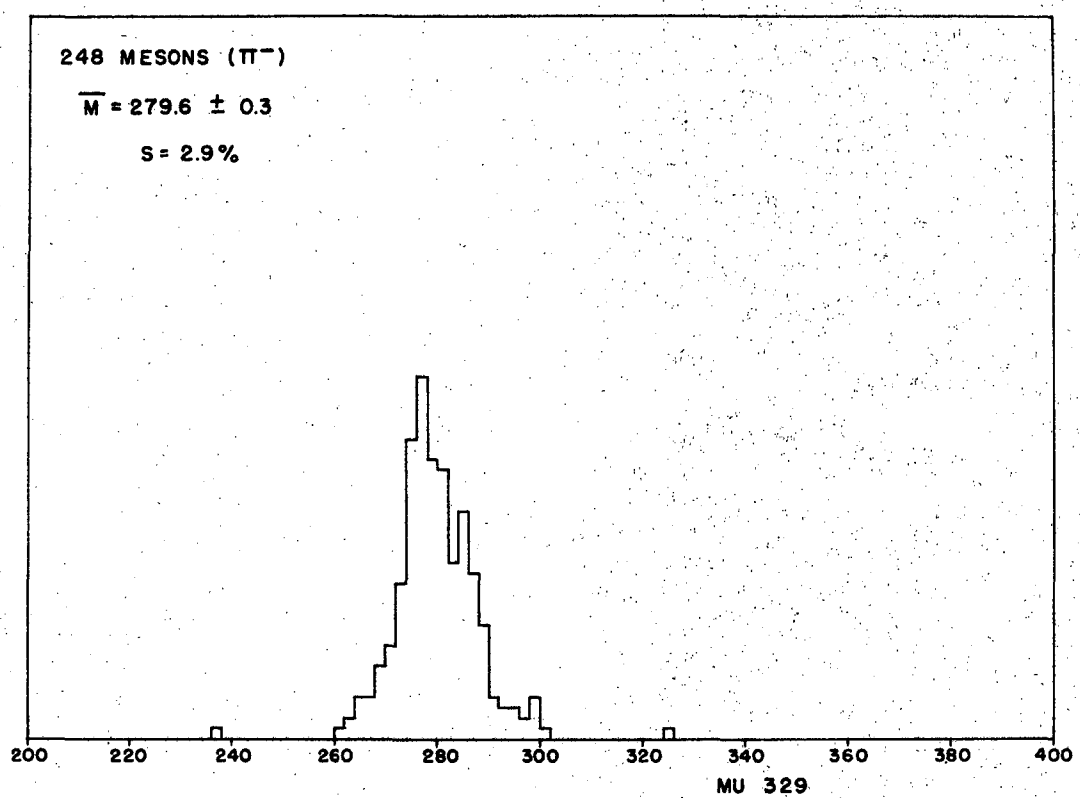
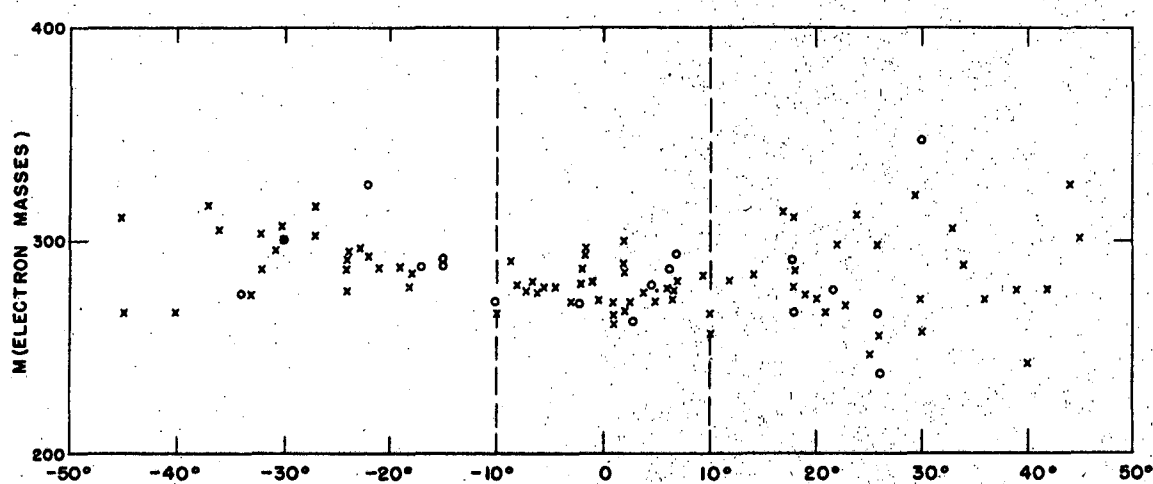


FIG. 6.112(6)

14276-1



MASS VALUES OBTAINED WITH OPEN HOLDER

MU 328

FIG. 6.112 (7)

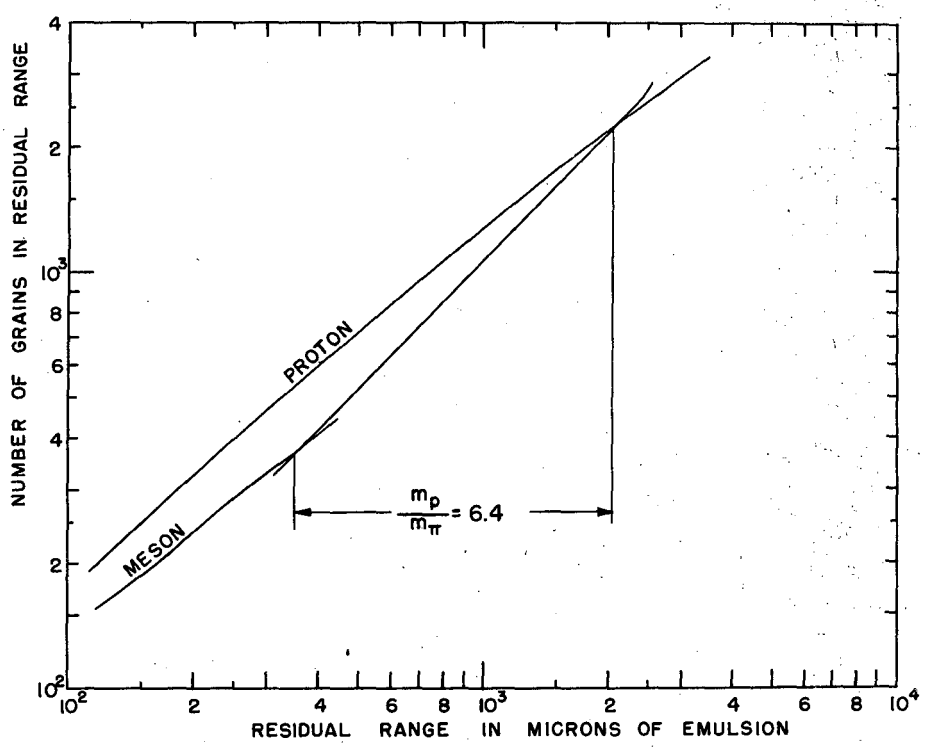


FIG. 6.113 (1)

MU 564

14131-1

general range energy relation (9.2-5) (for $z \cong 1$) $R = m\ f\ (E/m)$ permits the determination of the ratio of masses of two particles by comparing the grain density of their tracks. One method of computing the mass ratio is to form a plot of the logarithm of the number of grains in the residual range vs. the logarithm of the residual range for each particle.

The function f (E/m) may be rewritten g(v), where f and g are related, though undefined, functions. Hence from 9.2(4)

$$\frac{R}{m} = g(v) \qquad 6.113(2)$$

and 6.113(1) may be rewritten

$$\frac{N}{m} = G(v) \qquad 6.113(3)$$

and therefore by dividing

$$\frac{R}{N} = H(v) \qquad 6.113(4)$$

it follows that a 45° line on a plot of log N vs. log R represents a line of constant v.

Relation 6.113(2) shows that the ratio of the masses of two particles is equal to the ratio of their ranges provided that they both move with the same velocity. Hence the intersection of a 45° line with the two curves of log N vs. log R gives two abscissae, whose values give the ratio of the masses.

The above method of plotting was employed in the experiment of Bowker. He has kindly furnished the representative plot of Fig. 6.113(1). One disadvantage of the method is the small angle between the curves of grain count and the 45° line which causes a 1 percent error in grain count to result in approximately 5 percent error in computed mass.

In Bowker's study the meson tracks were obtained in 100 micron thick Ilford C-2 plates exposed successively to mesons and then to protons coming from targets

in the cyclotron in such a manner that the particles were traveling nearly parallel to the plane of the emulsion and therefore had a high probability of remaining in the emulsion for their entire range. Most of the meson tracks observed entered the edge of the emulsion and had a range of 400 to 900 microns.

In making grain counts on tracks, the number of grains in a clogged length of track was assumed to be equal to the clogged length times the average grain diameter in unclogged portions of the track. Tracks were rejected which had large angle scattering, or which had any part of their length within 10 microns of the top or bottom of the emulsion. Only meson tracks of length greater than 400 microns and proton tracks of length greater than 2000 microns were accepted. These conventions were adopted to reduce subjective errors and errors caused by non-uniform development. The angle of dip of the tracks in the emulsion was considered in the calculations, and corrections were made for the approximately 50 percent shrinkage in thickness of the emulsion during development.

The results showed that the method was moderately satisfactory for π mesons of as small a range as 200 microns, and correspondingly, for protons of range as little as 1200 microns. The variation of the logarithm of the number of grains with the logarithm of the range was found to be linear in C-2 emulsions for proton lengths greater than 600 microns. However, it was found that the emulsions showed a striking non-uniformity in sensitivity in an area extending 2 to 4 mm in from the long edges of the plates, so that mesons near the edges showed large errors in calculated mass. Much of this effect was later found to be due to aging, since freshly cut edges on plates were more uniform.

The result of the grain count of 18 mesons and 7 protons by Bowker gave a value of 264^{+26}_{-22} electron masses for the mass of the π^- meson. Barkas et al. employed similar conventions for clogging but did not take as great care in considering particle location. They report a mass value of 305 electron masses for

the π^- meson and 202 electron masses for the μ^- meson. Van Rossum reports a mass of 280 ± 15 electron masses based on 17 proton and 13 meson tracks in C-2 plates exposed to the cyclotron.

The method of grain counting on mesons obtained as described in Sec. 6.21 furnishes the only value obtained in this laboratory for the mass of the μ^- meson. It does not provide as accurate a value for the mass of the other mesons as the method of H ρ and range described in Section 6.112 above. However, as will be shown in Section 6.15, the combination of grain counting with H ρ and range permits a calculation of the charge on the meson.

6.12 Stars produced by π^- mesons

It has been found[1] at Berkeley that (73.2 ± 2) percent of the π^- mesons which end in the emulsion initiate stars of one or more prongs. This fraction does not vary beyond the above limits with any emulsion sensitivity from C2 to G5. Surveys[2] of NTB3 and G5 emulsions show that, of 184 stars, there were 4 prongs whose ionization corresponded to that of a proton of between 50 and 80 Mev. Since this ionization may be beyond the limits of sensitivity of C2 emulsion, it follows that about 2 percent of all emitted heavy particles may be missed in C2 emulsion. The meson is always approximately at rest when the star is formed, so that only the rest energy of the meson is responsible for the nuclear disintegration. In the (26.8 ± 2) percent of the mesons which do not show an observable star prong, it is presumed that the energy given to the nucleus has been lost through the emission of one or more fast neutrons. Adelman and Jones have made a tabulation of the number of prongs per star for 512 π^- mesons in C2 emulsion (Fig. 6.12(1).)* The following conventions were used:

---

* Adelman and Jones have kindly given permission to use Figs. 6.12(1) and 6.12(2) from their forthcoming paper in Science.

a) Mesons initiating one or more fragments of definite direction are said to produce a star.

b) If a star prong is shorter than 5 microns but has a definite direction, it is considered to be a nuclear recoil. For example a star with four fragments, one of which is a recoil, is called a 4-prong star, but is accounted for in the hatched portion of the graph.

c) Some mesons stop in the emulsion without giving rise to any fragment and are recorded in the column of 0 prongs. (38.7 ± 5) percent of these mesons exhibit a club, a group of grains at the terminus, with no definite direction. These mesons are represented by the shaded area in the column of 0 prongs.

Fig. 6.12(2) is a collection of typical meson stars. Fig. 6.12(3) shows a highly enlarged meson ending with a typical club; it has not been possible to ascertain in every instance whether the club is due to a short recoil, to scattering very near the end of the meson range, or to ionization from the meson and associated electrons. Fig. 6.12(4) shows a meson causing hammer tracks. Such tracks, which indicate that a heavy fragment comes to rest in the emulsion and splits into two equal lighter fragments, are interpreted as being due to Li^8 nuclei which decay according to the following scheme:

$$Li^8 \longrightarrow \underset{\downarrow \atop 2\alpha}{Be^8} + \beta^-$$

These "hammer tracks" are found in about 0.3 percent of the meson induced stars observed at this laboratory.

