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Recent experiments on pion production have shown the presence of a strong pion-pion interaction in the isotopic-spin-one state.[1-3] These experiments have established the existence of a resonance (the ρ meson) at a ω value of 750 Mev, where ω is the total energy of the two pions in their barycentric frame. The full width at half maximum of the resonance is approximately 130 Mev.[2] In these experiments, pions were scattered from protons in a hydrogen bubble chamber. Of the two groups of reactions

$$\text{(a)} \quad \pi^{\pm} + p \rightarrow \pi^{\pm} + \pi^{0} + p$$

and

$$\text{(b)} \quad \pi^{\pm} + p \rightarrow \pi^{\pm} + \pi^{+} + n\,,$$

(a) has received the most attention because a measurement of the recoil proton fixes ω^2 and Δ^2 (where Δ is the four-momentum transfer from the initial- to the final-state nucleon) for an event of the desired type. An extrapolation procedure for analysing these experiments, suggested by Chew and Low,[4] involves the study of those collisions in which Δ^2 is small. It was postulated that, for small Δ^2, the one-pion exchange interaction would predominate. To date, several experimenters[3,5] have reported some success in analysing the pion-pion interaction by the extrapolation method.

In the experiment reported here, we study reactions (b) with an incident pion momentum of 1.75 Bev/c. We find evidence of a pion-pion interaction in the $(\pi^+\pi^-)$

system, although the extrapolation method of analysis appears to fail. There is strong evidence for processes other than the one-pion exchange even at relatively low momentum transfers.

Negative and positive pions were extracted from a beryllium target placed in an almost field-free region of the Bevatron primary beam. They were formed into an external beam and focused onto a 10-cm-thick liquid-hydrogen target. Detection apparatus consisted of plastic scintillation counters and their associated equipment. The counters were arranged in two groups. The main group consisted of 84 trapezoidal prisms arranged to fit on a section of the surface of a sphere of 160-cm radius with the hydrogen target at its center. Looking from the target at the counter array, one would see the elements grouped in a series of seven concentric rings. Each ring subtended a polar angular interval of 8 deg. The array extended from 4 to 60 deg. The rings were divided into twelve elements, each with a 30-deg azimuthal angle. All the counters were 15-cm-thick in order to be effective in detecting neutrons by recoil protons and n-p reactions on carbon. Each counter element was coupled to a photomultiplier tube by a hollow aluminum light guide. The second group of counters was 0.6 cm thick and was designed to detect pions that emerged at scattering angles from 60 to 145 deg. This group of counters was placed close to the hydrogen target. The angular resolution for these counters was 20 deg in polar angle and 30 deg in azimuthal angle.

The spatial coordinates of the two pions and the neutron were determined within the resolutions mentioned above. The time of flight of the neutrons from the hydrogen target to the main counter array was measured by comparing the time of arrival of the pions ($\beta=1$) with the time of arrival of the neutrons. The entire range of flight times was divided into seven intervals with mean energies and r.m.s. widths as cited in Table I. Also listed are the corresponding values of the variable p^2/μ^2, which is related to Δ^2 and the neutron kinetic energy by

$$p^2/\mu^2 = (M_n/M_p)\,(\Delta^2/\mu^2 + (M_p - M_n)^2/\mu^2).$$

Table I. Values of mean energy and mean $(p/\mu)^2$ for seven time-of-flight intervals.

Time bin	Mean energy and r.m.s. width	Mean$(p/\mu)^2$ and r.m.s. width
τ_1	54±14	5.2±1.3
τ_2	38±12	3.6±1.1
τ_3	29±10	2.8±1.0
τ_4	23±8	2.2±0.8
τ_5	18±7	1.7±0.7
τ_6	13±5	1.3±0.5
τ_7	10±5	1.0±0.5

Data were handled and processed electronically. Whenever a pion was scattered from the incident beam and a delayed pulse came within the neutron time-of-flight interval, the output of each counter was recorded on magnetic tape. Each two-pion, one-neutron event was thus characterized by seven quantities: the polar angles θ and the azimuthal angles ϕ for the three particles, and the time of flight τ of the neutron. The beam bending magnets determined the momentum of the incident pion. The efficiency for detecting neutrons was measured in a separate experiment at the Lawrence Radiation Laboratory's 184-in. -cyclotron.[6] To discriminate against background from neutral pions, a 1/4-in. thick sheet of lead was placed across the faces of both counter arrays.

The tapes thus produced were analysed by using an IBM 709 computer with a program that selected those events with a two-pion, one-neutron signature. Five measurements are required to determine completely the kinematics. Since seven measurements were made, two consistency checks were available for a kinematic fit of the data to further discriminate against background.

