PARTICLE PRODUCTION AT HIGH TRANSVERSE MOMENTUM*

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We have measured $d^2\sigma/d\Omega dp$, the differential cross section for the production of $\pi^\pm$ mesons, at high $P_\perp$, in 12.5-GeV/c proton-proton collisions. We covered the range $P_\perp^2 = 1.0$-4.0 (GeV/c)^2 and the cross section appears to break at about 1.5 (GeV/c)^2. Thus, $d^2\sigma/d\Omega dp$ appears to be the sum of two Gaussians in $P_\perp$.

We have recently measured the differential production cross section $d^2\sigma/d\Omega dp$ for the production of $\pi^\pm$ mesons at high transverse momentum in 12.5-GeV/c proton-proton collisions. This experiment extended the range of an earlier experiment[1] which showed that $d^2\sigma/d\Omega dp$ was Gaussian in $P_\perp$ at small transverse momentum. We now varied $P_\perp^2$ over the range 1.0-4.0 (GeV/c)^2 while holding the center-of-mass longitudinal momentum fixed at $P_l^{\text{c.m.}} = 0.6$ (GeV/c). 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.

The experiment was performed on the slow extracted beam of the zero-gradient synchrotron (ZGS) at Argonne National Laboratory. About 1.5×10^{11} protons of 12.50 GeV/c were extracted during the 500-msec spill every 3 sec. 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 less than $\frac{1}{2}$%. The beam spot at our target was a circle of about 1 cm.

The number of protons hitting our target was measured by two monitor 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 passing through 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. During each calibration run, the number of monitor counts was recorded. We determined the number of protons passing through the Au foil (and thus the target) by doing a standard radiochemical analysis of the foil. 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. These windows resulted in a target-empty effect of about 8% as determined by target-empty runs. There was an additional 1% effect due to "frosting" on the flask. This target employed one of the newly developed He-cooled liquid-hydrogen refrigerators, which behaved very well, and allowed the use of the thin windows.

Our detection system for the produced π mesons was a single-arm spectrometer. This was similar to that used in an earlier experiment[1] except that the first three scintillators were placed downstream of the B magnet to reduce their singles rates. As shown in Fig. 1, it contained a C magnet which served as a steering magnet to compensate for the different laboratory angles as we varied $P_\perp^2$, and a B magnet which bent the pions through 8° for momentum analysis. These two magnets were set so that the π mesons always emerged from the B magnet exactly along the central axis of the spectrometer.

The phase space subtended by our spectrometer was the intersection of the two phase-space strips subtended by the S_1 and S_5 counters. The other counters in the spectrometer were all overmatched. The center-of-mass phase-space bite was typically $\Delta\Omega\Delta p = 1\times10^{-5}$ sr GeV/c.

The Cherenkov telescope $C = C_1C_2C_3$ served to tag the particles as π mesons. C_1 and C_2 were

