PION-NUCLEON SCATTERING IN THE $T = 1/2$ STATE AS DEDUCED FROM RECENT EXPERIMENTS

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The recent experiments to which we here refer are:

(1) Elastic pion-proton scattering for pion energies between 300 and 700 MeV [1].

(2) Elastic charge-exchange scattering for the energy range 500 to 1300 MeV [2].

(3) Recoil proton polarization measurements for pion energies between 500 and 1000 MeV [3].

We also will report on the present status of the phase shift problem as developed independently by Roper and Cence [4].

Persons involved in these effortsare noted in the references.

I. ELASTIC SCATTERING, 300 TO 700 MeV

The measurements made at eight energies in this region were to provide the ability to trace the phenomena continuously from the accurate data at 310 MeV to the extensive data above 500 MeV. We are particularly concerened with an understanding of the 1512 MeV state («600 MeV resonance») which bears a nunclear relationship to present symmetry schemes and pole trajectory analysis.

These new scattering data have been used by several persons attempting phase shift analyses, but we shall here discuss only an amplitude analysis by Ogden which indicates certain amplitudes prominent in the region.

For the $\pi^- p$ scattering Ogden assumed the Breit-Wigner resonances to exist (see Table 1).

Table 1

State	E_{res}^{cm}, MeV	$F = \frac{\Gamma_{el}}{\Gamma}$	Γ, MeV
P_{33}	1238	1,0	165
D_{13}	1512	0,8	110
F_{15}	1688	0,9	100

He then was able to satisfy the data by requi ring:

(1) A pure-imaginary $S_{1/2}$ amplitude, of magnitude 0.27 λ over the 300-700 MeV region.

(2) A pure-imaginary $P_{1/2}$ amplitude of magnitude 0.35 λ similarly extending over the region.

(3) A $D_{5/2}$ amplitude beginning weakly at 400 MeV and rising rapidly after 600 MeV.

This description of amplitudes is not unique, but it involves strongly those for which there are physical reasons for expecting importance, as we shall later indicate. The constancy of their values (except of course for the λ variation) is not to be seriously regarded since the problem is too much simplified, but the identity of the strong amplitudes we consider to be significant.

These results will be subsequently combined with the charge-exchange scattering data to obtain the pure $T = 1/2$ differential scattering.

II. CHARGE-EXCHANGE SCATTERING

Angular distributions and absolute values were obtained at eight energies between 533 MeV and 1310 MeV. In Fig. 1 we show the results for two of the energies, near 600 MeV and near 900 MeV, respectively. The total cross section for producing a neutral final state, and the various partial cross sections, including η° production, have been presented in a preceding paper by V. Z. Peterson.

In Fig. 2 are displayed the coefficients of a cosinepower-series expansion of $d\sigma/d\omega$ for the charge-exchange scattering as functions of incident pion energy. Results from a recent experiment of Lind et al [5] as 315 and 371 MeV have been included. The behaviour of a_3 and a_5 shows the growth of the familiar $F_{5/2}D_{5/2}$ interference above 700 MeV.

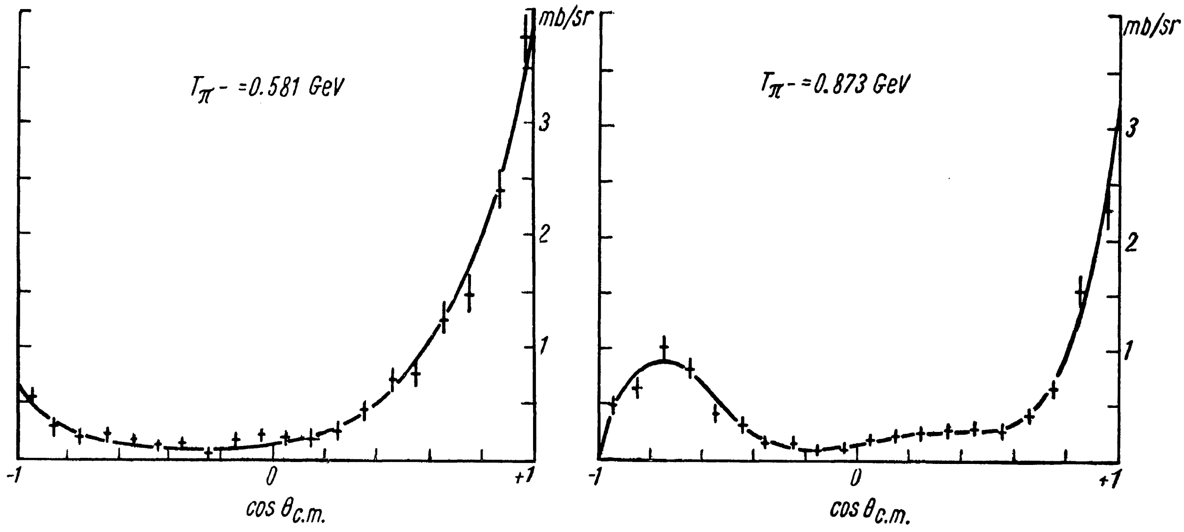

Fig. 1. Charge-exchange differential cross-section.

