RANGE DISTRIBUTION OF 122 MEV π^+ AND π^- MESONS IN BRASS

by

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ABSTRACT

Range Distribution of 122 Mev π^+ and π^- Mesons in Brass, by Carolyn B. Parker, submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Physics, August 31, 1953.

Ilford C-3 stripped emulsions embedded in brass absorbers were exposed to the 122 Mev π^+ and π^- meson beams of the University of Chicago synchro-cyclotron by Dr. M.B. Scott, formerly of this laboratory, in December 1951. The plates were oriented parallel to the beam.

The purpose of this report is to present an analysis of the range distribution of 122 Mev π^+ and π^- mesons in brass as recorded by the nuclear plates. It is also desired to get some information on the total cross section for nuclear interaction.

One plate exposed in separate runs to π^+ and π^- beams was scanned. Negative pions were distinguished by the fact that when they come to rest in an emulsion they generally produce nuclear stars. Positive pions were identified by the fact that when they come to rest in the emulsion they decay into μ mesons.

The distribution of π^+ meson ranges in brass when subjected to statistical tests yielded a Gaussian distribution with a mean of 66.8 ± .014 mm. and a standard deviation of 5.0 ± .005 mm. Similarly the π^- distribution was found to have a mean of 66.8 ±

.007 mm. and a standard deviation of 5.5 $\pm$ .005mm. These results give a range in brass of 56.7 gm/cm^2 for 122 Mev pions which is in agreement with Aron's[1] calculated value.

Total cross section calculations indicate cross sections for π^+ and π^- mesons at 122 Mev are not noticeably different.

INTRODUCTION

The discovery of mesons was not the result of a single observation, but the conclusion of a series of experimental and theoretical investigations. In 1935 Yukawa[2] proposed his celebrated meson theory of nuclear forces. This theory, developed along the formalism of electromagnetic theory, predicted that the "quantum", or meson, associated with the short range of the nuclear field would have a rest mass of about 137 times the mass of the electron. Direct experimental proof for the existence of particles with mass intermediate between the proton and electron came in 1937 with observations of Neddermeyer and Anderson[3] in their cosmic ray studies.

Now if mesons were to be related to nuclear forces, there should be a strong interaction between mesons and nuclei. The experiment of Conversi, Pancini and Piccioni[4] excluded the supposition that cosmic ray mesons observed at sea level could be identified with the Yukawa particle. This problem could be resolved, however, by postulating that there was more than one kind of meson.

The artificial production of mesons was first achieved by E. Gardner and C.M.G. Lattes in 1948.[5] In their experiments they used the 380 Mev internal of α beam produced by the Berkeley 184-inch synchro-cyclotron. A target was bombarded inside the cyclotron. Charged mesons produced by the beam were bent from the beam by the cyclotron magnet and detected in suitably placed nuclear emulsions.

These experiments produced evidence that there was a type of meson that interacted strongly with nuclei. While cosmic ray studies were still of fundamental importance, the production of mesons in the laboratory added greatly to the analysis of physical properties of mesons.

A meson of mass 276.1 ± 2.3 Me,[6] where Me is the mass of the electron, was discovered to have the property of strong interaction with nuclei, as shown by star formation upon absorption in the nuclei, its production by nuclear collision, and nuclear scattering. Such mesons have zero or unit electric charge, both positive and negative, and zero spin.[7,8] This type of meson is called a π meson or simply a pion.

The charged pion decays spontaneously in free space into a neutrino and a charged μ meson, or muon, with a mean lifetime of $(2.54 \pm 0.11) \times 10^{-8}$ sec.[9-11] The muon, which is found to have very little interaction with matter, is the type which must be identified with the weakly interacting type observed in cosmic radiation at sea level. The muon has a mass of 2096 ± 2.4 M_e[12] and spin of $\frac{1}{2}\hbar$. It decays with a mean lifetime of $(2.92 \pm 0.32) \times 10^{-8}$ sec.[13] into two neutrinos and an electron or positron. The neutral pion decays with a mean lifetime of about 1×10^{-14} sec.,[14] converting its rest mass of 264 M_e into two high energy gamma rays of about 70 Mev each.

The purpose of this paper is to determine the range distribution of 122 Mev positive and negative pions in brass as recorded by Ilford C-3 stripped emulsions embedded in brass absorbers.

The nuclear plates were exposed to the 122 Mev pion beams from the University of Chicago synchro-cyclotron by Dr. M.B. Scott, formerly of this laboratory, in 1951. It is also desired to get information on the total cross section for nuclear interaction.

In view of current studies being made of production of high energy mesons, nuclear interactions, etc., it is desirable to determine experimental ranges in absorber material and compare them with theoretical range-energy values which have been used extensively in practically all of the experiments. Since brass is quite often used as absorber material, information about ranges would be useful. Also a study of range distribution for monoenergetic mesons would illustrate how near constant is the range of a particle of given energy. Fluctuations in ranges will apparently occur because of the discontinuous nature of the ionization processes.

As for the pion-nucleon interaction, one of the most direct ways to gather information is the study of the magnitude and angular distribution of pion scattering by nuclei. Hydrogen lends itself much more readily to theoretical analysis than complex nuclei. Initial evidence on the interaction of negative pions of 55 to 85 Mev energy with protons indicated a much smaller cross section than expected.[15,16] H.L. Anderson,[17,18] et al, continued these transmission experiments to higher pion energies. These investigations showed that the total cross section rises above 80 Mev, reaching an apparent maximum value of $(66 \pm 6) \times 10^{-27}$ cm.^2 at 150 Mev.

The interaction of negative pions with heavier nuclei is certainly of physical interest, in spite of the difficulty of theoretical interpretation. General features of pion-nucleon coupling can be deduced from such a study. Studies of the total nuclear cross section of negative pions in various attenuating materials has been shown to be independent of energy between 85 Mev[15] and 137 Mev.[19] In all cases the cross section was close to the geometrical value of $\pi A^{2/3} (\frac{\hbar}{\mu c})^2$. This energy independence is contrary to the energy dependence of the total cross section shown by pions on protons. Specific total nuclear cross sections for negative pions determined for copper which are of interest to us are 990 ± 50 mb by Chedester[15] at 85 Mev, 1005 ± 70 mb at 109 Mev and 1010 ± 60 mb at 133 Mev by Martin[16]. This compares with a geometrical area of 977 mb.

