PION PRODUCTION IN HIGH-ENERGY PROTON-PROTON COLLISIONS*

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We measured the differential production cross section for producing pions in 12.2-GeV/c p-p collisions on lines of fixed P_l and $P_\perp$ in the c.m. system. We found that $d^2\sigma/d\Omega dp$ is maximum at $P_l=0$, in disagreement with our earlier result, which supported the two-center model. We have evidence that the earlier result is wrong. It also appears that in the c.m. system, $d^2\sigma/d\Omega dp$ is factorable into functions of P_l and $P_\perp$. In the $P_\perp$ dependence we found a very sharp forward peak of the form $e^{-15P_\perp^2}$.

We have measured the differential production cross section, $d^2\sigma/d\Omega dp$, for the production of $\pi^\pm$ mesons, in 12.2-GeV/c proton-proton collisions. This experiment repeated and extended the range of two earlier experiments.[1,2] Many other groups[3] have also studied particle production in collisions of protons with hydrogen and heavy nuclei. However, the lack of a complete theory makes comparisons between data at different energies and on different targets difficult.

The quantity $d^2\sigma/d\Omega dp$ is the cross section for the production of a single π meson in the phase-space region $\Delta\Omega\Delta p$, independent of what other particles are produced. Thus it is the cross section for the process

$$p+p\to\pi^\pm+\text{anything}. \qquad (1)$$

This is not the cross section for any single channel but is instead the sum of the cross sections for an ensemble of channels such as

$$\begin{aligned} p+p&\to\pi^++p+n,\\ &\to\pi^++\pi^-+p+p,\\ &\to\pi^++\pi^-+\pi^0+p+p, \end{aligned} \qquad (2)$$

etc. The parameters varied in these measurements were P_l and $P_\perp$, the two components of the momentum of the produced pion in the c.m. system.

The experiment was performed on the new second slow-extracted proton beam (EPB II) of the zero-gradient synchrotron (ZGS) at Argonne. About 2×10^{10} protons of 12.2 GeV/c were extracted during the 0.5-sec spill every 3.0 sec. This extraction was simultaneous with that in EPB I and had an extraction efficiency of about 30%. The angular divergence of the beam was about ±3 mrad and the momentum spread was less than ±10 MeV/c. The uncertainty in the absolute value of the momentum was about 1%. The beam spot at our target was a circle of about 1 cm diam.

The number of protons hitting our target was measured by two telescopes, each made up of three small scintillation counters, $M=M_1M_2M_3$ and $N=N_1N_2N_3$. As shown in Fig. 1, these both looked at our target so that the number of counts in these monitors was proportional to the number of protons hitting the target. To obtain the ratio of protons to monitor counts we took calibration runs with a gold foil placed in the proton beam several feet upstream of the target. The uncertainty in these calibrations was about 5%. Our target was a vertical 3-in.-diam liquid-hydrogen flask. The flask window and vacuum window were both 0.003-in. H-film. Our detection system for the produced π mesons was a single-arm spectrometer as shown in Fig. 1. It contained a magnet C which served as a steering magnet to compensate for the different laboratory angles resulting as we varied $P_\perp$ and P_l. It also contained two bending magnets (B_1 and B_2) each bending through about 5.5° for momentum analysis. These three magnets were always adjusted so that the central π mesons emerged from the B_1 magnet going exactly along the central axis of the spectrometer, and thus passed through the center of all the counters. The phase space subtended by our spectrometer (typically 10^5 GeV/c sr in the c.m. system) was the intersection of the two phase-space strips subtended by the counters S_1 and S_5, and all other counters were overmatched. The number of events was determined by the eightfold coincidence $SC=S_{123}S_{45}C_{123}$. The threshold Cherenkov counter (C_2) tagged the particles as π mesons.

