# PION-PROTON ELASTIC SCATTERING AT HIGH MOMENTUM TRANSFERS\*

J. Orear, R. Rubinstein, D. B. Scarl, and D. H. White

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

and

### A. D. Krisch

The University of Michigan, Ann Arbor, Michigan, and Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

#### and

## W. R. Frisken, A. L. Read, † and H. Ruderman

Brookhaven National Laboratory, Upton, New York (Received 24 June 1965)

In this Letter we report measurements of 8 and 12 GeV/c  $\pi^+$  and  $\pi^-$  elastic scattering on hydrogen which extend the previously measured<sup>1,2</sup> angular distributions well beyond the forward diffraction peak. At an incident pion momentum of 8 GeV/c, we have measured elastic differential cross sections for values of the invariant four-momentum transfer squared, -t, from 1.2 to 6.0  $(\text{GeV}/c)^2$ , corresponding to center-of-mass scattering angles from 33.8° to 81.2°. At 12-GeV/c incident pion momentum our measurements covered a range of -t from 1.2 to 3.5  $(\text{GeV}/c)^2$ , corresponding to centerof-mass angles from 27.1° to 47.4°. For most of these momentum transfers, cross sections were measured for incident negative pions, positive pions, and protons.

The experimental arrangement is shown in Fig. 1. The beam transport system<sup>3</sup> selected particles produced at  $4\frac{1}{2}^{\circ}$  to the circulating proton beam of the Brookhaven AGS and focused them on an  $8\frac{1}{2}$ -in.-long liquid-hydrogen target 2700 in. from the internal G-10 target. The momentum resolution of the beam was  $\pm 1\%$ , producing approximately 10<sup>6</sup> pions at 8 GeV/c or  $3 \times 10^5$  pions at 12 GeV/c for an AGS pulse of  $5 \times 10^{11}$  protons on the internal beryllium target. The beam was 1 in. wide and  $1\frac{1}{2}$  in. high at the hydrogen target and was designed to have an angular divergence of  $\pm 2.5$  mrad. A threshold gas Cherenkov counter discriminated against protons and kaons in the beam.

The scattered pions were momentum analyzed by a standard bending magnet whose gap was 30 in. wide, 6 in. high, and 72 in. long, and were detected in a triple scintillation counter telescope. In general, three of these telescopes corresponding to three different scattering an-



FIG. 1. The magnet and counter arrangement.  $B_1$ and  $B_2$  are the incident beam counters,  $\check{C}_1$  is a threshold Cherenkov counter, and T is the hydrogen target.  $P_1$ ,  $P_2$ , and  $P_3$  are the scintillation counters in the three proton telescopes, and  $\pi_1$ ,  $\pi_2$ , and  $\pi_3$  are the counters in the three pion telescopes.  $\check{C}_2$  is a Cherenkov counter in the pion telescopes used to eliminate accidentals due to proton-proton scattering.

gles were used at one time. The solid angles in the center of mass subtended by the individual telescopes ranged from 1.0 to 3.5 msr and their momentum resolution ranged from  $\pm 8$  to  $\pm 17\%$ . A typical counter size was 6 in. by 6 in.

The recoil protons were momentum analyzed by a specially built large-aperture magnet whose gap was 120 in. wide, 24 in. high, and 36 in. long. The detection system for the protons was similar to that for the pions except that variations in the incident pion momentum, the angular divergence of the beam, and the size of the interaction region were allowed for by making the proton counters a calculated amount larger than kinematically necessary. This permitted the pion telescopes to determine the solid angle for elastic scattering. The momentum resolution of the recoil-proton magnet-telescope system ranged from  $\pm 21$  to  $\pm 45\%$ . A typical proton counter was 19 in. wide by 31 in. high.

