haven National Laboratory for their help in the execution of this experiment. We thank the technical support staff of the Multiparticle Spectrometer and of the On-Line Data Facility for their valuable aid. We also wish to acknowledge the assistance of S. Eiseman during the data taking. This research was supported in part by the U. S. Department of Energy under Contract No. EY-76-C-02-0016, in part by the National Science Foundation, and in part by the City University of New York PSC-BHE Research Award Program.

[1]S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, CERN Report No. TH-401 and TH-412, 1964 (unpublished); J. Iizuka, Prog. Theor. Phys. Suppl. 37–38, 21 (1966); J. Iizuka, K. Okada, and O. Shito, Prog. Theor. Phys. 35, 1061 (1966).

[2]S. Okubo, Phys. Rev. D 16, 2336 (1977), and University of Rochester Report No. UR641, 1977 (unpublished).

[3]H. Lipkin, in Proceedings of the Fifth International Conference on Experimental Electron Spectroscopy, Boston, Massachusetts, April 1977 (to be published) (Fermilab Conf. 77165-THY); S. Glashow, private communication.

[4]E. D. Platner *et al.*, Nucl. Instrum. Methods 140, 549 (1977).

[5]Strictly speaking, some of the background events could be $\bar{p}p$ since the threshold Čerenkov counter just vetoes pions and lighter particles. However, the peak at the known $\varphi$ mass shows that the $\varphi\varphi$ events are a clean sample; the corresponding $p\bar{p}$ effective mass would be 1907 GeV, a region free of known resonances.

# Measurement of the Energy Dependence of Elastic $\pi p$ and $pp$ Scattering at Large Angles

K. A. Jenkins and L. E. Price
*Columbia University, New York, New York 10027*

and

R. Klem, R. J. Miller, and P. Schreiner
*Argonne National Laboratory, Argonne, Illinois 60439*

and

H. Courant, Y. I. Makdisi, M. L. Marshak, E. A. Peterson, and K. Ruddick
*University of Minnesota, Minneapolis, Minnesota 55455*
(Received 1 December 1977)

We have measured $\pi^{\pm}p$ and $pp$ elastic differential cross sections in the range $|\cos\theta_{\text{c.m.}}| < 0.35$ for incident momenta from 2 to 9.7 GeV/$c$ for $\pi^-p$ and $pp$ and from 2 to 6.3 GeV/$c$ for $\pi^+p$. We find that the fixed-c.m.-angle $\pi p$ differential cross sections cannot be described as simple functions of $s$. The data are compared to the energy and angular dependence predicted by the constituent model of Gunion, Brodsky, and Blankenbecler.

It is generally believed that hadrons are composite particles. In this context, one attractive model for large-angle hadron-hadron scattering involves scattering of the constituents (e.g., quarks) of the projectile and target particles. An early encouragement for this approach was the apparent success of the dimensional counting rule,[1] which predicts the asymptotic energy dependence of differential cross sections at large fixed angles. The rule predicts that at constant c.m. angle, $d\sigma/dt \propto s^{-n}$, where $n = m - 2$ and $m$ is the sum of the number of quarks in the initial and final states of the interaction, $s$ is the square of the c.m. energy, and $t$ is the square of the four-momentum transfer. It has been claimed that previous data agree with the predicted exponents (7 for photoproduction of pions, 8 for $\pi p$ and $Kp$ elastic scattering, and 10 for $pp$ elastic scattering) for laboratory momenta above 5 GeV/$c$. However, in the $\pi p$ case the comparison is based on very few data points with generally large statistical uncertainties. While the $pp$ data have much better statistics, the case for $s^{-10}$ is debated in the literature.[2]

We are reporting here some results from a new experiment which supplement and check the existing $pp$ data and provide enough additional $\pi^-p$ data for a stringent test of the dimensional counting rule.

This high-statistics experiment measured the differential cross section, $d\sigma/dt$, for $-0.35 < \cos\theta_{\text{c.m.}} < 0.35$ from 1.9 to 9.7 GeV/$c$ for $\pi^-p$, from 1.9 to 6.3 GeV/$c$ for $\pi^+p$, and from 1.9 to 9.0 GeV/$c$ for $pp$ interactions. The momentum region was covered in 2% steps. The experiment was performed at the Argonne National Laboratory zero-gradient synchrotron. The experimental apparatus, shown in Fig. 1, was designed to allow large data-taking rates, to have a simple and smooth geometric acceptance, and to give high angular and momentum resolution.

