PRODUCTION OF MULTIMESON RESONANCES BY π^+p INTERACTION AND EVIDENCE FOR A $\pi\omega$ RESONANCE*

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In this Letter we want to report the measurement of various partial cross sections of the reaction $\pi^+ + p \to \pi^+ + p + X$ at 3.43 and 3.54 BeV/c, where X represents all known multimeson resonances: ω, η, ρ^0, f^0, and φ. We also present evidence for a $\pi\omega$ resonance at 1.22 BeV with a full width of 0.100 ± 0.020 BeV.

After analyzing about 5500 four-prong events produced by π^+ in the BNL 20-in. hydrogen bubble chamber (1000 events by 3.43-BeV/c π^+ and 4500 events by 3.54-BeV/c π^+), we identified 1837 events as

$$\pi^+ + p \to \pi^+ + p + \pi^+ + \pi^-, \tag{1}$$

1919 events as

$$\pi^+ + p \to \pi^+ + p + \pi^+ + \pi^- + \pi^0, \tag{2}$$

454 events as

$$\pi^+ + p \to \pi^+ + \pi^+ + \pi^+ + \pi^- + n, \tag{3}$$

and 63 events as

$$\pi^+ + p \to \pi^+ + p + K^+ + K^-. \tag{4}$$

The details of the analyzing methods have been described elsewhere.[1] Using a known total cross section[2] of 28.6 ± 0.46 mb, we have calculated the partial cross sections for the four reactions. These cross sections are shown in Table I, together with all partial cross sections of the production of multimeson resonances. We also show the corresponding cross sections for lower incident momenta as reported by James and Kraybill,[3] and Alff et al.[4] The multimeson resonances play a prominent role in these reactions. In the following we want to present some details of the production of these resonances at our energies.

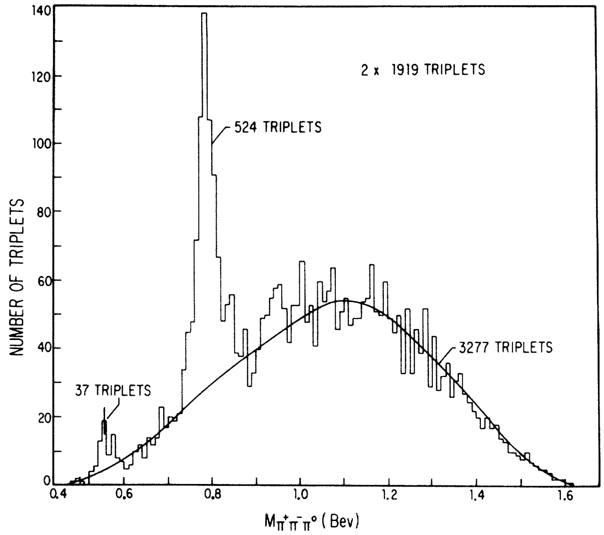

FIG. 1. Effective-mass distribution of $\pi^+\pi^-\pi^0$ triplets from the reaction $\pi^+ + p \to \pi^+ + p + \pi^+ + \pi^- + \pi^0$. The solid line is a phase-space estimate of the background.

(A) Production of ω mesons and evidence for a $\pi\omega$ resonance. —In Fig. 1 we plot the effective-mass distribution of the $\pi^+\pi^-\pi^0$ triplet from Reaction (2). This distribution clearly shows the

Table I. Cross sections in millibarns.

