Columbia University).

†Present address: Physics Department, College of William and Mary, Williamsburg, Virginia.

‡Present address: Physics Department, Stanford University, Stanford, California.

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$$F = \tfrac{1}{16}\alpha^2 CR_D \left[1 + \tfrac{5}{8}\alpha^2 + \left(1 - \frac{m}{M_D}\right)\frac{\alpha}{\pi} - 0.656\frac{\alpha^2}{\pi^2} - \frac{2}{\pi}\alpha^3 \ln\alpha^{-1}\right].$$

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STRUCTURE IN THE PION-PROTON TOTAL CROSS SECTION BETWEEN 2.5 AND 5.5 BeV/c†

A. Citron,* W. Galbraith,‡ T. F. Kycia, B. A. Leontić, R. H. Phillips, and A. Rousset§
Brookhaven National Laboratory, Upton, New York

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The total cross sections of $\pi^\pm$ on protons in the momentum interval 2.5 to 5.5 BeV/c have been measured with high precision in a transmission experiment at the Brookhaven alternating gradient synchrotron. This Letter reports the new preliminary data obtained with a statistical accuracy of 0.05% for π^--p and 0.08% for π^+-p cross sections and at momentum intervals of 100 MeV/c. The results indicate two statistically significant new pion-nucleon resonances, one in each of the two isotopic spin states. Previous measurements[1,2] in this momentum interval with a statistical accuracy of 0.5%-1% did not reveal any structure. The newly found resonances and their characteristics are summarized in Table I.

The secondary pion beam was taken from a Be target at a production angle of +9° to the internal proton beam of the AGS. The particles were focused and momentum analyzed onto an intermediate-focus momentum slit, set for a full width of 1.0% at half-height. The second half of the beam transport system was a reflection about the first focus of the first half with both analyzing magnets deflecting the beam by angles of 9°. The relative momenta were set to better than 0.05% using a Hall plate and a nuclear fluxmeter. The absolute momenta are estimated to be known to better than 0.25%.

The pions were identified by a differential gas Cherenkov counter[3] situated directly behind the first focus. The angular acceptance of the Cherenkov radiation was set at 10 milliradians. This was done in order to count efficiently π mesons in a beam which had a vertical angular divergence of ±3 milliradians and a horizontal angular divergence of ±5 milliradians at the first focus. Multiple air scattering was reduced by vacuum pipes and helium bags. The final pion image had a full width at half height of one inch or less. The π-meson flux varied from 2×10^4/pulse to 4×10^4/pulse depending upon the primary-beam energy and secondary-beam momentum.

The hydrogen target[4] was 120 inches long with its center situated 170 inches ahead of the second focus. It was of special, double jacketed design to provide long-term density stability.

Table I. Some parameters of the two new resonances.[a]

Isotopic spin	Kinetic energy, lab (BeV)	Momentum, lab (BeV/c)	$4\pi\lambda^2$, c.m. (mb)	Total energy, c.m. (BeV)	Full width, c.m. (BeV)	Height (mb)
$\frac{1}{2}$	3.10	3.24	3.69	2.645 ±0.010	0.23	0.85
$\frac{3}{2}$	3.63	3.77	3.11	2.825 ±0.015	0.26	0.40

[a]These values are preliminary.

The inner cylinder was $5\frac{3}{4}$ in. in diameter; the outer concentric cylinder 15 in. in diameter. The outer cylinder was filled with liquid hydrogen; its vapor pressure was maintained constant to better than four parts in 10^3, thus providing a constant temperature bath for the inner cylinder. The liquid hydrogen in the inner cylinder was closed off, resulting in a bubble-free liquid whose density was constant to better than three parts in 10^4. The liquid hydrogen reservoir for the outer cell had a capacity of 285 liters. A six-hour settling-down time was allowed after each filling. The target required filling only once every four days. An identical system was used for the dummy which had a vacuum in the inner cell.

All the counter signals were split and used in two parallel sets of electronics, one containing Chronetics[5] circuitry and the other Brookhaven nanologic circuitry (HEEP). The pion telescope consisted of the Cherenkov counter preceded by two scintillation counters and followed by a third scintillation counter which defined the beam at the entrance to the hydrogen target. Two linear output scintillation counters, before and after the final telescope counter, provided a means of pulse-height discrimination which reduced the twofold accidental counting rate by a factor of 100. The consequent reduction in the π-meson counting rate was only 4%. π mesons which passed through the target were detected in seven transmission counters, situated at the second pion focus. The outputs from these counters were individually placed in coincidence with the telescope counters and scaled. Numbers on scalers were transferred by a scanning system onto punched tape; a typed record of the numbers was also provided. The data on the tape were transferred to IBM cards which were then processed through an IBM-7094 computer to check the data for internal consistency and to calculate the partial cross sections.

An iron absorber was placed behind the transmission counters followed by another scintillation counter which was used to eliminate coincidences between the telescope and transmission counters in order to reject muons. In the momentum range 3.0 to 5.5 BeV/c, 3 feet of iron absorber was used; at lower momenta, between 2.5 and 3.3 BeV/c, the iron thickness was reduced to $2\frac{1}{2}$ feet. The iron thickness was kept to a minimum to avoid stopping slow muons.