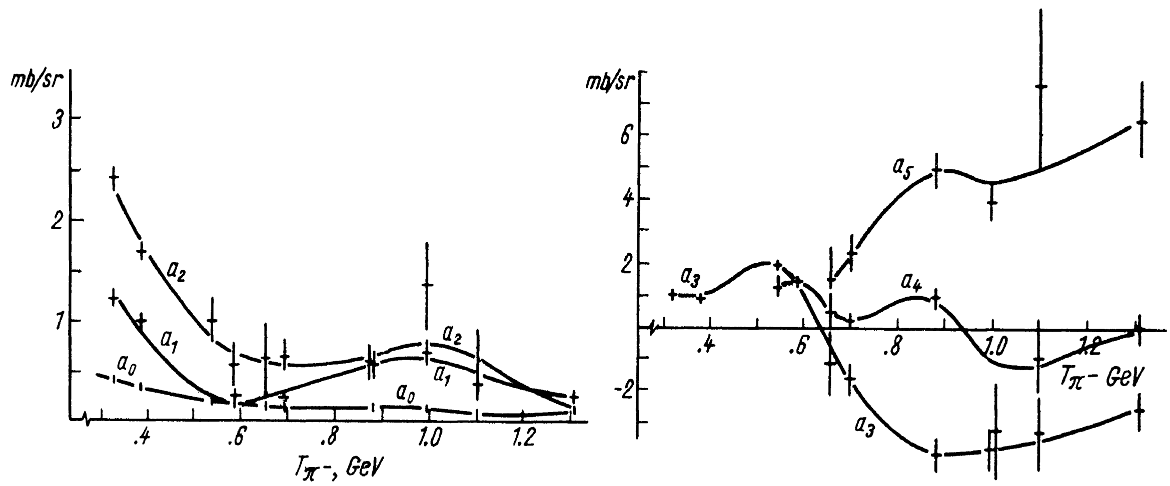

Fig. 2. Cosine series coefficients for charge-exchange scattering.

III. THE $T=1/2$ ELASTIC SCATTERING

By utilizing the charge-exchange data with that for π^+p and π^-p scattering, we have constructed the differential scattering for the pure $T = 1/2$ state. The first four cosinepower-series coefficients are plotted in Fig. 3. The coefficients a_4, a_5 and a_6 are not displayed; but a_5 grows to the very large positive value of 28.5 millibarrs/ster at 900 MeV. It is thus clear from the a_3 and a_5 behaviour that the $F_{5/2}D_{5/2}$ interference is predominantly a $T = 1/2$ phenomenon, the effects being more pronounced here than in π^-p scattering and absent in π^+p scattering.

We call attention to the peak in a_0 at 450 MeV, and the abrupt rise in a_2 between 500 and 600 MeV. These are probably related phenomena in the following way by the behaviour of S and D waves:

(1) a_0 is deflected from its rise toward a maximum at 600 MeV by the effect of the $S_{11}D_{13}$ interference term occuring in a_0 which subtracts from the various positive terms such as D_{13}^2 etc. ($P_{11}P_{13}$ will also provide a subtractive term, but is very small because of the phase values of P_{11} and P_{13}).

(2) In a_2 the $S_{11}D_{13}$ makes a strong positive contribution and accounts for the abrupt increase at an energy near the η° threshold.

The sharp onset of S-wave η° production shown by Peterson in the preceding paper, produces a strong S_{11} amplitude, and its interference with the D_{13} amplitude as the latter grows toward its large value at 600 MeV accounts for these phenomena. It is not possible

