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Production Cross Sections for π^+- and π^--Mesons by 340-Mev Protons on Carbon and Lead at 90° to the Beam*

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Carbon and lead targets were bombarded by 340-Mev protons produced by the Berkeley 184-inch synchro-cyclotron. The spectrum of π^+- and π^+-mesons produced at 90°±12° to the beam was measured by the use of nuclear emulsions embedded in absorbers. The total cross section for the production of π^+-mesons from carbon at this angle is $(2.3\pm0.5)\cdot10^{-28}$ cm² ster^{-1}, and the π^+ to π^- ratio is 5.1±1.0. For lead the cross section for π^+-mesons at this angle is $(7\pm2.1)\cdot10^{-28}$ cm² ster^{-1} and the π^+ to π^- ratio is 1.5±0.4.

I. INTRODUCTION

THE artificial production of mesons was first achieved by E. Gardner and C. M. G. Lattes in 1948.[1] In their experiments they used the 380-Mev internal α-particle beam produced by the Berkeley 184-inch synchro-cyclotron. The experiment was carried out by bombarding a target on a probe inside the cyclotron. The charged mesons produced by the beam were bent away from the beam by the cyclotron magnet and were detected in suitably placed nuclear emulsions.

When the 184-inch cyclotron was converted so that protons could be accelerated to 340 Mev, and when subsequently these protons were deflected out of the cyclotron tank, the experimental possibilities for studying production of mesons were greatly improved. First, all the energy was concentrated in a single nucleon so that meson-production cross sections could be expected to be much greater. Second, it was of great help in these experiments to have the beam out of the vacuum tank and free of the cyclotron magnetic field even though one lost a factor of about a thousand in intensity in bringing the beam out.

The problem of the production of charged π-mesons from a light and a heavy nucleus by protons was undertaken. For the light nucleus carbon was chosen, and for the heavy nucleus lead was chosen. The method of detection was by means of nuclear emulsions which had been found to be very good for identifying mesons.

II. EXPERIMENTAL METHOD

The deflected proton beam from the cyclotron passes through a slit just outside of the cyclotron tank and then through a steering magnet. The beam then goes through a long evacuated pipe which passes through the main concrete shielding around the cyclotron. While passing through this shielding the beam is collimated once more. It then emerges into a concrete shielded pace known as the "cave" where the experiment is set up. The energy of the beam is 340±5 Mev. For this experiment the beam was collimated to a cross section at the target of about $1\frac{1}{4}\times1\frac{1}{4}$ square inches. The current was approximately 4×10^{-11} amp.

The arrangement of the apparatus in the cave is shown schematically in Fig. 1. The beam enters the cave through the exit window of the evacuated pipe. It then passes through the target under investigation. The targets used were graphite and lead rectangular foils 3 in.×5 in. and of various thicknesses. The beam continues in air and is finally caught in a Faraday cup of sufficient area and thickness to catch and stop all the protons.[2] The charge collected by the Faraday cup was accumulated on a condenser whose voltage was measured at convenient intervals. In this way the number of protons bombarding the target is known to ±5 percent and one can calculate the absolute cross

* Some of the results of this experiment were given at the Physical Society meeting at Stanford University in December, 1949, and Phys. Rev. **78**, 496 (1950).
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[1] E. Gardner and C. M. G. Lattes, Science **107**, 270 (1948).
[2] The Faraday cup and associated circuits were kindly made available by Mr. V. Z. Peterson.