In the earlier studies of negative pion-nuclei interaction nuclear track emulsion was used. Negative pion energies were studied in the regions 30-35 Mev and 30-110 Mev respectively by Bradner and Rankin[20] and Bernardini, Booth, Lederman and Tinlot.[21-24] In the energy region where these experiments can be compared, the total nuclear interaction cross sections were given as nuclear area for elements of the emulsion.

Fewer studies have been made of positive pion interactions with attenuating materials in the energy region in which we are interested. As a preliminary indication (of what might be expected) James Tracy[25] found a total nuclear interaction cross section of 548 ± 129 mb for aluminum as compared with a geometrical area of 551 mb. for 70-100 Mev interval.

It was hoped this analysis would give some idea of comparative total nuclear cross sections for positive and negative pions.

II. EXPERIMENTAL METHOD

We will consider experimental conditions when the nuclear plates were exposed and indicate interpretation of data.

A. Pion Beam

Our first consideration will be the mechanism of the pion beams. A beryllium target 2" in the direction of the beam, 1 1/2" high and 1/4" thick was bombarded with the internal 450 Mev proton beam of the Chicago synchro-chclotron thus producing pions. The negative pions emitted in the forward direction were deflected outward by the magnetic field of the cyclotron. Pions were separated according to their energy by the cyclotron field which deflected those of higher energy less, those of lower energy more. The fringing field of the cyclotron focused a sizeable fraction of mesons of given momentum in a fairly parallel beam. Channels were cut in the six foot steel shield which separated the cyclotron from the experimental room. A number of beams having different energies could then enter the experimental room. In this experiment only the 122 Mev beam was utilized.

The geometry of the positive pion beam was the same as for the negative pion beam. Positive pions were obtained by reversing the direction of both the cyclotron and deflecting magnetic fields with respect to directions for negative pions. Then positive pions emitted in backward direction from the proton beam passed through the same channel as did negative pions of the same energy.

However, since backward emission is less favorable for pions, the number of positive pions obtained in this way is much smaller than the number of negatives. This fact is evident in our nuclear plates,where we note that even for an exposure to the π^+ beam of 5 times as long as for the π^- beam, we find relatively few π- μ decays.

B. Experimental Arrangement

The arrangement of apparatus is shown in Fig. 1. The Be target was at a radius of 9 ft. 6 3/4 inches. Mesons emitted by the target were bent by the cyclotron fringing field into the channel. After passing through the deflection magnet they were slowed down by brass absorbers placed in the beam parallel to the beam direction. Nuclear emulsions were embedded in the absorbers. In this study mesons were observed and identified in the emulsion at the ends of their track. The position of a meson in the emulsion revealed its range in brass, as the meson had to traverse a certain thickness of absorber material to reach the particular point in the emulsion.

A 45° sector magnet, shown in the diagram, was used to deflect the mesons and separate them from undesirable radiation coming through the channel in the shield..

Pions were detected by using scintillation counters. The ones used were 1 in. x 1 in. x 1 cm. thick stilbene crystals spaced 40 inches apart. Coincidence circuits recorded the double coincidence when a particle traversed this pair of counters. The doubles count per target watt minute was computed for the π^+ and π^- beams. The readings obtained thereby and used in our analysis are 1345.1 per watt-minute for the positive pion beam and 20,371.7 per watt-minute for the negative pion beam.

The absorber block with embedded nuclear plates is shown in the diagram. This brass block was in two sections held together by brass screws. The sections had dimensions 4 in. x 5 in. x 1 1/4 in. with a slot 1/8 inch deep and 1 inch wide. cut in one side to hold the emulsions. From the end of the slot to the edge placed toward the beam the distance was .7 inch. The other end was .25 inch from the back edge of the block. The dimensions of the absorber were large enough so that the portion of the photographic plate which was scanned was effectively surrounded by an infinite sea of brass. This relationship assures there will be no significant loss of particles from the absorber due to multiple scattering.

The plates used were Ilford C-3 emulsions without glass supports, referred to as pellicles. Two 200 micron pellicles, each wrapped in cellophane, were placed together in the slot holder. A brass slab thick enough so as to completely fill the slot was inserted. The brass holders were inserted directly in the beam.

C. Target

Beryllium ($\rho = 1.85$ gm/cm^3) was the meson producing target of the synchrocyclotron in this experiment. The meson output of the machine was monitored by a thermocouple connected to the target. The target was connected through a calibrated heat leak to a large cylindrical drum, capable of maintaining itself at a fairly constant temperature by radiation. The thermocouple junctions were so connected across the heat leak that the emf developed is a function of the heat flow across the leak. A record was made on a Brown potentiometer of emf developed. This was read as watts of power developed by the proton beam in the target.

For two minute clicks on the tape the relation $1.964\ D_2 = 1.348\ D_1$ was found to hold for determining the number of watt min. recorded by the potentiometer. Here D_1 and D_2 represent deflection readings at beginning and end of the time interval, readings being taken from the graphical record. Readings taken from the tape may be used to determine the number of watt min., in accord with the above empirical relation.

D. Detector

Nuclear emulsions served as detectors. Those used were Ilford type C-3, 1 in. x 3 in., with an emulsion thickness of 200 microns. These plates are sufficiently sensitive to render visible the entire track of a μ meson originating from the decay of a π meson in the emulsion. The plates, however, are not so sensitive as to obliterate the characteristic increase in ionization when a meson approaches the end of its range. In this type of emulsion fast electrons are not observed.

E. Detection Efficiency

The efficiency of the detector may be found using the relation

$$\text{Fraction caught in emulsion} = \frac{\text{stopping power of emulsion}}{\text{stopping power of brass}} = \frac{R_{br}}{R_{em}} \cdot ld$$

R_{br} and R_{em} are residual ranges corresponding to a meson of energy Eres. R_{em} = thickness of emulsion = 200 microns.

The width of the emulsion is l, in this case 1 inch. The value of d is .02/2.54 in. For brass and emulsion the ratio $\frac{R_{br}}{R_{em}}$ is $\frac{1}{2.63}$.

This gives a value for fraction caught in the emulsion equal to 29.96×10^{-4} or 0.3×10^{-2}.

III. SCANNING AND CLASSIFICATION OF MESONS

A. Scanning

The emulsions were scanned with an American Optical Spencer binocular microscope with oil immersion objectives of 60x together with 10x oculars. Events suspected of being mesons were examined under higher magnification using 97x objectives and 15x oculars.

The method of scanning was as follows. Horizontal rows were scanned by locking in the vertical coordinate of the stage and noting particles ending in the emulsion which looked like mesons. The stage was then unlocked and these endings examined under higher magnification. Tracks were also followed to where they entered the emulsion to assist in identification. By using reference mesons at the bottom or top edge of the field the stage could be reset quite accurately. Successive rows were scanned with a certain amount of overlap so that mesons at the edge of the field would not be overlooked.