Reaction	Final state $\pi^+ + p \to$	Incident momentum (BeV/c) 2.08[a]	2.34[b]	2.62[b]	2.9[b]	3.43	3.54
1	$\pi^+ + p + \pi^+ + \pi^-$	3.64 ± 0.2	3.2 ± 0.2	3.5 ± 0.3	3.1 ± 0.2	3.3 ± 0.3	3.5 ± 0.2
2	$\pi^+ + p + \pi^+ + \pi^- + \pi^0$	2.75 ± 0.15	3.1 ± 0.2	3.6 ± 0.3	4.1 ± 0.2	3.7 ± 0.3	3.6 ± 0.2
3	$\pi^+ + \pi^+ + \pi^+ + \pi^- + n$	0.27 ± 0.04	0.27 ± 0.06	0.37 ± 0.08	0.56 ± 0.06	0.98 ± 0.1	0.83 ± 0.07
4	$\pi^+ + p + K^+ + K^-$	<0.0056				0.12 ± 0.035	0.12 ± 0.02
5	$\pi^+ + p + \omega^0$	1.6 ± 0.2	1.8 ± 0.2	1.6 ± 0.2	1.6 ± 0.2	1.2 ± 0.2	1.06 ± 0.10
6	$\pi^+ + p + \eta$	0.6 ± 0.2	0.75 ± 0.15	0.75 ± 0.18	0.80 ± 0.15	0.30 ± 0.13	0.23 ± 0.06
7	$\pi^+ + p + \rho$	1.5 ± 0.2	1.4 ± 0.25	1.4 ± 0.25	0.95 ± 0.20	1.06 ± 0.2	1.1 ± 0.15
8	$\pi^+ + p + f^0$					<0.1	<0.07
9	$\pi^+ + p + \varphi$					0.02 ± 0.02	0.02 ± 0.01

[a] See reference 3.
[b] See reference 4.

ω meson at 785 MeV. Applying a factor of 1.1 to correct for unobserved neutral decay modes of the ω, we find for the cross section of the reaction

$$\pi^+ + p \to \pi^+ + p + \omega \qquad (5)$$

a value of 1.2 ± 0.2 mb at 3.43 BeV/c and of 1.06 ± 0.1 mb at 3.54 BeV/c. As was observed in our preliminary report,[1] Reaction (5) is dominated by $N_{3/2,3/2}^*$ formation. [See the Dalitz plot[5] at Fig. 2(a).] We find that (48 ± 6)% of the ω mesons are produced according to the reaction $\pi^+ + p \to N_{3/2,3/2}^* + \omega$. Also we observe in the Dalitz plot [Fig. 2(a)] a grouping of events around the value $M_{\pi\omega}^2 = 1.5\ \mathrm{BeV}^2$. This effect is more clearly seen in Fig. 2(b), a plot of the effective-mass distribution of the $\pi^+\omega$ pairs of Reaction (5). The peak at about 1.22 BeV contains 60 ± 14 events above the background estimate (solid line, 50% phase space from $\pi^+ + p \to p + \pi^+ + \omega$ and 50% from $\pi^+ + p \to N_{3/2,3/2}^* + \omega$). In order to verify that this peak is not due to the $N_{3/2,3/2}^* + \omega$ events, we take these events off and plot in Fig. 2(c) the effective-mass distribution of $\pi^+\omega$ pairs of the remaining events. This distribution still shows a peak at 1.22 BeV. We interpret this peak as a possible $I = 1$, $\pi\omega$ resonance (let us call it B). Its position is at 1.22 BeV and it has a full width of 0.100 ± 0.020 BeV. We do not seem to observe this resonance in the mass spectrum of 4π ($\pi^+\pi^+\pi^-\pi^0$) when the