No detailed energy balance has been made for any particular star since it is generally impossible to distinguish the α -particle tracks from those of heavier nuclei or to estimate the energy of the neutrons emitted from the star. The use of very thick emulsions should make it possible to obtain occasional particularly favorable cases of the type in which all tracks end in the emulsion, and then a

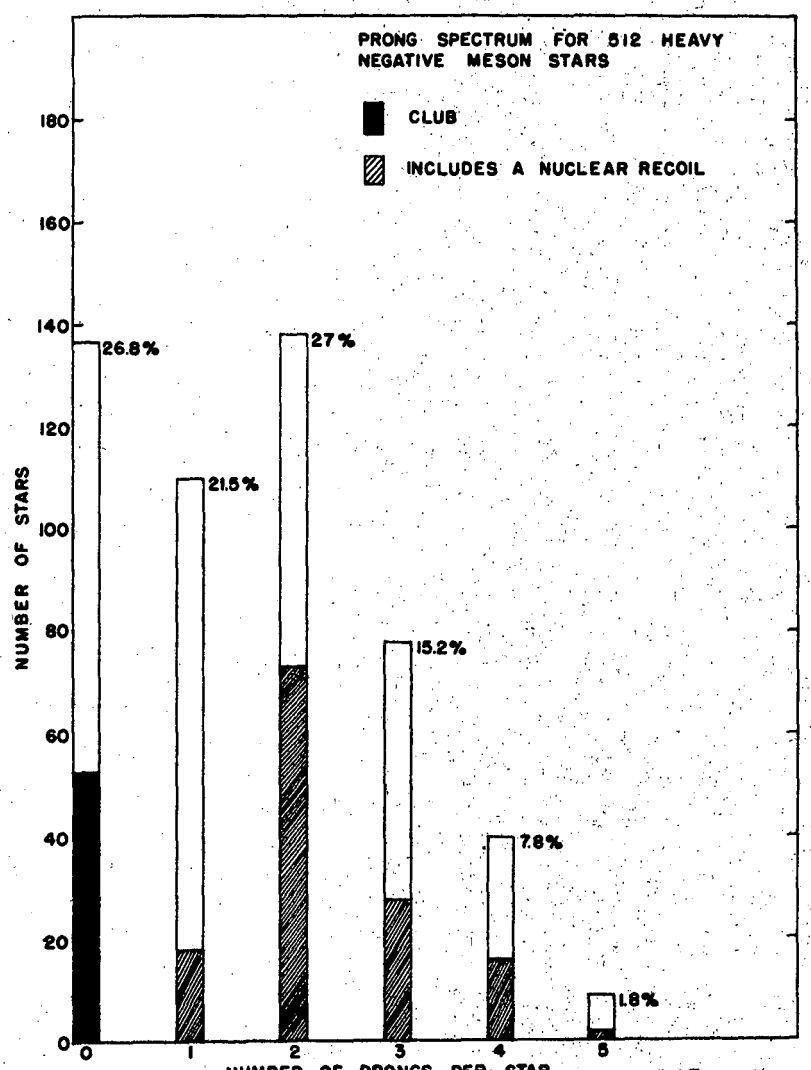

PRONG SPECTRUM FOR 512 HEAVY NEGATIVE MESON STARS
CLUB
INCLUDES A NUCLEAR RECOIL
NUMBER OF STARS
0
20
40
60
80
100
120
140
160
180
26.8%
21.5%
27%
15.2%
7.8%
1.8%
0
1
2
3
4
5
NUMBER OF PRONGS PER STAR
MU 347
14128-1

FIG. 6.12 (1)

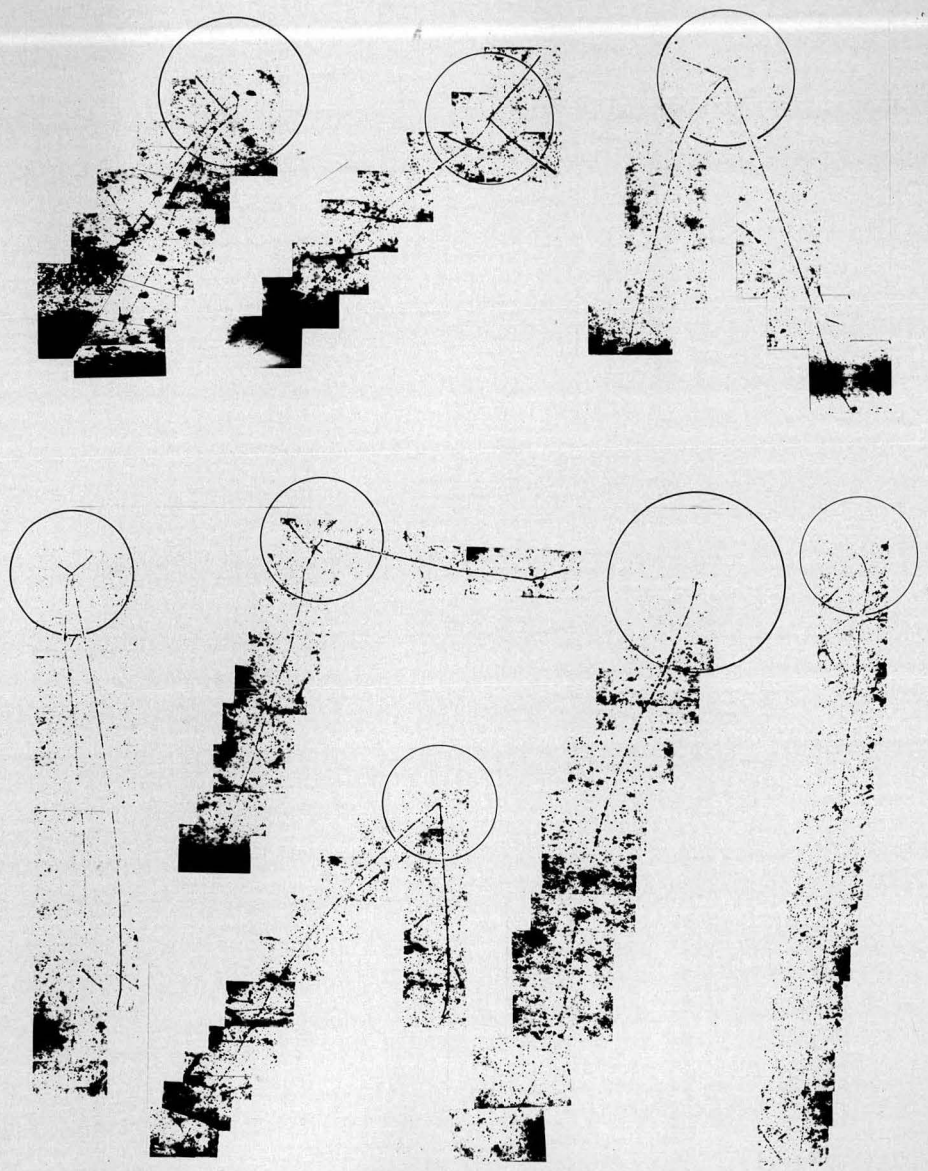


FIG. 6. 12 (2)

OZ 732

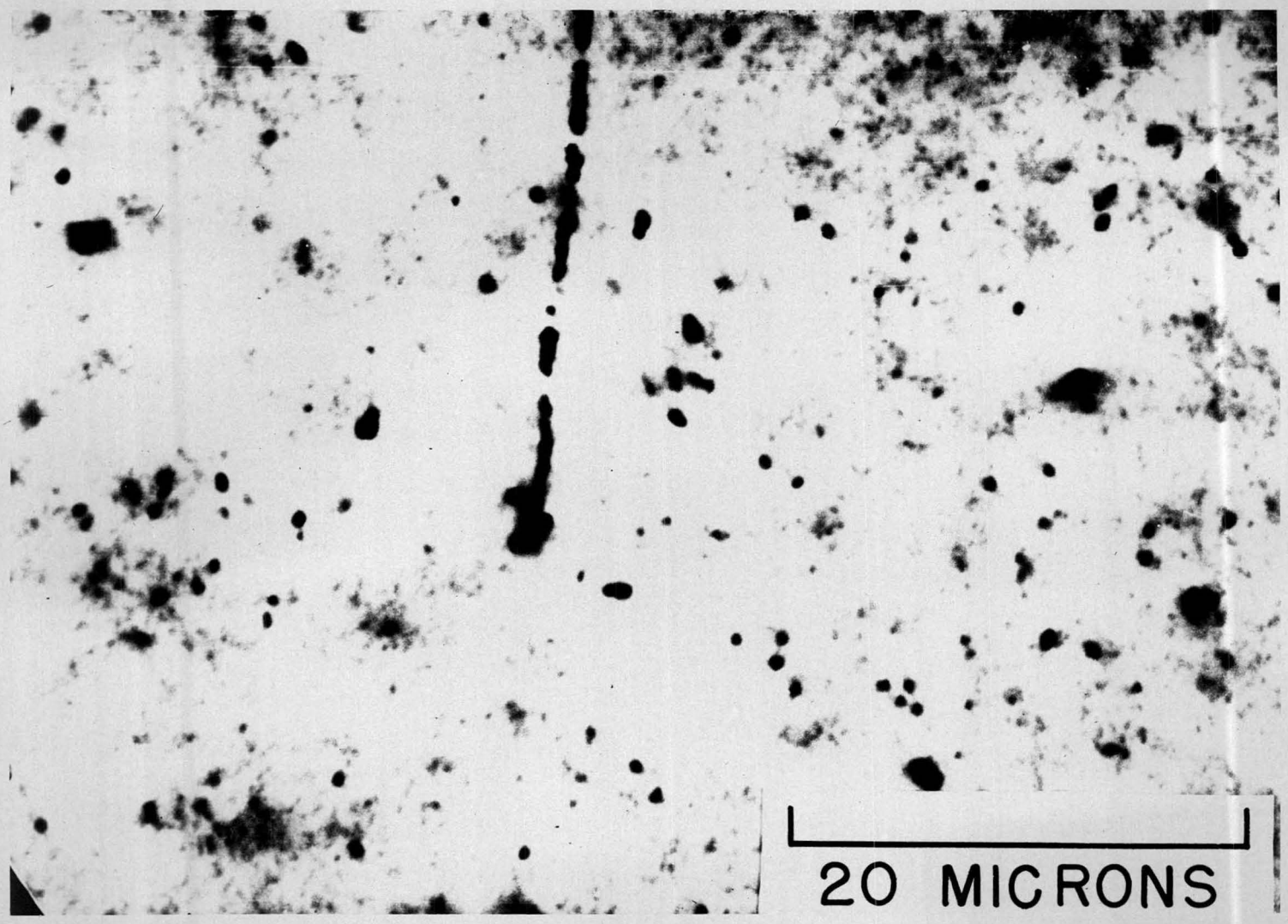


FIG. 6.12 (3)

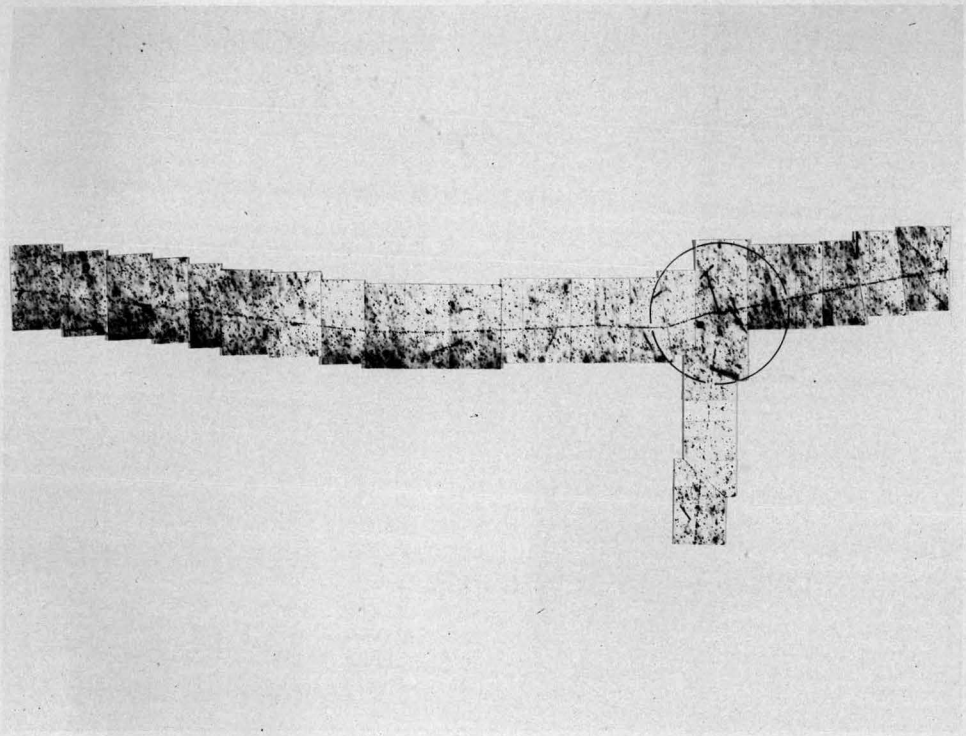


FIG. 6. 12 (4)

KODAK—STEEL
OZ 727

complete measurement of the energy may be obtained by simple momentum analysis.

A statistical study of the energy liberated by the meson when captured in nuclei of the emulsion has been made by Heidmann and LePrince-Ringuet.[3]

6.13 Decay of π^- mesons

There is little evidence to indicate that π^- mesons ever produce μ^- mesons after coming to rest in the emulsion. Only two cases[1][2] which could possibly be interpreted as $\pi^- - \mu^-$ decay have been seen in more than 4000 meson tracks studied; but the time required for a 4 Mev π meson to stop in emulsion is approximately 1.3×10^{-11} sec., or 10^{-3} half-lives, so that decay during passage through the emulsion would be expected in about 10^{-3} of observed mesons. The two cases noted could also be due to π^+ mesons which scattered into the emulsion.

It is thought, therefore, that the π^- meson which comes to rest is captured by a nucleus in a time short compared with the $\sim 10^{-8}$ sec. half-life for spontaneous decay and hence that π^- mesons decay only in flight.