The transmission counters subtended, at the center of the target, solid angles ranging from 0.43 to 6.9 millisteradians. Each gave a partial cross section but only the central three were used in the linear extrapolation to zero solid Data from the smallest two showed effects of multiple scattering. The partial cross sections given by the largest transmission counters fitted well to a straight-line extrapolation at low momenta but departed from it smoothly with increase in momentum. Due to the excess of π mesons showering through, cross sections taken at 3.0 BeV/c with $2\frac{1}{2}$ feet of iron required corrections of +0.250 mb for π^+-p cross sections and +0.100 mb for π^--p cross sections, in order to bring the data into agreement with those taken at 3.0 BeV/c with three feet of iron. Cross sections at lower momenta were scaled by the same ratios.

π^+-p total cross sections were measured simultaneously with both Chronetics circuitry and HEEP circuitry operating under similar conditions and the measurements agreed to within ±0.2% over the complete range from 2.5 to 5.5 BeV/c. The Chronetics data are given in Fig. 1(a). A 0.40-mb bump can be seen centered at 3.77 BeV/c. The same behavior was observed in HEEP data.

In measuring the π^--p total cross sections the muon anti was removed from the HEEP circuitry, but not from Chronetics. The Chronetics data are shown in Fig. 1(b). A small bump is seen centered at 3.24 BeV/c. Again the same behavior was observed in HEEP data in spite of the fact that the π beam was contaminated with muons. This clearly indicated that a possible variation

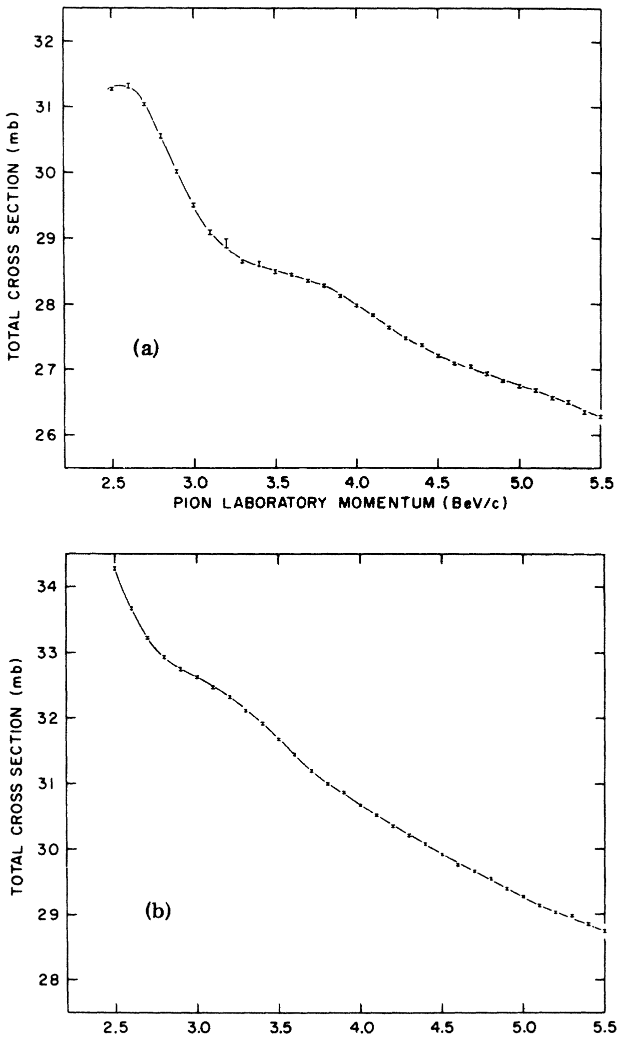

FIG. 1. The pion-proton total cross section. (a) π^+p; (b) π^-p.

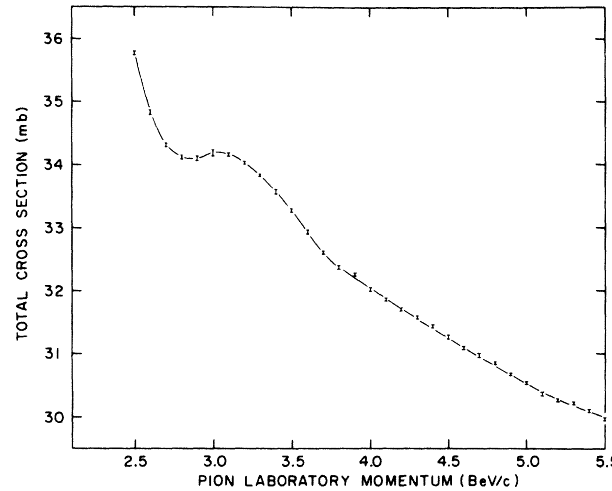

FIG. 2. The pion-proton total cross section in the isotopic-spin-$\frac{1}{2}$ state.

in the muon contamination was not causing a spurious bump. Total cross section of π^- mesons on aluminum were also measured with a statistical accuracy of 0.10%. They are compatible with a smooth curve as expected due to the smearing effects of the Fermi momentum and the $T=\frac{1}{2}$ and $T=\frac{3}{2}$ mixture. These results add to our confidence in the physical reality of the observed bumps in the hydrogen data.

