π^+ Production in Al and C by 209-Mev Polarized Protons*

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The production of π^+ mesons by 209-Mev polarized protons incident on aluminum and carbon has been studied at production angles of 92° (for both elements) and 120° and 144° (for Al alone). Normalized right-left asymmetries of the order of -0.5 are observed at 92° in both elements and for mesons in the range 26–51 Mev. The asymmetry appears to decrease rapidly with increasing production angle. The absolute production cross sections are determined with statistical uncertainties of about 10%. The cross sections at 92° are approximately proportional to the atomic weights of the two target materials, and the angular distribution in Al is almost isotropic for all meson energies.

THE production of π^+ mesons by polarized protons in the process

$$p+p\rightarrow\pi^+ +d$$

has been studied theoretically by Marshak and Messiah,[1] who predicted that interference between s and p waves would result in a right-left asymmetry in the production cross section. This asymmetry was expected to be a maximum at 90° production angle, and to decrease sharply at smaller and larger angles. Crawford and Stevenson[2] and Fields *et al.*[3] have investigated this process at 315- and 415-Mev proton energies, respectively, and have hound a very considerable asymmetry at 90°. We report here some measurements of π^+ production by 209±6 Mev polarized protons in aluminum and carbon.

The phenomenon with which we are concerned is essentially different from the two-body reaction mentioned above, in that we place no restrictions on the configuration of the nucleus after emission of the meson, other than those imposed by energy conservation. The results of the experiment are therefore expected to provide a test of our understanding of meson production in complex nuclei, rather than of the theory of meson-proton interaction. The problem has not been treated theoretically because of the considerable complexity of the transition matrix, even under rather radically simplifying assumptions. In view of the large magnitude of the effects observed, a theoretical investigation becomes more interesting.

METHOD

(a) Polarized Proton Beam

The polarized proton beam was produced in the usual manner by scattering 235-Mev protons at 15° "to the left" from a carbon target in the 130-inch cyclotron. It was then focused by a wedge magnet and collimated by a pair of slits (Fig. 1). The result is a beam of about 10^7 protons per second at maximum cyclotron intensity, having a cross section of about 2.0 in.×3.75 in., an angular divergence in the horizontal plane of ±1°, and a polarization of (89±2)%. The energy of protons entering the target was 212±3 Mev and the loss in the target was about 6 Mev. The beam intensity was measured throughout the experiment by the use of a parallel plate air ionization chamber interposed between the first and second slits. The ionization chamber was calibrated by counting the proton beam directly with a twofold scintillation counter telescope of effective cross section 1/64 in.^{2} This gave an absolute measure of the beam density, and the beam intensity was then obtained by integrating the density over the full cross section of the beam.

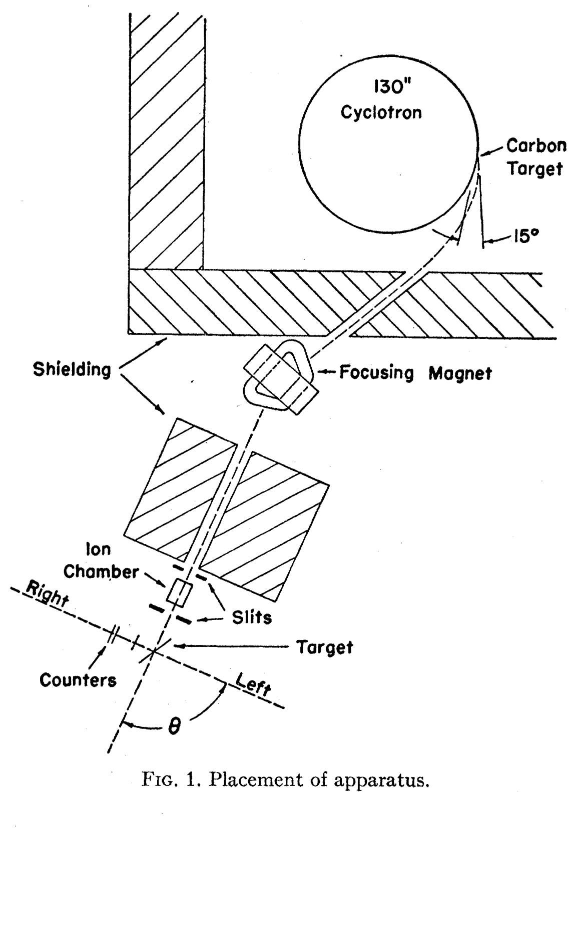

FIG. 1. Placement of apparatus.