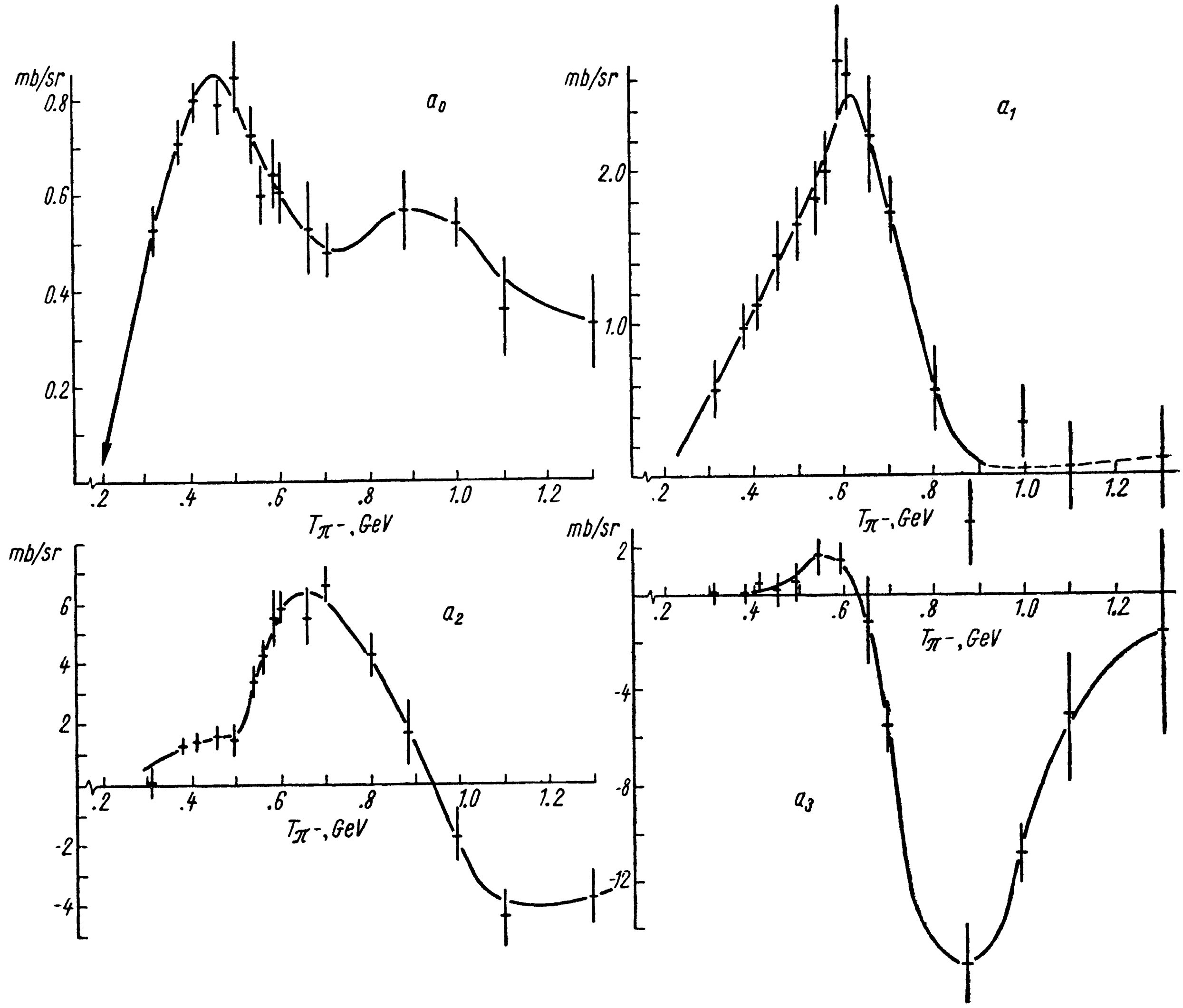

Fig. 3. Cosine series coefficients for $T = 1/2$.

at present to say whether or not the $T = 1/2$ enhancement in cross section reported by Bareyre et al. [6], is related to the a° maximum; but the energy is in agreement, and S_{11}^2 and P_{11}^2 terms contribute to a_0.

The peaking of a_1 at 600 MeV is dominated by $P_{11}D_{13}$ interference. Its assymetric character is explained by the $P_{13}D_{13}$ contribution which is small but positive below the resonance, and negative above the resonance. (The P_{13} phase is negative in this region, and the $P_{13}D_{13}$ term in a_1 has a negative coefficient. The result is a positive contribution for D_{13} phases below 90° and negative above 90°).

We thus infer in this region a prominent S_{11} amplitude associated with η° production, a prominent P_{11} amplitude, and a resonant D_{13} amplitude. The P_{13} has a negative phase shift in this region in all acceptable phase shift sets, and the $P_{11}P_{13}$ interference is a small effect. The P_{11} strength is believed to be due to the $T = 0$, $J = 0$, $\pi\pi$ interaction which is observed consistently in the reaction $\pi^- p \to \pi^+\pi^- n$ and $\pi^\circ\pi^\circ n$. The $D_{3/2}$ amplitude is enforced by a final-state combination of the N_{33}^* isobar and an S-wave pion, but the basis for resonant behaviour is as yet nuclear.

