PRODUCTION OF PION RESONANCES IN $\pi^+ p$ INTERACTIONS*

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About ten thousand interactions of positive pions with protons have been studied with the BNL 20-in. liquid hydrogen bubble chamber. The chamber was operated in the separated beam set up at the AGS by the Yale-Brookhaven groups.[1] Thirty thousand pictures were taken at an incident momentum of 2.34 BeV/c, fifteen thousand at 2.62 BeV/c, and thirty thousand at 2.90 BeV/c. Events within a fiducial volume were selected for measurement on digitized projectors and were then kinematically reconstructed and fed into a GUTS fitting program which tried various production hypotheses for each event configuration. At the time an event was scanned, an ionization code was assigned to each track depending on whether it appeared minimum ionizing, medium, or heavy. Using this scheme, tracks dipping at less than 40° could be reliably identified as either protons or pions up to a momentum of 1 BeV/c, while tracks dipping between 40° and 60° could be so labelled up to 600 MeV/c.

An event was accepted as fitting a hypothesis if its χ^2 was below a cutoff chosen so that only an estimated 3% of correctly identified events would have been rejected, and if the fitted momenta for all tracks were consistent with the ionization code numbers. In the two-prong interactions any event fitting elastic scattering was taken to be in that category, even if it also fitted some other production hypothesis. With these criteria the fraction of ambiguous four-prong events was 8%, while about 15% of the two-prong interactions could not be uniquely identified. Table I shows the cross sections for the various production processes computed by assigning the ambiguous events with appropriate weights into their various categories.

A striking feature of the interactions is the dominance of pionic resonant states as shown in Fig. 1, where the $\pi^+\pi^0$ mass spectrum from reaction 1 (see Table I), the $\pi^+\pi^-$ distribution from reaction 3 and the $\pi^+\pi^-\pi^0$ masses from reaction 4 are shown. ρ production accounts for about 40% of both the single and the double pion events, while the η and ω account for approximately 5% and 50%, respectively, of all $\pi^+\pi^-\pi^0$ production. The cross sections for production of these states are shown in Table I where the values for the η and the ω have been corrected to include the decays of these particles via neutral modes.

Breit-Wigner resonance curves with the parameters shown in Table II have been superimposed on phase-space backgrounds for the two pion masses, and a phase-space curve has been drawn for events outside the peaks on the triple pion distribution. For present purposes the ρ^0 has

Table I. Cross sections in millibarns.

Reaction	$\pi^+ + p \rightarrow$	π^+ momentum (BeV/c) 2.34	2.62	2.90
1	$\pi^+ + p + \pi^0$	4.7 ± 0.3	···	3.6 ± 0.3
2	$\pi^+ + \pi^+ + n$	2.2 ± 0.25	···	2.1 ± 0.3
3	$\pi^+ + p + \pi^+ + \pi^-$	3.2 ± 0.2	3.5 ± 0.3	3.1 ± 0.2
4	$\pi^+ + p + \pi^+ + \pi^- + \pi^0$	3.1 ± 0.2	3.6 ± 0.3	4.1 ± 0.2
5	$\pi^+ + \pi^+ + \pi^+ + \pi^- + n$	0.27 ± 0.06	0.37 ± 0.08	0.56 ± 0.06
6	$p + \rho^+$	2.1 ± 0.3	···	1.4 ± 0.2
7	$\pi^+ p \rho^0$	1.4 ± 0.25	1.4 ± 0.25	0.95 ± 0.2
8	$\pi^+ p \eta^0$	0.75 ± 0.15	0.75 ± 0.18	0.80 ± 0.15
9	$\pi^+ p \omega^0$	1.8 ± 0.2	1.6 ± 0.2	1.6 ± 0.2