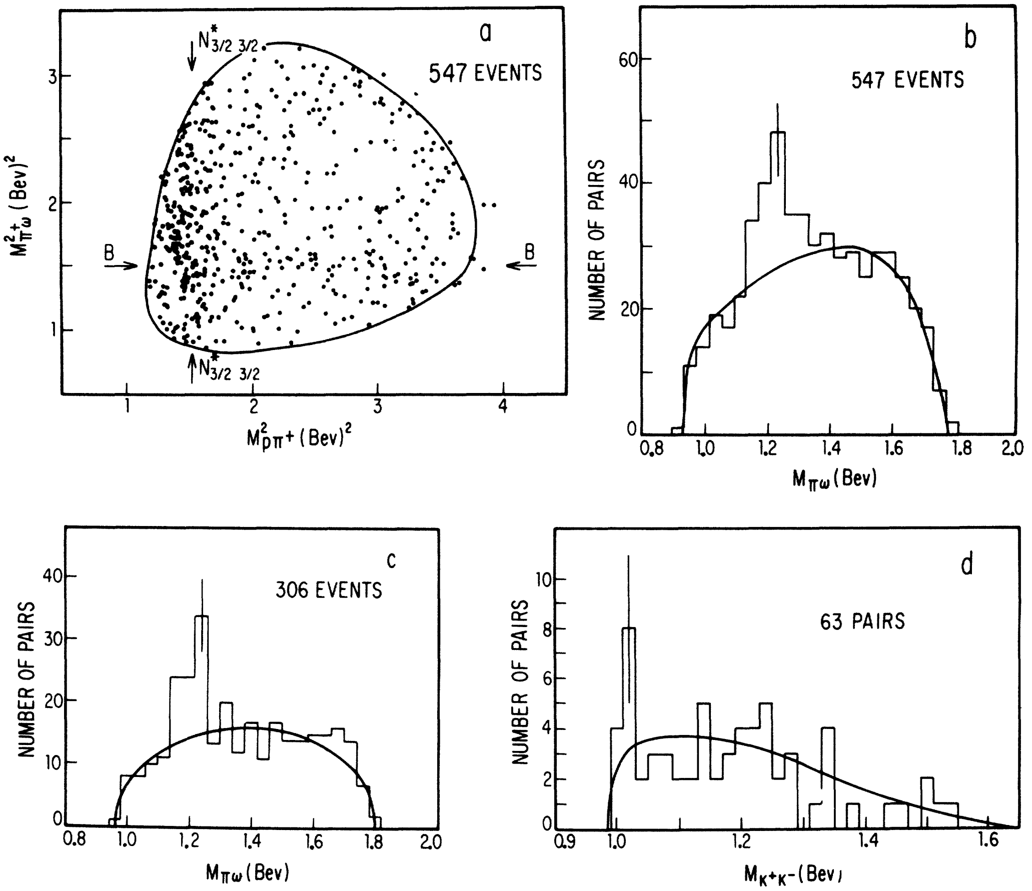

FIG. 2. (a) Dalitz plot of the reaction $\pi^+ + p \to p + \pi^+ + \omega$. (b) Effective-mass distribution of $\pi^+\omega$ pairs from the reaction $\pi^+ + p \to p + \pi^+ + \omega$. (c) Effective-mass distribution of $\pi^+\omega$ pairs from the reaction $\pi^+ + p \to p + \pi^+ + \omega$ when $M_{p\pi^+}$ is outside the N^* mass range (1150-1350 MeV). (d) Effective-mass distribution of K^+K^- pairs from the reaction $\pi^+ + p \to \pi^+ + K^+ + K^-$. In (b), (c), and (d) the solid lines are phase-space estimates (see text).

$\pi^+\pi^-\pi^0$ triplets are not in the range of the ω mass. An upper limit of 0.5 can be established for the ratio of decay ($B \rightarrow \pi^+ + \pi^+ + \pi^- + \pi^0$, direct)/($B \rightarrow \pi^+\omega$). Work is progressing to try to determine spin and parity of the B. An assignment 1^-, as suggested by Frazer, Patil, and Watson,[6] would require strong decays into 2π and $2K$. We are in the process of looking for these decay modes in the reactions $\pi^+ + p \rightarrow p + \pi^+ + \pi^0$ and $\pi^+ + p \rightarrow p + K^+ + \bar{K}^0$. Because B has $I = 1$, the 2π decay mode would be forbidden for strong interactions if it has even spin. Biswas[7] has suggested a spin parity 1^+ which would have the 2π and $2K$ decay modes forbidden for both strong and electromagnetic interactions.

This resonance is also observed by Kirz and Miller[8] who studied the reaction $\pi^- + p \rightarrow \pi^- + p + \omega$ at 3.24 BeV/c. From the same reaction at 4 BeV/c, Bondar et al.[9] seem to observe a maximum at 1.22 BeV in the $\pi^-\omega$ mass spectrum for events of low momentum transfer. It is interesting to notice that this is the first time that a resonance between a pion and a multipion resonance is observed.

(B) Production of η mesons. —Figure 1 also shows a peak of 37 ± 8 triplets at 560 MeV corresponding to the mass of the η. Using a factor of 3.5 to correct for the neutral decay mode of the η mesons,[4] we find for the cross section of the reaction $\pi^+ + p \rightarrow \pi^+ + p + \eta$ a value of 0.30 ± 0.13 mb at 3.43 BeV/c and of 0.23 ± 0.06 mb at 3.54 BeV/c.