The high-intensity, two-stage, secondary beam had a momentum spread of ±5%. A nineteen-bin hodoscope at the first focus permitted tagging of the incident particle momenta with a resolution of ±0.25%. The absolute momentum of the beam was determined to ±0.5%. Two ethylene-filled threshold Cherenkov counters were used to identify incident $\pi$'s, $K$'s, and $p$'s. The direction and position of each beam particle were measured by two $x$-$y$ hodoscopes with resolutions of ±3 mrad and ±3 mm.

The beam of a few million particles per 0.6-sec spill was focused on a 30-cm-long liquid-hydrogen target. The scattered projectile particle and the recoiling proton were detected by the double-arm multiwire-proportional-chamber spectrometer. Each arm consisted of three pairs of vertical and horizontal chambers, which could be rotated to concentrate on c.m. angles of 90°. The resolution of each arm was ±3 mrad in the laboratory scattering angle. At the end of each arm was a threshold Cherenkov counter used to identify the scattered particles when kinematics could not distinguish between the pion and proton. There was no magnet in the detector.

The experiment trigger consisted of a coincidence of the beam-defining counters ($B_1$, $B_2$, $B_3$, and $\overline{BH}$) and the four counters of the multiwire-proportional-chamber arms ($L_1$, $L_2$, $R_1$, and $R_2$). In addition, to suppress background due to inelastic scatters, the trigger required anticoincidence with eight veto counters surrounding other areas. These were multilayer lead-scintillator sandwiches, which detected both charged particles and photons from $\pi^0$ decay. An additional single-layer anticoincidence counter rejected noninteracting beam particles. The trigger and veto counters covered approximately $3.5\pi$ sr in the c.m. solid angle.

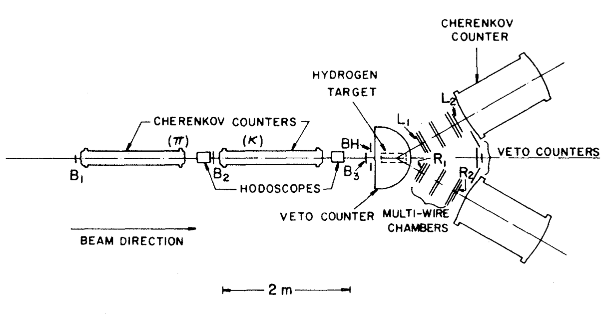


FIG. 1. Plan view of the experimental apparatus.

The acceptance for elastic scattering was calculated by a Monte Carlo simulation, and is a smooth function of $\cos\theta_{\mathrm{c.m.}}$ with a peak value typically 22%.

The data were recorded on magnetic tape and partially analyzed on line. The total pion and proton flux was $1.4\times10^{12}$ particles, resulting in $2.8\times10^7$ triggers, from which $1.3\times10^6$ elastic scatters were recognized. Elastic events were selected by using the coplanarity of the incoming, scattering, and recoiling tracks, and the angles of the scatter and recoil. The remaining inelastic background was subtracted by fitting the coplanarity distribution for each momentum and scattering-angle bin by the sum of a Gaussian and a background polynomial. Backgrounds ranged from 1% at the lowest momentum to 25% at the highest. The data were also corrected for random accidental vetoing, nuclear absorption after scattering, ambiguous momentum determination, and chamber-hodoscope inefficiencies. A typical total correction factor was 1.5. We estimate that the normalization is uncertain to ±10%. This error is not included in the data plotted below.

To compare to the dimensional counting rule, the data are binned in intervals of 2% in the laboratory momentum and 0.1 in $\cos\theta_{\mathrm{c.m.}}$. The $\pi^\pm p$ and $pp$ elastic differential cross sections at several angles are shown in Fig. 2, along with power-law predictions of the dimensional counting rule and all previous $\pi p$ data[3-8] above 3 GeV/$c$ at these angles.

The $pp$ data are inconsistent with one value of $n$ over the entire energy range. Several previous experiments have reported breaks in the slope of the 90° cross sections plotted against a variety of parameters.[9,10] The disagreement with $s^{-10}$ in our data is a reflection of these breaks. Plotted against $-t$, the logarithm of the 90° cross section shows changes of slope at $t\cong-3$ GeV$^2/c^2$ and $t\cong-6.5$ GeV$^2/c^2$, as reported earlier. Looking at other angles, we find that the breaks occur at approximately constant $t$. However, the energies at which these breaks occur may not be high enough for the dimensional counting rule to apply. We have therefore fitted the 90° data by $d\sigma/dt=as^{-n}$ for $s>12$ GeV$^2$. The result is $n=10.07\pm0.11$ with a $\chi^2$ of 30 for 24 degrees of freedom. We note, however, that several other forms fit the