6.14 Half-life of π^- mesons

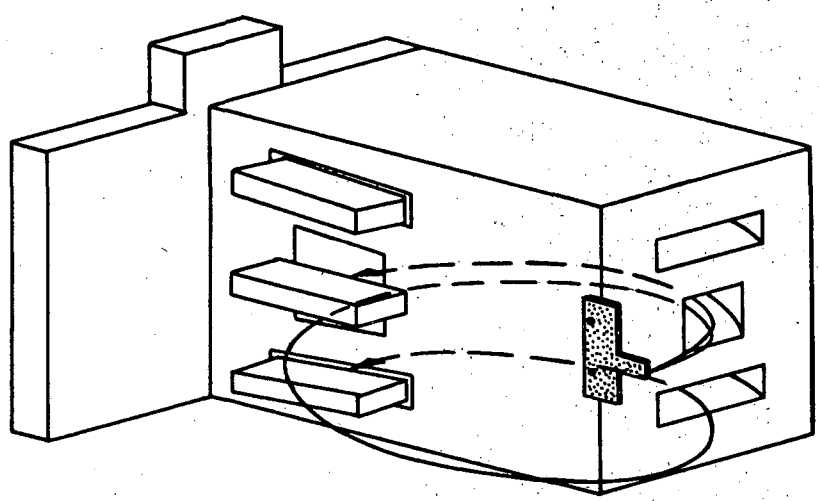
The first estimates of the half-life of artificially produced mesons were made by Lattes[1] in conjunction with mass measurements, by looking for a difference between the number of mesons entering plates at $+30^\circ$ and -30° from the normal to the edge. Fig. 6.112(7) shows the number of mesons as a function of angle θ for mesons observed in plates exposed in the arrangement described in Section 3.11. The time of flight for the $+30^\circ$ orbit is 3×10^{-9} sec., while that for the -30° orbit is 6×10^{-9} sec. Since no significant difference in the number of mesons was obtained, it was concluded that the half-life for decay of the π^- mesons is larger than 5×10^{-9} sec.

A direct measurement of the half-life of the π^- meson was made by Richardson[2] with the apparatus shown schematically in Fig. 6.14(1) and in the photograph of Fig. 6.14(2). Mesons formed at the target and traveling initially in approximately

the same direction as the beam could pass through the central channel. Those with the correct vertical component of motion could spiral downward through the central channel and the lower channel as shown. Photographic plates were placed opposite the exit of the channel to record mesons which described 1/2 revolution and 1 1/2 revolutions.

At the radial distance of 76 inches from the center of the cyclotron, where the target was placed for most of the experiments, the vertical focusing of mesons is negligible compared with the statistical uncertainties of the experiment. Hence, if no decay took place, it was expected that the ratio of mesons in the two plates would be 3 to 1. A direct experimental check of this geometrical ratio was made by Martinelli and Panofsky by substituting a plutonium α-particle source for the target and determining the ratio of the number of α-particles going through the two channels under conditons identical to those of the exposure except for a reversed magnetic field. The ratio of 3.2 to 1 which they obtained was used for the calculations of the meson half-life.

Only star-producing mesons were counted to assure that heavy π^- mesons alone were being considered. 254 mesons were observed in the 180° position and 48 in the 540° position for the same area of scanning. If there had been no decay, 92 mesons would have been expected in the 540° position. Richardson used a mass of 286 m_e for the meson and calculated the time for one revolution to be 7.2×10^{-9} seconds. The current value of 276 m_e would alter the time for one revolution to 6.95×10^{-9}. By assuming that the abnormal decrease was due to the decay in flight of the π^- mesons, Richardson obtained the value of $0.77^{+0.21}_{-0.15} \times 10^{-8}$ seconds for the half-life, or 1.1×10^{-8} seconds for the mean life. The values based on a mass of 276 m_e are $0.74^{+0.21}_{-0.15} \times 10^{-8}$ seconds for the half-life, and 1.06×10^{-8} seconds for the mean life. The value of the mean life depends heavily on the number of mesons in the 540° plates. Background was high and Richardson found only about



APPARATUS FOR MEASURING HALF-LIFE OF π^- MESON

MU 341

FIG. 6.14 (1)

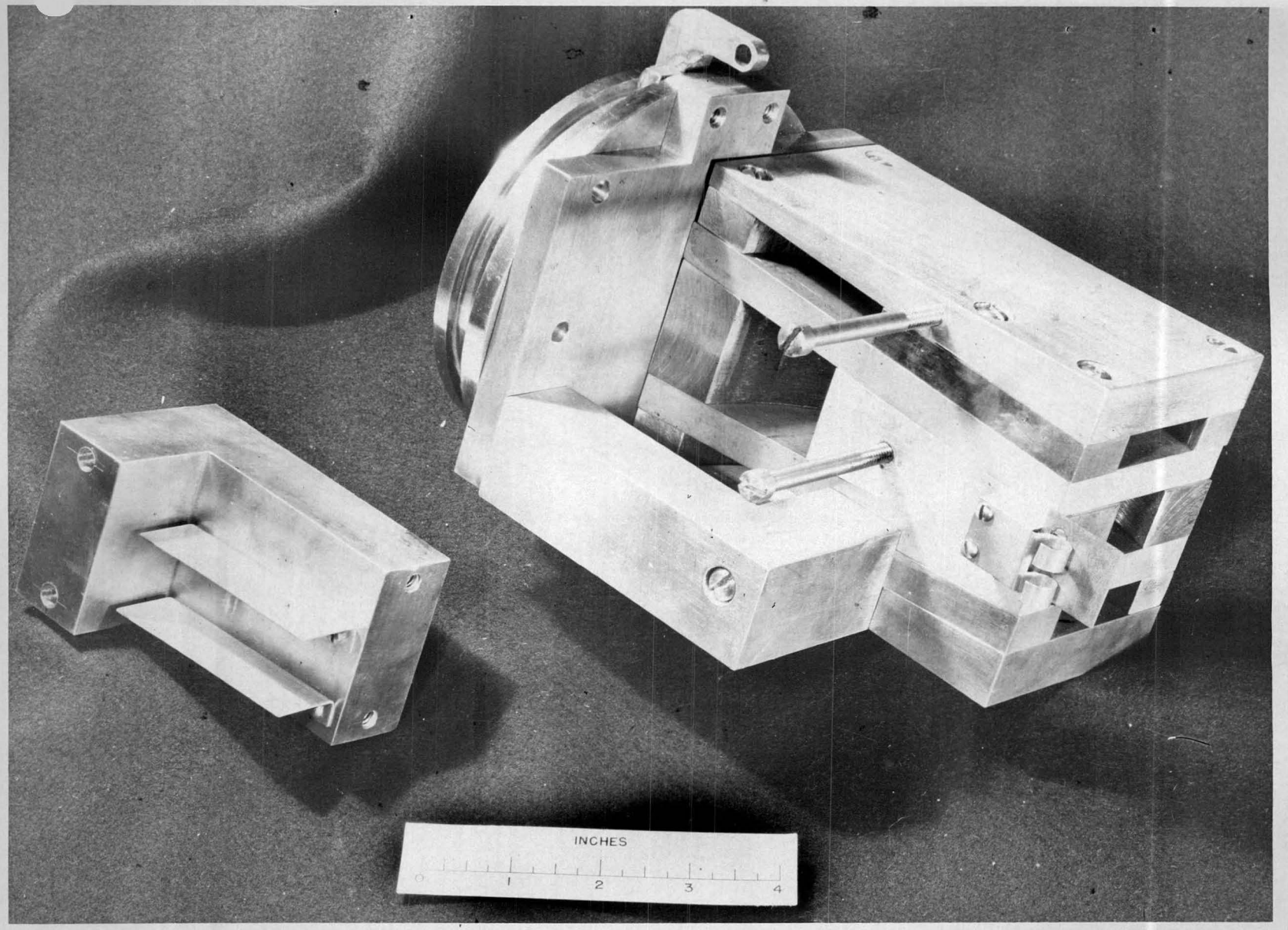


FIG. 6. 14 (2)

two mesons per plate in this position.

6.15 Charge on the π meson

Cloud chamber studies of cosmic ray mesons have indicated that the charge on the μ meson is equal in magnitude to the electronic charge. This result implies that the charge on the π meson is also equal in magnitude to the charge of an electron.

By combining the equations for meson mass obtained by the two methods of Sections 6.112 and 6.113, it can be shown that the charge on the π meson is indeed very close to that of an electron.

In the equations of those sections, it was assumed that the charge on the meson is equal to that of the electron. If the charge is ze, then equations 6.112(2) and 6.112(3) become:

$$E = K\, m^{1-n}\, R^{n}\, z^{2n}, \quad \text{and} \qquad 6.15(1)$$

$$E = 1/2\, \frac{z^2 e^2}{mc^2}\, (\overline{H\rho})^2 \qquad 6.15(2)$$

It is seen that $\overline{H\rho}$ and range actually permit calculation of the quantity $mz^{\frac{2(n-1)}{2-n}}$ rather than m itself.

In grain counting, it is found that the plot of log N vs log R approximates a straight line; hence a power law approximation of equation 6.113(1) is valid, and the relation between grain count and range involves the quantity $mz^{\frac{2n}{1-n}}$ rather than m. (cf Section 9.2).

From the results of Section 6.113 and Section 6.311*, we have

$$\frac{z^{\frac{2(n-1)}{2-n}}}{z^{\frac{2n}{1-n}}} = \frac{276 \pm 6}{264^{+26}_{-22}}$$

* The mass of the positive meson is used here since it is felt that this value is more reliable than that of Section 6.112 due to uncertainty in the cyclotron magnetic field.

Putting in the value of 0.58 for n, and solving these two equations for z gives for the charge on the meson

$$ze = 0.99 \pm 0.03\ e$$

The calculated value of z is not very sensitive to changes in n or the mass values, although a change of z from unity causes the mass calculated according to two methods to change in opposite directions. It is clear that the charge of the π meson is not much different from the charge of an electron.

6.21 Star production by μ^- mesons

The measurements of Conversi et al. (1)-(5) on the half-lives of μ^- mesons in medium heavy elements show that a majority of these mesons are captured by nuclei before decaying. It might be expected offhand that some of the captured μ^- mesons would give up their rest energy to produce nuclear stars as the π^- mesons do.

No experimental arrangement yet tried for cyclotron bombardments has produced μ^- mesons in a plate without π^- mesons also being present. Accordingly, investigations of star formation by μ^- mesons have employed ordinary holders of the type shown in Fig. 4.13(1) and plates have been searched for mesons with direction and range different from the π^- mesons coming from the target. Different observers (6) have made cursory studies using plates at approximately 7 inches from the target. At this distance, π^- mesons have approximately 4 mm range in the emulsion, while μ^- mesons emitted within approximately 30° of the backward direction by these π^- mesons are expected to have a sufficiently shorter range to be distinguished from the π^- meson endings. The points marked by an x, and lying below the line of minimum range in Fig. 4.13(2), represent star-forming mesons; however, they could be scattered π mesons; their ranges are in no instance sufficiently short to permit their assignment to μ^- mesons. Lattes used a similar arrangement to observe μ mesons which had been emitted in a forward direction and hence had greater range than the π mesons. Barkas (7) obtained emulsions containing an increased proportion

of μ mesons by placing plates on top of the normal target holder so that particles coming directly from the target could not reach the emulsion. However, light mesons formed by decay of upward spiraling π mesons could reach the emulsion. It is theoretically possible to reconstruct the trajectories of the μ mesons on the basis of a knowledge of their mass and paths in the emulsion; and, in many cases, to fit these trajectories to the paths of π^- mesons coming from the target.

The results of all three methods are inconclusive and the most that can be said is that none of the workers found any definite cases of μ^- stars, in a total of approximately 30 events. This is in agreement with the conclusions of Chang[8], who found no charged particles associated with the endings of 53 μ^- cosmic ray mesons. A brief discussion of Chang's results is contained in Section 8.1.

6.311 Mass of the positive meson by radius of curvature and range

The mass of the π^+ meson was measured by Barkas et al.[1] who used the same method of $H\rho$ and range that was described in Section 6.112 for the π^- meson. The plate holder, shown in Fig. 3.12(1), had a channel of smaller radius than the holder of Fig. 6.112(1), in order to accept μ^+ mesons of just under 4 Mev. When ranges were measured two distinct groups were found as shown in Fig. 6.311(1). These two groups correspond to two types of mesons of mass approximately equal to 285 and 215 electron masses. The origin of the light mesons was discussed in Section 5.2. Frances Smith[2] has recalculated the mass values, using the latest magnetic field measurements and range-energy relation. The results are 278 $\pm$ 8 e.m. for the mass of the π^+ meson and 212 $\pm$ 6 e.m. for that of the μ^+ meson.

A slightly more precise calculation[2] of the π^+ meson mass has been made from new range measurements on mesons traveling in the more uniform cyclotron field between 74 in. and 80.5 in. radius. After all corrections are applied, the mean value obtained for the masses of 85 heavy positive mesons is 276 $\pm$ 6 electron

masses. The probable error quoted arises mainly from systematic errors. The probable errors (not probable errors of the mean) are:

Uncertainty in the range-energy curve	3.9 mass units
Finite size of the target	1.9 mass units
Straggling in the range of mesons	1.7 mass units
Angle of entrance of mesons in plates	0.6 mass units

Fig. 6.311(2) shows a histogram of the calculated masses.

6.312 Mass measurements by comparison with proton range

Preliminary experiments have been made by Bishop et al.[1] with a mass measuring technique[2] which does not require a knowledge of the absolute value of the cyclotron magnetic field or a precise knowledge of the range-energy relation.