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[1] R. E. Marshak and A. M. L. Messiah, Nuovo cimento **11**, 337 (1954).
[2] F. S. Crawford, Jr., and M. L. Stevenson, Phys. Rev. **97**, 1305 (1955).
[3] Fields, Fox, Kane, Stallwood, and Sutton, Phys. Rev. **96**, 812 (1954).

(b) Targets

The meson-producing targets were plane sheets of aluminum (0.911 g-cm^{-2} thick) and carbon (0.931 g-cm^{-2} thick), and were large enough to intercept the entire proton beam. They were mounted in a vertical plane, the orientation of which could be controlled remotely by rotation about a vertical axis. The angle of the target plane with the proton beam was set at 30°; the target was always placed in "reflection geometry" with respect to the meson detector.

(c) Beam Center Line

The beam center line is defined optically as the line bisecting the wedge magnet aperture, and passing through the point of maximum proton beam density at the target position. Mapping of the beam density at the target position showed the distribution to be symmetrical; it is therefore assured that the effective solid angles at the detector in right and left positions are identical. The beam distribution at the exit of the magnet is known from previous work to be approximately symmetrical. Asymmetries in the beam distribution at either position could introduce an angular error, and thus a geometrical asymmetry. We believe this angular error to be quite small (less than 20′ of arc), and in any case to have a completely negligible effect on the results, since the meson production cross section is found to be almost isotropic in the laboratory frame.

(d) Meson Detector

The meson detector consists of a triple scintillation counter array which identifies mesons by virtue of their π-μ decay in the second counter. A copper absorber placed between counters one and two determines the minimum range of detected mesons, while the thickness of counter two and of the target determine the range

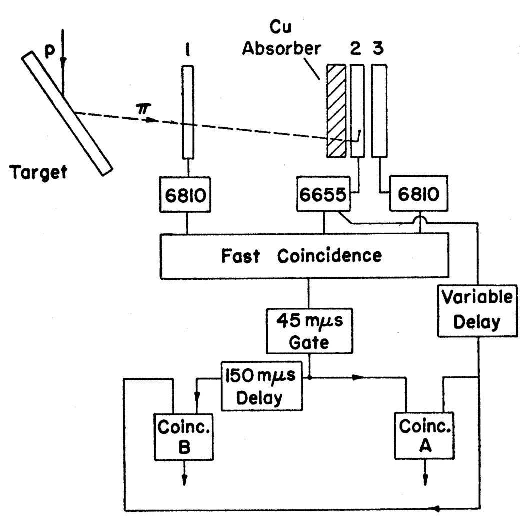

FIG. 2. Block diagram of electronic circuitry.

interval accepted. A block diagram of the circuitry is shown in Fig. 2. Counter three is placed in anticoincidence with a fast 1-2 coincidence and the event 1-2-$\bar{3}$ generates a gate of about 45 mμsec duration. The gate is applied to one input of a double-coincidence circuit A, and after a delay of 150 mμsec, to one input of circuit B. From the anode of the type 6655 photomultiplier of counter two, we derive a pulse which has been carefully shaped by partial clipping; the object of clipping is to shorten the pulse as much as possible without introducing any appreciable overshoot which might paralyze the coincidence circuits and make them insensitive to π-μ events. This pulse, after appropriate amplification and delay, is connected to the other inputs of circuits A and B. The time relationship of the gates and the shaped pulse were set in the following two ways:

(1) The shaped pulse from a stopped meson or proton appears 25 mμsec before gate A and therefore 175 mμsec before gate B.

(2) The shaped pulse appears 25 mμsec before gate B, and therefore long after gate A.

In the first case, coincidences with gate A are expected to consist of π-μ decays, π-μ-e events, and random events; coincidences with the B gate contain π-μ-e events, but are mostly random events. In the second case, coincidences with the B gate contain π-μ, π-μ-e, and random events, but coincidences with the A gate must be purely random. Throughout the experiment, equal amounts of data were taken with the two delay settings. We then compute the true counting rate by taking the differences of the two coincidence rates and averaging over the two delay settings. Any errors introduced by having different effective gate lengths at A and B are thus almost entirely eliminated.