Measurements were made with two target conditions--flask full and flask empty--and two delay conditions--normal and abnormal. To achieve the abnormal delay conditions, we added sufficient delay to the neutron channels so that any slow particles detected must traverse the flight path with $\beta > 1$ to be correlated with the two charged pions. This condition gave a measurement of the purely accidental neutron background. In terms of the four possible target and delay conditions--full-normal, empty-normal, full-abnormal, and empty-abnormal--the net partial cross sections are given by

$$\frac{d^2\sigma}{d(p^2)d(\omega^2)} = \frac{d^2\sigma_{FN}}{d(p^2)d(\omega^2)} - \frac{d^2\sigma_{EN}}{d(p^2)d(\omega^2)} - \frac{d^2\sigma_{FA}}{d(p^2)d(\omega^2)} + \frac{d^2\sigma_{EA}}{d(p^2)d(\omega^2)} \; .$$

The neutron counting efficiency was taken into account in the calculation of $d(p^2)d(\omega^2)$.

In Fig. 1(a) we present the results of our calculation of $d\sigma/d(\omega^2)$, which is obtained from the double distributions by using

$$d\sigma/d(\omega^2) = \int_{p^2_{min}(\omega^2)}^{p^2_{cutoff}} [d^2\sigma/d(p^2)d(\omega^2)] \; d(p^2),$$

where $p^2_{cutoff} = 6\mu^2$. For fixed ω^2, $p^2_{min}(\omega^2)$ is imposed by kinematics. This distribution confirms the presence of a resonance in the $(\pi^+\pi^-)$ system at $\omega = 750$ Mev with a width of approximately 220 Mev. To correct for finite resolution of our apparatus, we performed a Monte Carlo calculation, assuming the one-pion exchange model with a p-wave pion-pion resonance. The resultant $d\sigma/d(\omega^2)$ distribution, as seen by our apparatus, agrees with the observed distribution for a pion-pion resoance with a full width at half maximum of about 190 Mev. The $(\pi^+\pi^+)$ distribution is of somewhat smaller magnitude and appears relatively flat.

If we assume that the contribution from the one-pion exchange process dominates in the region of low-momentum transfers, we can obtain $\sigma_{\pi\pi}$ from the equation given by Chew and Low:[4]

$$d^2\sigma/d(p^2)d(\omega^2) = (f^2/\pi)(M_n/M_p)^2 \frac{(p^2/\mu^2)}{(p^2+\mu^2)^2} \left[(\omega^4/4) - \omega^2\mu^2 \right]^{1/2} (1/q_{1L})^2 \sigma_{\pi\pi}(\omega^2) \qquad (1)$$

by an integration over p^2. Figure 1(b) gives the results of this integration.

Our attempts to obtain the pion-pion cross section by the extrapolation method are shown in Fig. 2 for $(\omega/\mu)^2 = 16, 18, 20, 24$, and 28. In the $(\pi^+\pi^+)$ system, the $\sigma_{\pi\pi}$ obtained by extrapolation is ~ 10 mb for $\omega^2/\mu^2 = 16, 18$, and 20. For higher energies, the extrapolation procedure seems to break down. For the $(\pi^+\pi^-)$ system, the extrapolation method appears to fail completely.

In addition to the $d\sigma/d(\omega^2)$ distribution, we have also determined the $d\sigma/d(\omega)_{\pi n}$ distribution from our data. Since in our experiment we cannot distinguish the charge of the final-state pions, our plot is the relative frequency of occurrence of the variable $\omega_{\pi n}$. The final state $(\pi^+\pi^+)$ contains identical particles, so this condition imposes no restriction. In Fig. 1(c), we notice a marked peaking in the vicinity of the (3/2, 3/2) and (1/2, 5/2) pion-nucleon resonances.

Recently Yang and Treiman have proposed a method of testing the validity of the one-pion exchange model.[7] In the rest frame of the incident pion, the distribution of the plane defined by the final-state pion momenta $\vec{p}_{\pi 1}$ and $\vec{p}_{\pi 2}$ must be isotropic about $\vec{q} = \vec{p}_n - \vec{p}_p$ if a single pion is exchanged. Our $(\pi^-\pi^+)$ data (see Fig. 3) shows a marked anisotropy for $p^2/\mu^2 = 3.6$ and 5.2. For lower momentum transfers, the distribution appears flat within the statistics. For the $(\pi^+\pi^+)$ system, the anisotropy is less pronounced and may not be statistically significant.

This experiment confirms the position and approximate width of the resonance in the two-pion system corresponding to the ρ meson. However, we feel that the result of the Yang-Treiman test, the peaking of $d\sigma/d(\omega)_{\pi n}$ around the pion-nucleon resonances, and the partial failure of the extrapolation method make it impossible to infer from our data any further details of the pion-pion interaction based on the one-pion exchange model of analysis.