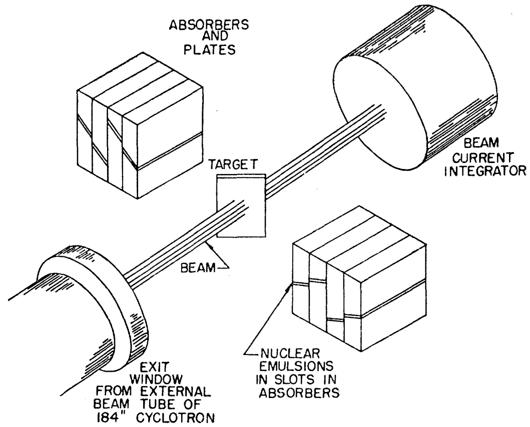

FIG. 1. Schematic drawing of the arrangement of the apparatus in the "cave."

sections. One of the advantages of having the beam out of the tank is the ease with which the beam current can be integrated.

When a nucleus like carbon or lead is bombarded by 340-Mev protons, one obtains at any angle to the beam a spectrum of π^+- and π^--mesons. To study such a spectrum the following scheme was used: The mesons emitted by the target are slowed down by absorbers which are placed at a given angle to the beam. Nuclear emulsions are embedded in the absorbers. The mesons are observed and identified in these emulsions at the ends of their tracks. Consequently the position of a meson in the emulsion reveals its energy, since it had to traverse a certain thickness of absorber material to reach the particular point in the emulsion. Furthermore a count of the number of mesons stopped in a certain volume of emulsion can be directly correlated to the number of mesons of a certain energy interval emitted into a certain solid angle by the target.

Figure 1 shows the absorber blocks with the embedded nuclear plates that make up the detectors. In this experiment the absorbers were located at 90° to the beam. The absorber blocks were 3 in.×3.5 in. ×0.982 in. with a 15° cut to hold the plates. A piece of black masking tape around the cut kept the plates from being light struck. The absorber block nearest the target was at a distance of 7.15 cm from the center of the target. It was made of aluminum and stopped mesons of energies from 0 to 37 Mev. The next absorber block which was placed immediately behind the first was made out of copper and was capable of stopping mesons from 37 to 85 Mev. The third absorber was also made of copper and covered the range between 85 and 125 Mev. The absorbers were large enough so that the scanned portions of the photographic plates were effectively surrounded by an infinite sea of absorber medium. Thus except near the extreme edges, there was no significant loss of particles from the absorber due to multiple scattering.

The photographic plates used were Ilford Nuclear Research plates, type C-3, with an emulsion thickness of 100 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 are not so sensitive, however, as to obliterate the characteristic increase in ionization when a meson approaches the end of its range. Fast electrons are not observed in this type of emulsion.

In principle, it would be desirable to expose the photographic plates for a sufficiently long time to give a high density of mesons and make the counting very rapid. This, however, cannot be done in practice. The cross section for the scattering of protons by the target nuclei is of the order of a thousand times larger than the meson-production cross section. Consequently the duration of the exposure necessary to produce a plate such that a meson can be reliably recognized amidst other tracks is entirely controlled by the background radiation.

The background consists, first, of all charged particles which come directly from the target, and second, from the ambient flux of radiation in the cave which arises from collimating and stopping the proton beam. The background from the target is unavoidable in the present arrangement. The background due to the ambient radiation is reduced by lead shielding (not shown in Fig. 1) placed around the absorbers which hold the photographic plates. These two sources of background lead to a qualitative difference in the appearance of a plate which records low energy mesons from one which records high energy mesons. At 90° to the beam, the low energy plates show background tracks with a preferred orientation, namely pointing to the target. On the other hand, the plates exposed in a position to record the high energy mesons show background tracks oriented in all directions; which indicates that here the charged particles do not come directly from the target. These charged particles are produced by the ambient neutron flux.