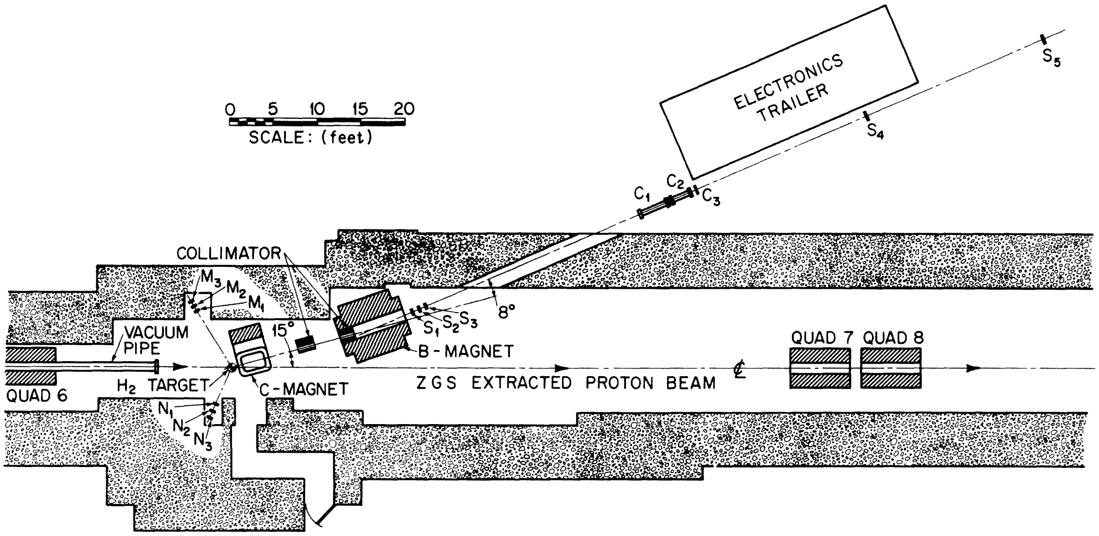

FIG. 1. Layout of experiment. The incident protons come down the ZGS extracted beam and strike the hydrogen target. The scattered protons are detected by the spectrometer.

threshold Cherenkov counters filled with ethane, and C_3 was a scintillation counter used only to reduce accidentals. C_2 was run in coincidence and C_1 was not used for this run. The appropriate ethane pressures for C_2 were experimentally determined by running pressure curves. The detection efficiency was greater than 99% at all momenta.

The electronic logic began with the signals from S_1, S_2, and S_3 forming the S_{123} coincidence while the signals from S_4 and S_5 formed the S_{45} coincidence. Similarly, the signals from C_2 and C_3 formed the C coincidence. The number of particles passing through the spectrometer was then determined by the threefold coincidence SC. The accidental rate in SC was determined by a time-to-amplitude converter (TAC) which was triggered by the SC signal. This TAC was connected to a pulse-height analyzer so that the time-of-flight spectrum between S_3 and S_5 could be measured and displayed. In this spectrum the true events appeared as a large peak 1.3 nsec wide on top of a flat region 30 nsec wide caused by accidentals. The accidental rate was accurately determined from the flat region and subtracted from the peak. The subtraction was always less than 1%.

The differential production cross section was calculated from the formula

$$\frac{d^2\sigma}{d\Omega dp} = \frac{\text{events}}{I_0(N_0\rho t)\Delta\Omega\Delta p}. \qquad (1)$$

The quantity I_0 is the number of incident protons as measured by our monitors. The uncertainty in I_0 was about 5%. 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; $\Delta\Omega\Delta p$ is the c.m. phase-space volume.

There were several corrections and uncertainties involved in determining the number of events. The statistical error varied from 1 to 10%. The accidental correction was negligible. The total target-empty subtraction was $9 \pm 2\%$. A correction was made for nuclear interaction of π mesons in the spectrometer of 1.13 ± 0.02. The decay of the π mesons before reaching the end of the spectrometer required a correction of 5 to 9% with an uncertainty of $\pm 2\%$. No correction was made for multiple Coulomb scattering because in-scattering is equal to out-scattering in a single-arm spectrometer with small $\Delta\Omega\Delta p$. 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 Fig. 2. These values are preliminary but should not change by more than 5%. We have also plotted data from an earlier experiment.[1] The normalizations appear to agree within 10%.

In Fig. 2 we have plotted the c.m. production cross section $d^2\sigma/d\Omega dp$ against the square of the transverse momentum of the produced π meson $P_\perp^2$. The quantity $P_l^{\text{c.m.}}$ was held fixed at 0.6 GeV/c while the incident proton momentum was