Meson tracks were generally identifiable by inspection. A meson is identified as such by virtue of its characteristic small angle coulomb scattering and rapid increase in ionization and thus grain density near the end of the track. The process of scanning adjacent rows was continued until about 60% of the total area had been scanned. Approximately equal horizontal strips on each edge were not scanned, thus eliminating distortion effects.

A track to be accepted had to end at a distance of at least five microns from the surface of the emulsion. Since measurements yielded a shrinkage factor of 0.5 in depth of the emulsion, this distance corresponded to 10 microns before development. The thickness measurement of the plate was made by taking readings at a number of places with the aid of the calibrated scale on the fine focus control of the microscope used for scanning.

B. Classification of Mesons

Mesons in emulsions have well known characteristics which enable us to recognize them and to say what kind of mesons they are. Negative pions which come to rest in an emulsion generally produce nuclear stars.[26] A positive pion which comes to rest in the emulsion decays into a positive muon and a light neutral particle, presumably a neutrino. Studies of magnetically sorted mesons[27] show that 73 ±2 per cent of the negative pions produce a nuclear star of one or more observable prongs in emulsions of the type used here. The other 27 per cent of the negative mesons end in the emulsion without initiating an observable nuclear star. Hence we can distinguish between positive and negative pions when they appear together in an emulsion.

Next we consider a more detailed classification based on the actual appearance of mesons in the emulsion.

1. A meson ends in a star of two or more prongs or a single heavy prong. This is identified as a negative pion and called σ_n meson depending on the number of prongs. This identification is made as no stars have been observed from positive pions or

muons. However, it has been shown that 3 ±1 percent of negative muons stopped in emulsions form stars.[28] In this experiment, this amounts to a negligible correction.

2. A meson enters the emulsion and stops with no observable event. This is classified as a ρ meson and may be one of the following:

(a) It may be a positive muon originating from a positive pion which has come to rest in the brass absorber surrounding the emulsion.

(b) It may be a negative pion which has a zero prong star. This occurs for 27 per cent of the stopped negative pions. This number we may determine by reference to the number of definitely identified negative pions, i.e. those having one or more prongs.

(c) It may be a positive or negative muon from a positive or negative pion which decayed in flight.

3. A meson stops in the emulsion and emits another meson which has a range of about 600 microns. This is identified as the decay of a positive pion into a positive muon.

4. A meson stops in the emulsion by emitting a particle which makes a thin lightly ionizing track. The particle leaves the emulsion too soon to be positively identified. This event was classified as a negative pion if there was a short heavy "club" or recoil track leaving the end of the pion, and as a positive pion if there was not.

This classification is in accordance with data of F. Adelman and S. Jones (reported in article by Richman, Weissbluth, and Wilcox)[29] who found that in a sample of tracks of stopped negative pions, there were 14 events which could have been confused with a positive pion-muon decay. Of these events, 12 exhibited the short heavy club. This consideration introduced a small uncertainty (less than 1 per cent) in the total number of negative pions and even less of an error in the total number of positive pions.

IV. EXPERIMENTAL RESULTS

A. Prong Spectrum of Negative Pions

The prong spectrum for meson induced stars as determined by scanning the photographic plate is shown in Table I. This is compared with the Adelman[30,31] distribution. The agreement is good. Hence we are justified in dividing the total number of meson stars with one to five prongs by the fraction of negative pions giving visible stars (0.73) to obtain the total number of negative pions ending in the emulsion.

TABLE I

Prong Spectrum of Negative Pions

Number of Prongs	0	1	2	3	4	5
Adelman Distribution	27%	24%	24%	16%	8%	1%
Observed Distribution	(calc.) 87.5	75	74	54	28	5
Observed % of Stars	27%	23.2%	22.8%	16.7%	8.7%	1.5%

B. Distribution of π^- Mesons

The ranges of 236 negative pions with observable prongs as expressed in position coordinates of the meson ending were recorded. Measurements were made using the two stage micrometer screws. The definition of a star prong used by Adelman and Jones[30] was adopted for this study. According to their definition, any track of length greater than one micron, and having a well defined direction of emergence from the star center is a prong.

The distribution for mesons having observable prongs is shown by the solid line histogram in Fig. 2. This represents the distribution of mesons which came to the end of their range in the emulsion detector.

The plate was scanned in horizontal rows. The horizontal coordinate, parallel to the long edge, we will refer to as the X coordinate. The vertical coordinate, which was locked in scanning, we will call the Y coordinate. Measurements were made of the shrinkage of the emulsion in the X direction to determine the factor to be applied to correct the X reading. The relation found was X corr. = 1.064 X obs. The true range reading could be determined by adding 17.76 mm. to this value as the edge of the emulsion was 0.7 in. from the front edge of the brass block.

The area scanned was 60.5% of the total area as determined by readings of Y coordinates of area scanned with respect to Y coordinates for the total area. It was noted that there was a slight shrinkage in the one inch dimension of the emulsion.

The hypothesis that the experimental distribution of ranges can be represented by a normal curve can be tested. A normal distribution has the property that the percentage of total frequency outside range $\overline{X} \pm \sigma$ is 32% approximately, percentage outside $\overline{X} \pm 2\sigma$ is 5% approximately and range $\overline{X} \pm 3\sigma$ includes practically the whole distribution.[32] Here $\overline{X}$ is the mean and σ the standard deviation.

The distribution illustrated in Fig. 2 was found to have a mean of 53.1 ± .007 mm. and a standard deviation of 5.16 ± .005 mm.

C. Distribution of π^+ Mesons

The intensity of the positive pion beam was much less than for the negative beam. Although the emulsions were exposed for two minutes to the negative pion beam and ten minutes to the positive beam, there were still considerably more star producing mesons.

The ranges of 55 positive pions were recorded by position coordinates of the scanned emulsion. A plot of number vs. distance along the plate is shown in histogram of Fig. 2. The corrections to be applied to range readings are the same as for negative pions. Application of statistical tests to the plotted distribution yielded a mean of 53.10 ±.014 mm. and a standard deviation of 4.67 ± .005 mm. Further tests showed the distribution was normal.

D. Distribution of ρ Mesons

The distribution of ρ mesons is included for analysis although results are not used directly. This classification can include types of both positive and negative mesons.

One type included is the negative pion with zero prongs. This is indistinguishable from muons of either sign so we determine this number, not by direct observation, but as .27% of the total number of negative pions.