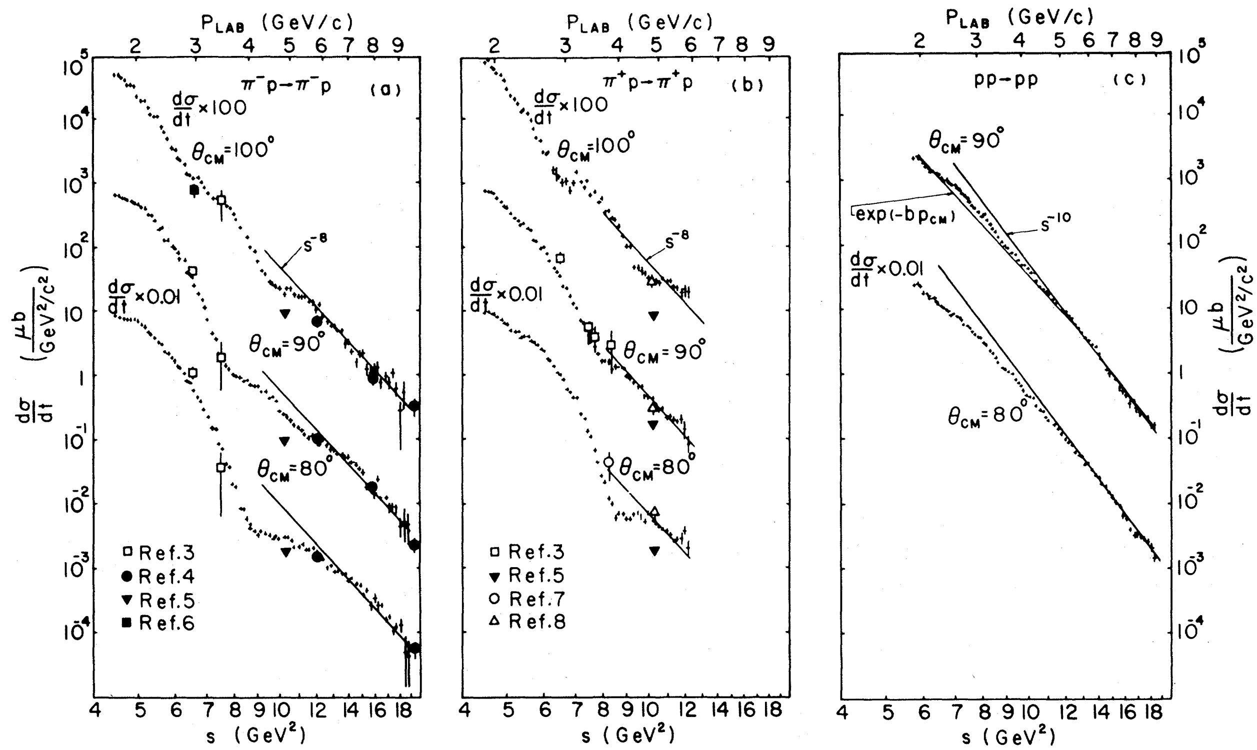


FIG. 2. Differential cross sections for elastic $\pi^+p$, $\pi^-p$, and $pp$ scattering measured in this experiment for some representative angles. The lines are the predicted $s$ dependence of Ref. 1. Previous data (Refs. 3–8) for $\pi^+p$ and $\pi^-p$, above 3 GeV/$c$ at these angles, are also plotted.

data equally well at these energies.[11]

The $\pi^{\pm}p$ data are more complicated. Both $\pi^-p$ and $\pi^+p$ have a dip (at $s \cong 7$, 8, and 9 GeV$^2$ for 100°, 90°, and 80°, respectively) which is due to a constant dip at $t = -2.8$ GeV$^2/c^2$. It is clear from the figure that there are significant departures from any power law $s^{-n}$, even beyond this constant dip. Some fits to the $\pi^-p$ data are shown in Table I. Our data agree well with the data of Ref. 4 which is the previous evidence for $s^{-8}$ behavior, yet in the same energy range ($12 \leqslant s \leqslant 19$ GeV$^2$) our more detailed data yield smaller exponents. If the lower limit of the fit is made sufficiently high ($s > 16$ GeV$^2$), the data are consistent with $s^{-8}$ at all angles. However, the remaining range of $s$ is then quite small and the errors on the fitted exponents are large. Data at higher $s$ will be needed to determine if the predicted power law is really established above $s = 16$ GeV$^2$. The $\pi^+p$ data disagree with the dimensional counting rule, but they do not extend to very high energy.