The experimental arrangement that we have described works well for studies of meson production at angles of 90° and larger with respect to the direction of the beam. As one goes from 90° forward, that is, toward the direction of the beam, however, one finds that the background of scattered particles increases very rapidly; this makes the scanning of the plates difficult except for very light exposures. For studying the production of mesons at the smaller angles it is best to use some method of reducing the direct background from the target, such as bending the mesons away from the beam in a channel which is placed inside of a magnetic field.[3]

III. CLASSIFICATION OF MESONS

The well-known characteristics of mesons in emulsions enable one to find the mesons and very often to

[3] Cartwright, Richman, Whitehead, and Wilcox, Phys. Rev. 78, 823 (1950).

say what kind of mesons they are. The facts are as follows: A positive π-meson which comes to the end of its range decays into a positive μ-meson and another light neutral particle which is presumably a neutrino.[4] On the other hand, negative π-mesons which come to rest in the emulsion generally produce nuclear stars.[5] It has been found from studies[6] on the prong distribution of stars from magnetically sorted mesons that 73 ± 2 percent of the negative π's produce a nuclear star of one or more observable prongs in emulsions of the type used here. The remaining 27 percent of the π^- mesons end in the emulsion without initiating an observable nuclear star; in these cases, presumably, neutrons or photons are emitted. Thus it is seen that positive and negative π-mesons have characteristics which render them distinguishable when appearing together in an emulsion.

We now 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 of a single heavy prong. This is identified as a π^--meson. No stars have been observed from π^+- or μ^+-mesons. It has been shown[7] that 8.7 ± 1.7 of the μ^--mesons stopped in emulsions form stars. This gives a negligible correction in our experiment.

2. A meson ends with the emission of another meson. The secondary meson is identified as such by virtue of the characteristic small angle scattering and the rapid increase in grain density near the end of its track. Furthermore, the track is about 600 microns long which is the range in emulsion of a μ-meson originating from a stationary π-μ decay. This is then a π-μ decay. A π-μ decay is counted as a π^+-meson.

3. Mesons appear in the emulsion and stop with no observable subsequent events. Such a meson, designated as a ρ-meson may be one of the following types: (a) It may be a μ^+-meson originating from a π^+-meson which has come to rest in the glass or absorber surrounding the emulsion. Such mesons need not be counted. (b) It may be a negative π-meson which does not initiate a star with observable prongs. This occurs, as mentioned above, for 27 percent of the stopped π^--mesons. Such mesons are taken into account by the correction applied to the number of definitely identified negative π-mesons. (c) The ρ-meson may be a positive or negative μ from a positive or negative π which decayed in flight. An over-all correction for decay in flight is applied and will be discussed in Sec. IV.

4. A meson stops in the emulsion with the emission of a particle which makes a thin, lightly ionizing track. The secondary track leaves the emulsion in a distance too short to make it possible to identify the particle which produced it. It is clear that this is either a π-μ decay or it is a π^--meson which produced a one-prong lightly ionizing star. To decide on the classification of these mesons, we go back to some data which has been obtained by F. L. Adelman and S. B. Jones with magnetically sorted π^--mesons. They have found that out of 65 one-prong stars produced by π^-'s, 14 had fast prongs and were confusable with π-μ endings. However, out of these 14 cases, 12 had short heavy recoils which we call "clubs." It is known that π-μ's do not exhibit such clubs. Only 2 out of the 65 π^- mesons did not exhibit such clubs and would then be confusable with π-μ events. So by examining these cases for "clubs" we will make less than a 1 percent error in the total number of π^--mesons, and it turns out even less of an error in the total number of π^+-mesons.

IV. CALCULATION OF CROSS SECTION

Let a total of n protons be incident on a target having m nuclei per cm^2. Let the cross section for the production of mesons per unit solid angle at the angle θ to the beam and per unit energy interval at the energy E be denoted by $d\sigma/d\Omega dE$. The mesons are observed by scanning a certain volume of emulsion embedded in the absorber. Let a given volume element be at a distance R from the target and be at such a depth in the absorber to stop mesons around the energy E. It is easy to show that if one observes N mesons per unit volume of emulsion then

$$\frac{d\sigma}{dEd\Omega}=\frac{NR^2}{nm(dE/dx)_{\text{em}}}, \tag{1}$$

where $(dE/dx)_{\text{em}}$ is the energy loss per unit distance of mesons of energy E in emulsion.

