BACKWARD PEAKS IN ELASTIC PION-PROTON SCATTERING FROM 6 TO 17 GeV/c*

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The energy dependence, charge dependence, and angular distributions of pion-proton elastic scattering near 180° have been measured at beam momenta from 5.9 to 17.1 GeV/c. The 180° cross sections decrease with energy as $P_{\rm lab}^{-1.1}$ for π^--p and $P_{\rm lab}^{-1.4}$ for π^+-p. At all energies the π^+-p backward peak is quite sharp and has a width about $\frac{1}{2}$ that of the forward diffraction peak. The π^--p backward peaks are about twice as wide as the forward diffraction peak and appear to go through a maximum before reaching 180°.

The existence of a backward peak in the pion-proton differential cross section is now well established, and several explanations have been proposed.[1] The purpose of the present experiment was to obtain more accurate angular distributions and to extend the energy range covered. We report here a detailed study of π-p elastic scattering at center-of-mass angles 165°-180° made at the Brookhaven alternating-gradient synchrotron (AGS). Angular distributions were obtained at 5.9, 9.9, 13.7, and 16.3 GeV/c for negative pions, and 5.9, 9.9, 13.7, and 17.1 GeV/c for positive pions.

The experimental arrangement is shown in Fig. 1. About 5×10^5 particles per AGS pulse, defined by scintillation and Cherenkov counters, were incident on a 24-in.-long liquid-hydrogen target T. Both the scattered pion and the recoil proton were detected in scintillation-counter telescopes, 11 for the pions ($\pi_1\pi_2\pi_3$) and up to six for the protons (P_1P_2). The pions were momentum analyzed by the magnet M_1, which had an aperture of 120 in.×24 in. and was 36 in. long. A typical pion telescope had a momentum resolution of ±30% and a solid angle of 1 msr in the c.m. system. Recoil protons were momentum analyzed by magnets M_2 and M_3 with typical resolutions of ±7%. M_3 was not used at 6 GeV/c. A threshold Cherenkov counter (C in Fig. 1) was used to veto forward pions and was particularly useful for π^+-p scattering where the unscattered beam passed very close to the proton counters.

A triggering signal for the spark chambers SC1-SC2 was derived from a coincidence between the incident beam, any pion telescope, and any proton telescope, with resolving times in the range 6-15 nsec. The backscattered pions produced tracks in SC1 and, after deflection in M_1, in SC2. The trigger rate varied from 10^{-1} to 10^{-2} per AGS burst. The angle and momentum resolution of the counter telescopes was such that the fraction of elastic events varied from 7 to 40% of the triggers.

The spark-chamber film was measured initially on the Brookhaven National Laboratory Physics Department flying-spot digitizer.[2] Events in which a track was successfully located in the spark chambers SC2 were retained, and all other pictures were scanned and measured by hand. Assuming the track to be an elastically scattered pion, it was extrapolated through magnet M_1 to the target and required to pass through a fiducial volume. For tracks satisfying this criterion, the track nearest to the elastic position in SC1 was chosen and the

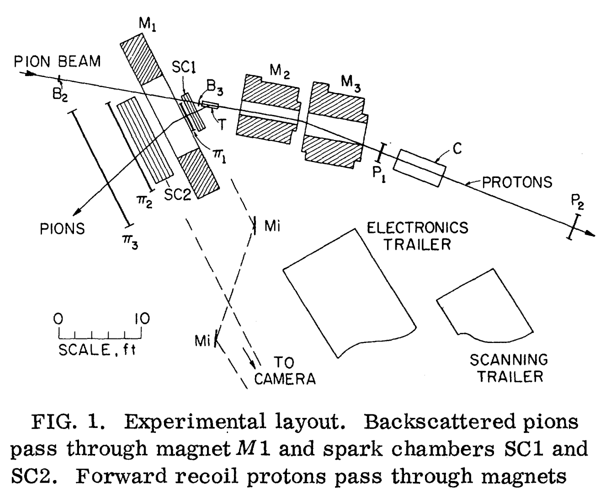

FIG. 1. Experimental layout. Backscattered pions pass through magnet $M1$ and spark chambers SC1 and SC2. Forward recoil protons pass through magnets $M2$ and $M3$. The symbols π_1, π_2, π_3, P_1, and P_2 stand for banks of scintillation counters. B_2 and B_3 are beam counters, T is the liquid-hydrogen target, C is a threshold gas Cherenkov counter, and Mi are mirrors.