Consider the Equation 6.112(4) for the mass of a meson in terms of the magnetic rigidity $(\overline{H\rho})_\pi$ in a magnetic field, and the range R_π in emulsion:

$$m_\pi = \left[\frac{e^2(\overline{H\rho})_\pi^2}{2c^2 K R_\pi^{\,n}}\right]^{\frac{1}{2-n}} , \qquad 6.312(1)$$

where

$$E_\pi = K\, m_\pi^{\,1-n} R_\pi^{\,n} , \qquad 6.312(2)$$

and a similar equation for the mass of a proton:

$$m_p = \left[\frac{e^2(\overline{H\rho})_p^2}{2c^2 K R_p^{\,n}}\right]^{\frac{1}{2-n}} \qquad 6.312(3)$$

Dividing and rearranging terms shows that

$$\frac{m_\pi}{m_p} = \left[\frac{(\overline{H\rho})_\pi \;/\; (\overline{H\rho})_p}{R_\pi / R_p}\right]^{\frac{2}{2-n}} \frac{R_\pi}{R_p} . \qquad 6.312(4)$$

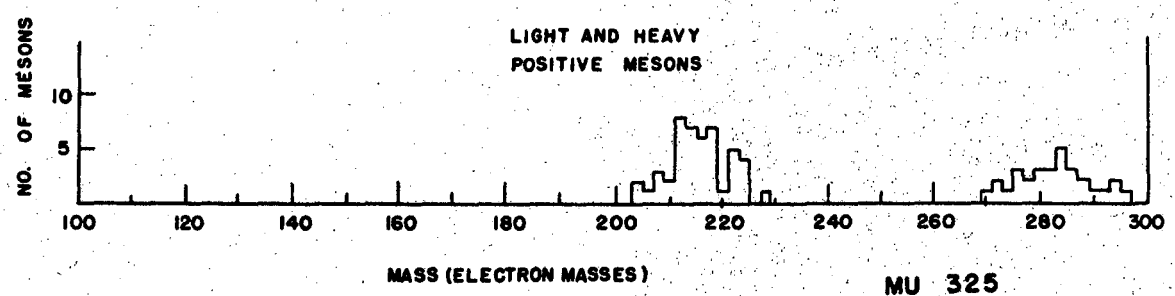

LIGHT AND HEAVY
POSITIVE MESONS
NO. OF MESONS
10
5
100
120
140
160
180
200
220
240
260
280
300
MASS (ELECTRON MASSES)
MU 325

FIG. 6.311(i)

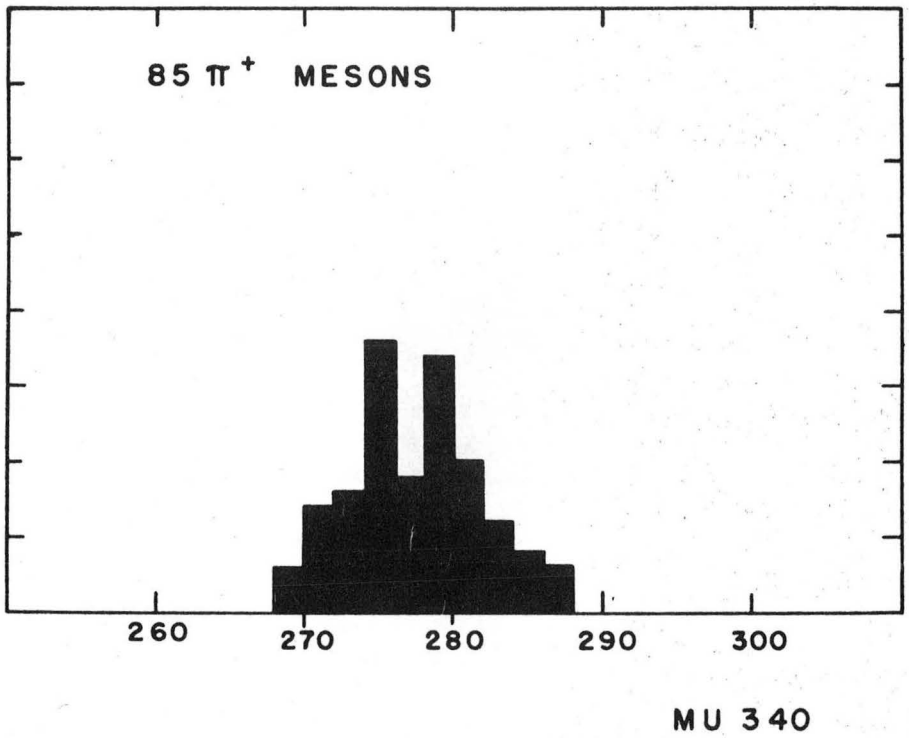


FIG. 6.311 (2)

Now let us see under what circumstances the term in the parentheses is equal to unity:

The ranges of two ions having the same charge and velocity but different mass are connected by the relation:

$$R_{\pi}(E) = \frac{m_{\pi}}{m_p} R_p\left(\frac{m_p}{m_{\pi}} E\right) , \qquad 6.312(5)$$

which is independent of any specific range-energy curve.

Therefore we can conclude that protons and mesons which have the same initial velocity will have ranges obeying the relation

$$\frac{R_{\pi}}{R_p} = \frac{m_{\pi}}{m_p} = \frac{(\overline{H\rho})_{\pi}}{(\overline{H\rho})_p} . \qquad 6.312(6)$$

Equation 6.312(6) may be derived in a relativistically correct manner without assuming any specific form of range-energy relation.

In order to perform this mass comparison a plate was exposed to obtain protons of 27 Mev and mesons of 4 Mev which were known to satisfy the relation 6.312(6) to the first approximation. It has been found possible to obtain plates in which the proton tracks are very close together and thus have accurately the same energy. Hence, it is permissible to average proton ranges. The ratio of each meson range to this average proton range was calculated, and a plot was made of $\ln \frac{R_{\pi}}{R_p}$ vs. $\ln \frac{(\overline{H\rho})_{\pi}}{(\overline{H\rho})_p}$. The intersection of the straight line through these points with a 45° line through the origin gave the correct mass ratio. Such a plot is shown in Fig. 6.312(1). The resulting meson mass agrees with the value of 276 ± 6 given in Section 6.311 above.

A new mass determination is now being made, by using a method of mass comparison to avoid dependence on absolute magnetic field and range-energy data. Improvements are being made at the same time in the mechanical details of the

experiment to permit more accurate measurement of target-to-plate distance.

6.32 Decay of π^+ mesons

A study of π^+ mesons obtained with a channel shown in Fig. 3.12(1) indicated[1] that more than 95 percent of π^+ mesons decay into μ^+ mesons after coming approximately to rest. The ranges of the μ^+ mesons were all equal within the limits of straggling. Lattes[2] obtained a value of 595 $\pm$ 9 microns for the range of 14 μ^+ mesons at Berkeley, and about 614 $\pm$ 5 microns for the range of 31 cosmic ray mesons at Bristol. These values correspond to 4.13 $\pm$ 0.04 Mev and 4.21 $\pm$ 0.02 Mev for the energy of a meson of mass 212. A value of 4.18 $\pm$ 0.04 Mev has been arbitrarily chosen for the calculations of the present paper. Further range measurements are being made by S. Jones.

There is no apparent correlation[3] between the direction of the π^+ and the μ^+ meson for plates exposed in the magnetic field of the cyclotron. Experiments to test the theory of Wentzel[4] have been made by Richman, Weissbluth, and Wilcox[5] with mesons produced in a low magnetic field area outside the cyclotron. Preliminary results do not show any angular correlation.

The 4 to 5 percent of the π^+ mesons that are seen not to produce μ^+ mesons cannot be accounted for by assuming that they end near the surface of the emulsion, since there are uneventful endings near the center of C3 and NTB emulsions.[6] The possibility that the non-decaying particles are μ^+ mesons instead of π^+ mesons is being explored by L. Alvarez and F.M. Smith, who in their experiments are using channels with 4 inch radius to eliminate μ mesons from decay of π^+ mesons at rest in the target, and to produce widely different π^- and μ^- ranges of any μ^+ mesons produced by decay in flight. At the time of this writing it seems possible that the mesons with uneventful endings are spurious, and that all π^+ mesons at rest decay to μ^+ mesons.

There is no good evidence that π^+, μ^+, or μ^- mesons ever produce stars.

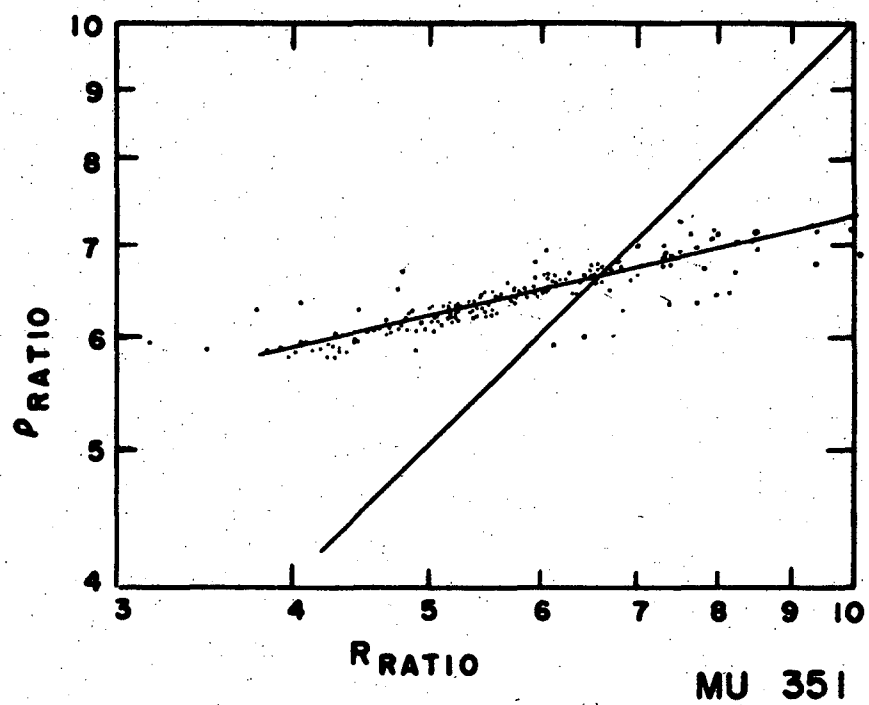


FIG. 6.312(1)

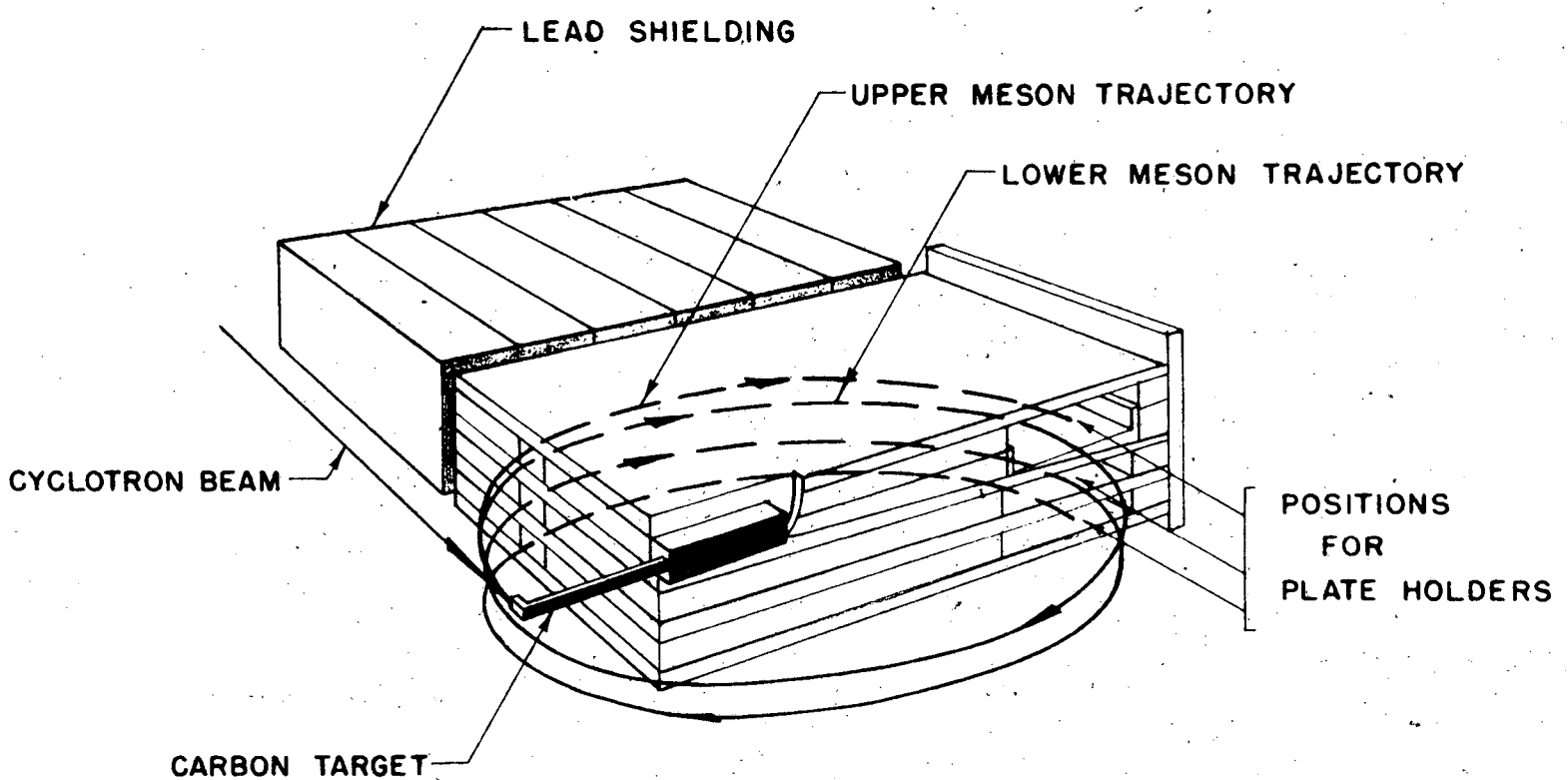
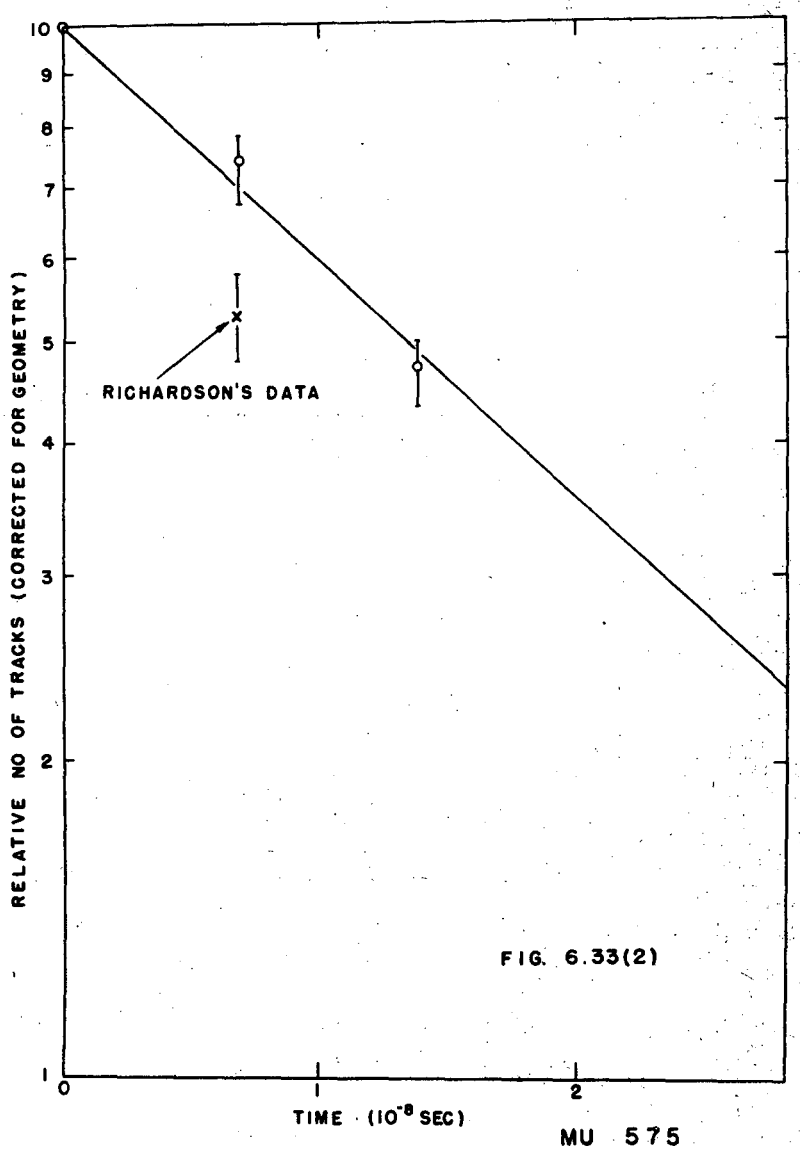


