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RELATIVE ENERGY DISTRIBUTION OF LOW ENERGY Pi- -MESONS FROM 390 MEV ALPHA-PARTICLES ON CARBON. STAR FORMATION BY Mu- -MESONS

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Stanley B. Jones and R. Stephen White

August 30, 1950

Berkeley, California

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RELATIVE ENERGY DISTRIBUTION OF LOW ENERGY π^--MESONS FROM 390 MEV ALPHA-PARTICLES ON CARBON.

STAR FORMATION BY μ^--MESONS.

Stanley B. Jones* and R. Stephen White

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University of California, Berkeley, California

August 30, 1950

ABSTRACT

A part of the energy spectrum of π^--mesons generated with the Berkeley 184-inch cyclotron by the bombardment of 0.1 gm/cm^2 of carbon with 390 Mev alpha-particles has been investigated. The π^--mesons were registered in nuclear emulsions. Relative values for the numbers of π^--mesons with energies up to 14 Mev were determined at angles up to 60° with the beam direction. The maximum of the energy distribution function apparently occurs at an energy greater than 12 Mev. Some information about the star prong spectrum for μ^--mesons is obtained from a region of the emulsion forbidden, except for scattering, to π^--mesons.

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INTRODUCTION

A few months after mesons were first artificially produced by the 184-inch Berkeley cyclotron by alpha-particle bombardment,[1] an experiment was undertaken to determine the relative energy and angle distribution functions for π^--mesons generated by the 390 Mev alpha-particle beam incident upon a carbon target. It was expected that the meson energies would extend up to a maximum of only a few Mev for an alpha-particle energy of 390 Mev. Such an energy spectrum could be conveniently studied with the then available cyclotron air lock. Results of the experiment, concluded some time ago, appear to indicate that the most probable meson energy lies above the part of the spectrum studied. Publication of results has been withheld because the range-energy curve for emulsion and glass in the pertinent energy region were in question. Recently, these curves have been experimentally determined over the necessary region by Bradner[2] et al. and, in addition Aron[3] has recalculated the glass curve. The portions of the energy and angle distribution spectra on which the apparatus supplied data have now been calculated.

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[1] E. Gardner and C. M. G. Lattes, Science 107, 210 (1948).
[2] H. Bradner, F. Smith, W. Barkas and A. Bishop, Phys. Rev. 77, 462 (1950).
[3] W. Aron, private communication.

Although the most probable π^--meson energy was apparently not reached, publication of results seems worthwhile because at the present time no meson experiments with the alpha-particle beam are in progress and none are contemplated in the near future.

OBSERVATION OF THE MESONS

The π^--mesons were generated in the 184-inch cyclotron by an alpha-particle beam striking a carbon target and were registered in nuclear emulsions. A schematic diagram of the experimental arrangement is presented in Fig. 1. The alpha-particle beam is shown circulating in the clockwise direction and striking a carbon target at a radius of 81 inches where the beam energy is 390 Mev. Some of the π^--mesons produced leave the target in the plane of the alpha-particle beam, moving in the general direction of the beam and then are deflected in the counterclockwise direction into the nuclear emulsions as illustrated. The path of these mesons may make an angle θ with the beam direction at the target from either side of the beam. We defined θ as positive if the meson initially started inward and negative otherwise, as shown in Fig. 1.

The carbon target was one inch square and had a thickness of 0.1 gm/cm^2. Most of the alpha-particles were found to hit a region of the target less than 1/8 inch from the leading edge when the target was monitored with thin polystyrene. The activity of the polystyrene was due to positrons from the C^{11} formed by the reaction $C^{12}(\alpha,\alpha n)C^{11}$.

The nuclear emulsions used were of the one inch by three inch Ilford C-2 100 micron type. They were placed in stacks of 4 high with a blank glass plate on the top and bottom. After exposure in the plate holder, the plates were developed according to standard procedure. A plate from the center of the stack was selected for examination with the aid of a binocular microscope at a magnification of about 600x.

All meson tracks found ending in the emulsion were recorded and labeled either σ (star-forming) or ρ (non-star-forming). Only σ-mesons were used for determining the energy distribution function for the π^--mesons since there was a possibility that a few π^+-mesons and μ^+-mesons stopped in the emulsions and since some of the mesons were certainly μ^--mesons. The σ-meson count should be representative of the number of π^--mesons since a fixed fraction, 73.2 ± 2.0 percent[4], of the π^--mesons form stars, μ^+-mesons and π^+-mesons do not form stars, and there is evidence to be discussed later that μ^--mesons seldom if ever initiate stars. It may be worth while to point out that in the group of over 400 mesons observed in this experiment, no π-μ ending, indicative of a π^+-meson, was seen.