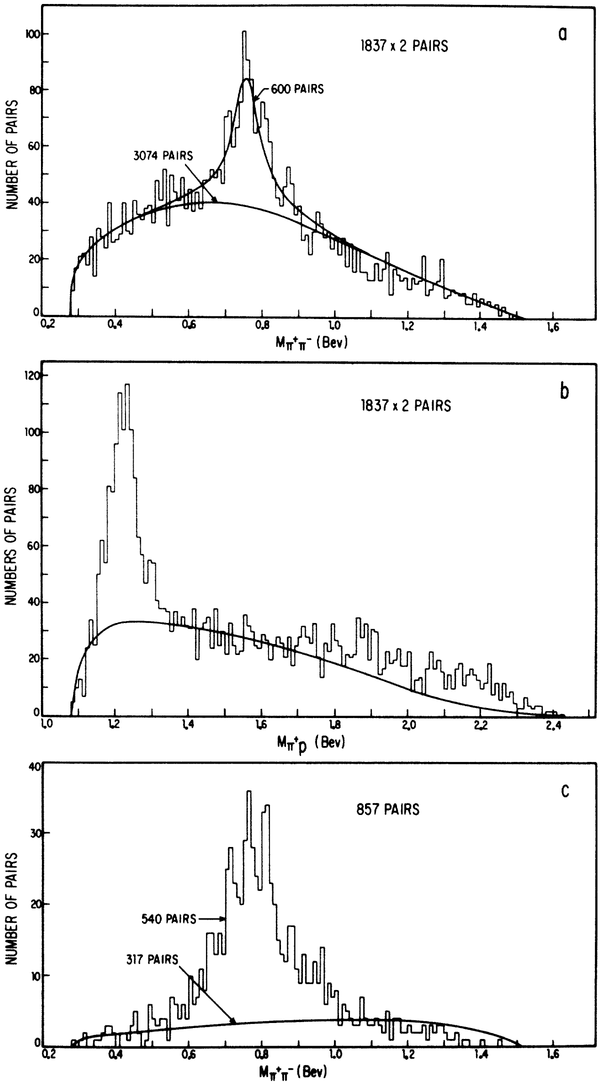

FIG. 3. Effective-mass distributions of pairs from reaction $\pi^+ + p \rightarrow \pi^+ + p + \pi^+ + \pi^-$: (a) $\pi^+\pi^-$ pairs, (b) $p\pi^+$ pairs, (c) $\pi^+\pi^-$ pairs which accompany a $p\pi^+$ pair with $M_{p\pi^+}$ between 1150 and 1350 MeV and with a small momentum transfer ($\Delta^2 < 30\mu^2$, μ = mass of charged pion). Solid lines are phase-space estimates of the background, except in (a) where we also fit the peak at 0.760 BeV with a Breit-Wigner curve (see text).

(C) Production of ρ^0 mesons. —Figure 3(a) shows the $\pi^+\pi^-$ mass spectrum of Reaction (1). This spectrum shows a ρ^0 peak above phase space which can be fitted to a Breit-Wigner curve with $M_\rho = 760 \pm 10$ MeV and $\Gamma = 90 \pm 10$ MeV. The cross section for the reaction $\pi^+ + p \rightarrow \pi^+ + p + \rho^0$ is 1.06 ± 0.2 mb at 3.43 BeV/c and 1.10 ± 0.15 mb at 3.54 BeV/c. The Reaction (1) is also dominated by the $N_{3/2,3/2}^*$ formation as shown by the histogram of the effective mass of the π^+p pairs [Fig. 3(b)]. [The disagreement with phase space (solid line) at the region of higher mass could be due to a reflection of the $N^* + \rho^0$ events.] When we plot [Fig. 3(c)] the effective-mass distribution of $\pi^+\pi^-$ pairs which accompany a $p\pi^+$ pair with an effective mass in the region of $N_{3/2,3/2}^*$ (1150 MeV $< M_{p\pi^+} <$ 1350 MeV) and with a small momentum transfer ($\Delta^2 < 30\mu^2$, μ = mass of a charged pion), we get a big ρ^0 peak which contains about 90% of the ρ^0 production in Reaction (1).[10] This fact agrees with the hypothesis that in Reaction (1) the ρ^0 mesons are produced through the reaction $\pi^+ + p \rightarrow N_{3/2,3/2}^* + \rho^0$ following a one-pion exchange (OPE) model as illustrated by Fig 4(a). Further support for this hypothesis is the isotropy of the Yang-Treiman angle distribution in the ρ^0 rest frame for the $N^* + \rho^0$ events. It is interesting to notice that in the ρ^0 rest frame, we get an asymmetric $\cos\theta_{\pi\pi}$ distribution ($\theta_{\pi\pi}$ = angle between incident and outgoing π^+), instead of the