Another type is the positive muon which originated from the positive pion that stopped in the brass absorber surrounding the emulsion. We are not interested in such mesons.

Finally we may have positive or negative muons from pion decay in flight. These are of interest as from them we can get an estimate of the muon-pion ratio in the beam incident on the brass block.

It would be difficult to obtain a reliable calculation of expected muon contamination of the beams. Most of the muon contamination is believed due to π-μ decay in the vicinity of the target where there were an enormous concentration of pions of all energies and angles. The fringing field of the cyclotron focused muons of proper momentum into the channel.

The muons from π-μ decay in the channel had a small probability of having the proper momentum and angle to enter the plates after passing through the deflection magnet. The number of π-μ decays after the particle had traversed the deflection magnet was small.

We cannot identify the muons by inspection. However, in the range distribution histogram, muons clearly show up beyond the pion range. The spectra of ρ mesons is shown in Fig. 4. The high energy tail on the right is attributed to muons.

The complete muon spectra is not shown as it was beyond the edge of the plate. Assuming the muons have a symmetrical distribution we can make a rough estimate of the number of muons

The total obtained in this manner agrees with the Chicago results[19] of about 7 per cent in both beams. The emulsions we used were insensitive to electrons. The electron content of the 122 Mev beam was found to be less than 1% at Chicago. The total beam contamination will be estimated as 7 ± 4 per cent in both beams.

The range of the ρ mesons was found to be 54.8 ± .004 mm. The higher value being attributed to the muon content. This is the uncorrected range value, being a position with respect to the nuclear plate only.

V. INTERPRETATION OF RESULTS

A. Range - Energy Values

Theoretical range energy values will be compared with our experimental results. First we will discuss theoretical calculations.

The rate of energy loss for a heavy particle is given by[33]

$$\frac{-dE}{dx} = \frac{4\pi e^4 z^2}{mv^2} NZ \left[\log_e \frac{2mv^2}{I} - \log_e (1-\beta^2) - \beta^2 \right] \qquad (1)$$

in which

m = electronic mass

e = electronic charge

ze = charge of heavy particle

NZ = number of electrons per unit volume of stopping material

$\beta = \frac{v}{c}$; where c is the velocity of light

I = mean excitation potential

This formula holds when $v \gg U_k$ where U_k is the velocity of the orbital electrons in the K shell of the atoms of the stopping medium. The assumption is that the heavy particle loses energy along its path solely through ionization and excitation of the atoms of the stopping material. Effects due to bremstraklung, nuclear interactions and meson production have been neglected.

In the above equation, the quantity of I is given by

$$Z \log_e I = \sum_{n,l} f_{n,l} \log_e A_{n,l} \qquad (2)$$

where $f_{n,l}$ are the oscillator strengths appearing in spectra and $A_{n,l}$ the corresponding excitation energies. The $f_{n,l}$'s are subject to the condition

$$\sum_{n,l} = f_{n,l} = Z \qquad (3)$$

This definition of I by eq. (2) is not too useful as the evaluation is too difficult for systems of many electrons. However, F. Block,[34] on the basis of the Fermi-Thomas model of the atom with several electrons, has shown that $I = kZ$, where the constant k must be evaluated empirically. A value of $k = 11.5$ is indicated by measurements of P.R. Wilson,[35] This value is used in calculations of Aron[1] for range and rate of energy loss up to the hundred million volt region for heavy particles in various stopping media.

The range, R, of the particle may be obtained by numerical integration

$$R(E) = \int_{E_0}^{E} \left(\frac{dx}{dE} \right) dE + R(E_0) \qquad (4)$$

$R(E_0)$ may be obtained from experimental data.[35,36] This value may be determined from the range of the particle in air at the energy E and the experimentally measured ratio of the stopping power in air to the medium in question.

Specifically we consider proton ranges first. The range of a proton in copper in mg cm^{-2} may be obtained by reference to Aron's range-energy values, as his values are based on the same relations as we have presented. We may convert this to range in brass in cm. by dividing by density, $\rho = 8.49$ gm cm^{-3}.

We may now determine the range of pions very simply from the range of protons in the same material, namely brass.

Given a pion and a proton which we refer to as particles 1 and 2 respectively we may write"

$$\frac{\frac{dE}{dx(1)}}{\frac{dE}{dx(2)}} = \frac{Z_1^2 \; V_2^2 \; N_1 Z_1 \log e \; \left(\frac{2mv_1^2}{I_1} - \log e \; (I-\beta^2)_1 - -\beta_1^2 \right)}{Z_2^2 \; V_1^2 \; N_2 Z_2 \log e \; \frac{2mv_2^2}{I_2} - \log e \; (1-\beta^2)_2 - \beta_2^2 \,)} \qquad (5)$$

where

$\frac{dE}{dx(1)}$ is collision energy loss for pion

$\frac{dE}{dx(2)}$ is collision energy loss for proton

Z_1, Z_2 are atomic numbers for pion and proton respectively

V_1, V_2 are velocities of pion and proton respectively

N_1, N_2 are number of atoms per unit volume of stopping material for respective particles

Z_1, Z_2 represent atomic numbers of stopping materials for particles, pion and proton respectively

I_1, I_2 are mean excitation potentials of stopping materials for respective particles.

Given conditions

$V_1 = V_2$

and in this case

$Z_1 = Z_2$

$N_1 = N_2$

$Z_1 = Z_2$

$I_1 = I_2$

our equation reduces to the expression

$$\frac{\frac{dE}{dx}(1)}{\frac{dE}{dx}(2)} = 1 \quad \text{or} \quad \frac{dE}{dx}(1) = \frac{dE}{dx}(2) \qquad (6)$$

From equation (6) we get the relation

$$R_{\pi}(E) = \frac{M_{\pi}}{M_p} R_p\left(\frac{M_p}{M_{\pi}} E\right) \qquad (7)$$

where $R_{\pi}(E)$ is range of pion at an energy E, and $R_p\left(\frac{M_p}{M_{\pi}} E\right)$ signifies the range of the proton at an energy $\frac{M_p}{M_{\pi}} E$.