ANALYSIS OF THE DATA

The function $n(E,\theta)$ that was investigated in this experiment represents the relative number of π^--mesons leaving the target per unit meson energy interval per unit solid angle as a function of π^--meson energy, E, and angle, θ, when a 390 Mev alpha-particle beam is incident upon a 0.1 gm/cm^2 carbon target. The study was restricted to angles, θ, within 60° of the beam direction. It was anticipated that the π^--meson energy interval taken from 2 to 14 Mev, would be adequate for obtaining the major parts of the energy spectra. The procedure used in finding the function from the data was to correlate a region of the photographic plates with an energy and angle interval for π^--mesons leaving the target. The meson density in the region provided a measure of the desired function. The analysis

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[4] F. L. Adelman and S. B. Jones, Science 111, 226 (1950).

was complicated, first, by the scattering of the mesons in the photographic plates and, second, by the fact that the meson energies and angles were double valued functions of the positions of the meson end points on the plates since mesons of a particular energy, E, leaving at a particular angle, $+\theta$, do not end at the same position on the plate as those leaving at $-\theta$.

Details of the analysis follow. The positions of all the mesons observed were plotted with respect to the target with the assumption that the plot represented the meson density in the central plane between the cyclotron dees. This plot is shown in Fig. 2. The next step was to mark out areas on the meson plot that corresponded to particular π^--meson energy and angle intervals. First, meson orbits for particular angles and energies at the target were laid out by stepwise graphical construction since the rapidly falling off magnetic field in this region very much complicated a mathematical treatment. When the point and angle at which a meson would strike the photographic plates was established, the position where it would end in the emulsion was computed. This was done by taking a group of 100 mesons and observing the fractions of the range traveled in glass and emulsion for each energy. Then the penetration into the plate, neglecting scattering, could be determined from the range energy curves in emulsion and glass[2,3]. Aron's theoretical curve for protons in glass of a composition similar to that used by Ilford is within the probable error of the experimental curve measured by Bradner et al.[2], and was used in obtaining the ranges in glass. Once the endings for particular energies and angles were established, a chart such as that shown in Fig. 3, denoting the boundaries of particular energy and angle intervals, was constructed. Because mesons leaving the target at angles equal in magnitude but different in sign did not stop at the same position in the photographic plates, the lines representing constant energy and angle values had to be drawn as weighted mean values. A point determining a boundary was taken on the straight line connecting the points for the plus and minus angles. The ratio of its distances from the end points was weighted inversely as the ratio of the numbers of mesons of positive and negative θ that stop in the emulsion. The weighting factor, W, is the product of D, the fraction which survive decay in flight; F, the ratio of the meson density to the meson density that would be obtained if the focusing effect of the horizontal component of the magnetic field were not effective; and 1/S, the reciprocal of the length of the meson orbit, the solid angle correction:

$$W = \frac{DF}{S}$$

D was calculated using the mean-life of the π-meson [5,6,7] which was taken to be 2.6×10^{-8} sec. The D values were calculated relative to 1.00 for π^--mesons leaving at zero degrees to the beam direction. The focusing factor, F, representing the familiar focusing effect of the fringing of a cyclotron's magnetic field on a charged beam was found graphically. An initial small vertical velocity was assumed for a π^--meson of energy, E, and angle, θ, and the vertical displacement was numerically integrated point by point along the trajectory. The net displacement divided into the displacement without focusing gave the focusing factor, F. Theory and empirical trials showed that the fractional focusing is independent of the particular value of a small vertical velocity and the vertical position of the point of origin at the target. It was found in all cases t

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[5] J. R. Richardson, Phys. Rev. 74, 1720 (1948).
[6] E. Martinelli and W. Panofsky, Phys. Rev. 74, 465 (1950).
[7] O. Chamberlain, R.F. Mozley, J. Steinberger, C. Wiegand, Phys.Rev. 79 394 (1950)

the magnetic field fell off so slowly in the first half of the trajectory that the defocusing was less than 1 percent; however, in the last half of the trajectory, the magnetic field fell off very rapidly for the higher energy mesons and for a 14 Mev meson with $\theta = +60^\circ$ the focusing was 33 percent. Typical vertical trajectories are shown in Fig. 3. The solid angle, $d\Omega$, that a small region of the nuclear emulsion subtends for meson of energy E and angle θ is given by $d\theta d\phi$ where $d\phi$ is the vertical angle and $d\theta$ is the corresponding horizontal angle. Since θ appears on the diagram, the effect of the value of $\Delta\theta$ on the solid angle is automatically taken into account. It is necessary to make a separate correction for $\Delta\phi$. The values of these corrections for representative energies are given in Table I for plus and minus angles from which one finds the final weighting factors W^+ and W^-.