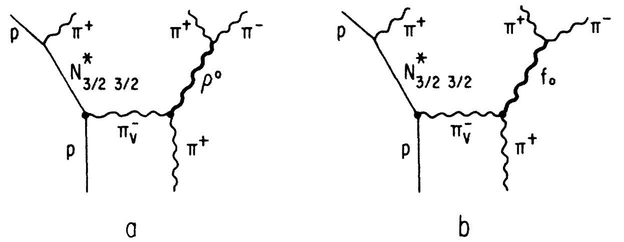

FIG. 4. Diagrams illustrating some processes of production of multimeson resonances by pion-nucleon interaction (see text).

expected $\cos^2\theta$ distribution for a pure $I=1$, $J=1$, $\pi\pi$ resonance. This distribution is, however, very similar to the one observed in the reaction $\pi^-+p\to n+\rho^0$.[11] It has been suggested that this asymmetry could be due to an interference with an S and D wave ($I=0$) background.[11]

(D) Production of f^0 mesons. —As shown by Figs. 3(a) and 3(c), we do not seem to observe the f^0 meson[12] ($I=0$, $\pi\pi$ resonance at 1250 MeV). Our data yielded an upper limit to the cross section of the reaction $\pi^++p\to\pi^++p+f^0$ of 0.1 mb for 3.43 BeV/c and 0.07 mb for 3.54 BeV/c. Aitchison,[13] using an OPE exchange model for production of ρ^0 and f^0 [see Figs. 4(a) and 4(b)] predicts the ratio of the two cross sections at 3.54 BeV/c to be

$$R=\sigma(\pi^+pf^0)/\sigma(\pi^+p\rho^0)=\tfrac{1}{6}(\text{width of } f^0/\text{ width of } \rho^0).$$

Our results give

$$R<0.07/1.1\sim 1/15.$$

If one takes the width of f^0 to be the same as the width of ρ^0 as indicated in reference 12, then our result is in contradiction with the prediction of Aitchison. For this prediction to agree with our results, the width of f^0 must be about 1/2.5 the width of the ρ^0.

(E) Production of ϕ mesons. —Figure 2(d) shows the mass spectrum of the K^+K^- pairs from Reaction (4) events. We observe a small peak at 1.020 BeV. If we interpret this peak as due to the ϕ meson,[14] and assume an equal number of unobserved $K_1{}^0K_2{}^0$ decays of the ϕ meson,[14] we get for the cross section of the reaction $\pi^++p\to\pi^++p+\phi$ a value of 20 ± 20 μb at 3.43 BeV/c and 20 ± 10 μb at 3.54 BeV/c. This is to be compared with the value of 1.2 ± 0.2 and 1.06 ± 0.1 mb for the cross section of $\pi^++p\to\pi^++p+\omega$ at the same energies and of 50 ± 6 μb for the cross section of the $K^-+p\to\Lambda+\phi$ reaction at 1.95 BeV/c.

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NUCLEON AXIAL-VECTOR FORM FACTOR

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High-energy neutrino experiments at CERN and Brookhaven will soon be able to give some information on the nucleon axial-vector form factor, through separate measurements of $\nu n \to pl$ and $\bar{\nu}p \to n\bar{l}$ cross sections.[1] We report here a dispersion-theoretical estimate of the rate of decrease of this axial-vector form factor F with increasing momentum transfer. F is defined by

$$(E_N E_{\bar{N}}/M^2)^{1/2}\langle 0|A_\mu|N\bar{N}\rangle = \bar{v}_{\bar{N}}\{\gamma_5\gamma_\mu F(s) - 2i\gamma_5 K_\mu G(s)\}u_N, \tag{1}$$

where A_μ = weak axial-vector current, $K_\mu = \frac{1}{2}(P_{\bar{N}} + P_N)_\mu$, M = nucleon mass (with pion mass μ taken to be unity), and $s = 4K^2$. Here and in the following, the trivial isotopic spin dependences will be suppressed.