The constituent-interchange model of Gunion, Brodsky, and Blankenbecler[12] predicts an energy dependence agreeing with the dimensional rule, but in addition, predicts an energy-independent

TABLE I. Value of the exponent $n$ in fits to $\pi^-p$ data of the form $d\sigma/dt = as^{-n}$. (d.f. stands for degrees of freedom.)

| $\theta_{c.m.}$ | $12 \leqslant s \leqslant 19$ GeV$^2$ | | $14 \leqslant s \leqslant 19$ GeV$^2$ | | $16 \leqslant s \leqslant 19$ GeV$^2$ | |
|---|---|---|---|---|---|---|
| (deg) | $n$ | $\chi^2$/d.f. | $n$ | $\chi^2$/d.f. | $n$ | $\chi^2$/d.f. |
| 80 | $6.1 \pm 0.2$ | 49/23 | $7.3 \pm 0.4$ | 25/15 | $10.3 \pm 1.6$ | 10/7 |
| 90 | $6.7 \pm 0.2$ | 45/23 | $8.2 \pm 0.4$ | 19/15 | $9.9 \pm 1.8$ | 8/7 |
| 100 | $7.6 \pm 0.3$ | 34/22 | $6.2 \pm 0.6$ | 16/14 | $4.0 \pm 2.7$ | 7/6 |

angular shape at high energies. Even though the $s^{-8}$ rule does not work in detail, we compare our data to the angular prediction. In Fig. 3, we have plotted the ratio of the cross section to the 90° cross section for three of the higher momenta for $\pi^- p$ scattering. The ratios qualitatively show the predicted energy-independent shape. The ratios do not agree with the prediction for momenta lower than 6 GeV/$c$.

To conclude, we have reported high-statistics, high-resolution data on $\pi^\pm p$ and $pp$ elastic scattering. The $pp$ data agree with the dimensional counting rule for $12 \leq s \leq 19$ GeV$^2$, but the $\pi^- p$ data do not. The $\pi^- p$ data tend to agree with the rule, and with the constituent-interchange model, at the highest energies of the experiment, but data at still higher energy will be needed to confirm or refute the agreement. The models do not agree with the $\pi^+ p$ data in the more limited energy range.

We would like to thank the staff of the Argonne National Laboratory zero-gradient synchrotron for their assistance in performing this experiment. We also thank W. Petersen for work done in the early part of the experiment. This work was supported by the U. S. Energy Research and Development Administration and the National Science Foundation.

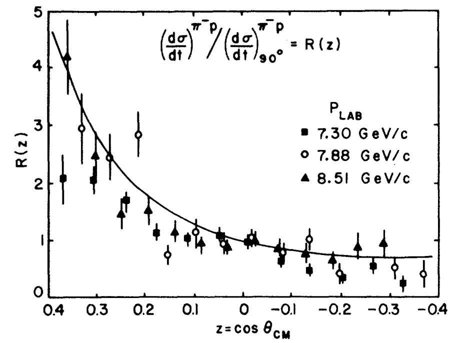


FIG. 3. Ratio of the differential cross section to the 90° differential cross section for $\pi^- p$ at several momenta, along with the predicted ratio of Ref. 12.

[1]S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973); V. A. Matveev, R. M. Muradyan, and A. N. Tavkhelidze, Lett. Nuovo Cimento 7, 719 (1973).

[2]V. Barger, F. Halzen, and J. Luthe, Phys. Lett. 42B, 428 (1972); B. Schrempp and F. Schrempp, Phys. Lett. 55B, 303 (1975); A. W. Hendry, Phys. Rev. D 10, 2300 (1974).

[3]C. T. Coffin *et al.*, Phys. Rev. 159, 1169 (1967).

[4]D. P. Owen *et al.*, Phys. Rev. 181, 1794 (1969).

[5]A. Eide *et al.*, Nucl. Phys. B60, 173 (1973).

[6]M. Fellinger *et al.*, Phys. Rev. Lett. 23, 600 (1969).

[7]P. L. Bastien *et al.*, Phys. Rev. D 3, 2047 (1971).

[8]D. R. Rust *et al.*, Phys. Rev. Lett. 24, 1361 (1970).

[9]C. W. Akerlof *et al.*, Phys. Rev. 159, 1138 (1967).

[10]R. C. Kammerud *et al.*, Phys. Rev. D 4, 1309 (1971).

[11]We get good fits with $d\sigma/dt = a\exp(-bp_{\mathrm{c.m.}})$; $d\sigma/dt = a\exp(-b\sqrt{s})$; and $d\sigma/d\Omega = (a/s)\exp(-bp_t)$. These forms were motivated by the discussion in Ref. 9. The forms $\exp(-b\sqrt{s})$ and $\exp(-bp_{\mathrm{c.m.}})$ appear to extrapolate well to lower energies.

[12]J. F. Gunion, S. J. Brodsky, and R. Blankenbecler, Phys. Rev. D 8, 287 (1973).