The 8-GeV/c  $\pi^-$  cross sections at -t of 4, 5, and 6 (GeV/c)<sup>2</sup> were measured using a slightly different geometry in which both the scattered pion and recoil proton were momentum analyzed by the large-aperture magnet. This permitted the use of counter telescopes subtending larger solid angles (7.2 to 11.8 msr) in the center of mass and increased the counting rate for these very low cross-section points. The momentum resolution of the pion telescopes for these points was about  $\pm 13\%$ , and the momentum resolution of the proton telescopes was about  $\pm 16\%$ . As a check, measurements of cross sections at -t = 2 and 3 (GeV/c)<sup>2</sup> were made with both the large and small solid-angle geometries and agreed closely.

The positive beams contained approximate-

Incident particle	$P_0$ (GeV/c)	$\cos\theta_{\rm c.m.}$	-t (GeV/c) <sup>2</sup>	$(d\sigma/d\Omega)_{c.m.}$ $(\mu b/sr)$	$d\sigma/dt$ $[\mu{ m b}/({ m GeV}/c)^2]$
π-	8	0.8305	1.20	$34.3 \pm 3.4$	$30.4 \pm 3.1$
		0.7881	1.50	$17.0 \pm 2.0$	$15.1 \pm 1.8$
		0.7542	1.74	$7.38 \pm 0.66$	$6.55 \pm 0.58$
		0.7175	2.00	$3.05 \pm 0.73$	$2.71 \pm 0.65$
		0.6822	2.25	$0.64 \pm 0.09$	$0.57 \pm 0.08$
	•,	0.6469	2.50	$0.23 \pm 0.07$	$0.20 \pm 0.06$
		0.6158	2.72	$0.053 \pm 0.021$	$0.047 \pm 0.019$
		0.5763	3.00	$0.073 \pm 0.022$	$0.064 \pm 0.019$
		0.5057	3.50	$0.118 \pm 0.035$	$0.104 \pm 0.031$
		0.4350	4.00	$0.063 \pm 0.042$	$0.056 \pm 0.038$
		0.2938	5.00	$0.094 \pm 0.046$	$0.083 \pm 0.041$
		0.1526	6.00	0 + 0.037	0 + 0.032
$\pi^+$	8	0.8305	1.20	$37.8 \pm 3.4$	$33.5 \pm 3.0$
		0.7881	1.50	$16.7 \pm 1.7$	$14.8 \pm 1.5$
		0.7542	1.74	$8.10 \pm 0.89$	$7.18 \pm 0.79$
		0.7175	2.00	$3.75 \pm 0.64$	$3.33 \pm 0.57$
		0.6822	2.25	$1.00 \pm 0.21$	$0.89 \pm 0.19$
		0.6469	2,50	$0.234 \pm 0.070$	$0.207 \pm 0.062$
		0.6158	2.72	$0.155 \pm 0.089$	$0.137 \pm 0.079$
		0.5763	3.00	$0.049 \pm 0.023$	$0.043 \pm 0.020$
		0.5057	3.50	$0.148 \pm 0.111$	$0.131 \pm 0.098$
Þ	8	0.7394	1.74	$14.9 \pm 1.5$	$14.0 \pm 1.4$
		0.6630	2.25	$5.34 \pm 0.85$	$5.02 \pm 0.80$
		0.6256	2.50	$5.30 \pm 0.63$	$4.99 \pm 0.59$
		0.5926	2.72	$3.69 \pm 0.62$	$3.47 \pm 0.58$
		0.5507	3.00	$2.41 \pm 0.33$	$2.27 \pm 0.31$
		0.4758	3.50	$1.64 \pm 0.27$	$1.54 \pm 0.26$
$\pi^{-}$	12	0.8891	1.20	$21.1 \pm 1.7$	$12.2 \pm 1.0$
		0.8614	1.50	$12.1 \pm 1.0$	$7.02 \pm 0.56$
		0.8152	2.00	$1.35 \pm 0.26$	$0.78 \pm 0.15$
		0.7783	2.40	$0.22 \pm 0.06$	$0.13 \pm 0.04$
		0.6767	3.50	0 + 0.027	0 + 0.015
$\pi^+$	12	0.8891	1.20	$12.8 \pm 1.9$	$7.42 \pm 1.11$
		0.8614	1.50	$5.95 \pm 1.1$	$3.45 \pm 0.62$
		0.8152	2.00	$0.88 \pm 0.41$	$0.51 \pm 0.23$
		0.7783	2.40	$0.58 \pm 0.21$	$0.34 \pm 0.12$
Þ	12	0.8848	1.20	$26.5 \pm 2.4$	$16.0 \pm 1.5$
		0.8559	1.50	$14.3 \pm 1.4$	$8.62 \pm 0.86$
		0.8079	2.00	$8.81 \pm 1.2$	$5.31 \pm 0.69$
		0.7695	2.40	$3.64 \pm 0.91$	$2.19 \pm 0.54$
		0.7599	2.50	$3.30 \pm 1.1$	$1.99 \pm 0.66$