Among the intermediate states that can contribute to the imaginary part of F, we will keep only the one with the lightest mass, i.e., the 3π state, and will further assume that this is approximated by the $\pi\rho$ state. We will use the generalized unitarity and N/D formulation appropriate for 3-particle intermediate states only as a guide,[2] but will treat the ρ as if it were stable as much as possible. Under such an assumption one needs the matrix elements $\langle\pi\rho|N\bar{N}\rangle$ and $\langle 0|A_\mu|\pi\rho\rangle$.

(a) The $\langle\pi\rho|N\bar{N}\rangle$ amplitude. – For the discontinuities across the dynamical cuts of this amplitude we will use Born approximation with one nucleon exchange. This is a strong assumption,[3] with which, however, the problem simplifies considerably, because it contributes to only the following three invariant amplitudes:

$$2(E_N E_{\bar{N}} E_\pi E_\rho/M^2)^{1/2}\langle\pi\rho|N\bar{N}\rangle = \bar{v}_{\bar{N}}\{i\gamma_5\eta^*\cdot K\alpha(s,\cos\theta) + i\gamma_5\eta^*\cdot P\beta(s,\cos\theta) + i\gamma_5\sigma_{\mu\nu}Q_\mu\eta_\nu^*\lambda(s,\cos\theta)\}u_N, \tag{2}$$

where η = polarization vector of ρ, $Q_\mu = \frac{1}{2}(P_\rho - P_\pi)_\mu$, $P_\mu = \frac{1}{2}(P_N - P_{\bar{N}})_\mu$, and θ = c.m. scattering angle. From invariance considerations, the matrix element $\langle 0|A_\mu|\pi\rho\rangle$ is of the form

$$2(E_\pi E_\rho)^{1/2}\langle 0|A_\mu|\pi\rho\rangle = \eta\cdot KQ_\mu A(s) + \eta_\mu B(s) + \eta\cdot KK_\mu C(s). \tag{3}$$

The form factor C may be relatively large because it receives contribution via a one-pion state. But it is clear that C cannot contribute to any $J = 1$ state. From Eqs. (1), (2), and (3),

$$\operatorname{Im}F(s) = (q/2\sqrt{s})\lambda^J(s)B(s) \quad (s > 42), \tag{4}$$

where

$$\lambda^J(s) \equiv \int_{-1}^{1}\lambda(s,\cos\theta)\frac{Mq}{p}\cos\theta\frac{d\cos\theta}{8\pi},$$

and q and p = magnitudes of ρ and N c.m. momenta, respectively. We now write a set of N/D equations for $\lambda^J(s)$. We will denote by the subscript 1 the $N\bar{N}$ channel with $J = 1$, $\tau = 1$, and parity +; and by subscripts 2 and 3 the two mutually orthogonal $\pi\rho$ states with these same quantum numbers, such that $\lambda^J(s)$ corresponds to the reaction $1 \to 2$. Thus

$$\lambda^J(s) = \sum_{j=1}^{3} N(s)_{1j}D^{-1}(s)_{j2}, \tag{5}$$

$$N(s)_{ij} = \frac{1}{\pi}\sum_K\int_L \frac{[\mathrm{disc}ND^{-1}(s')]_{ik}D(s')_{kj}}{s'-s}ds', \tag{6}$$

$$D(s)_{ij} = \delta_{ij} + \frac{1}{\pi}\int_R \frac{q'^3 N(s')_{ij}}{2\sqrt{s'}(s'-s)}ds', \tag{7}$$

where L denotes the dynamical cuts and R the physical cuts. In Eq. (7), a subtraction may be required. We will solve these equations by the first iterations in a determinantal approximation, replacing the discontinuities across the dynamical cuts by the Born-approximation contributions.

Consider first $N(s)_{22}$, corresponding to $\pi\rho$ scattering. The Born approximation with one-pion