Application of the above relation to our specific case gives

$$R_{\pi}\ (122\ \text{Mev}) = \frac{276.1}{1836} R_p\left(\frac{1836}{276} \cdot 122\ \text{Mev}\right) \qquad (8)$$

$$R_{\pi}\ (122\ \text{Mev}) = .1502\ R_p\ (841\ \text{Mev}) \qquad (9)$$

Reference to Aron's[1] table of ranges gives a value of 370.9 gm-cm^2 for range of a 841 Mev proton in copper. Insertion of this value above yields

$$R_{\pi}(122\ \text{Mev}) = 55.6\ \text{gm-cm}^2. \qquad (10)$$

B. Corrected Ranges of Pions

The true range can be determined by making corrections described in the section on experimental results. The relation obtained is that the true range, R, is equal $(R_{em} - 7.05)\ 1.064 + 17.78$ mm., where R_{em} is X coordinate position as read on the microscope and 7.05 is microscope reading at front edge of the emulsion.

Insertion of the appropriate value gives for the range of

122 Mev pions in brass

$$R = (53.1 - 7.05)\ 1.064 + 17.78$$

$$R = 66.78 \text{ mm.}$$

Insertion of density of brass, 8.5 gm/cm^3 yields a range of 56.7 gm-cm^2. This compares favorably with the calculated value of 55.6 gm-cm^2 obtained using Aron's[1] range-energy relations.

VI. TOTAL NUCLEAR CROSS SECTION

The total cross section for nuclear absorption and large angle scattering can be determined by the decrease in flux of mesons incident on the absorber face. Without the absorber the flux is $N'_o(E)$. Insertion of a thickness t of brass reduces this to

$$N'_o = N_o \, e^{-\frac{N\sigma\rho t}{A}} \qquad (1)$$

where ρ is the density, N is Avagadro's number, A is the atomic weight and σ is the total cross section.

Mesons traversed a thickness of brass, were slowed down and observed at the end of their range in nuclear emulsions. Hence in this calculation, t corresponds to the measured range of the meson in brass.

The total number of mesons observed in emulsion, N'_o, may be obtained by applying appropriate corrections to the number actually seen. The number, N_o, of mesons expected to stop in the emulsion may be determined by using the calculated value of the fraction caught, as explained in the section on detection efficiency, and multiplying by number of mesons recorded by counters.

Specifically we will calculate the total nuclear interaction cross section for negative pions first. The total number of negative pions found is the number observed, 236, divided by 0.73 to account for zero prong pions and also divided by 0.605 to account for the fraction of total region scanned. This gives a total of 535 mesons for N'_o .

Readings of the recorder tape of 15.2 for D_1 and 26.9 for D_2 yield 32.3 watt-min. for a two minute run of the negative pion beam. This is converted to mesons counted per square inch by multiplying by the number of counts per watt-minute for the π^- beam, namely 20,372. The value so obtained is 658,000 mesons counted / in^2. The fraction caught as previously determined is 0.3×10^{-2}. Hence the number of π^- mesons in the emulsion is $0.30 \times 10^{-2} (6.58) \times 10^5 = 1,974$.

We substitute these relations in eq. 11 applying at the same time a 7% correction for beam contamination and a 10% correction to numbef of mesons observed as the criterion for acceptance of mesons allows us to cover only 0.9 of emulsion depth.

$$\frac{535}{.9} = 1974(.93)\, e^{-\sigma \frac{(6.02 \times 10^{23})\, 8.5(6.68)}{65}} \tag{12}$$

$$.324 = e^{-.52 \times 10^{24} \sigma} \tag{13}$$

$$2.303 \log .324 = -.524 \times 10^{24} \sigma \tag{14}$$

$$\frac{2.303\ (.489)}{.524} \times 10^{24} = \sigma \tag{15}$$

$$\sigma = 2.14 \times 10^{-24} \text{ cm}^2 \text{ or } 214 \text{ mb.} \tag{16}$$

Recorder readings for positive pions for a ten minute run yield 103.65 watt-min. This yields 139,417 mesons counted / in.^{2}

$0.3 \times 10^{-2} (1.394 \times 10^5) = 418.2,\ N_o$

The total number of positive pions seen was 55. The corrected number obtained was 55/.605 or 91. Applying the muon correction factor as well as factor dependent on depth scanned we get

$$\frac{91}{.93(.9)418.2} = e^{-.524 \times 10^{24}} \tag{17}$$

$$2.303 \log 25.81 = -.524 \times 10^{24} \tag{18}$$

$$\frac{2.303\ (.5882)}{.524} \times 10^{-24} = \tag{19}$$

$$= 2.58 \times 10^{-24}\ \mathrm{cm}^2 \text{ or } 258\ \mathrm{mb} \tag{20}$$

The total nuclear cross section which we have determined experimentally differs from geometrical area and the results of others[15,16] by a factor of about two. This difference is probably attributable to the fact that the meson beam impinging on the absorber may not have been large in transverse dimensions compared to the root mean square displacement that the mesons underwent in reaching the end of their range. The ion optics of the Chicago meson beam as well as can be judged in retrospect was such as to give uniform irradiation for dimensions of one inch.

BIOGRAPHICAL SKETCH

I was born in Gainesville, Florida, on November 18, 1917 and educated in public schools in Tampa, Florida, graduating from Middleton High School in 1933. I attended Fisk University in Nashville, Tennessee, 1934-1938, receiving my B.A. degree in physics in June 1938. Honors received included magna cum laude in general studies and departmental honors in physics.

From 1938-1940 I taught in the high school in Gainesville, Florida. I attended the University of Michigan, 1940-41, receiving my M.A. degree in physics in June 1941. I taught at Huntington High School, Newport News, Virginia, 1941-1942 and was instructor of physics at Bluefield State Teachers College, Bluefield, West Virginia, 1942-1943.

For the period 1943-1947 I was employed as research physicist at Wright Field, Dayton, Ohio. From 1947-1951 I was assistant professor of physics at Fisk University, Nashville, Tennessee.

In September 1951 I entered the M.I.T. Graduate School in Physics. During the summer of 1952 I was employed as a physicist at Geophysics Research Division, Air Force Cambridge Research Center, Cambridge, Massachusetts. In May 1953 I was elected an associate member of Sigma Xi Scientific Research Society at M.I.T..