The experiment as sketched above would be straightforward except for one complication: the possible generation of "feed-through" pulses at the 6655 anode which simulate π-μ events. These false events may be caused by very large energy losses in counter two, such as would result from star formation by an energetic proton. Such pulses may be 50 times as large as the pulse from the decay μ meson, and may "stretch" to a length exceeding 25 mμsec, in spite of the clipping and shaping. Since the rate of protons incident on the meson detector was sometimes more than 10^4 as great as the meson counting rate, such rare events were a potential source of error. The methods of estimating this error are discussed in the next section.

PROCEDURE

(a) Calibration of the Meson Detector

After preliminary surveys of the background problem, we realized that the settings of gain and the evaluation of the efficiency for detection of π^+ mesons could most easily be accomplished by calibrating the equipment in a meson beam of known characteristics. We therefore

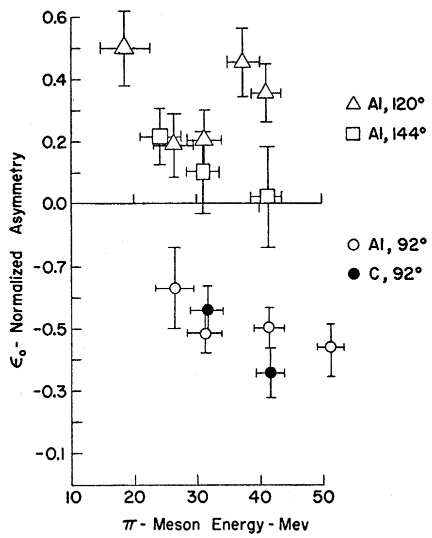

FIG. 3. Normalized asymmetries as a function of meson energy and production angle in the laboratory frame.

placed the counter array in the 46-Mev π^+ beam of the cyclotron, determined the absorber which stopped the largest fraction of mesons in counter two, and studied the response of the detector as a function of the relevant amplifier gains, photomultiplier voltages, and delays. As a routine procedure, we measured the dependence of counting rate as a function of the delay of the shaped pulse relative to the two gates; these delay curves invariably gave the proper π^+ lifetime over a range of two or more mean lives. The actual delays to be used in the proton beam were chosen on the basis of preliminary studies of the probability of "feed-through" events. The ratio of counts to gates at the chosen delay settings (after correction for random coincidences and for imperfect anticoincidence efficiency of counter three) gave directly the efficiency of counting incident π^+ mesons; this efficiency varied from about 26% to 32% in various runs.

(b) Operation in the Proton Beam

The counter array was transferred to the proton beam position and the beam intensity set so that the true counting rate was of the same order as the random rate. This condition was a function of the absorber in the meson detector and the angle of the detector to the proton beam. For example, with no meson absorber, and at 90°, it was impractical to operate the cyclotron above one-quarter of the maximum intensity. Since we deduced that the meson yield was almost independent of the angle, whereas the gate rate increased sharply with decreasing angle, we did not attempt any measurements at angles less than 90°. The background rate was much more favorable at backward angles, where it was usually possible to operate the cyclotron at near maximum intensity.

Measurements were performed for both Al and C targets at 90°, and for Al only at 120° and 145°. These angles are those defined by the beam center line and the axis of the detector telescope, and differ slightly from the effective mean angles because of the inclination of the target plane to the detector axis. We find the effective angles to be 92°, 120°, and 144° assuming the meson angular distribution to be isotropic in the laboratory frame, in accordance with the observations. The angular resolution (half-width at half-maximum) is about $\pm 10°$ for the 92° and 120° angles, and $\pm 7.5°$ for the 144° angle. At each angle, and for each absorber, the array was operated for equal integrated beams at symmetrical left and right positions, and at the two delay settings. After several days of operation, and at the end of each run, the array was checked in the meson beam; no appreciable changes in the operating conditions were noted. The results presented in the next section include the combined data of two runs of six and ten days duration.

(c) Contamination by "Feed-Through" Events

We have indicated that our primary concern was that large counter two pulses might simulate π-μ events. We describe here a series of checks which establish that the contribution of such spurious events was small, but probably not completely negligible. First, it was clear that the detected particles originated in the target: the yield without target was only $(3\pm 3)\%$ of the yield with target. Next, the dependence of the yield on the delay between the shaped pulse and the gates was quite consistent with that expected for π mesons: the reduction in yield for a change of two half-lives was 0.33 ± 0.09, to be compared with the expected 0.25. To obtain more quantitative limits on the contamination by spurious events, the following tests were made:

(1) The "meson" yield was measured with the incident proton energy reduced to 150 Mev by inserting the appropriate absorber before the first collimating slit. This energy is well below the threshold for producing mesons of sufficient energy to be counted. With the meson absorber set to select mesons of energy 31.3 ± 5.6 Mev, we obtained a yield of $(4\pm 4)\%$ of the yield with full energy protons. This gives a lower limit to the contamination expected with full energy protons, because the energies of particles from the target are considerably degraded.