FIG. 6.33 (1)
SCHEMATIC VIEW OF APPARATUS


RELATIVE NO OF TRACKS (CORRECTED FOR GEOMETRY)
10
9
8
7
6
5
4
3
2
1
0
1
2
TIME (10⁻⁸ SEC)
RICHARDSON'S DATA
FIG. 6.33(2)
MU 575

6.33 Half-life of π^+ mesons

Martinelli and Panofsky[1] have measured the half-life of positive mesons by using a modification of Richardson's π^- half-life apparatus as shown in Fig. 6.33(1). In the experiment with positive mesons the geometry of the apparatus was calibrated by using a strong thick alpha source (Am^{241}) with a thin covering. Alpha-particles were emitted with energies up to 2.5 Mev. Exposures were made in the proton beam rather than in the α-particle beam in order to take advantage of the high cross sections for meson production. The target was placed at 65 inches from the center of the cyclotron and the channel accepted mesons with a radius of curvature between 4 1/2 and 6 inches. Thus, the entire meson trajectory was in a region of fairly uniform field. $\pi^+ - \mu^+$ decays were counted in Ilford C3 plates placed at 180°, 540°, and 900°. Upon applying the geometrical corrections, a half-life for the meson of $1.37^{+.10}_{-.12} \times 10^{-8}$ sec. was obtained. The data are plotted in Fig. 6.33(2).*

Approximately 50 percent of the error is statistical, and approximately 50 percent is due to background from high energy mesons that penetrate the channel. Blank runs were made in order to establish the size of the background.

Although Martinelli and Panofsky's value is higher than that of $0.74^{+.21}_{-.15} \times 10^{-8}$ sec. obtained by Richardson for the half-life of the π^- meson (Section 6.14), the difference does not seem large enough to imply that there is a difference between the half-lives of positive and negative π mesons.

6.41 Masses of the μ^+ and μ^- mesons

The measurements discussed in Section 6.311 gave a value for the mass of the μ^+ meson of 212 ± 6 e.m. The meager information from grain counting[1] of μ^- mesons indicates that the mass of the μ^- meson is approximately the same.

Fig. 6.41(1) is a histogram of mass values obtained for μ^+ mesons.

---

*Martinelli has kindly given permission to use the figures from his thesis.

6.42 $\pi^+ - \mu^+$ decay and the mass of the neutretto

The uniformity of range of μ^+ mesons, as well as the lack of angular correlation of π^+ and μ^+ tracks, implies that the π^+ meson has essentially come to rest before it decays into a μ^+ meson of approximately 4 Mev kinetic energy.(1) Another particle must also be given off during the decay in order to provide momentum balance. Conservation of charge requires this particle to be uncharged.

When the kinetic energy and momentum given to this neutral particle are eliminated from the equation of conservation of energy and momentum, the following expression for the mass of the neutral particle is obtained:

$$m_\nu = m_\mu \left[1 + \left(\frac{m_\pi}{m_\mu}\right)^2 - 2\frac{m_\pi}{m_\mu}\left(1 + \frac{E_\mu}{m_\mu c^2}\right)\right]^{1/2} \qquad 6.42(1)$$

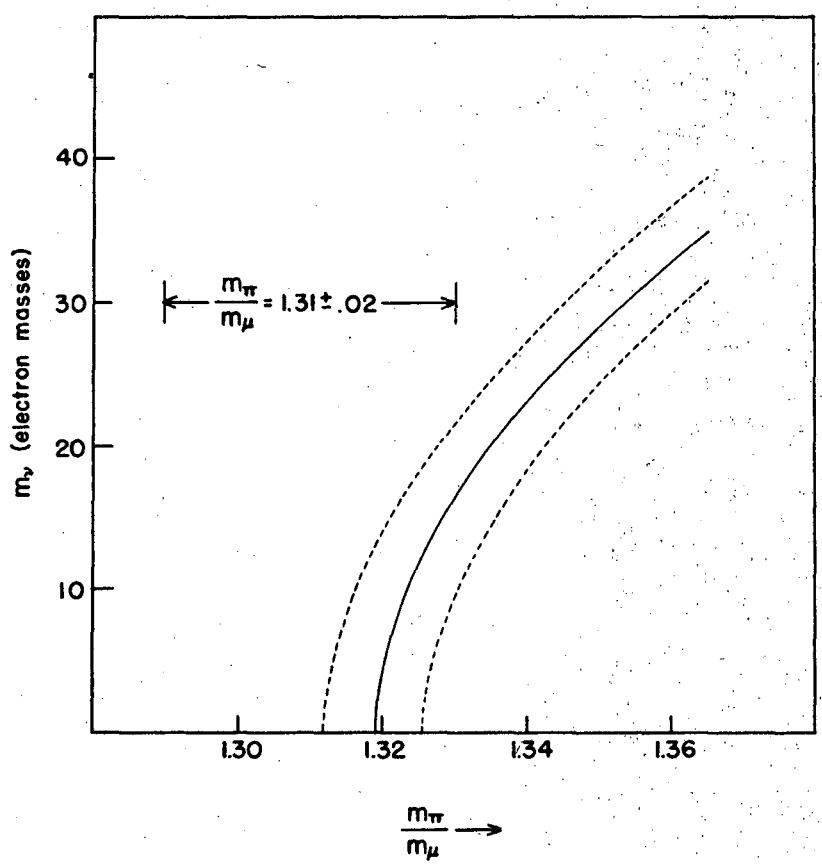
where E_μ is the kinetic energy given to the μ meson.

A plot of m_ν as a function of m_π/m_μ is given in Fig. 6.42(1). The values of $E_\mu = 4.18 \pm 0.04$ Mev, and $m_\mu = 212 \pm 6$ e.m. were used in plotting the curves. The solid curve is drawn for $E_\mu = 4.18$, $m_\mu = 212$; and the dashed curves for $E_\mu = 4.14$, $m_\mu = 218$, and $E_\mu = 4.22$, $m_\mu = 206$. For the ratio m_π/m_μ the experimental range of values of $m_\pi/m_\mu = 1.31 \pm 0.02$ is shown. Values of m_ν between zero and 25 electron masses are thus consistent with the π^+ and μ^+ mass values quoted in Sections 6.311 and 6.41.

The graph of Fig. 6.42(1) shows that the calculated mass of the neutretto is quite sensitive to changes in the assumed values of m_π/m_μ and E_μ and therefore that very accurate mass measurements and μ^+ decay energy values are needed in order to establish the neutretto mass even within a literal error interval of a few Mev.

6.43 Decay of the μ^+ meson

Very few observations have been made at Berkeley on positron tracks emanating from the ends of μ^+ meson tracks. Three such events have been seen but the



ALLOWED MASS OF THE NEUTRETTO

MU 339

FIG. 6.42 (1)

electron background in plates exposed to the cyclotron is so severe that positron tracks were not detected to come from the ends of 20 other known μ^+ meson tracks. Cosmic ray evidence[1][2][3][4] indicates that nearly every μ^+ meson track ending is joined by an associated electron track.

7. Production of Mesons by X-rays from the Synchrotron

7.1 Introduction

E. McMillan, J. Peterson and R.S. White have graciously permitted the abstracting of data and the use of figures from their[5] paper in Science. All the following information on synchrotron exposures comes from the paper or from helpful discussion with J. Peterson and W.K.H. Panofsky.

The 340 Mev circulating electron beam of the Berkeley synchrotron[1] contracts because of radiation and magnetic field increase until it strikes a 20 mil platinum target within the machine. The x-ray beam produced by the impact of the electrons on the target has a half-width at half maximum of 0.0067 radian, and the number of x-ray quanta in equal energy intervals is approximately inversely proportional[2] to the quantum energy up to the upper limit of 335 Mev as would be expected theoretically.[3] The x-ray intensity measured behind 1/8 inch of lead at one meter from the target is ordinarily about 1000 to 1500 r per hour. The r unit has been used for convenience to designate beam level; a calibration by Blocker et al.[4] of the unit in terms of the circulating beam of the synchrotron shows that 1 r per hour corresponds to about $10^6/250$ electrons per pulse at a repetition rate of 3 3/4 pulses per sec. They have determined that one r corresponds to 4.9×10^7 quanta traversing a 1 inch diameter target, where the number of quanta is defined as the integrated x-ray energy divided by the upper limit energy.

Note added 12/7/49: The normal beam level is now given in units of R, which is 250 times the r unit.

Mesons are produced by this x-ray beam in passing through a carbon block, and are recorded in nuclear emulsions. In the best exposures, yields of 100 mesons per square centimeter of 100 micron Ilford C-2 plates have been obtained by 2000 r runs on a carbon target 1 inch in diameter and 3 inches in length located 6 feet from the internal target. The length of runs is limited by random grain background due to x-rays and electrons striking the plates.

Plates placed out of the x-ray beam, but near the internal Pt target showed a very low meson yield. This result implies that the mesons are produced mainly by x-rays rather than by electrons.

7.2 Experimental arrangements

The two most important methods of exposure that have been used are the following:

1) A stack of plates is placed directly in the x-ray beam, with the emulsion surface parallel to the beam direction. In this arrangement many single grains are developed by the x-rays, and it is necessary to use Ilford F_3 plates, the least sensitive emulsion which will record mesons. Even with these plates the exposures that are permissible before plate blackening becomes too severe are low ($\sim$50 r). An average of one to two mesons per square inch can be obtained with this arrangement. The ratio of mesons to heavy particle tracks caused by photonuclear reactions is approximately one or two per thousand.