This spectrometer was rather similar to the one used in our most recent experiment[2]; howev-

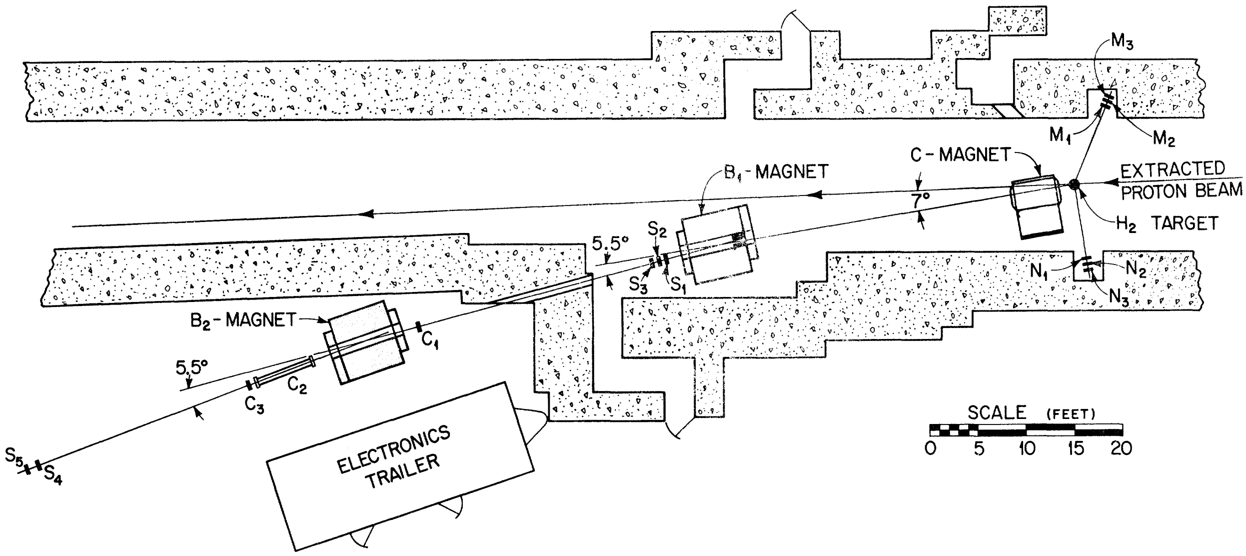

FIG. 1. Layout of experiment. The incident protons come down the ZGS extracted beam and strike the hydrogen target. The scattered protons are detected by the spectrometer.

er, it differed in an important way from the spectrometer used in our first experiment.[1] In the first experiment the counters $S_1S_2S_3$ were upstream of the magnet B_1 and thus the pions were not completely restored to the central axis in passing through $S_1S_2S_3$. The S_3 counter was supposedly defining and S_1 was overmatched, but for large lab angles some pions missed S_1. Thus S_1 reduced the phase-space bite. The resulting error in the calculation of $\Delta\Omega\Delta p$ gave the dip in the cross section as $P_l \to 0$ (large lab angles). An erratum with corrected $\Delta\Omega\Delta p$ is now being prepared.

The differential production cross section was calculated from the formula

$$\frac{d^2\sigma}{d\Omega dp}=\frac{\text{events}}{I_0(N_0\rho t)\Delta\Omega\Delta p}. \tag{3}$$

The quantity I_0 is the number of incident protons as measured by our monitors. N_0 is Avogadro's number; ρ is the density of liquid hydrogen, taken as 0.07; t is the target length, taken as 7.62 cm.

There were several corrections and uncertainties. The statistical error varied from 1 to 5%. The accidental correction was negligible. The target-empty subtraction was experimentally determined as about 25%. A correction was made for nuclear interaction of π mesons in the spectrometer of 1.19 ± 0.03. The decay of the π mesons before reaching the end of the spectrometer normally required a correction of 5 to 9% with an uncertainty of ± 2%. The correction for multiple Coulomb scattering was normally less than (5 ± 2)%. However for a few of the points, with low lab momentum, these two corrections each reached 15 to 45%, with uncertainties of 5 to 10%. Thus, the total point-to-point error, obtained by adding statistical and systematic errors in quadrature, was generally less than 10%. There was an additional 5% normalization uncertainty due to the calibration of the incident-proton flux. The data are shown in Figs. 2 and 3. These values are preliminary but should not change by more than 8%. We have also plotted data from earlier experiments.[1,2] The normalizations appear to agree within 10%.

In Fig. 2 we have plotted the measurements where $P_\perp$ was held fixed while P_l was varied. We have also plotted our earlier data,[1] which showed a dip at $P_l = 0$, and were considered evidence for a two-center model. The disagreement between the two experiments is clear. For the reason stated above we believe that the old data are wrong. Thus it appears that the pion-production cross section has an absolute maximum $P_l = 0$ and the experiment favors a one-center behavior.