(2) The yield was measured at a small angle (35°), at which position the gate rate was 25 times as large as at 90°. Thus any false counts originating from events proportional to the gate rate would be greatly emphasized relative to the meson events. After subtracting the estimated real meson contribution, we found a "feed-through" component which would amount to $(6.2\pm 3.5)\%$ of the yield at 90° with the same meson absorber as above. This figure is probably too large, since high-energy protons (the supposed cause of "feed-through" pulses) comprise a much larger portion of the flux from the target at 35° than at 90°.

We conclude that "feed-through" events contribute at most a few percent of the yield for this particular meson absorber and production angle. Unfortunately, the time involved in making these measurements was so large that it was not possible to undertake them at each meson absorber, and at each of the three angles. Since "feed-through" events probably depend on the absorber and angle, and may in fact be asymmetric, we are not able to apply a correction for them on the basis of the available data. We may note, however, that a symmetrical contamination of spurious events will make the measured asymmetry less than the true one; any contamination will increase the measured cross sections over the true ones.

(d) Geometrical Asymmetries

Although we have indicated that the experiment does not depend at all critically on alignment, we felt it desirable to see if the asymmetry in meson production was really zero if the protons were unpolarized. An unpolarized beam of the same energy and intensity as the polarized beam was produced by retracting all internal cyclotron targets, and placing an absorber near the wedge magnet; the absorber reduced the protons to the required energy and diffused the beam so that the distribution was certainly symmetrical at the target. With the same meson absorber used in the other checks, we measured an asymmetry of $(+9\pm7)\%$. This is small, and of the opposite sign to that found with the polarized beam; we therefore assume no geometrical contributions to the asymmetries.

RESULTS

(a) Asymmetries

Assuming that the counting rates corrected for random coincidences are a true measure of the π^+-meson yield, we obtain the asymmetry directly in the usual way:

$$\epsilon=(\text{left}-\text{right})/(\text{left}+\text{right}).$$

For ease in comparison with data from other experiments, we normalize these numbers to the asymmetries, ϵ_0, which would be produced by a completely polarized beam. The normalized asymmetries at the three angles are tabulated in Table I and shown in graphical form in Fig. 3.

TABLE I. Right-left asymmetries and cross sections for π^+ production by 209-Mev polarized protons. Note that the angles, energies, and cross sections are computed in the laboratory frame. The asymmetries are normalized to that expected for 100% polarized protons.

Element	Angle	Energy range (Mev)	Normalized asymmetry	Cross section (in units of 10^{-31} cm^2 sterad^{-1} Mev^{-1})
Al	$92°\pm10°$	23.3–29.5	-0.63 ± 0.13	4.76 ± 0.50
		28.5–34.1	-0.49 ± 0.06	4.82 ± 0.34
		39.2–43.9	-0.50 ± 0.07	3.06 ± 0.22
		49.2–53.4	-0.43 ± 0.08	1.55 ± 0.15
C	$92°\pm10°$	29.0–34.3	-0.56 ± 0.08	2.25 ± 0.24
		39.5–44.1	-0.35 ± 0.08	1.29 ± 0.14
Al	$120°\pm10°$	14.7–22.7	-0.50 ± 0.12	2.49 ± 0.25
		23.2–29.5	-0.19 ± 0.10	4.41 ± 0.44
		28.5–34.1	-0.20 ± 0.10	4.17 ± 0.43
		35.1–40.1	-0.45 ± 0.11	3.19 ± 0.29
		38.7–43.5	-0.35 ± 0.09	2.92 ± 0.23
Al	$144°\pm7.5°$	20.9–27.6	-0.22 ± 0.09	5.37 ± 0.43
		28.5–34.1	-0.10 ± 0.13	4.46 ± 0.47
		38.7–43.5	-0.02 ± 0.16	2.14 ± 0.28