Table I. The elastic differential scattering cross sections.

ly as many protons as pions at 8 GeV/c and three times as many protons as pions at 12 GeV/c. Also, at some of the large momentum transfers the proton elastic cross sections were as much as 30 times higher than the pion cross sections. Since the pion-proton and proton-proton elastic-scattering kinematics are nearly identical at these energies, the positivepion cross sections were obscured by accidental coincidences between a proton elastic-scattering event and a signal from the beam Cherenkov counter caused by an unrelated beam pion. Therefore, a gas  $(SF_6 \text{ at atmospheric pres-}$ sure) threshold Cherenkov counter was put in the scattered pion telescopes to insure that only pion-proton scattering was measured. The efficiency of this Cherenkov counter was measured during the  $\pi^-$  runs and ranged from 50 to 86% for various values of -t at 8 GeV/c. At 12 GeV/c the efficiency was between 90 and 100%.

Standard commercial modules were used for electronic logic. An elastic-scattering event consisted of coincident signals from the beam counters, the three counters of a pion telescope, and the three counters of the corresponding proton telescope. With a circuit-resolving time of 10 nsec, the counting rates in the individual telescopes were low enough to make accidental coincidences completely negligible. Elastic-scattering events were counted at rates varying from 20 per hour to one every five hours. As a check on our entire counting system, proton-proton elastic-scattering cross sections were measured at each value of incident momentum and -t by counting positive incident particles with the Cherenkov counters switched out of the logic. The proton-proton elastic cross sections measured in this way are presented in Table I, and fit well with previously measured<sup>1,4</sup> cross sections at higher and lower momentum transfer.

The measured cross sections were corrected for muons, electrons, and kaons in the incident beam (4-8%), absorption in the counter telescopes, hydrogen target, and air (10-16%), decay of the scattered pions (2%), and a measured empty-target effect arising from scattering from the Mylar walls of the target (3%). A systematic error of  $\pm 5\%$  for these correction factors was added to the statistical counting errors. Contamination due to inelasticscattering events whose kinematics were similar to those of elastic scattering was estimated in three ways: Crossed channels were counted in which a pion telescope was put into coincidence with an unrelated proton telescope, measurements were made at the same value of incident momentum and -t but using counter telescopes which subtended very different solid angles in the center of mass, and runs were made with the target filled with liquid nitrogen to provide a material with no free protons. These checks indicated that the inelastic background was generally below 5%, and a  $(5 \pm 5)\%$ correction to the data was made. Exceptions were 8-GeV/c points at -t of 4, 5, and 6 (GeV/  $(c)^2$  in which the crossed-channel background subtraction amounted to more than 50%. An additional systematic error of  $\pm 20\%$  was added to the statistical error for these three points to allow for uncertainties in the background subtraction.