It is interesting that the P_l distribution is much flatter than the $P_\perp$ distribution (see Fig. 3). In fact a contour of constant cross section is a long cigar-shaped curve. At higher energies it will be interesting to see if this distribution continues to become longer (as suggested by a Lorentz-contracted spherical interaction region) or else eventually splits into two separate distributions (as suggested by the two-center model).

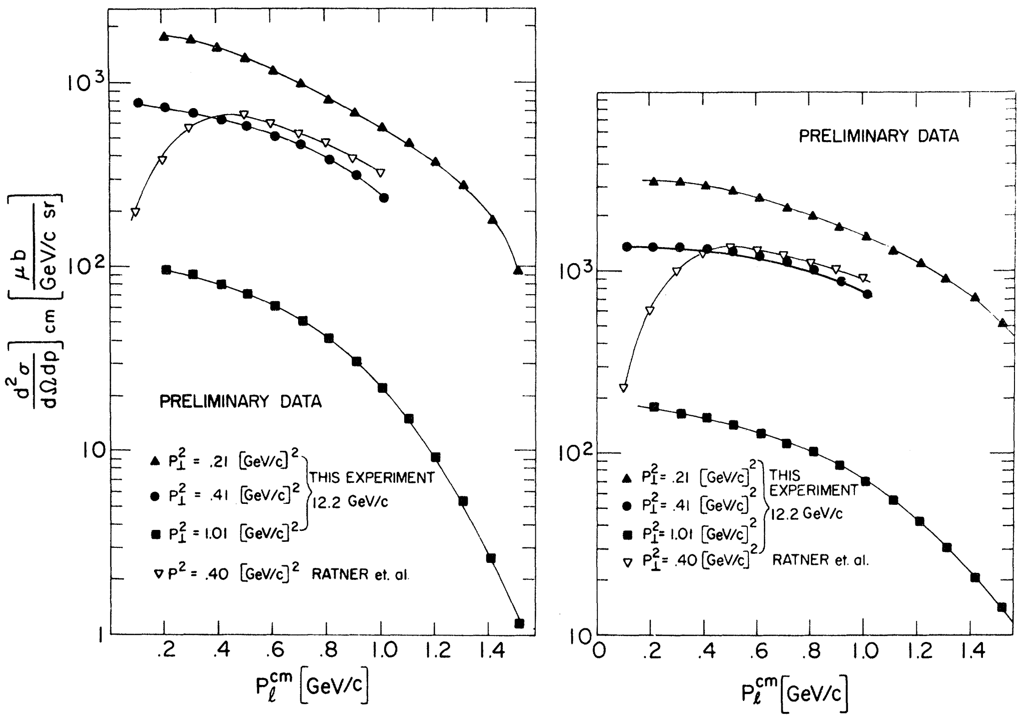

FIG. 2. Plots of $d^2\sigma/d\Omega dp$ against P_l for $P_\perp$ held fixed. The lines are freehand fits to the data.

Figure 2 also suggests that $d^2\sigma/d\Omega dp$ is factorable into functions of P_l and $P_\perp$ in the c.m. system;

$$d^2\sigma/d\Omega dp = F(P_l)G(P_\perp). \qquad (4)$$

This can be seen by noting that the shapes of the three curves at different values of $P_\perp$ are quite similar, except near the kinematic cutoff. Alternately we could consider these data as a study of the $P_\perp$ dependence at some ten values of P_l and clearly these $P_\perp$ dependences are quite similar. The theoretical significance of this factorability is not yet clear, but it is interesting experimental observation.

In Fig. 3 we plotted the measurements of the $P_\perp$ dependence, with P_l fixed, along with some earlier measurements.[1,2] One purpose of these measurements was to check data[1] taken with the spectrometer which gave the unfortunate error in the P_l dependence. However no errors were expected (because the lab angle was not too large) and indeed no significant disagreement was found as shown in Fig. 3.