TABLE I

Energy of π^--Mesons(Mev)	Angle with Beam Direction(degs)	F+	D+	S+ (cm)	F-	D-	S- (cm)
14	±60	1.33	.91	30.5	1.00	1.09	6.80
11		1.26	.91	27.0	1.00	1.09	5.85
8		1.19	.91	23.0	1.00	1.09	4.87
5		1.11	.91	18.9	1.00	1.09	3.80
2		1.04	.91	11.3	1.00	1.09	2.26
14	±30	1.23	.96	25.3	1.00	1.04	13.6
11		1.17	.96	22.3	1.00	1.04	11.7
8		1.12	.96	19.0	1.00	1.04	9.74
5		1.08	.96	15.1	1.00	1.04	7.56
2		1.04	.96	9.05	1.00	1.04	4.52
		F	D	S			
14	0	1.12	1.00	19.4			
11		1.09	1.00	17.0			
8		1.07	1.00	14.2			
5		1.04	1.00	11.3			
2		1.02	1.00	6.79			

Once the weighted points were determined for integral values of the π^--meson energy in Mev and for values of θ equal to 0°, $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$, a diagram such as that shown in Fig. 2 was drawn in. The weighting factors combined so that the resultant curves lie very close to the negative θ curves. This was due to the strong influence of the short trajectories of the mesons with θ negative.

$n(E,\theta)$, the number of π^--mesons per unit energy interval per unit solid angle leaving the target, is found in the following way. Let ΔN be the number of σ-mesons in the interval $\Delta\theta$, ΔE. Then

$$\Delta N = \Delta N_{\theta+} + \Delta N_{\theta-}$$

and
$$\Delta N_{\theta+} = \Delta N \frac{W^+}{W^+ + W^-}$$

$\Delta N_{\theta+}$ is the number of σ-mesons in ΔN that had θ positive, and similarly for $\Delta N_{\theta-}$. By definition

$$n_{\theta+} \sim \frac{\Delta N_{\theta+}}{\Delta\Omega \Delta E \, D_{\theta+} F_{\theta+}}$$

where
$$\Delta\Omega = \frac{\Delta\theta t}{S}$$

t is the emulsion thickness and S is the length of the meson trajectory. It follows that

$$n_{\theta+} \sim \frac{1}{t\Delta\theta\Delta E} \left(\frac{\Delta N}{W_{\theta+} + W_{\theta-}}\right)$$

Likewise $n_{\theta-}$ and n_θ are proportional to the same quantity. If mesons from two or more plates are counted in a single angle and energy interval, the proper formula, then, is

$$n(\theta,E) \sim \frac{1}{\Delta\theta\Delta E\,(\sum_i R_i t_i)} \left(\frac{\Delta N}{W_{\theta+} + W_{\theta-}}\right)$$

where R_i is the ratio of the area scanned on plate i to the total area accessible to mesons in this interval.

The thickness, t, of the emulsion after development was measured. As only relative distributions were measured, the fractional shrinkage of the emulsion during development was not needed. It was assumed, however, that the fractional shrinkage was constant for all of the plates. The emulsion thicknesses after development are tabulated in Table II.

TABLE II

Plate No.	Distance from Target (in.)	t (microns)
357	1 - 4	51.6
354	4 - 7	53.8
351	7 - 10	47.2
348	10 - 13	52.4

In order to obtain sufficient statistics, the values of ΔN_{σ} were combined into groups. This was done in two ways. One grouping was made such that π^--meson energy distribution functions could be determined. Calculations were made for energy intervals of 2 to 6 Mev, 6 to 10 Mev, and 10 to 14 Mev for ranges of θ of 0°-30°, 30°-60°, and 0°-60°. The other grouping was chosen so that calculations of angular distribution functions could be done. The angular intervals used were 0°-30°, 30°-45°, and 45°-60° and the energy intervals were taken to be 2 to 8 Mev, 8 to 14 Mev, and 2 to 14 Mev. These two groupings of the data are tabulated in Table III. The calculated values of n together with the statistical probable error are also given.