Table I. Elastic scattering cross sections. $d\sigma/du$ is the differential cross section averaged over the interval of full width Δu. The systematic errors are the estimated uncertainties due to inelastic and empty-target subtractions. Errors on absolute cross sections must be a combination of both the statistical and systematic errors; however, the systematic errors have less influence on the relative errors between adjacent points of a given energy.

p_o (GeV/c)	$\cos\theta_{c.m.}$	u $(GeV/c)^2$	Δu $(GeV/c)^2$	-t $(GeV/c)^2$	$\frac{d\sigma}{du}$ $\mu b/(GeV/c)^2$	Statistical Error $\mu b/(GeV/c)^2$	Systematic Error $\mu b/(GeV/c)^2$
			$\pi^+p \to p\pi^+$				
5.9	-0.9987	0.055	0.01	11.145	41.52	1.19	0
	-0.9967	0.045	0.01	11.135	35.40	1.50	0
	-0.9948	0.035	0.01	11.125	29.38	1.65	0.30
	-0.9929	0.025	0.01	11.115	32.25	2.27	0.33
	-0.9899	0.01	0.02	11.100	20.81	1.79	0.20
	-0.9865	-0.0075	0.015	11.083	17.11	1.38	0.39
	-0.9836	-0.0225	0.015	11.068	16.23	1.30	0.39
	-0.9802	-0.04	0.02	11.050	12.89	1.10	0.34
	-0.9763	-0.06	0.03	11.030	8.48	0.72	0.25
	-0.9695	-0.095	0.05	10.995	4.45	0.35	0.27
	-0.9588	-0.15	0.06	10.940	1.55	0.17	0.19
9.9	-0.9988	0.0275	0.015	18.508	10.07	0.72	0.09
	-0.9971	0.0125	0.015	18.493	7.57	0.71	0.16
	-0.9957	0	0.01	18.480	6.66	0.72	0.15
	-0.9945	-0.01	0.01	18.470	5.65	0.78	0.13
	-0.9934	-0.02	0.01	18.460	4.98	0.74	0.12
	-0.9920	-0.0325	0.015	18.448	2.90	0.49	0.07
	-0.9903	-0.0475	0.015	18.433	2.48	0.40	0.12
	-0.9886	-0.0625	0.015	18.418	1.84	0.31	0.14
	-0.9866	-0.08	0.02	18.400	1.38	0.21	0.09
	-0.9832	-0.11	0.04	18.370	0.41	0.06	0.06
	-0.9758	-0.175	0.09	18.305	0.31	0.04	0.10
13.7	-0.9969	0.0125	0.015	25.773	4.89	1.08	0.05
	-0.9934	-0.005	0.02	25.755	2.95	0.36	0.07
	-0.9889	-0.0275	0.025	25.733	1.34	0.09	0.09
	-0.9824	-0.06	0.04	25.700	0.93	0.04	0.11
	-0.9754	-0.095	0.03	25.665	0.62	0.10	0.09
	-0.9674	-0.135	0.05	25.625	0.30	0.04	0.06
	-0.9544	-0.20	0.08	25.560	0.25	0.03	0.07
17.1	-0.9979	-0.01	0.02	32.020	2.75	1.32	0.37
	-0.9969	-0.025	0.02	32.005	1.49	0.56	0.52
	-0.9952	-0.0525	0.035	31.978	0.66	0.13	0.33
	-0.9920	-0.1025	0.065	31.928	0.46	0.05	0.18
	-0.9862	-0.1925	0.115	31.838	0.37	0.03	0.16
			$\pi^-p \to p\pi^-$				
5.9	-0.9987	0.055	0.01	11.145	6.45	0.42	0
	-0.9967	0.045	0.01	11.135	6.60	0.66	0
	-0.9933	0.0275	0.025	11.118	6.14	0.65	0
	-0.9885	0.0025	0.025	11.093	7.51	0.65	0
	-0.9841	-0.02	0.02	11.070	7.23	0.60	0
	-0.9802	-0.04	0.02	11.050	7.93	0.63	0
	-0.9753	-0.065	0.03	11.025	5.84	0.72	0
	-0.9685	-0.100	0.04	10.99	6.26	0.42	0
	-0.9588	-0.150	0.06	10.94	3.80	0.75	0
9.9	-0.9994	0.0325	0.015	18.513	2.23	0.13	0.02
	-0.9976	0.0175	0.015	18.498	1.93	0.15	0.02
	-0.9957	0	0.02	18.480	1.81	0.16	0.02
	-0.9931	-0.0225	0.025	18.458	2.15	0.19	0.04
	-0.9903	-0.0475	0.025	18.433	2.56	0.20	0.08
	-0.9877	-0.070	0.02	18.410	2.41	0.22	0.08
	-0.9846	-0.0975	0.035	18.383	1.85	0.17	0.06
	-0.9807	-0.1325	0.035	18.348	1.87	0.13	0.06
	-0.9753	-0.18	0.06	18.300	1.45	0.10	0.05
13.7	-0.9986	0.015	0.02	25.775	1.13	0.13	0.01
	-0.9951	-0.015	0.04	25.745	1.31	0.11	0.01
	-0.9903	-0.0575	0.045	25.703	1.03	0.11	0.03
	-0.9838	-0.115	0.07	25.645	0.89	0.07	0.03
	-0.9747	-0.195	0.09	25.565	0.70	0.05	0.03
16.3	-0.9967	-0.005	0.04	30.485	0.53	0.29	0.03
	-0.9894	-0.070	0.09	30.420	0.80	0.10	0.06
	-0.9761	-0.187	0.145	30.303	0.80	0.08	0.07