The emulsions were scanned with a Spencer binocular microscope using a magnification of about 600×. The microscopes were equipped with a special stage designed and built by Mr. W. M. Brower of the Physics Department machine shop which enable an observer to reset the scope within about two microns.

Since photographic emulsions do not preserve their thicknesses upon development it was necessary to devise a technique to determine the thicknesses prior to development. This was done in the following way: The nuclear plates to be used in the meson experiment were exposed to a very weak beam of 380-Mev α-particles which entered the plates at an accurately known angle of about 20° to the emulsion surface. The α-particle tracks are then found after the plates have been used in the experiment and developed. By measuring the projected length, L, of such a track in the plane of the emulsion the original thickness was easily calculated. In this way emulsion thicknesses can be measured to an accuracy of about 3 percent.

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[4] Lattes, Muirhead, Occhialini, and Powell, Nature **159**, 694 (1947); Lattes, Occhialini, and Powell, Nature **160**, 453, 486 (1947); Burfening, Gardner, and Lattes, Phys. Rev. **75**, 382 (1949).

[5] D. H. Perkins, Nature **159**, 126 (1947); Lattes, Occhialini, and Powell, Nature **160**, 453, 486 (1947).

[6] F. L. Adelman and S. B. Jones, Phys. Rev. **75**, 1468 (A) (1949).

[7] E. P. George and J. Evans, Proc. Phys. Soc. (London) **64**, 193 (1951).

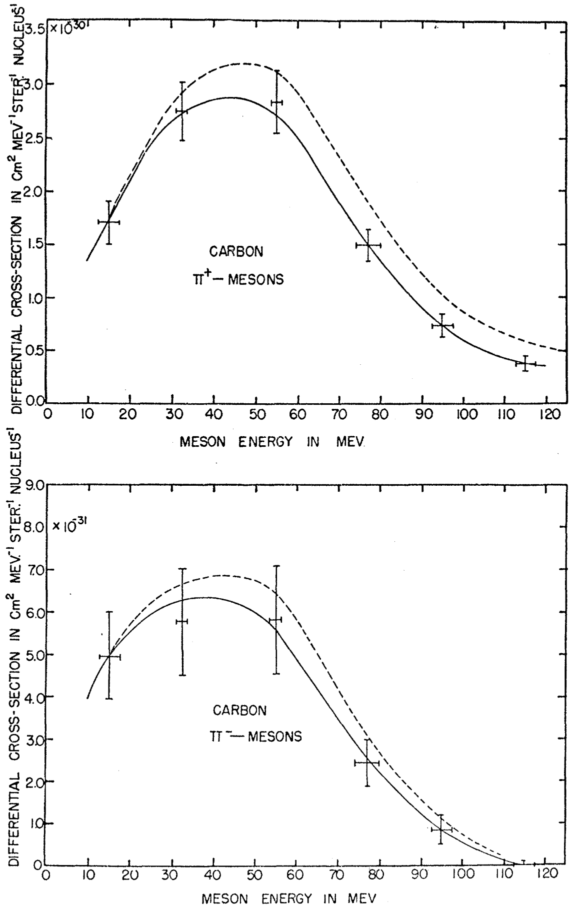

FIG. 2. Differential cross sections for the production of π^+- and π^--mesons by 340-Mev protons on carbon. Angle of observation $=90°\pm12°$ to the beam direction. The dashed curves are the experimental curves corrected for nuclear absorption of the mesons.