Figure 1. Experimental Arrangement

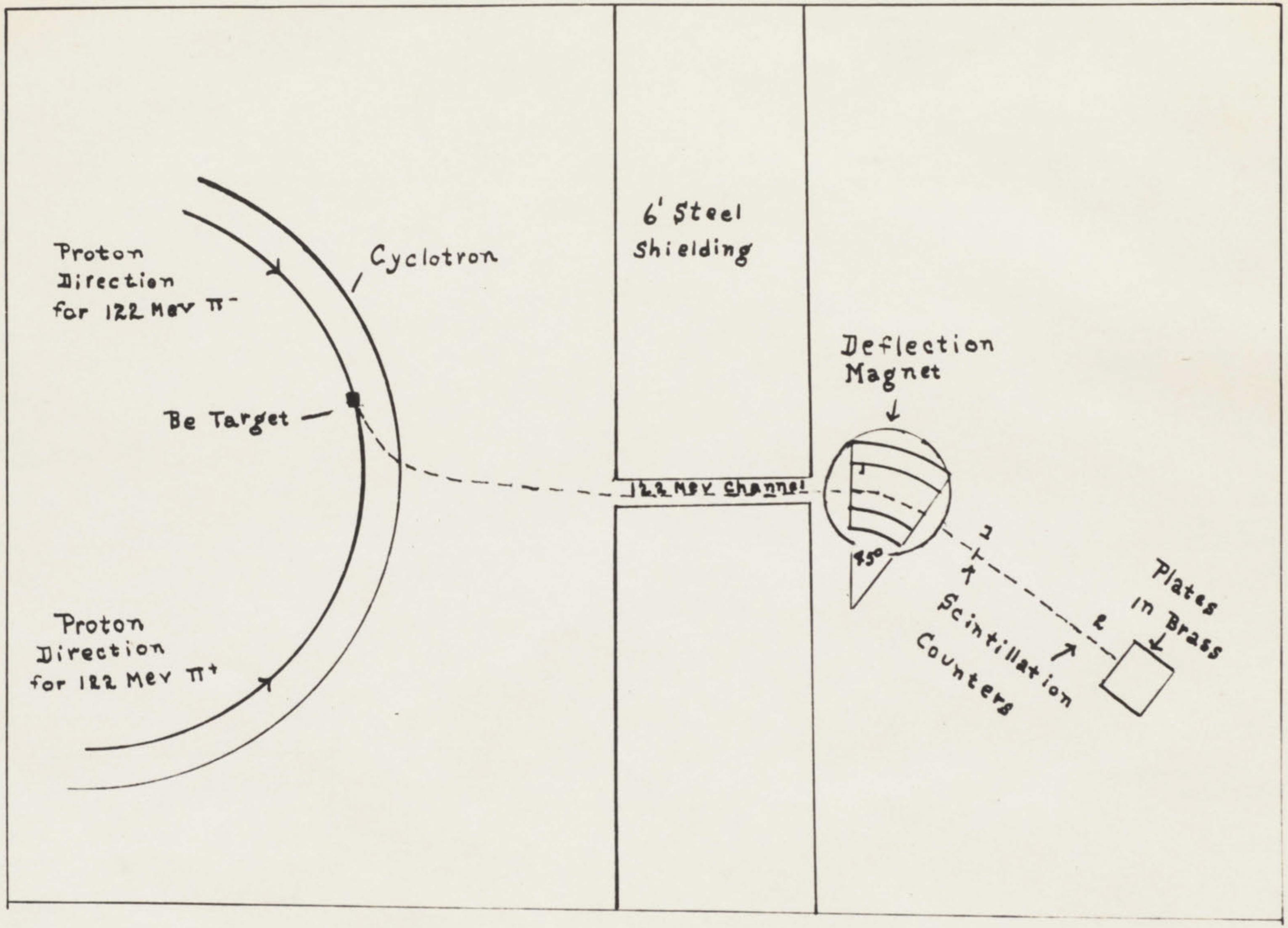

Fig 1 Experimental Arrangement

Figure 2. Distribution of π^- Mesons

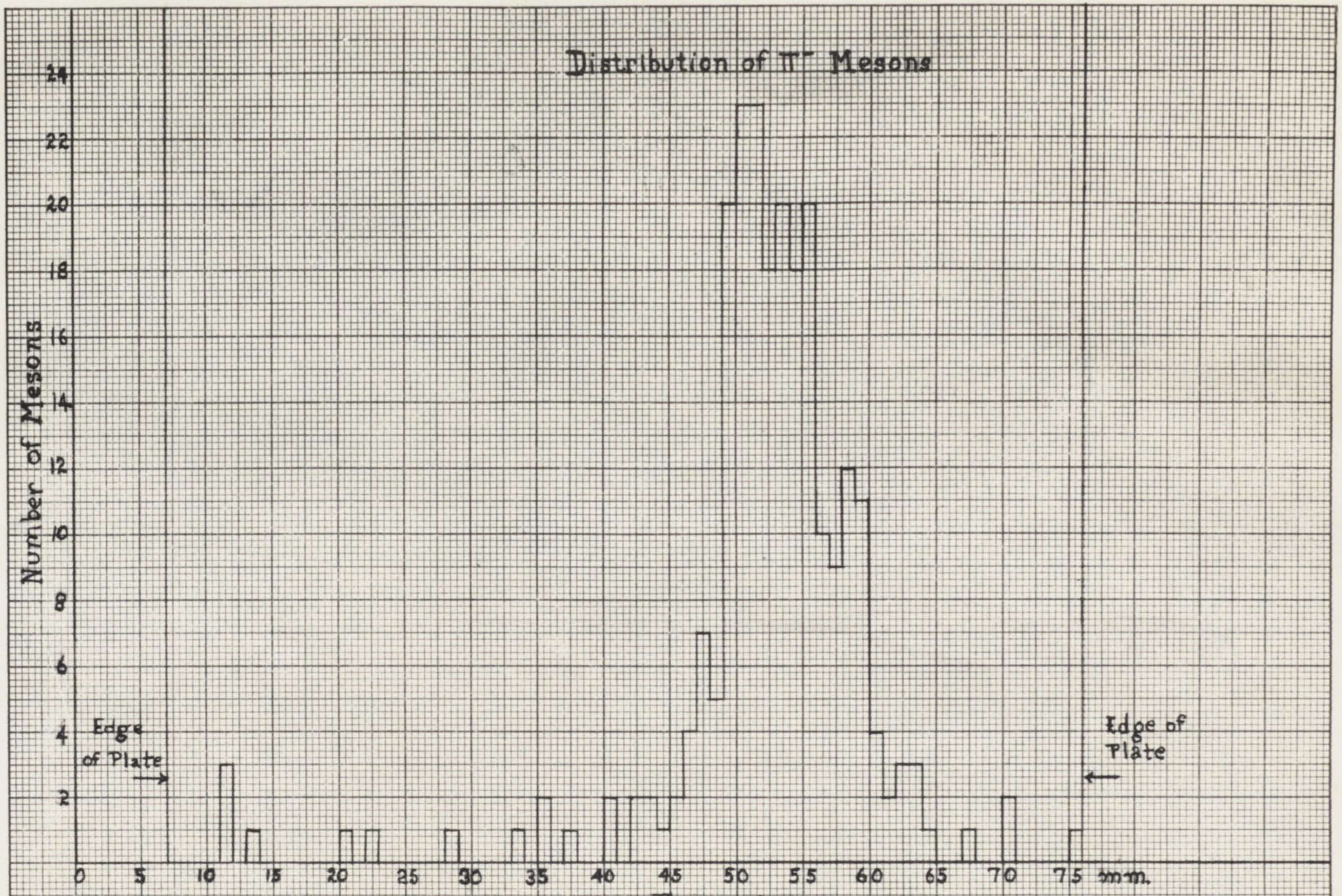
Distribution of π^- Mesons
Number of Mesons
24
22
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
mm.
Edge of Plate
Edge of Plate

Figure 2.