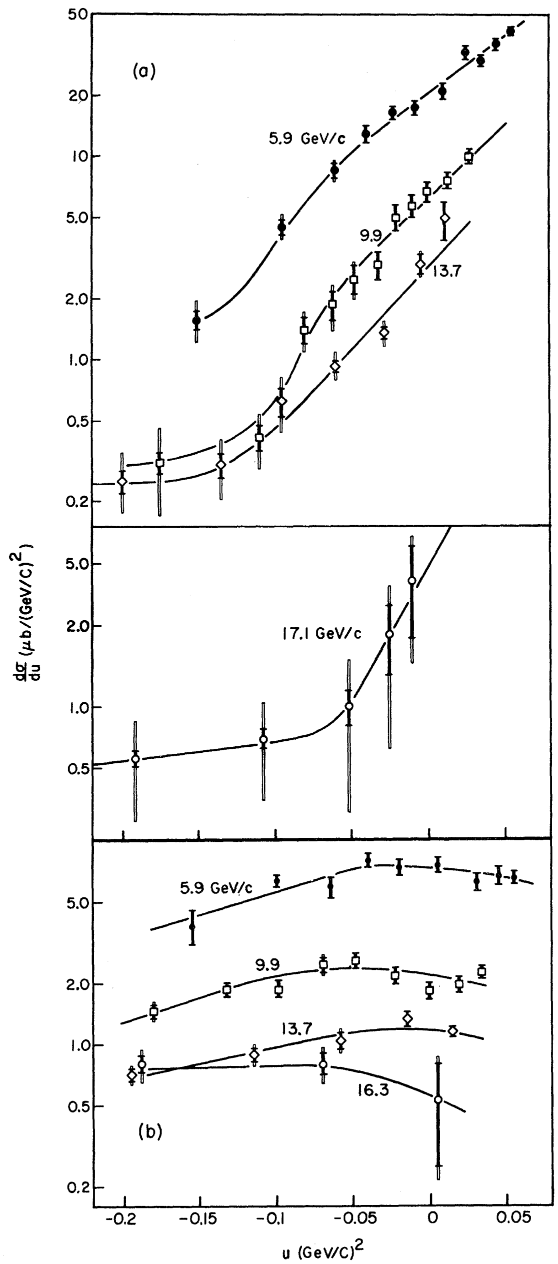

FIG. 2. Angular distributions of the backward peaks for (a) π^+-p and (b) π^--p. The curves are shown as guides for the eye, except for π^+p in the region $u > -0.06$, where the straight lines are least-squares fits. The heavy error bars are statistical errors only, and the light extensions are the systematic errors due to inelastic and empty-target subtraction; i.e., the extremities are the direct sum of statistical and systematic errors.

difference between the measured and calculated positions determined. Using this measurement, it was possible to obtain unambiguous separation of elastic from inelastic events.

Corrections were made for target-empty rate, for muon and electron contamination in the beam, for scanning losses, and for decay of the scattered pions. Solid-angle acceptance and the absorption of pions and protons in the scintillators, target, and other material were determined by Monte Carlo calculations.

The cross sections are listed in Table I together with their corresponding values of t and u. (t is the invariant four-momentum transfer squared and u the crossed invariant four-momentum transfer squared.) The values of $|t|$ are so large [up to 32 $(\text{GeV}/c)^2$] that one would expect direct-channel exchange contributions to be small. On the other hand, the values of $|u|$ are all less than 0.2 $(\text{GeV}/c)^2$ so that peripheral processes involving baryon exchange might be expected to give large contributions.