There are two corrections which need to be made to the cross section as calculated by Eq. (1): First, mesons produced in the target will decay during the time it takes them to go from the target to the end of their ranges in the emulsion. The mean life of the π^+-meson is $2.54\pm0.12\times10^{-8}$ sec.[8] The mean life of the π^--meson is $2.92\pm0.32\times10^{-8}$ sec.[9] The proper time which has elapsed from the time the meson is created until it comes to rest is given by $\int[(1-\beta^2)^{\frac{1}{2}}dx/\beta c]$ where β is the velocity of the meson divided by c, the velocity of light, dx is the element of path length and the integration is carried out over the entire path of the meson. This correction is never more than 4 percent of the number of observed mesons. Second, the method of detection used in this experiment, namely, slowing the mesons down until they stop in the emulsion introduces an appreciable error in the cross section due to nuclear absorption in the stopping material. To show the effect of this correction the absorption cross section has been taken to be equal to the geometrical cross section of the nucleus independent of the meson energy. The corrected spectra are given by the dashed curves. The effect of the nuclear scattering of the mesons would be to shift the whole spectrum to slightly lower energies. No corrections have been made for this effect.

RESULTS AND CONCLUSIONS

The differential cross section in cm² per Mev per steradian per nucleus for the production of π^+- and π^--mesons from carbon at $90°\pm12°$ is shown in Fig. 2. The probable errors shown on the graph are the purely statistical errors. These are valid for the relative values of the cross sections. The whole curve is subject to an added uncertainly of about ±15 percent in the absolute values of the cross sections. The dashed curves are the experimental curves corrected for the absorption of mesons assuming that the cross section for absorption is equal to the nuclear area independent of meson energy.

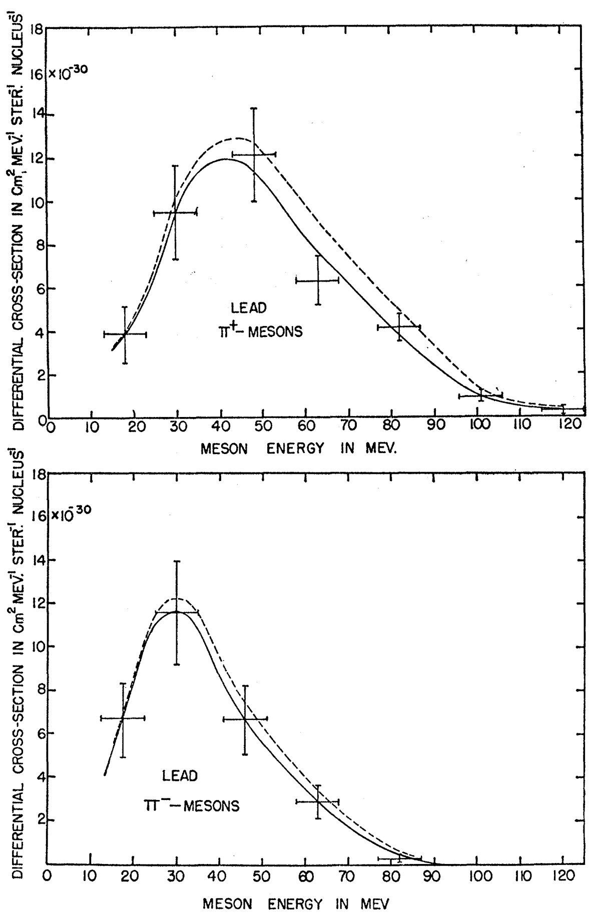

FIG. 3. Differential cross sections for the production of π^+- and π^--mesons by 340-Mev protons on lead. Angle of observation $=90°\pm12°$ to the beam direction. The dashed curves are the experimental curves corrected for nuclear absorption of the mesons.

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[8] Chamberlain, Mozeley, Steinberger, and Wiegand, Phys. Rev. **79**, 394 (1950).

[9] Lederman, Booth, Byfield, and Kessler, Phys. Rev. **83**, 685 (1951).

The integral over energy of the π^+ spectrum (including the absorption correction) is $(2.3\pm0.5)\times10^{-28}$ cm^2 ster^{-1}. The integral over energy of the π^- spectrum is $(4.5\pm1.3)\times10^{-29}$ cm^2 ster^{-1}. This gives an average ratio of π^+- to π^--mesons at this angle of 5.1 ± 1.0. The uncertainty in this ratio is the statistical error.