TABLE III

A. Energy Distribution

ΔE (Mev)	$\bar{E}$	$\Delta\theta$ (Degrees)	ΔN_σ	$\Sigma R_i t_i$ (Arbitrary Unit)	$\overline{W^+ + W^-}$ (Arbitrary Unit)	$n(\theta,E)$ (Arbitrary Unit)
2-6	4	0°-30°	30.5	25.8	23.1	4.3 ± 0.5
6-10	8		55.5	41.2	15.5	7.2 ± 0.7
10-14	12		72	31.8	12.6	15 ± 1
2-6	4	30°-60°	25	29.7	30.3	2.3 ± 0.3
6-10	8		35	30.7	20.2	4.7 ± 0.5
10-14	12		39	30.7	16.3	6.5 ± 0.7
2-6	4	0°-60°	55.5	28.1	28.6	2.9 ± 0.3
6-10	8		90.5	34.7	19.1	5.7 ± 0.4
10-14	12		111.0	31.2	15.5	9.6 ± 0.6

B. Angular Distribution

$\Delta\theta$ (Degrees)	$\bar{\theta}$	ΔE (Mev)	$\bar{E}$	ΔN_σ	$\Sigma R_i t_i$ (Arbitrary Unit)	$\overline{W^+ + W^-}$ (Arbitrary Unit)	$n(\theta,E)$ (Arbitrary Unit)
0-30	15	2-8	5	59	32.3	21.0	4.8 ± 0.4
30-45	37.5			29	27.6	24.5	4.8 ± 0.6
45-60	52.5			9	31.5	32.2	1.0 ± 0.2
0-30	15	8-14	11	99	34.7	13.2	12.0 ± 0.8
30-45	37.5			46	35.3	15.2	9.5 ± 0.9
45-60	52.5			15	26.3	20.2	3.1 ± 0.6
0-30	15	2-14	8	158	34.0	17.3	7.4 ± 0.4
30-45	37.5			75	33.2	20.0	6.3 ± 0.8
45-60	52.5			24	27.5	26.3	1.8 ± 0.2

The values of $n(\theta,E)$ are plotted in arbitrary units in Figs. 4 and 5. The energy distribution function is shown in Fig. 4 and the angular distribution function in Fig. 5. One may see from Fig. 4 that a maximum of the energy distribution has probably not been reached at an energy of 12 Mev. Fig. 5 indicates that the meson density falls off markedly when θ is increased from 0° to 52.5°.

STUDY OF μ^--MESONS

The region below the dotted line in Fig. 2 is inaccessible to π^--mesons unless they experience a large scatter. There were 15 mesons which ended in the part of this lower region which was scanned; only one of these made a star. Of the 14 non-star forming mesons there were two which had at their ends a "club". A "club" has been arbitrarily defined as a group of grains without direction which has a spatial extent in the emulsion of at least twice the width of the meson track near its ending. These are possibly grains due to recoil of the product nucleus on the ejection of a neutron. E. Gardner[9], using a technique similar to that described in this paper, found 13 mesons, one of which formed a star. Two of the non-star forming mesons formed a "club". He has kindly permitted us to add his statistics to our own. This information is summed up in Table IV.

TABLE IV

Observer	Mesons ending in μ^- area	No. of σ-mesons	No. of ρ-mesons	No. of mesons having clubs	Fraction of μ^--mesons which form stars	Fraction of μ^--mesons that have clubs
Authors	15	1	14	2		
Gardner	13	1	12	2		
Total	28	2	26	4	$\leq 0.07 \pm 0.03$	$\leq 0.14 \pm 0.05$

The number of μ^+-mesons that stopped in the region forbidden to π^--mesons is estimated to be < 5 percent of the μ^--mesons. This is in part due to the small value of 0.2,[10] for the ratio of the cross section for production of low energy π^+-mesons to that for π^--mesons and in part to the geo-

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[9] E. Gardner, private communication.

[10] W. H. Barkas, Phys. Rev. 75, 1467(A) 1949.

metry which was favorable for registering μ^--mesons rather than μ^+-mesons.