As seen in Fig. 2, the cross sections, as found previously,[1] do rise in the region of small u, and this effect continues at least up to 17 GeV/c. Figure 2(a) shows that the widths of the π^+-p backward peaks are all narrower than the forward π-p diffraction peaks. We note that the π^+-p backward peaks become even steeper in the region of $0.06 < -u < 0.15$ $(\text{GeV}/c)^2$. We believe that this effect is real, and we have preliminary results[3] from a quite different experimental arrangement which covers $140° < \theta_{\text{c.m.}} < 165°$ at 6 GeV/c to confirm this. The forward peaks when expressed as $d\sigma/dt \propto e^{At}$ have a width $A \approx 9$ $(\text{GeV}/c)^{-2}$, while the backward π^+-p peaks, when expressed as $d\sigma/du \propto e^{Au}$ in the region of $u \geq -0.06$ $(\text{GeV}/c)^2$ have $A = 13.1 \pm 0.6$ $(\text{GeV}/c)^{-2}$ for 5.9-GeV/c pions, 18.2 ± 1.9 for 9.9-GeV/c, 21.9 ± 2.7 for 13.7-GeV/c, and 27 ± 10 for 17.1-GeV/c. These least-squares fits are shown in Fig. 2(a) as straight lines. The chi-squared probability that these four slopes are the same is less than 1%. Hence it appears that the width of the π^+-p backward peak is decreasing with increasing energy. Similar widths and energy dependence of the width have been predicted by Chiu and Stack.[4]

At 180° the π^--p cross sections are about $\frac{1}{4}$ of the corresponding π^+ cross sections. However, the π^- backward peaks are several times wider than the π^+ backward peaks and each appears to go through a maximum before reaching 180°. The maxima seem to occur at about $-u \approx 0.05$ $(\text{GeV}/c)^2$. In the region $-u > 0.05$ $(\text{GeV}/c)^2$ our preliminary results[3] indicate that the π^--p slope at 5.9 GeV/c is (d/du) $(\ln d\sigma/du)$

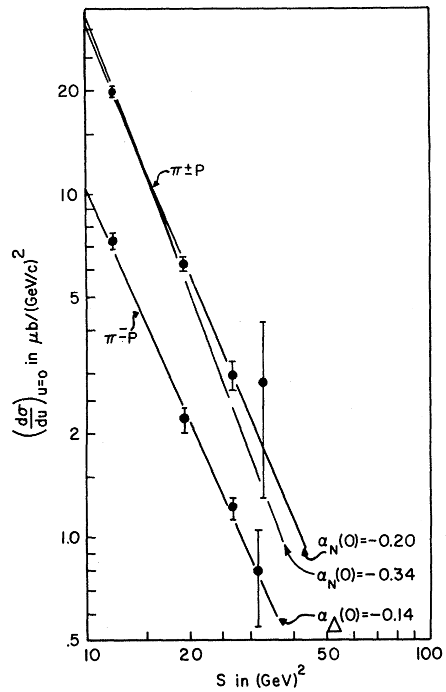

FIG. 3. Plot of $d\sigma/du$ at $u=0$ for π^+ and π^- vs s (the total c.m. energy squared). Power-law fits of the form $s^{2\alpha-2}$ are indicated by the straight lines shown.

$\approx 5\ (\mathrm{GeV}/c)^{-2}$.

The energy dependence of the cross sections $(d\sigma/d\omega)_{180°}$ at 180° are $(P_{\mathrm{lab}})^{-1.40\pm0.10}$ and $(P_{\mathrm{lab}})^{-1.10\pm0.12}$ for π^+ and π^-, respectively.

One of the explanations given for backward peaks is the possibility of Reggeized baryon exchange. Then, if only a single baryon trajectory is involved, the $u=0$ intercept of that trajectory can be obtained from the approximate relation[4,5] $(d\sigma/du)_{u=0}\propto s^{2\alpha(0)-2}$. For backward π^--p scattering only one trajectory, the Δ trajectory, is expected. We obtain $\alpha_\Delta(0) = -0.14\pm0.06$ from a least-squares fit to the $u=0$ cross sections at the four energies measured as shown in the full log plot of Fig. 3.

In the π^+-p case, a least-squares fit to the same expression gives $\alpha_N(0) = -0.20\pm0.05$. This parametrization makes sense only if one nucleon trajectory is the main contributor. From the size of the π^--p cross section, the contribution of the Δ trajectory is known to be small. If one drops the 5.9-GeV/c point because of possible contributions from s-channel resonances,[6] a least-squares fit to the 9.9-, 13.7-, and 17.1-GeV/c values at $u=0$ gives $\alpha_N(0) = -0.13\pm0.15$. These fits are to be compared with $\alpha_N(0)\approx -0.34$ which is expected from the usual Chew-Frautschi plot of the N_α trajectory and which can give an explanation for both the unusual sharpness of the π^+-p backward peak and the pronounced dip at $u = -0.15\ (\mathrm{GeV}/c)^2$.[4]

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