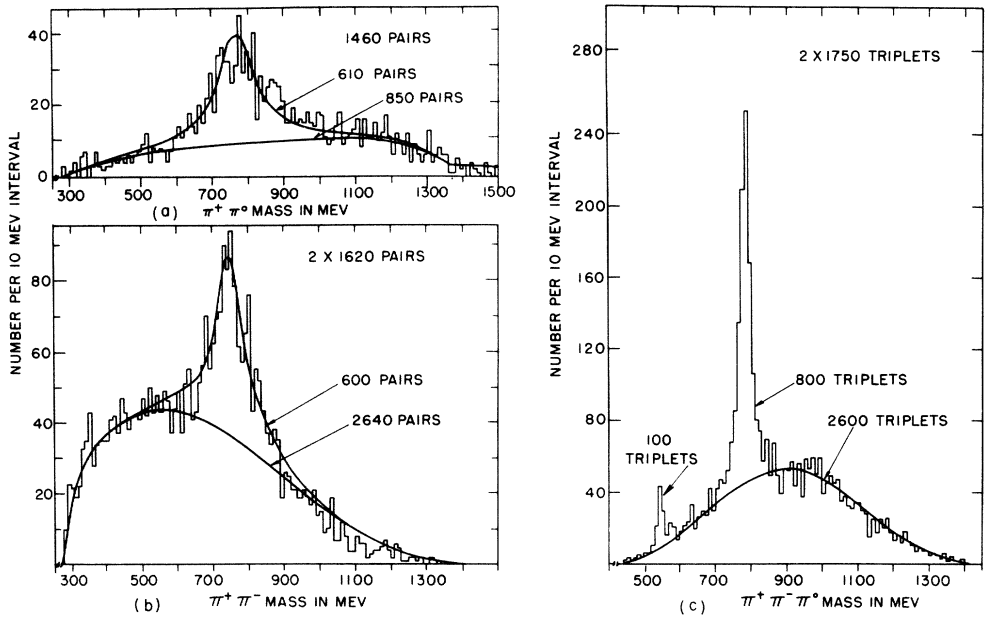

FIG. 1. Mass distributions (a) for $\pi^+\pi^0$ pairs from $\pi^+ + p \rightarrow \pi^+ + p + \pi^0$ events, (b) for $\pi^+\pi^-$ pairs from $\pi^+ + p \rightarrow \pi^+ + p + \pi^+ + \pi^-$ events, and (c) for $\pi^+\pi^-\pi^0$ triplets from $\pi^+ + p \rightarrow \pi^+ + p + \pi^+ + \pi^- + \pi^0$ events.

been fitted with a single resonance; a discussion of possible interference effects due to the 2π decay of the ω is given in the following Letter.[2] The observed widths of the η and ω are 20 MeV and 30 MeV, and upper limits have been placed on the natural widths of these particles by unfolding experimental resolution functions. These functions were obtained by plotting Gaussian ideograms of the errors assigned by GUTS to events near 550 and 785 MeV. The upper limits obtained and the η and ω masses are also shown in Table II.

The possibility that the ρ^0, η^0, and ω^0 are made with pion-nucleon isobars has been investigated by plotting the combined mass of the proton and that π^+ not in the resonant state. Fig. 2 shows the distributions and clearly indicates that rhos and omegas are produced predominantly with the $(\frac{3}{2}, \frac{3}{2})$ isobar. For etas the situation is not so clear, though there is some suggestion that here

Table II. Masses and widths of resonant states.

	Mass	Full width at half max
ρ^+	770 ± 10 MeV	Γ = 130 ± 10 MeV
ρ^0	750 ± 10 MeV	Γ = 100 ± 10 MeV
ω^0	782 ± 1 MeV	$\Gamma \leq$ 20 MeV
η^0	548 ± 1 MeV	$\Gamma \leq$ 10 MeV

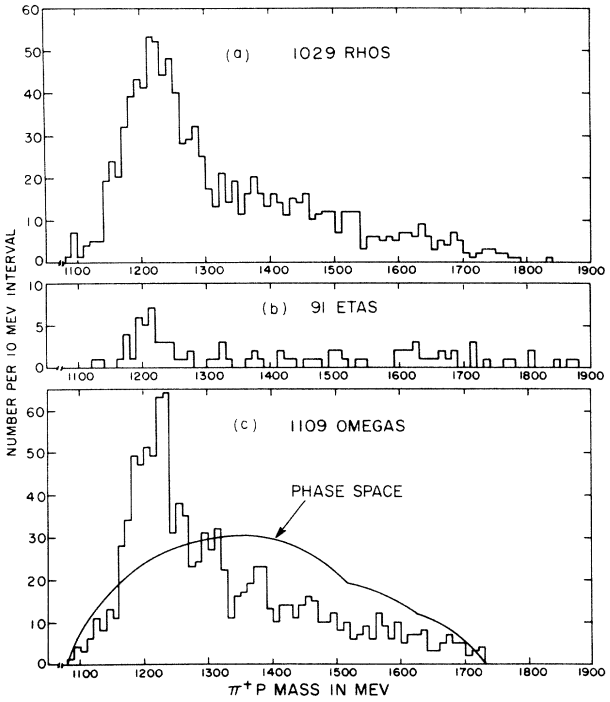

FIG. 2. The mass distributions for π^+-proton pairs produced (a) in association with $\pi^+\pi^-$ pairs from reaction 3 with mass between 680 and 830 MeV, and (b) in association with $\pi^+\pi^-\pi^0$ triplets from reaction 4 with $530 < M(\pi^+\pi^-\pi^0) < 580$, and (c) $750 < M(\pi^+\pi^-\pi^0) < 830$.