IV. POLARIZATION MEASUREMENTS

The polarization measurements of Eandi, et al. [3] may be summarized by the following table of the coefficients b_n in the expansion

$$P(\theta)\,\sigma(\theta) = \sin\theta \sum_n b_n \cos^n \theta.$$

The values of b_n are in millibarns (see Table 2).

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Table 2

$T\pi$	$b_0\times 10^2$		$b_1\times 10^2$		$b_2\times 10^2$	
	π^+	π^-	π^+	π^-	π^+	π^-
532	-14 ± 4	-25 ± 6	-57 ± 19	-146 ± 30	-62 ± 22	-157 ± 42
572	-5 ± 3	-16 ± 4	-38 ± 14	-149 ± 26	-43 ± 18	-277 ± 41
689	-2 ± 2	$+5\pm 3$	-41 ± 12	-75 ± 22	-24 ± 21	-207 ± 43
864	3 ± 2	-8 ± 3	10 ± 10	5 ± 10	77 ± 20	60 ± 35
981	0 ± 3	-26 ± 2	-25 ± 13	32 ± 9	39 ± 29	93 ± 27

These parameters are qualitatively understandable at the lower energies in terms of the amplitudes discussed above. They are of course employed in the phase shift studies.

V. PHASE SHIFT CALCULATIONS

R. J. Cence of the University of Hawaii and L. D. Roper of the Lawrence Radiation Laboratory (Livermore) have independently dealt with the phase shift problem using different procedures. Roper has parameterized the phase shifts as functions of the c. m. pion momentum by a power series expression, and has then sought to simultaneously fit all data at all energies. Cence has not imposed such constraints, but rather seeks to find separate solutions at successively higher energies by employing at each new energy an input array of phase shifts obtained at the last preceding energy. He thus develops a sequence of sets which should show the energy dependence of the phases without limiting their freedom to vary as nature may require. Both men utilize all existing types of data on cross sections and polarization.

The present results set forth by Roper for the vicinity of 600 MeV show a P_{11} resonance at 570 MeV and a D_{13} resonance at 650 MeV. Both are strongly inelastic. He had assumed in his input data a Breit — Wigner D_{13} resonance form. The χ^2 value of his fit to the total array of data in 2910, where he has employed approximately 1200 separate datum points and has admitted partial waves through $l = 4$.

The double resonance spanning 600 MeV seems unique to Roper's analysis. Actually these are both so strongly inelastic in his results that the behaviour of the real parts of the P_{11} and D_{13} phases is not crucial. While it is appealing to attempt to fit all data simultaneously, the question may be raised as to whether the constraints imposed by the parametering of the energy dependence may not enforce an unwarranted smoothness and other apparent phenomena. His predictions of physical results which have been subsequently measured have been very satisfactory however.

Table 3

δ_{real} (deg)	S_1	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	E_{17}
	28,3	44,6	−32,4	29,7	−4,2	5,1	−0,9
$\eta = e^{-2\delta}$ umag.	0,86	0,75	0,66	0,96	0,93	0,91	0,89
δ_{real} (deg)	S_3	P_{31}	P_{33}	D_{33}	D_{35}	F_{35}	F_{37}
	−28,2	−12,1	−17,9	3,5	−4,8	−0,1	2,6
$\eta = e^{-2\delta}$ umag.	0,87	0,89	0,92	0,98	0,98	0,99	0,96

The sequence of phase shift sets for various energies as generated by Cence are also excellent fits to the data. Cence has used some additional inelastic cross section data not available at the time of Roper's analysis. He began with the Vik-Rugge II solutions for 310 MeV, and imposed no assumed resonances except the P_{33} existing at 200 MeV.

None of Cence's phases pass through resonance behaviour, although certain phase excursions produce the amplitude variations required by the data. The χ^2 values of his fits at the various energies between 310 and 873 MeV lie between 30 and 100, and the numbers of datum points employed at the various energies range from 50 to 80. He includes partial waves through $l = 3$ only. The manner in which his S_{11}, P_{11}, P_{13} and D_{13} phases vary as the energy increases allows certain plausible speculations associated with thresholds and final state interactions which cannot be pursued within this space.

We present in the following Table 3 the set derived by Cence for 600 MeV. It is far more instructive to see the sequential values of the phases as the energy advances, but the array of data is of prohibitive extent.

In the $T = 3/2$ state the results of Cence and Roper are in rough agreement, as is also true for S_{11}. Cence started from the Vik-Rugge II values at 310 MeV. Roper begun with the Hamilton-Wolcock scattering lengths evaluated from data between 0—350 MeV.

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