It should be emphasized that this experiment cannot be made entirely free from contamination by π^--mesons as there is a finite probability for large scattering anywhere along a meson's path; therefore, the two star-forming mesons mentioned above could be π^--mesons which have undergone large scatters. This experiment does, however, put an upper limit of about 10 percent on the fraction of μ^--mesons which form stars. These results are in essential agreement with those of Chang[11] on cosmic ray mesons. Further study of μ^--mesons is planned at this Laboratory.

ACKNOWLEDGMENTS

The authors are indebted to Professor Ernest O. Lawrence for his continued interest in this work. We also wish to thank Professor R. L. Thornton, and Drs. Walter Barkas, Hugh Bradner, Eugene Gardner and C.M.G. Lattes for much helpful discussion. We are grateful to James Vale and the cyclotron crew for making the bombardments. This paper is based on work performed under the auspices of the Atomic Energy Commission.

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[11] W. Y. Chang, Rev. Mod. Phys. 21, 166 (1949).

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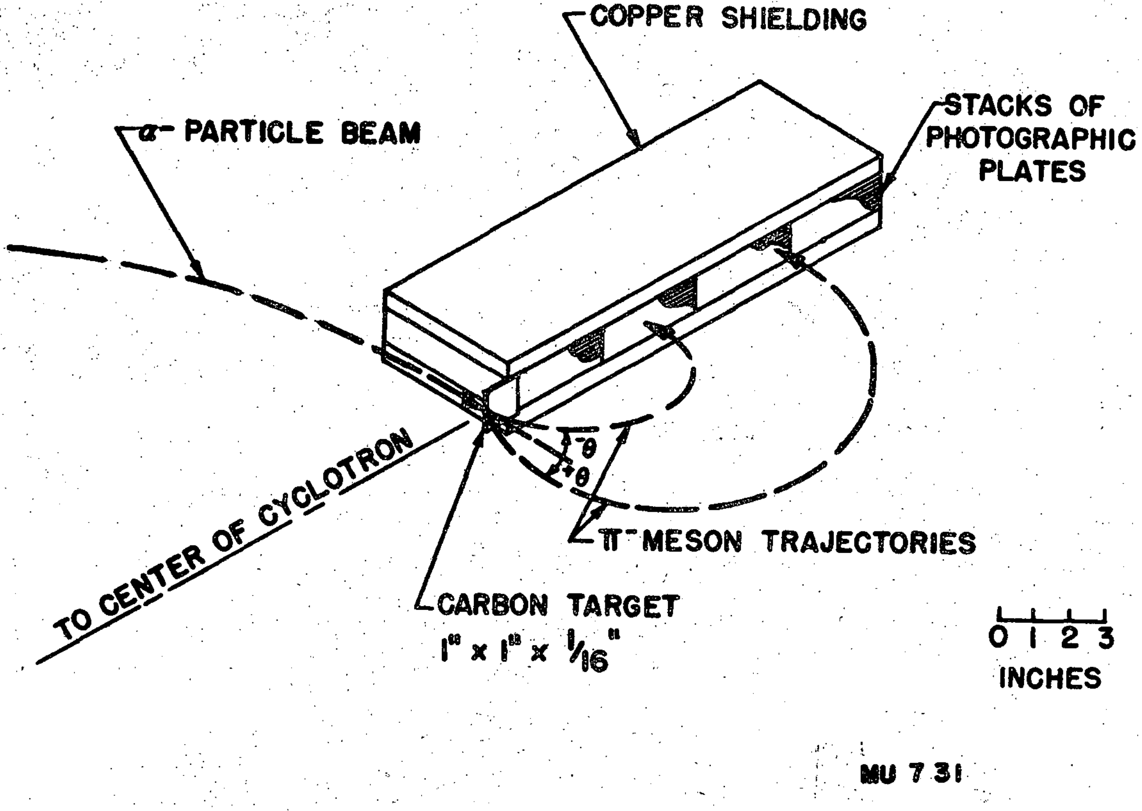

Figure 1
Schematic view of the exposure arrangement with the plate holder, carbon target, and nuclear emulsions in place.