2) The x-ray beam passes through a carbon block and the stacks of plates are placed approximately 2 inches from the core of the beam as shown in Fig. 7.2(1). This arrangement has been used for studies of meson production in carbon and will be used for other target elements. A primary lead collimator 6 inches thick with a 1 inch diameter tapered hole, and a secondary brass collimator 2 inches long with a 1 23/64 inch diameter hole shield the photographic plates from the direct x-ray beam. Ilford C2 plates are placed radially around the cylindrical carbon block

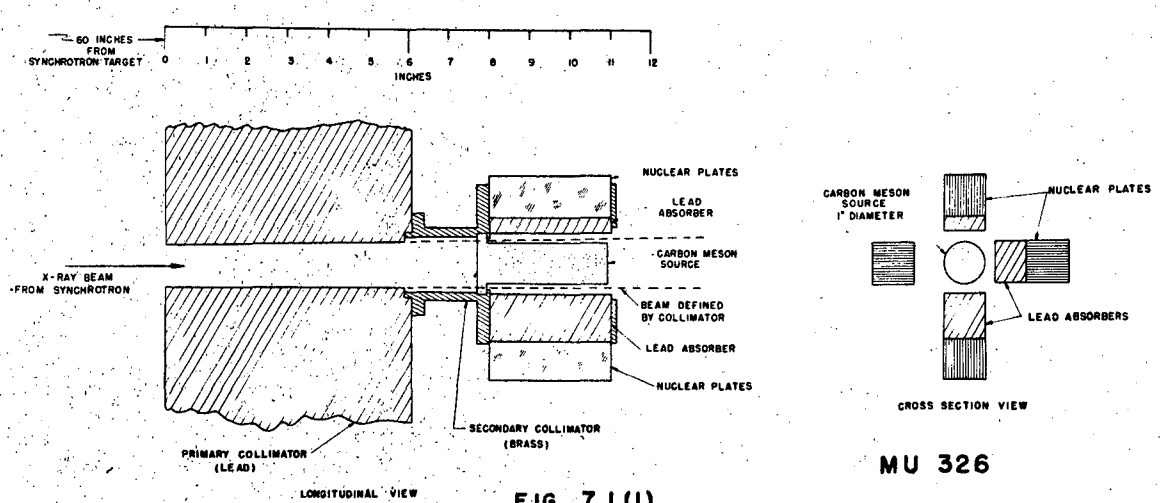


FIG. 7.1 (1)

MU 326

target, with different thicknesses of lead absorbers between the plates and the carbon, so that different energies of mesons can be studied. In this arrangement the plates have as many as 500 mesons in a 1 inch x 3 inch area, and the ratio of meson to heavy particle tracks is approximately 1/100. Only one π^- meson was found in a plate exposed without the carbon target.

7.3 Experimental results - Calculation of positive and negative π^- yields

No magnetic sorting of positive from negative mesons has been employed for mesons produced by the synchrotron and, therefore, the problem of distinguishing π^- mesons from π^+ mesons must be treated differently than it was in connection with internal cyclotron bombardments. μ^+ meson tracks can be confused with non-star forming π^- meson tracks. Similarly it may be impossible to distinguish a $\pi^+ - \mu^+$ event from a π^- star which has a single high energy proton if the emitted particle leaves the emulsion within 50 to 100 microns. In this case, however, the previous observations (Section 6.12) on magnetically sorted mesons in the cyclotron show that high energy single prong stars almost always show a "club" from a recoil of the residual nucleus.

It is known also (Section 6.12) from cyclotron observations that approximately 73 percent of all π^- mesons stopping in the emulsion produce stars, and that at least 95 percent of all π^+ mesons decay into μ^+ mesons.

Therefore in the computation of numbers of mesons of different types stopping in Ilford G-2 plates the total number of π^+ mesons was taken to be equal to the number of $\pi - \mu$ decays observed with questionable events that showed no "club" on the π track ending being counted as $\pi - \mu$ decays. It was thus assumed that no μ meson beginning in the emulsion would be missed, a reasonably valid assumption in the synchrotron exposures with C-2 emulsions. The total number of π^- mesons was taken to equal 1/0.73 of the number of meson stars (σ mesons) seen. Computations of yields with Ilford F-3 emulsions are subject to error because of the extreme

difficulty in seeing the beginnings of μ mesons at their origin in the π-μ decay. Therefore, the following discussions of results will apply only to observations on C-2 plates.

7.4 Ratio of positive and negative π meson yields

Since there is no statistically significant variation of the π^+/π^- ratio with meson energy between 30 and 150 Mev, all the data have been lumped together to provide the following totals, where σ are star forming mesons, π-μ are decays seen, and ρ are uneventful endings of meson tracks.

$$\sigma = 403 \qquad \pi\text{-}\mu = 327 \qquad \rho = 323$$

The ratio π^+/π^- is then calculated to be 1/1.7, with a statistical standard error of 8 percent.

Brueckner[1] has made a theoretical investigation of the ratio π^+/π^- to be expected at 90° from an x-ray beam, and finds that a value of the order of 1/2, independent of meson energy, is reasonable. He considers that the coupling to the photon field is larger for π^- + p than for π^+ + n because of the current contributed by the recoil proton. This effect, which increases with meson energy, balances the Coulomb effect on the meson wave function, which decreases with energy.

7.5 Energy and angular distributions and cross section

The experimental arrangement does not permit accurate determinations of the angle of emission of the mesons. However, an estimate of the angular distribution may be obtained by noting the direction of the high energy portions of the π meson tracks. The result indicates that the mesons are emitted with roughly spherical symmetry in the laboratory system.

A calculation of meson yield as a function of energy has been made by applying total area and stopping power vs. energy corrections to the numbers of tracks counted. The calculation assumed that the mesons were produced by a line source

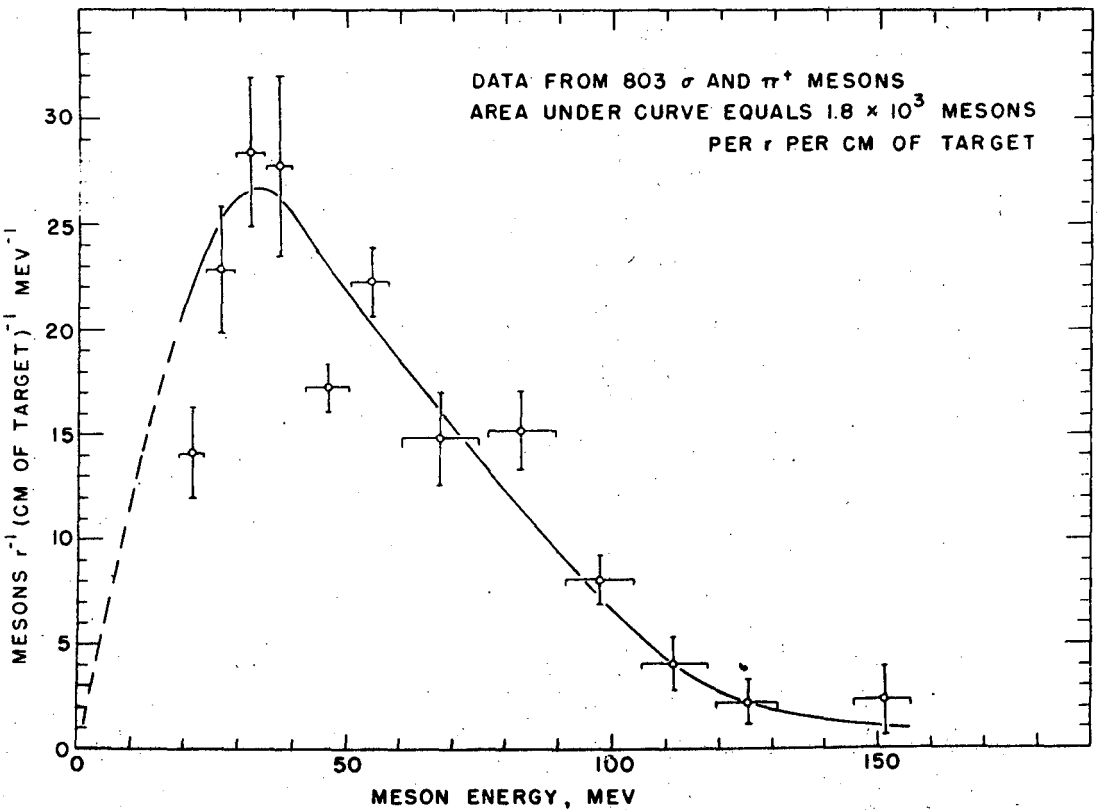


FIG. 7.5 (1)

MU 576

in the middle of the carbon cylinder, and neglected scattering or absorption, as well as the change in path length for mesons traveling at an angle through the absorber. A preliminary curve of the computed yield is shown in Fig. 7.5(1). The apparent lower limit to the energy arises from the treatment of the target as a line source of mesons. The dotted line is an estimate of the low energy distribution used for calculating the total cross section. The ordinates are expressed in terms of the "r" unit.

The total cross section for meson production, calculated on the basis of 4.9×10^{7} quanta per "r" unit, is 5×10^{-28} cm^{2} $quantum^{-1}$ $nucleus^{-1}$. The result is believed correct within a factor of 2.

8. Summary of Meson Properties

The characteristics of the artificially produced mesons described in the previous sections of this paper are consistent with the observations on cosmic ray mesons. Some of the extensive literature on cosmic ray mesons is included in the bibliography of UCRL 487.

The properties which appear reasonably well established are given in Table 8(1). The values of the cross section for production are estimates based on admittedly incomplete theory and are abbreviated in order to simplify the table. In the decay schemes the definite modes are indicated with an arrow and an estimate is indicated of the lower limits of the percentage of decays going by this scheme. Uncertain modes of decay are indicated by an arrow with a question mark and an upper limit is indicated for the percentage decaying by this scheme.

8.1 Notes on Table 8(1)

1. Spins of the mesons are deduced from conservation of spin in the following postulated reactions among neutrons (n), neutrino (ν), protons (p), electrons (β) and photons (γ), and mesons (π) and (μ). Other combinations are possible, but the ones given below are favored as being the simplest.

TABLE 8(1)

PARTICLE	MASS	CHARGE	SPIN	HALF-LIFE (sec.)	NUCLEAR INTERACTION	CROSS SECTION FOR PRODUCTION BY 345 MEV PROTONS (cm^2)	DECAY SCHEME AT REST IN MATTER	
π^+	276 ± 6	+1	0,1 (1)	$1.37^{+0.10}_{-0.12} \times 10^{-8}$	strong (2)	$\sim 2.2 \times 10^{-27}$ (3)	$\pi^+ \longrightarrow \mu^+ + \nu$ (4)	$\geqslant 99\%$
							$\pi^+ \longrightarrow ?\epsilon^+ + \nu$	$\leqslant 1\%$
π^-	276 ± 6	−1	0,1 (1)	$0.74^{+0.21}_{-0.15} \times 10^{-8}$	strong (2)	$\sim .45 \times 10^{-27}$ (3)	$\pi^- \longrightarrow$ nuclear "star" (5)	$73.2 \pm 2\%$
							$\pi^- \longrightarrow$?neutron emission	$26.8 \pm 2\%$
							$\pi^- \longrightarrow ?\mu^- + \nu$	$< 0.03\%$
π^0	~ 274 (11)	0	0 (1)	$10^{-14} > \tau > 10^{-21}$		$\sim 0.5 \times 10^{-27}$	$\pi^0 \longrightarrow ?\ 2h\nu$	
μ^+	210 ± 6 (9)	+1	1/2 (1)	$1.49 \pm 0.05 \times 10^{-6}$ (6)	weak	$\ll 10^{-31}$ (7)	$\mu^+ \longrightarrow \epsilon^+ + 2\nu$ (1)	$\geqslant 99\%$
μ^-	~ 210 (9)	−1	1/2 (1)	1.49 (8)(10) $\times 10^{-6}$ for low At. No. absorbers $\sim 0.75 \times 10^{-6}$ for Z = 10.	weak	$\ll 10^{-31}$ (7)	$\mu^- + p \rightarrow ?n + \nu$ (8)	
							$\mu^- \longrightarrow \epsilon^- + 2\nu$ (1)	
							$\mu^- \longrightarrow$?nuclear "star" (8)	$\leqslant 2\%$

Leighton, Anderson, and Seriff[1] have shown that the β spectrum from the decay of μ mesons is continuous from 0 to approximately 55 Mev as would be expected if the decay of the μ meson went according to the scheme

$$\mu^{(1/2)} \longrightarrow \beta^{(1/2)} + 2\nu^{(1/2)} , \qquad 8.1(1)$$

where the parentheses indicate spins.

The shape of the spectrum implies that there are only three particles emitted. The equation is written with neutrinos rather than γ-ray photons on the right hand side since the experiments of Piccioni[2] indicate that no photons appear in μ meson decay. It is possible, though less appealing, to write $\mu^{(0)} \longrightarrow \beta^{(1/2)} + \nu^{(1/2)} +$ neutretto$^{(0)}$. If the μ meson had integral spin, one might expect negative μ mesons to make stars.

The monoenergetic μ in $\pi^+ - \mu^+$ decay, requires that only two particles be given off. If the neutral particle is taken to be the same as the neutrino of beta decay, then the simplest equation is

$$\pi^{\left(\substack{0\\1}\right)} \longrightarrow \mu^{(1/2)} + \nu^{(1/2)} \qquad 8.1(2)$$

The thresholds and cross sections for π meson production in the cyclotron imply that only a single new particle is created in nucleon-nucleon collision, so that

$$p^{(1/2)} + p^{(1/2)} \longrightarrow p^{(1/2)} + n^{(1/2)} + \pi^{\left(\substack{0\\1}\right)}$$

In the case of neutral π mesons, the postulated decay into two photons implies that the spin is zero.

2. The π meson interacts strongly with the nucleus, as evidenced by production of stars, etc. It is probably the particle responsible for nuclear forces according to the theory of Yukawa.[3]

3. The cross section presented in the table is an approximation to the total

cross section for the production of π mesons by 345 Mev protons on carbon, based on measurements in a restricted region of energies and angles.

The same type of approximations give the total cross section for production of π^- mesons by 390 Mev α-particles on carbon.

4. π^+ mesons at rest always decay to give a monoenergetic μ meson with a range of approximately 600 microns corresponding to an energy of 4.18 $\pm$ 0.04 Mev (see Section 6.32).

5. Both negative and positive π mesons may decay in flight to μ mesons. The table gives only decay schemes for mesons at rest.