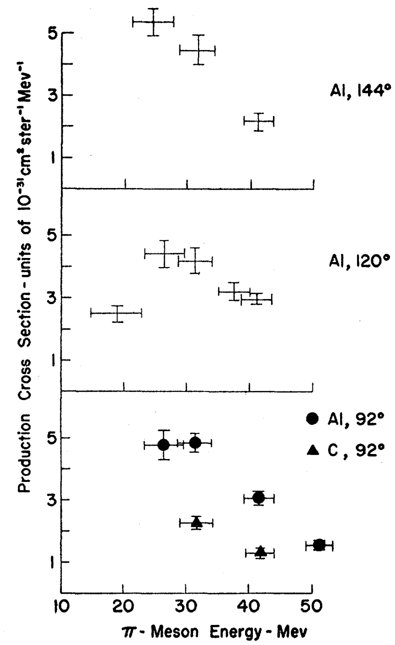

FIG. 4. Absolute differential cross section as a function of meson energy and production angle. Cross sections, angles, and energies are given in the laboratory frame.

(b) Cross Sections

The absolute meson production cross sections were calculated assuming no contamination from spurious events; they are tabulated in Table I and shown in Fig. 4. The statistical deviations include a 5% uncertainty in the proton beam intensity, and a 5% uncertainty in the meson detection efficiency. Corrections have been included for decay of mesons in flight, for nuclear absorption of mesons in the absorber, and for the dissimilar efficiency for counting π-μ-e events at the two delay settings. The solid angles were 0.18 steradian for the 92° and 120° angles, and 0.096 steradian for the 144° angle.

DISCUSSION

(a) Right-Left Asymmetry

Four significant features emerge:

(1) ϵ_0 is always negative, indicating a preponderance of mesons emitted to the right, the direction opposite to that of scattering of protons in the first target.

(2) The magnitude of ϵ_0 at 92° is quite large and is about the same for the two target materials.

(3) ϵ_0 decreases rapidly with increasing angle.

(4) ϵ_0 is about the same over the entire range of meson energies which we investigated (19 to 51 Mev).

The sign, magnitude, and approximate angular dependence of the asymmetry closely resemble those found by Crawford and Stevenson[2] at 315 Mev proton energy. This similarity is quite striking in view of the considerable qualitative differences in the two processes. The small dependence on atomic number and on meson energy, while it has no parallel in the elementary reaction, is also somewhat surprising.

(b) Cross Sections

The comparison of the yield of mesons from carbon and aluminum at 92° gives the result that the cross sections are very nearly in the ratio of the atomic weights. This is in accord with earlier studies by Clark,[4] and by Imhof, Easterday, and Perez-Mendez.[5] It is more difficult to compare the absolute cross sections with those of other workers, since so little published data exist. The most nearly comparable measurement is that of Gatchell,[6] who measured the 90° yield of π^+ mesons from Li^6 and Li^7 at 242-Mev proton energy, and found cross sections for production of 40-Mev mesons of 7.5×10^{-32} and 2.7×10^{-32} cm^2 Mev^{-1} $sterad^{-1}$ $nucleon^{-1}$ for the two isotopes, respectively. Our result, expressed in the same units, is 1.0×10^{-32} for 42-Mev meson energy. The higher cross section for lithium is doubtless due to the higher proton energy, but the difference in the isotopic yields emphasizes the strong dependence on nuclear structure.

The angular distribution over the range 92° to 144° in the laboratory frame is found to be essentially isotropic for mesons of energy less than 30 Mev, and only slightly anisotropic for the highest energy mesons. We therefore conclude that production takes place predominantly in low angular momentum states, as one might expect at proton energies so near the threshold for meson production. The large asymmetry is presumably a result of interference between orbital states of different parity, which implies that there is appreciable production in both s and p waves.

CONCLUSION

We have shown that there is a large asymmetry in the production of π^+ mesons by polarized protons incident on aluminum and carbon, and that this effect shows a striking resemblance to one found in the elementary p-p production process. In order to understand this result, it is evidently desirable to obtain more detailed information concerning the dependence of the asymmetry on meson energy, meson production angle, and proton energy. Unfortunately, the present method has three serious drawbacks: it is extremely time-consuming, it is not entirely free from systematic errors, and it is not applicable to the study of π^- production. We therefore plan no further measurements of this type unless a considerably improved technique can be developed. For example, if one could detect the complete π^+-μ^+-e^+ decay chain, the vulnerability to contamination by spurious events would be greatly reduced. The corresponding measurements for π^- and π^0 production can be attempted only with completely different methods.

[4] D. L. Clark, Phys. Rev. **87**, 157 (1952).

[5] Imhof, Easterday, and Perez-Mendez, Phys. Rev. **105**, 1859 (1957).

[6] E. K. Gatchell, Phys. Rev. **105**, 713 (1957).