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FIGURE LEGENDS

Fig. 1. (a) Cross section as a function of the square of the dipion barycentric energy; (b) integration of Eq. (1) over p^2/μ^2 in the physical region; (c) cross section as a function of final-state pion-neutron barycentric energy, $\omega_{\pi n}$. The Q value is given by $\omega_{\pi n} - M_n - \mu$; the positions of the $(\frac{3}{2}, \frac{3}{2})$ and $(\frac{1}{2}, \frac{5}{2})$ pion-nucleon resonances are indicated by arrows. The lower curves are for the final-state $(\pi^+\pi^+n)$, the upper curves for $(\pi^+\pi^-n)$.

Fig. 2. Extrapolation plots of the function

$$F(p^2, \omega^2) = (\pi/f^2)\,(M_p/M_n)^2\, \frac{q_{1L}{}^2 (p^2 + \mu^2)^2}{[(\omega^4/4) - \omega^2\mu^2]^{1/2}}\, d^2\sigma/d(p^2)d(\omega^2),$$

where the lower curves are for the $(\pi^+\pi^+n)$ final state, the upper curves for $(\pi^+\pi^-n)$, and $\sigma_{\pi\pi}(\omega^2) = -F(-\mu^2, \omega^2)$.

Fig. 3. Relative frequency of occurrence of the separation angle $\phi = \cos^{-1}(\hat{R}_{pn} \cdot \hat{R}_{\pi\pi})$, where $\hat{R}_{pn}$ is the unit normal to the proton-neutron scattering plane and $\hat{R}_{\pi\pi}$ is the unit normal to the plane of the two final-state pions. All quantities are defined in the rest frame of the incident pion. (a) is for the $(\pi^+\pi^-n)$ system, (b) for the $(\pi^+\pi^+n)$.