6. This value comes from experiments of Nereson and Rossi[4] on cosmic ray mesons.

7. Cross section for direct production via nucleon-nucleon collision is too small to be detected in the cyclotron.

8. Experiments by Conversi et al.[5] and by later workers[6][7][8] showed that μ^+ mesons decay in all absorbers. On the other hand μ^- mesons decay before being captured by nuclei of light elements, but they have a significantly high probability of being captured by nuclei of heavy elements. Cosmic ray evidence[9]-[12] implies that an electron is always associated with μ meson decay. The captured μ^- mesons might be expected to give nuclear stars like those seen in $\sim$ 73 percent of π^- meson endings. However, it has been shown by Chang[13] that heavy charged particles are rarely if ever emitted when μ^- mesons are stopped in nuclei from Al to Pb. The experimental conclusion was based on only 53 cloud chamber pictures and hence star production by μ^- mesons cannot be completely ruled out. Chang reports some evidence for low energy gamma-rays associated with μ^- meson capture, although Sard et al.[14] have found no high energy gamma-rays connected with the capture. Wheeler[15] interprets the low energy gamma-rays as being due to transitions of captured μ^- mesons between Bohr orbits, and concludes that the μ^- meson reacts with a proton to form a neutron and a neutral particle.

$$\mu^- + p \longrightarrow n + \mu_0$$

This closes the cycle begun by $n \longrightarrow p + \pi^-$; $\pi^- \longrightarrow \mu^- + \mu_0$

Since the neutral particle given off in $\pi^+ - \mu^+$ decay appears to have a very small rest mass, it is appealing to conclude that these particles are the same as the neutrino which is encountered in β decay.

It is not necessary, of course, to draw this conclusion, and the neutral particle of $\pi^+ - \mu^+$ decay could be a "meson" with zero spin, while the μ_0 of μ^- decay has spin 1/2.

9. The mean value of 210 for the μ meson mass is used in the table, although the best mass measurements give a value of 212 $\pm$ 6. This latter number is probably too large, as evidenced by the imaginary values deduced for the mass of the neutral particle in $\pi - \mu$ decay.

10. Nuclear capture or nuclear charge exchange(15) of μ^- mesons affects the apparent half-life. For absorbers of low atomic number the apparent half-life is the same as for μ^+ mesons.(16) The nuclear charge exchange becomes more important with increasing atomic number. It gives an apparent half-life of 0.75 x 10^{-6} sec. for Z $\simeq$ 10.

11. This number is from Panofsky's π^- capture experiment, April 1950.

9. Auxiliary Data

9.11 Energy available in the laboratory system for meson production

It was first pointed out by McMillan and Teller(1) that the momenta of nucleons in an α-particle and in the target nucleus may be compounded with the momentum of the α-particle to make available an increased energy for production of mesons in the nucleon-nucleon collision. Their argument assumed that the available momentum was proportional to the square root of the Fermi energy of approximately 20 Mev. While their calculations have perhaps some validity for high mass number targets, they are not correct for carbon and for other low Z targets, since they predict thresholds lower than the calculations of Barkas in Section 9.12.

For deuterons, the binding energy is only 2 Mev and hence the considerations of McMillan and Teller and Horning and Weinstein imply the π mesons would not be produced by 190 Mev deuterons.

(A more complete discussion of available energy was originally contemplated for this section; but at the present time the above paragraph represents the only pertinent information known to the writer.) An article is being written by T.B. Taylor for publication in the Physical Review.

9.12 Absolute threshold

An entirely different approach has been used by Barkas[1] for calculating thresholds for meson production. If one considers the process of meson production in the same manner as an ordinary nuclear reaction, a rigorous lower limit for the energy of the incident particles required for meson production is:

$$T^0 = \frac{\left[(m_\pi + M_1)^2 - (m + M)^2\right]}{2M} c^2 \qquad 9.12(1)$$

where T^0 is the kinetic energy of the bombarding ion, in the laboratory system

m is the mass of the bombarding ion

M is the mass of the target nucleus

m_π is the mass of the meson

M_1 is the sum of the masses of the other reaction products.

Table 9.12(1) gives some values of threshold energies calculated from 9.12(1) by using a meson mass of 276 electron masses.

9.2 Range-energy relations in nuclear emulsions

A range-energy relation for particles of arbitrary mass m and charge z may be obtained provided that a range-energy relation is known for some other charged particle. This may be shown readily as follows:

An equation giving rate of loss of kinetic energy $\frac{dE}{dx}$ for a charged particle

TABLE 9.12(1)

Absolute thresholds for Meson Production

(Using a value for the π meson mass of 276 e.m.)

Bombarding Particle	Target	Type of Meson	Other Products of Reaction	Threshold Energy (Mev)
p	C^{12}	π^+	C^{13}	150
p	C^{12}	π^-	$N^{12} + p$	173
α	C^{12}	π^+	N^{16}	194
α	C^{12}	π^-	F^{16}	200
d	C^{12}	π^+	C^{14}	154
d	C^{12}	π^-	C^{14}	158
n	C^{12}	π^+	$B^{12} + n$	167
n	C^{12}	π^-	N^{13}	148

in passing through matter may be written[1]

$$\frac{dE}{dx} = \frac{-4\pi(ze)^2 N}{m_\epsilon v^2} \left\{ Z \left[\ln \frac{2mv^2}{I} - \ln(1-\beta^2) - \beta^2 \right] - C_K \right\} \qquad 9.2(1)$$

where

ez = charge of the incident particle

Z = atomic number of the absorber

v = velocity of the incident particle

N = number of atoms per cubic centimeter of stopping material

I = average ionization potential of stopping material

m_ϵ = electron mass

β = v/c, c the velocity of light

C_K = a corrective term which must be applied in case v is comparable with the velocity of a K-electron of the stopping material but large compared with that of any other electron of the material.

This may be written in the general form

$$\frac{dE}{dx} = z^2 h(v) \qquad 9.2(2)$$

where the function $h(v)$ and the functions $g(v)$ and $f(\frac{E}{m})$ which follow are related, though at present defined only by relation 9.2(1).

Now since $E = m_o \Psi(v)$,

$$\frac{dE}{dx} = m_o \Psi(v) \frac{dv}{dx}, \qquad 9.2(3)$$

where m_o is the rest mass of the particle. Therefore,

$$R = \int_0^x dx = \frac{m_o}{z^2} \int_0^v \frac{\Psi(v)}{h(v)} dv = \frac{m_o}{z^2} g(v). \qquad 9.2(4)$$

It is sometimes convenient to rewrite this as a function of the energy E of the

particle:

$$R = \frac{m_o}{z^2} \; f\left(\frac{E}{m_o}\right) \qquad 9.2(5)$$

It has been found empirically that the relation between R and E can be approximated very closely by a power law for protons of 10 to 30 Mev. It follows from 9.2(5) that such an expression has the form

$$E = k\, m^{1-n}\, R^n\, z^{2n} \qquad 9.2(6)$$

The relations above are not valid for electrons, for which scattering has a large effect on measured range, but they have proven satisfactory for mesons. The equations imply that a proton and π meson of the same velocity have ranges in the ratio m_π/m_p. Now if a meson has energy E_π, the proton having the same velocity will have energy $\frac{m_p}{m_\pi} E_\pi$, and hence by 9.2(5) we may write for the range of a π meson of energy E

$$R_\pi(E) = \frac{m_\pi}{m_p} R_p\left(\frac{m_p}{m_\pi} E\right) \qquad 9.2(7)$$

where $R_p\left(\frac{m_p}{m_\pi} E\right)$ is the range of a proton with $\frac{m_p}{m_\pi}$ times the meson energy. According to these considerations, for example, a π meson of energy 5 Mev has a range approximately one-sixth that of a 30 Mev proton.

A range-energy relation was obtained by Lattes, Fowler, and Cuër[2] for protons up to 13 Mev in Ilford B1 emulsion. Their data were extrapolated by Camerini and Lattes[3] to give ranges with estimated accuracy of $\pm$ 8 percent in the 30 Mev region. Bradner et al.[4] have recently made a direct experimental determination of the range-energy relation for protons up to 39 Mev in Ilford C2 emulsion. A plot of their data along with that of Lattes is shown in Fig. 9.2(1). The curve is believed to give the energy accurate to 2 percent for protons in dry C2 or C3 emulsion. Fig. 9.2(2) shows an empirical fit to the experimental re-

lation for dry emulsion in the region of 17 to 39 Mev, according to the equation:

$$E_{(Mev)} = 0.251\ R_{(\mu)}^{0.581} \qquad 9.2(8)$$

9.2(8) is indistinguishable from the original extrapolation of Camerini and Lattes for protons of 4000 μ range. Monoenergetic protons for the recent measurement were obtained from the circulating beam of the cyclotron in the arrangement shown in Fig. 9.2(3). Protons striking the 1/8 in. x 1/16 in. x 3 in. copper ribbon target produced protons scattered in all directions with a variety of energies.

A nuclear track plate placed behind a short channel at the 80 inch radius recorded protons which left the target in the backward direction with the appropriate momentum. With an accurate knowledge of the magnetic field it was possible to calculate the energy of a proton entering along the normal to the edge of the plate. Plates were put at the 80 inch radius for all exposures and the target radius was varied to obtain different proton energies.

An approximate value for the range of protons in the glass backing of C2 plates was found by measuring the lengths of tracks which had traveled most of their range in the glass. The range of protons in the region of 30 Mev energy was found to be (18 ± 4) percent larger in glass than in dry C2 emulsion.

By applying the methods of this section to ranges of μ+ mesons in NTB and C2 emulsions, the range of 36 Mev protons in NTB emulsion was calculated to be (8 ± 1.5) percent larger than in C2 emulsion.

Grain Density

An expression for the grain density of singly charged particles in photographic emulsions can be obtained assuming only that the grain density $\frac{dN}{dR}$ is a function of the rate of loss of energy of an ionizing particle passing through the emulsion:

$$\frac{dN}{dR} = i\left(\frac{dE}{dR}\right)$$

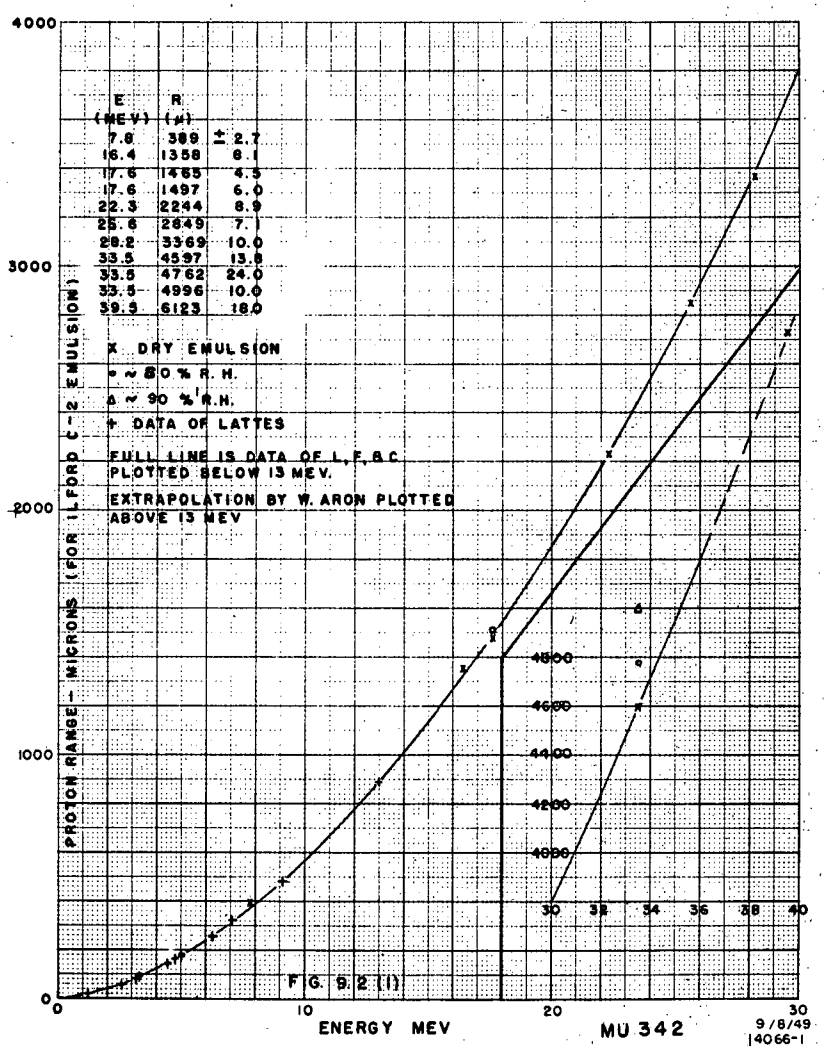
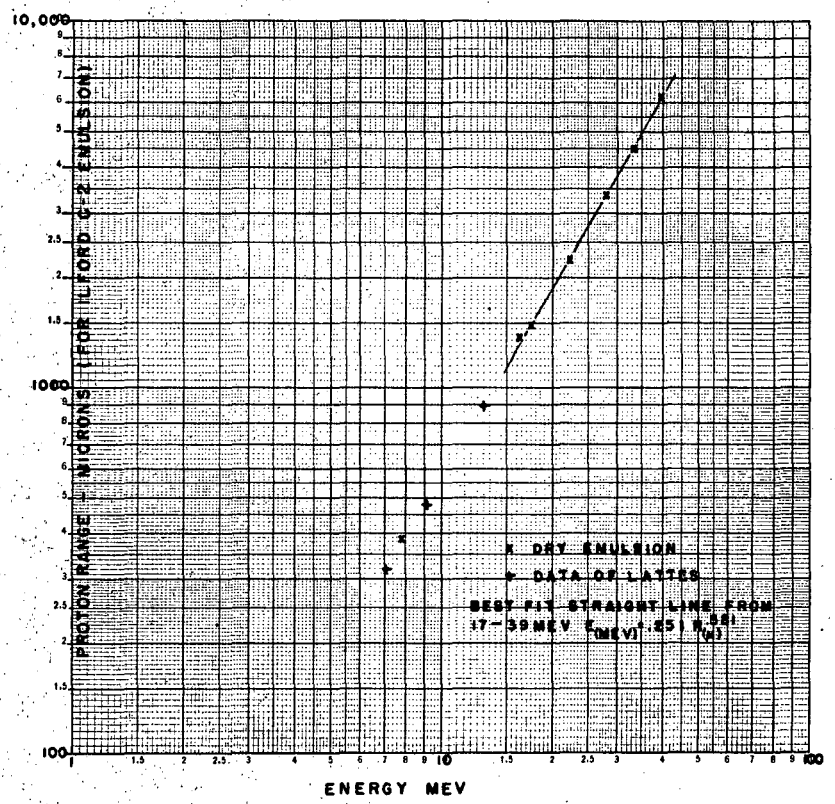