Figure 3. Distribution of π^+ Mesons

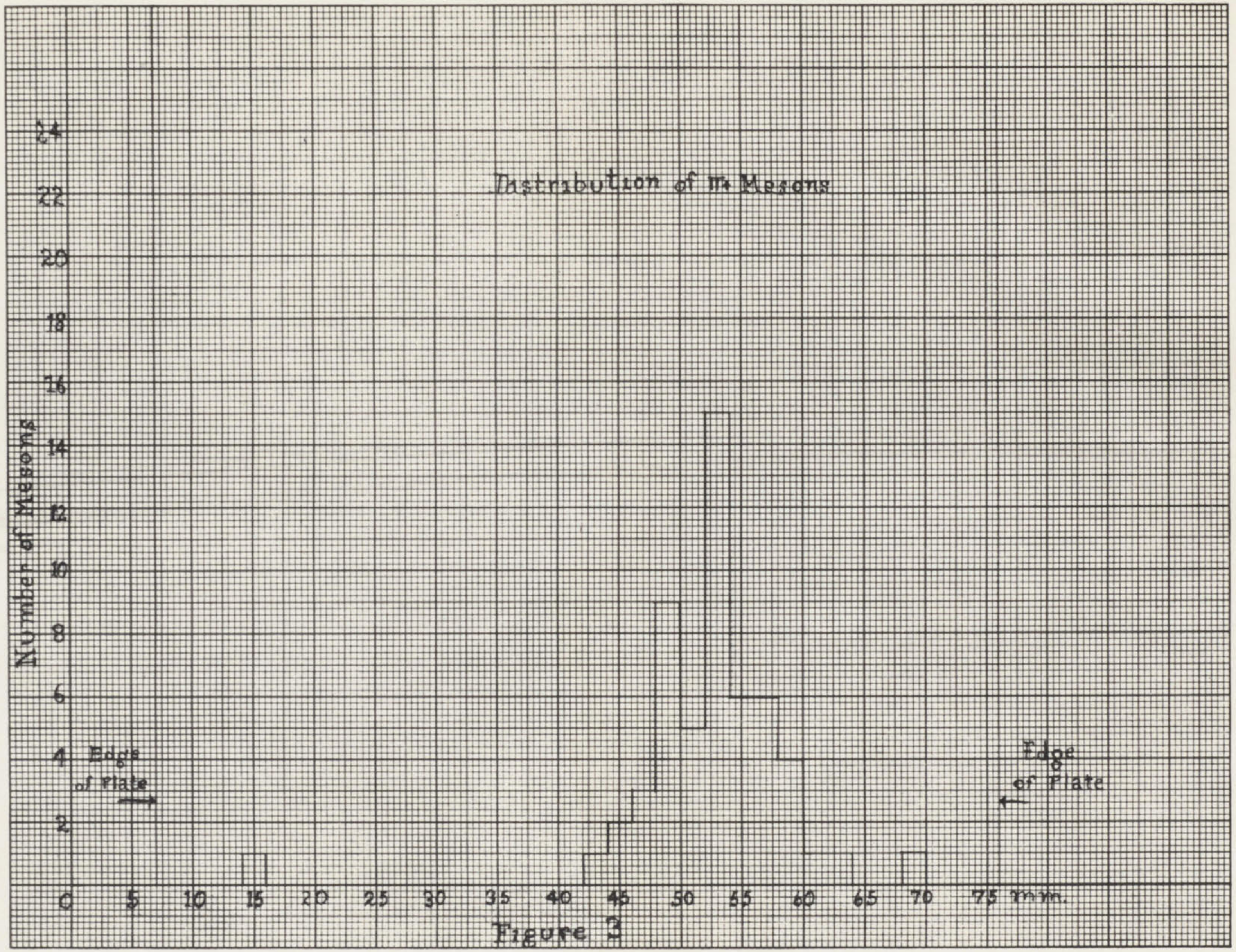
Distribution of π+ Mesons
Number of Mesons
24
22
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75 mm.
Edge of Plate
Edge of Plate