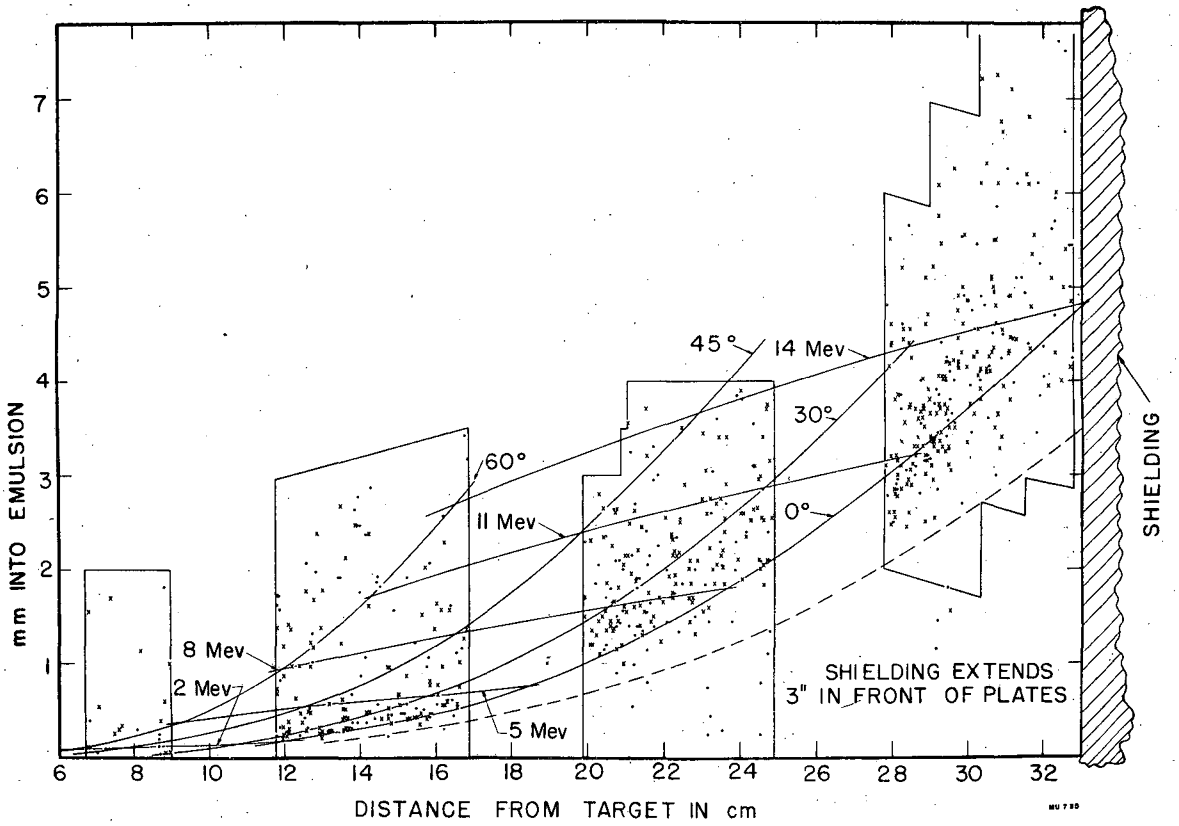

Figure 2

Plot of Meson endings in the photographic emulsions. An "x" represents the ending of a σ-meson (star-forming meson) and an "o" represents the ending of a ρ-meson (non-star forming meson)
The analysis curves are drawn in solid lines. Below the dotted line is the region of the plate which should not contain π^--mesons unless they experience large scatters. The dotted line was drawn in arbitrarily.