The results are presented in Table I. Figures 2 and 3 are plots of the elastic differential cross section,  $d\sigma/dt$  vs -t at 8 and 12 GeV/ c. Several features of the data are apparent. The  $\pi^+$  cross section is similar to the  $\pi^-$  cross section at all measured momentum transfers. At momentum transfers above -t of 1 (GeV/c)<sup>2</sup>,



FIG. 2. Elastic pion-proton differential cross sections for 8-Gev/c incident pions. Proton data from this experiment and pion and proton data from reference 2 are plotted for comparison. The line is drawn only as a guide.



FIG. 3. Elastic pion-proton differential cross sections for 12-Gev/c incident pions. Proton data from this experiment and pion and proton data from reference 2 are plotted for comparison. Again, the line is drawn only as a guide.

the pion cross section is still falling sharply while the proton-proton cross section falls with a less steep slope and becomes as much as 30 times larger than the equivalent pionproton cross section at the same energy and momentum transfer.

The large forward peak in the pion-proton elastic differential scattering cross section is similar to that seen in proton-proton scattering and can be interpreted as diffraction scattering from a disc whose absorption falls off as a smooth function of its radius.<sup>5,6</sup> The shoulder in the 8- and 12-GeV/c cross sections which occurs in the region of  $-t = 1.5 (\text{GeV}/c)^2$ and becomes even more pronounced at lower energies<sup>7,8</sup> is suggestive of a second diffraction maximum.<sup>9</sup> The fact that this structure occurs at nearly the same momentum transfer  $[1.2-1.5 (\text{GeV}/c)^2]$  for beam momenta from 2 to 12 GeV/c gives further support to the interpretation of a diffraction mechanism as the main contributor to pion-proton scattering in this region of momentum transfer.

As one goes to momentum transfers greater than -t=2.5 (GeV/c)<sup>2</sup>, the 8-GeV/c curve in Fig. 2 abruptly levels off and appears flat within the rather large errors. A statistical model<sup>10</sup> is consistent with a flat angular distribution in the region where the statistical scattering predominates over the vanishing diffraction scattering. The energy dependence of the statistical level can be written<sup>11</sup>

$$d\sigma/d\Omega = (\sigma_c/4\pi) \exp[-3.17(W-1.40)],$$

where  $\sigma_c$  is the cross section for formation of a compound state which decays statistically, and W is the total energy in the center of mass in GeV. With a  $\sigma_c$  of 2.6 mb, this expression agrees well with data at 3.6 GeV/ $c^8$ and our data at 8 GeV/c and predicts a statistical level of  $2.3 \times 10^{-3} \mu b/(\text{GeV}/c)^2$  at 12 GeV/ c. Our 12-GeV/c data do not extend to low enough cross sections to check this prediction.

One concludes that in many respects  $\pi$ -p scattering is quite different from p-p scattering at the energies studied here. The similarity between the 8- and 12-GeV/c curves suggests the possibility that higher energy  $\pi$ -p scattering will have the same features, i.e., a steeply falling forward peak with structure at  $-t \simeq 1.5$  (GeV/c)<sup>2</sup> followed by a large-angle flat part which drops exponentially with increasing energy.

We would like to thank Dr. W. Baker for his contributions to the planning and early stages of this experiment and Dr. R. Cool for his constant encouragement and aid. We are indebted to the administration and staff of the Brookhaven AGS for continuing assistance during the course of this experiment. The technical aid of O. Thomas, H. Sauter, and G. Munoz is gratefully acknowledged. We thank E. Coleman for his help during part of the run.

<sup>1</sup>K. J. Foley, S. J. Lindenbaum, W. A. Love, S. Ozaki, J. J. Russell, and L. C. L. Yuan, Phys. Rev. Letters 11, 425 (1963).

<sup>3</sup>A. L. Read and R. Rubinstein, Brookhaven National

<sup>\*</sup>Research supported in part by the National Science Foundation and the U.S. Atomic Energy Commission. This research was performed using the alternate gradient synchrotron at the Brookhaven National Laboratory.