The error to be assigned to the absolute value of $\pi^{\pm}$-p cross sections is estimated to be less than $\frac{1}{2}$% and the data agree within errors with previous data.[1,2]

The total cross section in the isotopic-spin-$\frac{1}{2}$ state was calculated point by point from the above data and the results are shown in Fig. 2. The bump at 3.24 BeV/c is now 0.85-mb high and stands out very well above the background. The bumps can be interpreted as isotopic-spin-$\frac{1}{2}$ and isotopic-spin-$\frac{3}{2}$ resonances in the pion-nucleon system.

The resonances continue to recur with alternating isotopic-spin states as has been empirically suggested from data at lower momenta.[6] However, it is not possible to ascribe spins unambiguously to the present resonances. They may be anywhere from $J_{1/2}=9/2$ and $J_{3/2}=11/2$ to $J_{1/2}=13/2$ and $J_{3/2}=15/2$ depending upon how one chooses Regge trajectories.

Recently, empirical relationships about π-N resonances[7] have been proposed which predict a $T=\frac{1}{2}$ resonance at 2.76 BeV and a $T=\frac{3}{2}$ resonance at 2.87 BeV. If we assign the number $\lambda=6$ for the present two resonances there is an agreement between the predictions within the errors given in reference 7.

Evidence for structure in pion photoproduction[8] has been observed and has been interpreted as resulting from two pion-nucleon resonances, one with mass 2.52 ± 0.04 BeV probably in $T=\frac{3}{2}$ state and the other with mass 2.7 BeV in $T=\frac{1}{2}$. The two resonances would have appeared in the π-p total cross section at pion-laboratory momenta of 2.9 and 3.5 BeV/c. They are not observed in our data.

Very recent π^--p charge-exchange data observed in the forward direction give also an indication of structure.[9] There seems to be qualitative agreement between these data and the value of the expression $\frac{1}{2}(k/4\pi)^2[\sigma(\pi^-p)-\sigma(\pi^+p)]$ as calculated from data presented here. There is, however, some quantitative disagreement on the momenta at which resonances occur. The structure in the charge-exchange data has been interpreted by the authors as a $T=\frac{1}{2}$ resonance at ~3.1 BeV/c (E^*~2.6 BeV), or as two $T=\frac{3}{2}$ resonances at ~2.6 and 3.5 BeV/c (E^*~2.4 and 2.7 BeV) or as a combination of all three of these together. Our present data and previous results[1] allow us to conclude that the structure observed in charge-exchange scattering can be explained as the combined effect of the three resonances at 2.5, 3.24, and 3.77 BeV/c. Presumably the discrepancy in energy is caused either by a large momentum variation in the difference of the real parts of the forward scattering amplitudes, $\frac{1}{2}(D^{-}-D^{+})^2$, or by the statistical errors in the charge-exchange data.

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*Permanent address: CERN, Geneva, Switzerland.

‡On leave of absence from Ecole Polytechnique, Paris, France.

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EXPERIMENTAL TESTS OF UNITARY SYMMETRY IN MESON-BARYON REACTIONS

H. Harari
Isarael Atomic Energy Commission, Soreq Research Establishment, Yavne, Israel

and

H. J. Lipkin
Department of Nuclear Physics, The Weizmann Institute of Science, Rehovoth, Israel
(Received 6 July 1964)

A large variety of relations among reaction amplitudes and cross sections are predicted on the basis of the SU(3) octet model.[1] However, experimental verification of these predictions is generally not feasible and has been done only in very few cases. Consider, for example, meson-baryon reactions of the form

$$m+B\to m+B,$$

where m and B denote pseudoscalar mesons and baryons belonging to the octet representations of SU(3). Straightforward calculation of the SU(3) predictions for these reactions involves 13 independent real parameters, characterizing 7 possible independent complex amplitudes.[2,3] Experimental cross sections are available for about 20 different m-B reactions, including some, like η and Ξ^0 production, for which data are not very accurate and are available for only a few energy values. The straightforward approach of fitting 20 pieces of data with 13 parameters in a set of nonlinear equations has not led to any significant results.[4]

We present here a few simpler predictions of SU(3) for these reactions, obtained with a slightly different approach, and the principal results of an analysis of meson-baryon reactions, comparing experimental facts with SU(3) predictions over a relatively wide energy range. Consider the following three sets of processes:

$$K^{-}+p\to K^{-}+p, \qquad (a_1)$$

$$\pi^{-}+p\to\pi^{-}+p, \qquad (a_2)$$

$$K^{-}+p\to\pi^{-}+\Sigma^{+}; \qquad (a_3)$$