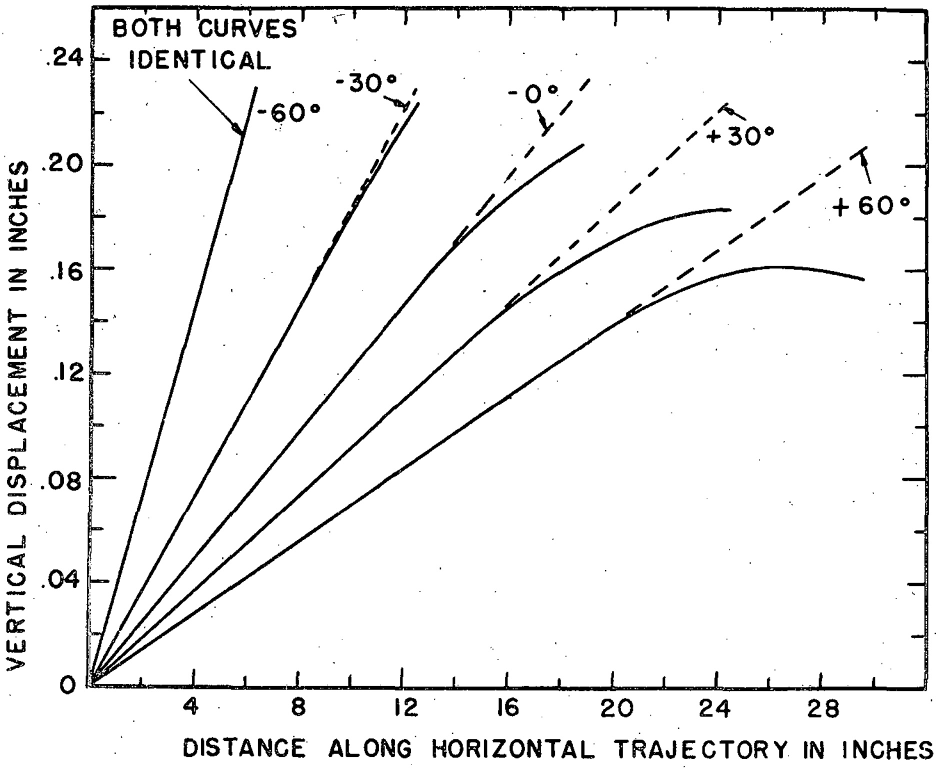

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Figure 3
Vertical focusing of π^--mesons of 133-Mev leaving at various horizontal angles, θ, with the beam direction.
The dotted lines are the vertical trajectories which would be followed in a constant magnetic field. The solid lines are the vertical trajectories calculated for the actual magnetic field of the 184-inch cyclotron. The assumed vertical velocity was different for each angle but all were of the order of 5×10^7 in. sec^{-1}.