<sup>†</sup>Presently on leave of absence at Lawrence Radiation Laboratory, University of California, Berkeley, California.

<sup>11, 425 (1963).</sup> <sup>2</sup>D. Harting, B. Elsner, D. O. Caldwell, A. C. Helmholz, W. C. Middelkoop, B. Zacharov, P. Dalpiaz, S. Focardi, G. Giacomelli, L. Monari, J. A. Beaney, R. A. Donald, P. Mason, and L. W. Jones, Nuovo Cimento 13, 60 (1965).

Laboratory Report No. BNL 9213 (unpublished).

<sup>4</sup>G. Cocconi, V. T. Cocconi, A. D. Krisch, J. Orear, R. Rubinstein, D. B. Scarl, B. T. Ulrich, W. F. Baker, E. W. Jenkins, and A. L. Read, Phys. Rev. <u>138</u>, B165 (1965).

<sup>5</sup>R. Serber, Rev. Mod. Phys. <u>36</u>, 649 (1964).

<sup>6</sup>A. D. Krisch, Phys. Rev. 135, B1456 (1964).

<sup>7</sup>D. E. Damouth, L. W. Jones, and M. L. Perl, Phys.

Rev. Letters <u>11</u>, 287 (1963).

<sup>8</sup>M. L. Perl, Y. Y. Lee, and E. Marquit, Phys. Rev. <u>138</u>, B707 (1965).

<sup>9</sup>L. M. Simmons, Phys. Rev. Letters <u>12</u>, 229 (1964). <sup>10</sup>G. Fast and R. Hagedorn, Nuovo Cimento <u>27</u>, 208 (1963).

<sup>11</sup>G. Fast, R. Hagedorn, and L. W. Jones, Nuovo Cimento 27, 856 (1963).

### BACKWARD ELASTIC SCATTERING OF HIGH-ENERGY PIONS BY PROTONS\*

### W. R. Frisken, A. L. Read, † and H. Ruderman

Brookhaven National Laboratory, Upton, New York

and

### A. D. Krisch

The University of Michigan, Ann Arbor, Michigan, and Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

#### and

# J. Orear, R. Rubinstein, D. B. Scarl, and D. H. White

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York (Received 24 June 1965)

A backward peak in the positive pion-proton elastic cross section has been reported<sup>1</sup> for 4-GeV/c incident pions as well as a hint that this peak might persist at higher energies.<sup>2</sup> We have studied backward elastic scattering of pions at 4 and 8 GeV/c, measuring cross sections for positive and negative pions at center-of-mass angles from 170° to 180° in the center of mass. We find a sharp peak in the backward direction for positive pions at a lower, flatter peak for negative pions at both 4 and 8 GeV/c.

The experimental arrangement was similar to that used in an experiment to measure forward elastic cross sections at high momentum transfers, which is reported in the preceding Letter.<sup>3</sup> Figure 1 shows the arrangement used for backward scattering. The backward-scattered pion and the forward-going proton were each momentum analyzed and detected in scintillation-counter telescopes. The solid angle in the center of mass, subtended by each telescope, ranged from 0.5 to 1.5 msr; the momentum resolution ranged from  $\pm 6$  to  $\pm 12\%$ . From two to five scattering angles were measured at one time, using a large fraction of the 120-in. by 24-in. gap of the pion magnet and the 30-in. by 6-in. gap of the proton magnet.

A threshold gas Cherenkov counter together



FIG. 1. The experimental arrangement.  $B_1$ ,  $\check{C}$ ,  $B_2$ , and  $B_3$  are the incident beam defining counters and T is the hydrogen target.  $\pi_1$  and  $\pi_2$  are the counters of the five pion telescopes, and  $P_1$ ,  $P_2$ , and  $P_3$  are the counters of the five proton telescopes. The incident pion beam passes through the large-aperture magnet before striking the target.