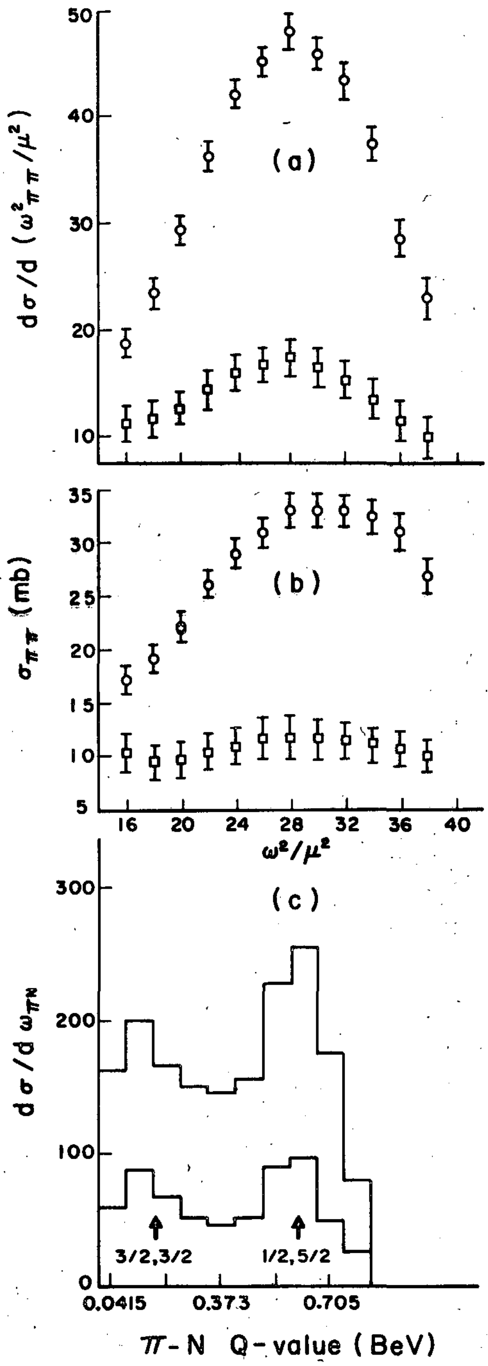

Fig 1

MUB-1071

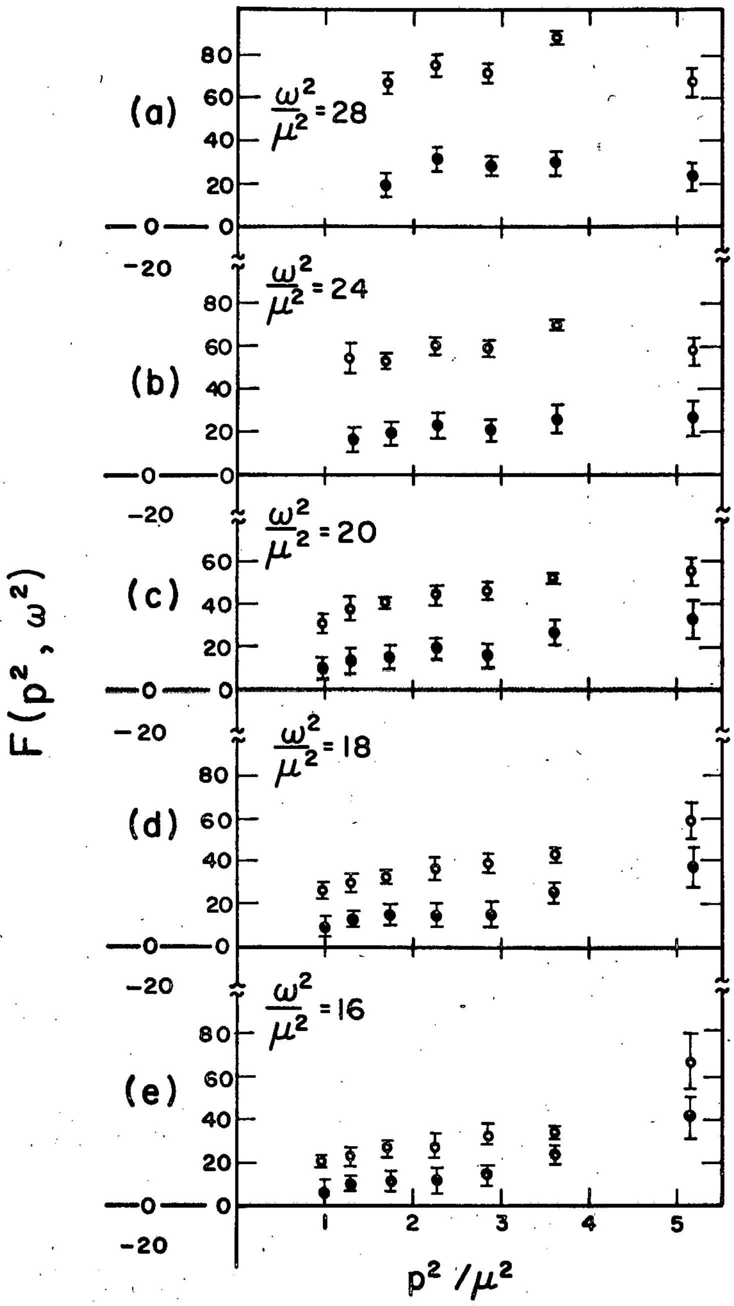

Fig 2

MUB-1073

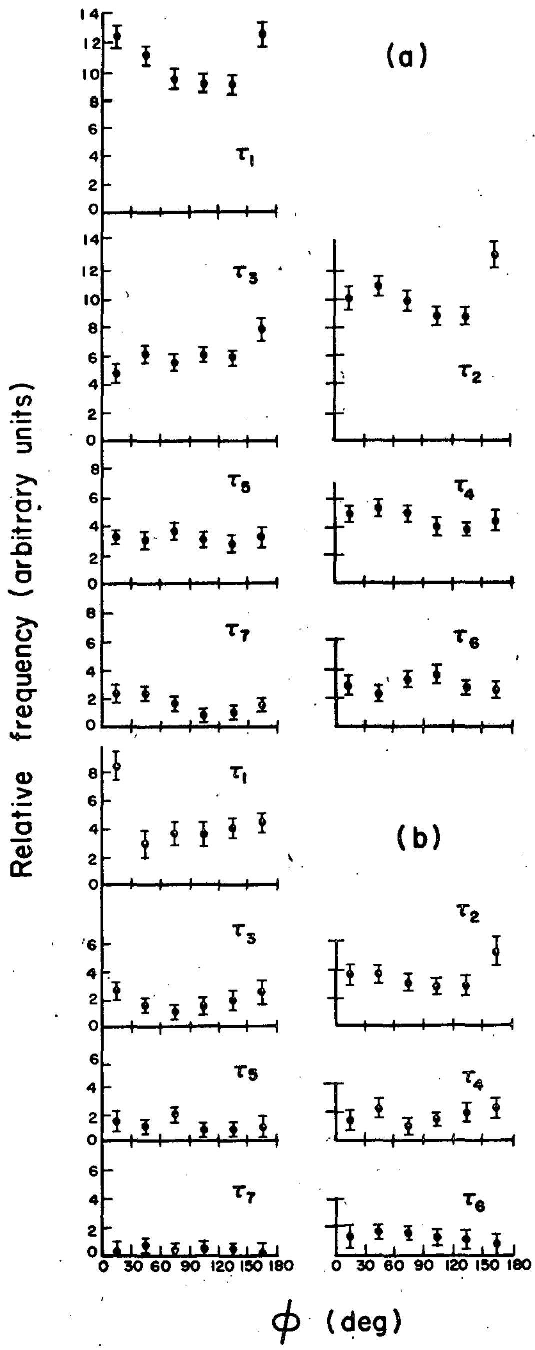

Fig 3

MUB-1072