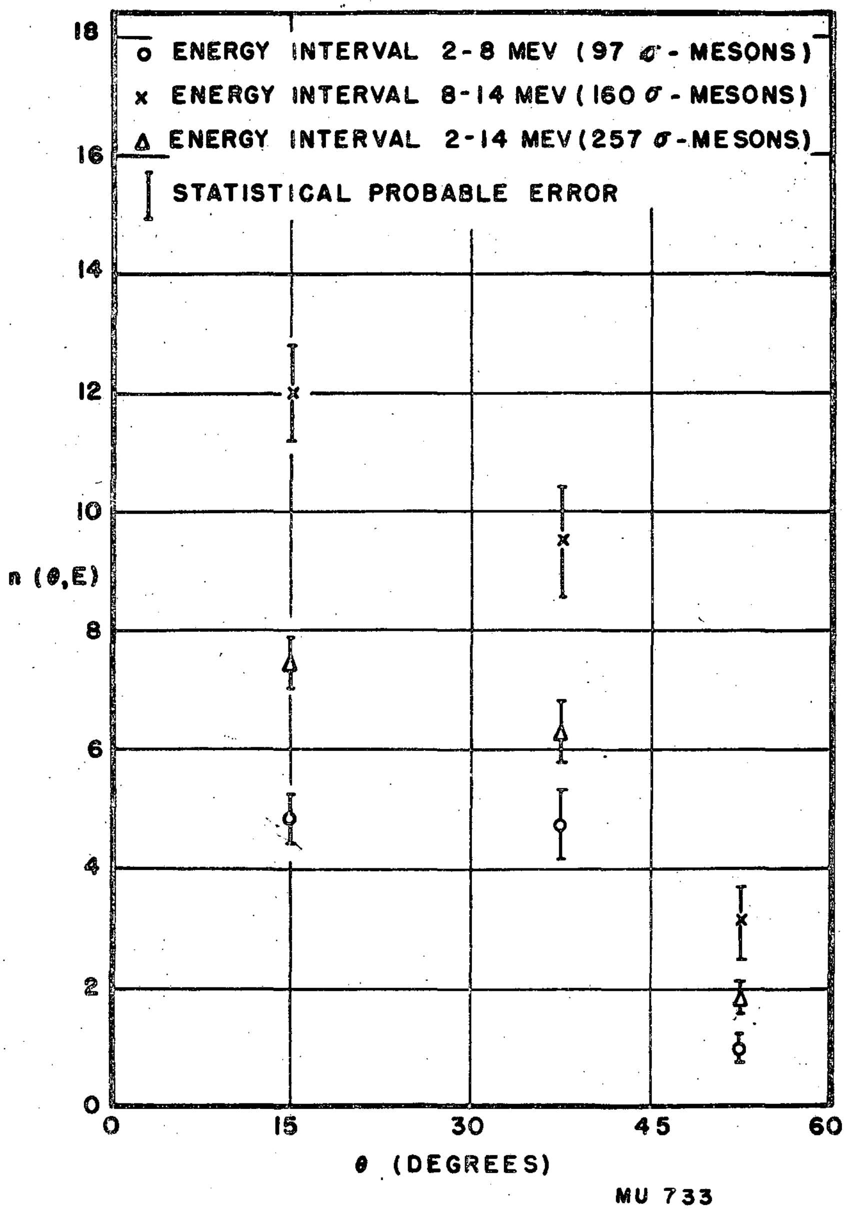

Figure 4
Relative values of the energy distribution functions measured for π^--mesons produced by 390 Mev alpha-particles bombarding 0.1 $\frac{gm}{cm^2}$ of carbon. Functions are given for angles of 0° - 30°, 30° - 60° and 0° - 60° with the beam direction. The ordinate is in arbitrary units.

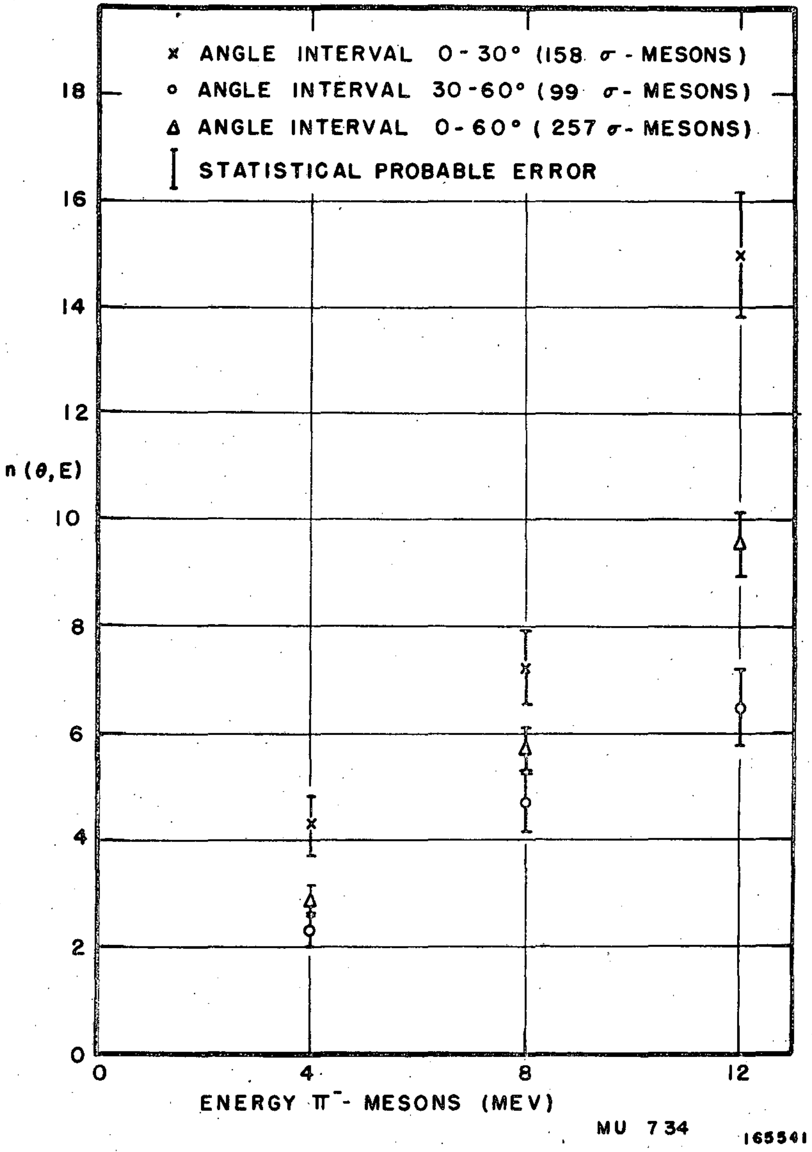

Figure 5
Relative values of the angle distribution functions measured for π^--mesons produced by 390 Mev alpha-particles bombarding 0.1 $\frac{gm}{cm^2}$ of carbon. Functions are given for energy ranges of 2-8, 8-14, and 2-14 Mev. The ordinate is in arbitrary units.