FIG. 9.2 (1)

Fig. 9.2(1)



MU 343

FIG. 9.2 (2)

14067-

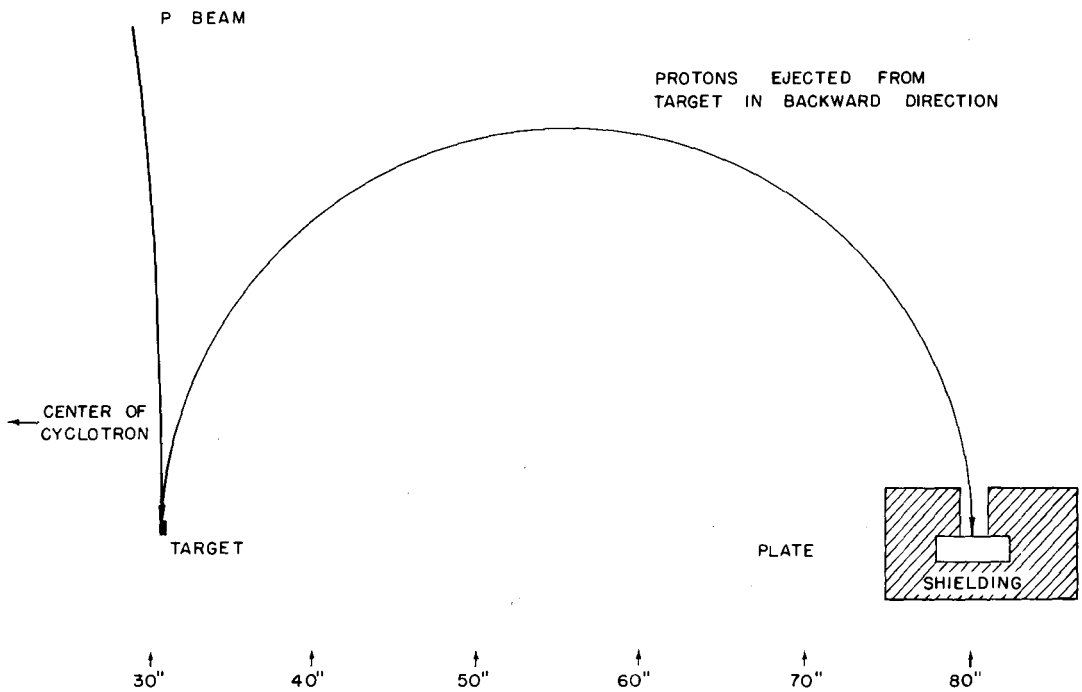


FIG. 9.2 (3)

OZ 715

But from 9.2(5) $$\frac{dE}{dR} = Z^2 j\left(\frac{R Z^2}{m}\right) \qquad 9.2(10)$$

Hence if $Z = 1$, $$N = mF\left(\frac{R}{m}\right) \qquad 6.113(1)$$

If the ion stopping in the emulsion has a charge Z, a relation can be obtained by assuming a power law connection between N and R. This is valid, since plots of log N vs. log R are found to be very nearly straight lines. (cf. Fig. 6.113-1).

Then $$N = a\, Z^{\frac{2n(1-\alpha)}{1-n}}\, m^{(1-\alpha)}\, R^{\alpha} \qquad 9.2(11)$$

Since the grain density of meson and proton tracks has been found to vary as 1/v over a large range of velocities it follows from 9.2(6) that

$$\alpha \doteq 1-\frac{n}{2} \doteq 0.71 \qquad 9.2(12)$$

Equation 9.2(11) implies that the relation between grain count and range involves m and Z in the form $mZ^{\frac{2n}{1-n}}$.

10. Acknowldegments.

Dr. W.K.H. Panofsky, Dr. E. Gardner, and Mr. F. Adelman deserve special thanks for careful proofreading and help in correcting the paper. Thanks also are expressed to Dr. L.W. Alvarez and Prof. E.O. Lawrence for advice and encouragement. Mr. T. Taylor has offered helpful discussions on the energy available for meson production.

Information Division
mkm/5-26-50

11. Bibliography

1 (1) E. Gardner and C.M.G. Lattes, Science 107, 270 (1948)

(2) W.M. Brobeck, et al., Phys. Rev. 71, 499 (1947)

(3) S. Sakata and T. Inoue, Prog. Theor. Phys. 1, 143 (1946)

(4) Y. Tanakawa, Prog. Theor. Phys. 2, 220 (1947)

(5) R.E. Marshak and H.A . Bethe, Phys. Rev. 72, 506 (1947)

(6) C.M.G. Lattes, G.P.S. Occhialini, C.F. Powell, Nature 160, 453, 486 (1947)

(7) E. McMillan and J.M. Peterson, Science 109, 438A (1949)

2 (1) C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini, C.F. Powell, Nature 159, 694 (1947)

(2) C.M.G. Lattes, G.P.S. Occhialini, C.F. Powell, Nature 160, 453, 486 (1947)

(3) W.G. MacMillan and E. Teller, Phys. Rev. 72, 1 (1947)

(4) W. Horning and M. Weinstein, Phys. Rev. 72, 251 (1947)

(5) M. Conversi, E. Pancini, and O. Piccioni, Phys. Rev. 71, 209 (1946)

(6) H. Yukawa, Phys. Math. Soc. Japan Proc. 17, 48 (1935)

(7) C.M.G. Lattes, H.Muirhead, G.P.S. Occhialini, C.F. Powell, Nature 159, 694 (1947)

3.11(1) Ilford Technical Data (1949)

3.2 (1) V. Peterson (private communication)

3.3 (1) W. Crandall and J. Hadley, UCRL 372 (Phys. Div. Quarterly Report, Feb.-April, 1949)

4.11(1) S.B. Jones and R.S. White, Phys. Rev. 75, 1468(A) (1948)

(2) V. Peterson, Phys. Rev. 75, 1469(A) (1948)

(3) W. Barkas, Phys. Rev. 75, 1109 (1948)

(4) R.L. Thornton and R.W. Senseman, Phys. Rev. 72, 872 (1948)

6.12 (1) F. L. Adelman and S. B. Jones, Phys. Rev. 75, 1468(A) (1949)

(2) E. Grunwald (private communication)
F. Adelman (private communication)

(3) J. Heidmann and L. LePrince-Ringuet, C. R. Acad. Sci. Paris, 226, 1716 (1948)

6.13 (1) W. H. Barkas (private communication)

(2) H. Bradner (private communication)

6.14 (1) C. M. G. Lattes (private communication)

(2) J. R. Richardson, Phys. Rev. 74, 1720 (1948)

6.2 (1) M. Conversi, E. Pancini, O. Piccioni, Phys. Rev. 71, 209 (1947)

(2) G. Valley, Phys. Rev. 73, 177 (1948)

(3) N. Nereson, Phys. Rev. 73, 565 (1948)

(4) N. Nereson, Phys. Rev. 74, 509 (1948)

(5) H. Ticho, Phys. Rev. 74, 1337 (1948)

(6) E. Gardner, S. B. Jones, C. M. G. Lattes (private communication)

(7) W. H. Barkas (private communication)

(8) W. Y. Chang, Rev. Mod. Phys. 21, 166 (1949)

6.311(1) W. H. Barkas, A. S. Bishop, E. Gardner, C. M. G. Lattes, F. M. Smith (to be published)

(2) F. M. Smith (private communication)

6.312(1) A. S. Bishop, H. Bradner, F. M. Smith, Phys. Rev. 76, 588(A) (1949)

(2) Suggested by C. M. G. Lattes; modified by W. H. Barkas

6.32 (1) F. M. Smith (private communication)

(2) C. M. G. Lattes (private communication)

(3) W. H. Barkas (private communication)

(4) G. Wentzel, Phys. Rev. 75, 1810 (1949)

(5) C. Richman, M. Weissbluth, H. A. Wilcox (private communication)

4.12(1) V. Peterson, Phys. Rev. 75, 1469(A) (1948)

4.13(1) S. B. Jones and R. S. White (to be published)

4.14(1) S. B. Jones and R. S. White, Phys. Rev. 76, 588(A) (1949)

(2) L. Aamodt, V. Peterson, R. Phillips (to be published)

4.15(1) V. Peterson (private communication)

4.16(1) E. Gardner, F. Smith and H. Bradner, Science (to be published)

(2) C. M. G. Lattes, H. Muirhead, G. P. S. Occhialini, C. F. Powell, Nature 159, 694 (1947)

(3) H. Bradner and H. A. Wilcox (private communication)

(4) H. Bradner and B. Rankin, New York Meeting Am. Ph. Soc., Feb.,1950.

4.21(1) W. Barkas, Phys. Rev. 75, 1467(A) (1949)

4.3 (1) H. York, B. J. Moyer, R. Bjorkland, Phys. Rev. 76, 187(A) (1949)

(2) R. Bjorkland, W. Crandall, B. J. Moyer, H. York (to be published)

5.2 (1) J. Burfening, E. Gardner, C. M. G. Lattes, Phys. Rev. 75, 382 (1949)

6.111(1) E. Gardner and C. M. G. Lattes, Science 107, 270 (1948)

6.112(1) W. H. Barkas, A. S. Bishop, E. Gardner, C. M. G. Lattes (to be published)

(2) D. Sewell (private communication)

(3) F. Bloch, W. W. Hansen, M. Packard, Phys. Rev. 70, 474 (1946)

(4) L. Henrich (private communication)

(5) L. Alvarez (private communication)

6.113(1) W. H. Barkas, E. Gardner, C. M. G. Lattes, Phys. Rev. 74, 1558(A) (1948)

(2) L. Van Rossum, Comptes Rendus 228, 676 (1949)

(3) J. K. Bowker (private communication)

(4) C. M. G. Lattes, G. P. S. Occhialini, C. F. Powell, Proc. Phys. Soc. 61, 173 (1948)

6.32 (6) F. M. Smith (private communication)

6.33 (1) E. A. Martinelli and W. K. H. Panofsky, UCRL-459 (Revised), (to be published in Phys. Rev.)

6.41 (1) W. H. Barkas, E. Gardner, C. M. G. Lattes, Phys. Rev. 74, 1558(A) (1948)

6.42 (1) C. M. G. Lattes, G. P. S. Occhialini, C. F. Powell, Nature 160, 453, 486 (1947)

6.43 (1) M. Conversi, E. Pancini, O. Piccioni, Phys. Rev. 71, 209 (1947)

(2) G. Valley, Phys. Rev. 73, 177 (1948)

(3) N. Nereson, Phys. Rev. 73, 565 (1948)

(4) H. Ticho, Phys. Rev. 74, 1337 (1948)

7.1 (1) E. McMillan and J. M. Peterson, Science 109, 438(A) (1949)

(2) W. M. Powell (private communication)

(3) W. Heitler, Quantum Theory of Radiation, 2nd Ed., p. 166 (1944), Oxford

(4) W. Blocker, R. Kenney, W. K. H. Panofsky (private communication).

(5) E. M. McMillan, J. Peterson, R. S. White, Sci. 110, 579 (1949)

7.4 (1) K. Brueckner (to be published in Phys. Rev.)

8.1 (1) R. B. Leighton, C. D. Anderson, A. J. Seriff, Phys. Rev. 75, 1432, 1466(A) (1949)

(2) O. Piccioni, Phys. Rev. 74, 1754 (1948)

(3) H. Yukawa, Phys. Math. Soc. Japan. Proc. 17, 48 (1935)

(4) N. Nereson and B. Rossi, Phys. Rev. 64, 199 (1943)

(5) M. Conversi, E. Pancini, O. Piccioni, Phys. Rev. 71, 209 (1947)

(6) G. Valley, Phys. Rev. 72 772 (1947)

(7) N. Nereson, Phys. Rev. 73, 565 (1948)

(8) H. Ticho, Phys. Rev. 74, 1337 (1948)

(9) M. Conversi, E. Pancini, O. Piccioni, Phys. Rev. 71, 209 (1947)

8.1 (10) G. Valley, Phys. Rev. 73, 177 (1948)

(11) N. Nereson, Phys. Rev. 73, 565 (1948)

(12) H. Ticho, Phys. Rev. 74, 1337 (1948)

(13) W. Y. Chang, Rev. Mod. Phys. 21, 166 (1949)

(14) R. O. Sard and E. J. Altheus, Phys. Rev. 74, 1364 (1948)

(15) J. A. Wheeler, Rev. Mod. Phys. 21, 133 (1949)

(16) M. Conversi, E. Pancini, O. Piccioni, Phys. Rev. 71, 209 (1946)

9.11 (1) W. G. McMillan and E. Teller, Phys. Rev. 72, 1 (1947)

9.12 (1) W. H. Barkas, Phys. Rev. 75, 1109 (1948)

9.2 (1) J. H. Webb, Phys. Rev. 74, 511 (1948)

(2) C. M. G. Lattes, P. H. Fowler, P. Cuër, Nature 159, 301 (1947)

(3) V. Camerini and C. M. G. Lattes, Ilford Technical Data (1947)

V. Camerini and C. M. G. Lattes, Ilford Technical Data (1948)

(4) W. H. Barkas, A. S. Bishop, H. Bradner, F. M. Smith, Phys. Rev. (in print)