also isobars are made. Charge independence then requires that the cross sections for $\pi^+ + p \to \pi^+ + p + \eta$ or ω, respectively, be nine times those for $\pi^- + p \to \pi^- + p + \eta$ or ω, provided that also in the latter reaction the isobar is produced. Data are available for $\pi^- p$ interactions at 2 BeV/c,[3] where the ω production cross section is (200 ± 60) μb, one ninth of the $\pi^+ p$ value at 2.35 BeV/c. The quoted η cross section of (110 ± 35) μb at 2 BeV/c is more than one ninth of that for η production in $\pi^+ p$ collisions, but because of the large errors, the ratio is not well determined.

Center-of-mass angular distributions for events with ρ, η, and ω masses are presented in Fig. 3. There is sharp forward peaking in the ρ^+ and ρ^0 distributions, which is to be expected on the basis of the single-pion exchange model previously found to be valid for charged ρ production[4] and confirmed by this experiment for $\pi^+ p$ ρ^0 events.

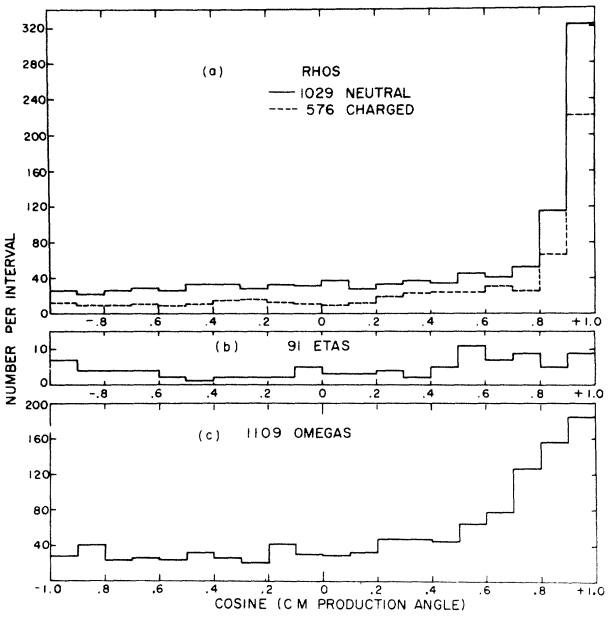

FIG. 3. Center-of-mass production angles for (a) rhos, (b) etas, and (c) omegas defined as in Fig. 2.

Resonances have been reported or suggested in other experiments in the $\pi^+ \pi^-$ system at 395,[5] 420,[6] 520,[5] 560,[7] and 1250 MeV,[8] in the $\pi^- \pi^-$ system at 620 MeV,[6] and in the $\pi^+ \pi^- \pi^0$ and $\pi^+ \pi^+ \pi^-$ systems at 625 MeV.[9] None of these are observed in the present work. Effective masses have also been computed for all other possible particle combinations and these also show no resonances. In particular, there is no resonance in the $T = \frac{5}{2}$ state.

Since these reported resonances are allegedly properties of the relevant systems of pions, their absence in this experiment and in others must be considered as significant as their appearance in the experiments reporting them.

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[1]C. Baltay, E. C. Fowler, J. R. Sanford, J. Sandweiss, H. N. Brown, W. B. Fowler, and M. Webster, BNL Bubble Chamber Group Internal Report C-29, 1962 (unpublished).

[2]C. Alff et al., following Letter [Phys. Rev. Letters 9, 325 (1962)].

[3]D. D. Carmony, F. Grard, R. T. Van de Walle, and N.-H. Xuong, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published).

[4]D. D. Carmony and R. T. Van de Walle, Phys. Rev. Letters 8, 73 (1962).

[5]N. P. Samios, A. H. Bachman, R. M. Lea, T. E. Kalogeropoulos, and W. D. Shephard, Phys. Rev. Letters 9, 139 (1962).

[6]C. Richardson, R. Kraemer, M. Meer, M. Nussbaum, A. Pevsner, R. Strand, R. Tovmig, and M. Block, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published).

[7]R. Barloutaud, J. Heughebaert, A. Leveque, J. Meyer, and R. Omnes, Phys. Rev. Letters 8, 32 (1962); B. Sechi Zorn, Phys. Rev. Letters 8, 282 (1962).

[8]A. Baker, H. Brody, V. Hagopian, and W. Selove, Phys. Rev. Letters 9, 221 (1962)].

[9]E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. Letters 8, 329 (1962).