It was now also possible to extend the measurements down to $P_\perp = 0$. As shown in Fig. 3 we found a very sharp forward peak in both π^+ and π^- production of the form

$$d^2\sigma/d\Omega dp \sim e^{-15P_\perp^2}. \qquad (5)$$

Several tests[4] were run to insure that this effect was not a systematic error and all tests were negative. Note also that the lab momentum was essentially constant in this region. Thus it appears that this forward peak is a real effect. However it is difficult to understand such a sharp and large [20 mb $(\text{GeV}/c)^{-1}$ sr^{-1} for π^+ at $P_\perp = 0$]

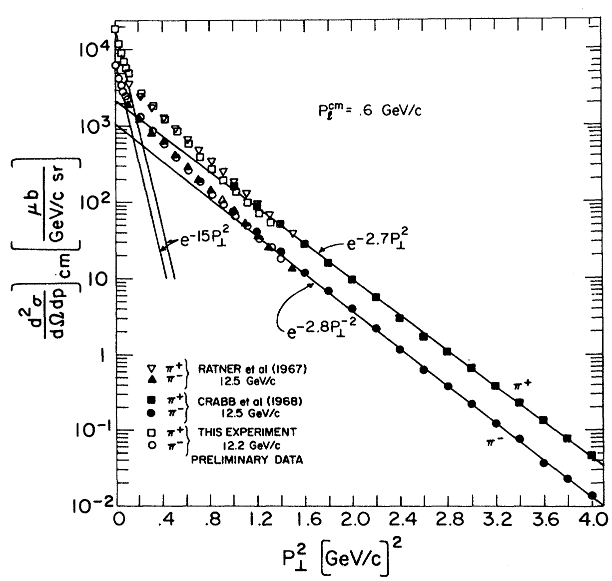

FIG. 3. Plot of $d^2\sigma/d\Omega dp$ against $P_\perp^2$ for P_l held fixed. The lines are straight-line fits to the data.

peak in the total pion-production cross section. We therefore feel that it is quite important for another experiment to verify this effect.

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[4]The target-empty effect was still about 25%. The production cross section decreased when we looked at negative angles. The Cherenkov pressure curves were completely flat over several hundred lb/in.^{2}.

PHOTOPRODUCTION OF CHARGED PION PAIRS ON PROTONS

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A high-statistics (100 000 events) measurement of photoproduction of charged pion pairs on protons is reported in two parts. First, the measured cross sections are presented in a three-dimensional data matrix where all the dynamical features are explicitly shown. Second, fitting the data in the energy region 2.6-6.8 GeV with various assumptions on ρ production indicates that $d\sigma/dt|_{t=0}$ for the photoproduction of ρ decreases with increasing energy similar to πN scattering.

We report an experiment on the reaction

$$\gamma p \to p\pi^+\pi^- \qquad (1)$$

at forward production angles, with incident energy between 2.6 and 6.8 GeV and in the di-pion mass (m) region from 500 to 1000 MeV/c^2.[1,2] With a total of 100 000 events, cross sections were measured at energy intervals of $\Delta E_\gamma = 0.6$ GeV and at mass intervals of $\Delta m = 30$ MeV/c^2.

The purposes of this experiment are (1) to study the detailed production mechanism of pion pairs without any theoretical assumptions by making an accurate measurement of the di-pion spectrum as a function of both mass and energy; and (2) to study the energy dependence of the forward ρ-production cross section by simultaneously fitting various assumptions for the ρ-production mechanism, mass, width, and a general background in m and p to the extensive data.

This measurement of the production cross section differs markedly from most previous measurements where one is limited by statistics or where the ρ cross sections were obtained from the measured $\pi\pi$ spectrum by assuming zero background.

The experiment.—This experiment was done at the DESY 7.5-GeV electron synchrotron using a bremsstrahlung beam with an average intensity of 3×10^{10} equivalent quanta/sec, a 60-cm H_2 target, and a pair spectrometer similar to the one described previously.[3] Two threshold Cherenkov counters in the system separated electrons from pions; protons were rejected by time of flight. During the experiment, magnetic fields were kept constant to 3 parts in 10^4 and counter voltages to ±5 V. Every 4 h a normalization run was made on ρ production with a carbon target and the system was found to be reproducible to ±1% during the entire period of running.

The 22 500 hodoscope combinations in the magnetic spectrometer defined a mass resolution of $\Delta m/m = \pm1.7\%$, and a momentum resolution of $\Delta p/p = \pm3.0\%$. The beam intensity was controlled such that the dead-time corrections were ≤2%