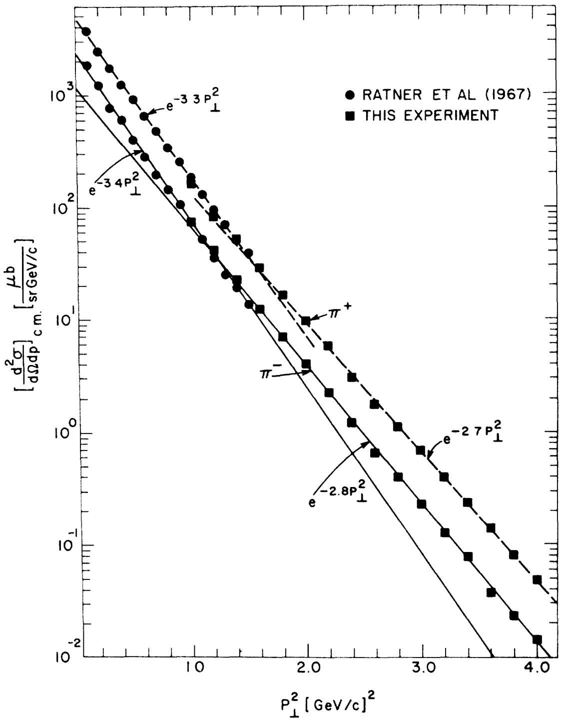

FIG. 2. Plot of $d^2\sigma/d\Omega dp$ against $P_\perp^2$ for P_l held fixed. The lines are straight-line fits to the data.

12.5 GeV/c. The process we observed was

$$p+p\to\pi^\pm+\text{anything}. \qquad (2)$$

Thus, $d^2\sigma/d\Omega dp$ was the probability of producing a single π meson in the region $\Delta\Omega\Delta p$, independent of what other particles were produced.

Clearly the most striking result is the break in both the π^+ and π^- cross sections. These breaks are reminiscent of the breaks in the p-p elastic cross section.[2,3] It will be interesting to see what relationships can be found between the elastic and inelastic breaks. We must note, however, that the two sets of slopes are quite different. The two observed inelastic slopes are about

$$3.3 \text{ and } 2.7\ (\text{GeV}/c)^{-2}, \qquad (3)$$

while the three elastic slopes are about[4]

$$9,\ 3, \text{ and } 1.2\ (\text{GeV}/c)^{-2}. \qquad (4)$$

These differences rule out the most trivial relations between the elastic and inelastic processes.

Another possibility is that the inelastic break is unrelated to the elastic break. The inelastic break might be evidence for the existence of at least two "inelastic" regions in the proton-proton interaction. By this we mean that the proton-proton interaction would have several regions from which mesons are emitted. The breaks in elastic scattering are evidence that there are three regions in the p-p interaction as seen by one of the incoming protons. If this picture is correct, then the three regions seen by incoming protons have radii

$$0.92 \text{ F},\ 0.52 \text{ F}, \text{ and } 0.34 \text{ F}, \qquad (5)$$

while the produced mesons are emitted from regions of radii

$$0.50 \text{ F and } 0.45 \text{ F}. \qquad (6)$$

It is strange[5] that the two inelastic radii are almost equal.

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[1]L. G. Ratner, K. W. Edwards, C. W. Akerlof, D. G. Crabb, J. L. Day, A. D. Krisch, and M. T. Lin, Phys. Rev. 166, 1353 (1968).

[2]C. W. Akerlof, R. H. Hieber, A. D. Krisch, K. W. Edwards, L. G. Ratner, and K. Ruddick, Phys. Rev. Letters 17, 1105 (1966), and Phys. Rev. 159, 1138 (1967).

[3]J. V. Allaby, G. Cocconi, A. N. Diddens, A. Klovning, G. Matthiae, E. J. Sacharidis, A. M. Wetherell, Phys. Letters 25B, 156 (1967); J. V. Allaby et al., Phys. Letters 27B, 49 (1968).

[4]A. D. Krisch, Phys. Rev. Letters 19, 1149 (1967). Note that we have used the fact that $\beta^2=0.86$ at 12.5 GeV/c.

[5]It is appropriate to comment on the fact that the break is at the overlap of the two experiments. At first sight this causes suspicion that the experiments may have some systematic error responsible for the change in slope. However, the experiments measure cross sections, not slopes. To have the slopes identical would require that our measurements be wrong by more than a factor of 2 at the endpoints. With 10 % quoted errors this is unlikely.