Figure 3 shows the equivalent curves for lead. The integral over energy of the π^+ spectrum for this nucleus is $(7\pm2.1)\times10^{-28}$ cm^2 ster^{-1}, and the integral over energy of the π^- spectrum is $(4.7\pm1.9)\times10^{-28}$ cm^2 ster^{-1}. An average positive to negative ratio of 1.5 ± 0.4 is then obtained.

The decrease in the average π^+ to π^- ratio as one goes from carbon to lead is to be expected since the ratio of neutrons to protons is much greater for lead than for carbon. It is interesting to look at the π^+ to π^- ratio as a function of the energy of the mesons. For carbon the total number of π^--mesons found is low and so it is not clear what is the behavior of this ratio except that there is some indication that it increases as a function of the energy. In the case of lead this behavior becomes clearer. Figure 4 shows a plot of the ratio of π^-- to π^+-mesons from lead as a function of meson energy, and here one sees a definite decrease in this ratio at the higher energies. It has been pointed out by Chew and Steinberger[10] that when π-mesons are produced in the collision of protons with complex nuclei, π^+-mesons would be favored over π^--mesons because of the Pauli exclusion principle. The opposite would be true if the bombarding particle were a neutron. Furthermore, for a given proton energy the π^+ to π^- ratio should increase with meson energy. The data from carbon and lead supports this conclusion. They also conclude that for a given meson energy, the π^+ to π^- ratio should decrease as the proton energy is increased. Recently Block, Passman, and Havens[11] have studied the production of π^+- and π^--mesons from carbon by 381-Mev protons at 90° to the beam. They find, contrary to the above ideas, that the average π^+ to π^- ratio has increased to 11 ± 3. This increase has come about in the following way: the π^+ production cross section has increased by about a factor of 2, but the π^- production cross section has not changed very much. This seems to indicate that the elementary processes of the production of a π^+- and a π^--meson are perhaps of different character.

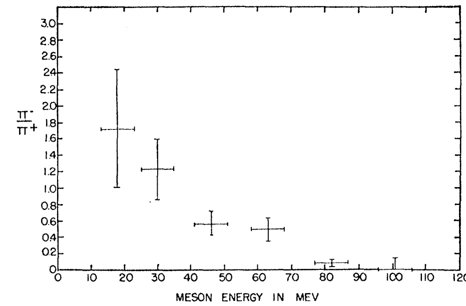

FIG. 4. The ratio of π^-- to π^+-mesons from lead at $90°\pm12°$ to the beam as a function of meson energy.

Henley and Huddlestone[12] have treated the production of π^+-mesons by protons on carbon from a phenomenological point of view. They have assumed that the mesons are produced in nucleon-nucleon collisions, and have used the measured cross sections of the production of π^+-mesons in proton-proton collisions without the contribution from deuteron formation.[2,13] The resulting spectrum of mesons at 90° to the beam depends rather critically on the momentum distribution that one takes for the nucleons. The theoretical problem has also been considered by Passman, Block, and Havens[14] from a similar point of view. They have used a Fermi degenerate gas model for the target nucleons, and have assumed that the final state nucleon-nucleon interaction is such that the π^+-meson always comes off with the maximum available kinetic energy. The agreement with the π^+ experimental data at 343 Mev and at 381 Mev turns out quite satisfactorily.

ACKNOWLEDGMENT

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[10] G. F. Chew and J. L. Steinberger, Phys. Rev. **78**, 497 (1950).
[11] Block, Passman, and Havens, Phys. Rev. **83**, 167 (1951).
[12] E. M. Henley and R. H. Huddlestone, Phys. Rev. **82**, 754 (1951).
[13] M. N. Whitehead and C. Richman, Phys. Rev. **83**, 855 (1951).
[14] Passman, Block, and Havens, Phys. Rev. **83**, 167 (1951).