Figure 3

Figure 4. Distribution of ρ Mesons

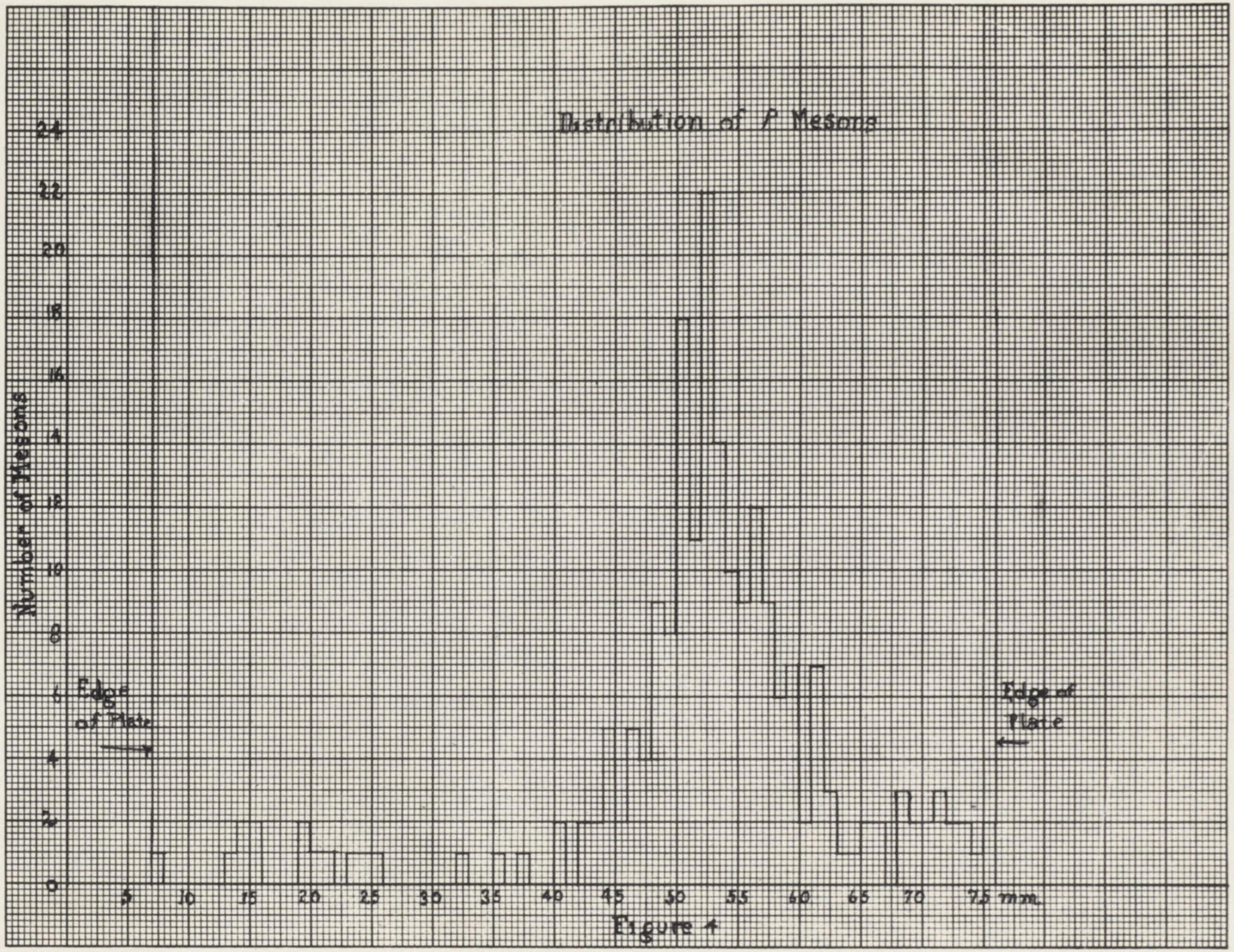
Distribution of ρ Mesons
Number of Mesons
0
2
4
6
8
10
12
14
16
18
20
22
24
Edge of Plate
Edge of Plate
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75 mm.

Figure 4

REFERENCES

1. W.A. Aron, B.G. Hoffman, F.C. Williams, AECU 663, May 28, 1951 (second revision 1949)

2. H. Yukawa, Proc. Math. Soc., Japan, vol. 17, p. 48, 1935.

3. S.H. Neddermeyer and C.D. Anderson, Phys. Rev., vol. 51, p. 884, 1937.

4. M. Conversi, E. Pancini and O. Piccioni, Phys. Rev., vol. 71, p. 209, 1947.

5. C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini and C.F. Powell, Nature, vol. 169, p. 694, 1947.

6. W. Birnbaum, F.M. Smith and W.H. Barkas, Phys. Rev., vol. 83, p. 895, 1951.

7. J.N. Steinberger, W.K.H. Panofsky and J. Stellar, Phys. Rev., vol. 78, p. 802, 1950.

8. R. Durbin, H. Loar and J.N. Steinberger, Phys. Rev., vol. 83, p. 646, 1951.

9. O. Chamberlain, R.F. Mozley, J.N. Steinberger and C. Wiegand, Phys. Rev., vol. 79, p. 394, 1950.

10. M.J. Jakobson, A.G. Schulz and J.N. Steinberger, Phys. Rev., vol. 81, p. 894, 1951.

11. W.L. Kraushaar, Phys. Rev., vol. 86, p. 513, 1952.

12. B. Rossi and N. Nereson, Phys. Rev., vol. 64, p. 199, 1943.

13. Lederman, Booth, Byfield and Kessler, Phys. Rev., vol. 83, p. 685, 1951.

14. A.G. Carlson, J.E. Hopper and D.T. King, Phil. Mag., vol. 41, p. 701, 1950.

15. C. Chedester, P. Isaacs, A. Sachs, and J. Steinberger, Phys. Rev., vol. 82, p. 958, 1951.

16. R.P. Shutt, E.C. Fowler, D.H. Miller, A.M. Thorndike and W.B. Fowler, Phys. Rev., vol. 84, p. 1247, 1951.

17. H.L. Anderson, E. Fermi, E.A. Long and D.E. Nagle, Phys. Rev., vol. 85, p. 934, 1952.

18. H.L. Anderson, E. Fermi, D.E. Nagle and G.B. Yorke, Phys. Rev., vol. 86, p. 413, 1952 and Phys. Rev., vol. 86, p. 793, 1952.

19. Ronald L. Martin, Phys. Rev., vol. 87, p. 1052, 1952.

20. H. Bradner and B. Rankin, Phys. Rev., vol. 80, p. 916, 1950.

21. G. Bernardini, E.T. Booth and L. Lederman, Phys. Rev., vol. 83, p. 1075, 1951.

22. G. Bernardini, E.T. Booth and L. Lederman, Phys. Rev., vol.83, p. 1277, 1951.

23. G. Bernardini, E.T. Booth, L. Lederman and J. Tinlot, Phys. Rev., vol. 80, p. 924, 1950.

24. G. Bernardini, E.T. Booth, L. Lederman and J. Tinlot, Phys. Rev., vol. 82, p. 105, 1951.

25. James F. Tracy, UCRL 2013, Nov. 16, 1952.

26. D.H. Perkins, Nature, vol. 159, p. 126, 1947.

27. F.L. Adelman and S.B. Jones, Phys. Rev., vol. 75, p. 1468, 1949.

28. Dora F. Sherman, Phys. Rev., vol. 90, p. 469, 1953.

29. Richman, Weissbluth and Wilcox, Phys. Rev., vol. 85, p. 161, 1952.

30. F.L. Adelman, S. Jones, Science, vol. 111, p. 226, 1950.

31. F.L. Adelman, Phys. Rev., vol. 85, p. 249, 1952.

32. A.M. Hood, Introduction to the Theory of Statistics, McGraw-Hill Book Co., Inc., New York, 1950.

33. M.S. Livingstone and H. Bethe, Rev. Mod. Physics., vol. 9, p. 263, 1937.

34. F. Block, Zeits Physics, vol. 81, p. 363, 1933.

35. R.R. Wilson, P.R., vol. 60, p. 749, 1941.

36. G. Meno, Ann. de Phys., vol. 1, p. 407, 1934.