Two-Prong Interaction by $\pi^+ + p$ Collisions at 2.77 BeV/c

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Two-prong interactions by 2.77-BeV/c π^+ on protons were investigated. The elastic scattering angular distribution shows an elastic exponential forward peak as well as two diffraction minima. The final state $\pi^+ + p + \pi^0$ involves significant production of ρ^+, N^{*+}, and N^{*++}. The final state $\pi^+ + \pi^+ + n$ shows no $T=2$ dipion resonance formation. Significant production of $\eta + N^{*++}$ is observed where the η decays into neutral final states.

INTRODUCTION

RECENT investigations of $\pi^+ + p$ interactions[1–3] in the momentum range of 1.5 to 5 BeV/c have shown the predominance of single- and double-resonance production in those interactions in which single or multiple pions are produced. Many investigators have analyzed with moderate success the mechanism of resonance production in terms of single-particle-exchange models with various modifications.[2–8] Relatively little work has been done on interactions involving more than one neutral particle. The present work is the last of a series of investigations on $\pi^+ + p$ interactions at 2.77 BeV/c. The results from strange-particle production[9] and four-prong events[2] have already been published. In the present work, we present data on the following reactions:

$$\pi^+ + p \to \pi^+ + p \quad (1)$$

$$\to \pi^+ + p + \pi^0 \quad (2)$$

$$\to \pi^+ + \pi^+ + n \quad (3)$$

$$\to \pi^+ + p + \text{missing mass (excluding single } \pi^0) \quad (4)$$

$$\to \pi^+ + \pi^+ + \text{missing mass (excluding neutron)}. \quad (5)$$

Reaction (2) involves significant production of ρ^+(760 MeV/c^2), N^{*++}(1238 MeV/c^2), and N^{*+}(1238 MeV/c^2). Because of limited statistics, we have made no effort to fit the decay angular correlations of these resonances to detailed models such as the Gottfried-Jackson model (single-particle exchange with absorption)[7,10–13] or a model which allows for a mixture of scalar and vector mesons as the exchanged particles.[8] Rather, we simply present the decay correlation angular distributions and, wherever meaningful, least-squares fits to these distributions.

Reaction (4) shows a clear formation of η and an indication of ω and ϕ. These resonances can decay into completely neutral particles, and a brief comparison with our previous results from the four-prong and strange-particle events will be given.

ANALYSIS METHOD

Our results are based on approximately 65 000 pictures taken in the BNL 20-in. (now 31-in.) liquid-hydrogen bubble chamber exposed to a beam of 2.77-BeV/c π^+. The details of the experimental arrangements have been published.[9]

Only the two-prong events appearing in the fiducial region were studied. Of 12 600 events found by scanning, about 8500 events were measured, and computed by BNL TRED–KICK programs. Only the events whose kinematic fits has the χ^2 probabilities greater than 0.1% were accepted as fitted events. If an event made a 4-constraint fit as reaction (1), it was accepted automatically, regardless of the existence of other fits, unless its χ^2 probability was lower by a factor of 10 than those of other possible fits. In the latter case, an event was examined for ionization information.

Events fitting any of the other reactions were examined on a scanning table for ionization consistency. Only the fit which gave ionization estimates consistent

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† Work supported under the auspices of the U. S. Atomic Energy Commission.

[1] Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I.C.)-München Collaboration, Phys. Rev. **138**, B897 (1965). This reference contains extensive earlier references on $\pi^{\pm} + p$ interactions, and the reader is referred to this paper for further references.
[2] S. S. Yamamoto, J. R. Smith, D. C. Rahm, and J. L. Lloyd, Phys. Rev. **140**, B730 (1965).
[3] C. Alff-Steinberger *et al.*, Phys. Rev. **145**, 1072 (1966).
[4] Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I.C.)-München Collaboration, Nuovo Cimento **34**, 495 (1964); **35**, 659 (1966).
[5] Aachen-Berlin-CERN Collaboration, Phys. Letters **22**, 533 (1966).
[6] I. Derado, V. P. Kenney, and W. D. Shephard, Phys. Rev. Letters **13**, 505 (1964).
[7] J. D. Jackson, J. T. Donohue, K. Gottfried, R. Keyser, and B. E. Y. Svensson, Phys. Rev. **139**, B428 (1965). This reference contains extensive references on both theoretical and experimental work on the single-particle-exchange mechanism.
[8] I. Derado *et al.*, Phys. Letters **24**, 106 (1967).
[9] S. S. Yamamoto, L. Bertanza, G. C. Moneti, D. C. Rahm, and I. O. Skillicorn, Phys. Rev. **134**, B383 (1964).
[10] J. D. Jackson and M. Pilkuhn, Nuovo Cimento **33**, 906 (1964); **34**, 1841 (1964).
[11] K. Gottfried and J. D. Jackson, Nuovo Cimento **33**, 309 (1964); Phys. Letters **8**, 144 (1964); Nuovo Cimento **34**, 735 (1964); **34**, 1843 (1964).
[12] J. D. Jackson, Nuovo Cimento **34**, 1644 (1964).
[13] J. D. Jackson, Rev. Mod. Phys. **38**, 484 (1965).

TABLE I. Partial cross sections.

Final state	Cross section (mb)
$\pi^+ + p$	7.70 ± 1.32
$\pi^+ + p + \pi^0$	4.88 ± 0.23
$\pi^+ + \pi^+ + n$	2.59 ± 0.15
$\pi^+ + p$ + missing mass	3.06 ± 0.16
$\pi^+ + \pi^+$ + missing mass	1.69 ± 0.10

with visual examination was accepted. Even with the ionization check, about 3% of the total events remained ambiguous. Most of the ambiguous events were between reactions (2) and (3). Various effective-mass plots using only these ambiguous events interpreted first as reaction (2) and second as reaction (3) did not seem to show any structure (such as the ρ peak) which occurred in the effective-mass plots using unambiguous events. Thus we concluded that neither reaction (2) nor reaction (3) dominated the ambiguous events. Since a comparison between plots with *all* events and the same plots with only the unambiguous events showed no significant discrepancy, the ambiguous events were excluded from further analysis.

The ambiguous events, however, were apportioned out according to the ratios of the unambiguous events for cross-section measurements.

CROSS SECTIONS

Table I lists the partial cross sections for reactions (1)–(5). The errors include an estimate of systematic errors. In order to correct for the scanning loss in the elastic events of reaction (1), we plotted the distributions of the normal to the scattering plane with respect to the axis which is perpendicular to the camera plane. The distribution is isotropic until the cosine of the c.m. scattering angle (defined as $\hat{p}_{\pi^+\mathrm{beam}} \cdot \hat{p}_{\pi^+}$) becomes greater than 0.85. After the cosine exceeds 0.975, many events are lost because many of the recoil protons have a range less than 2 mm and are no longer visible to the

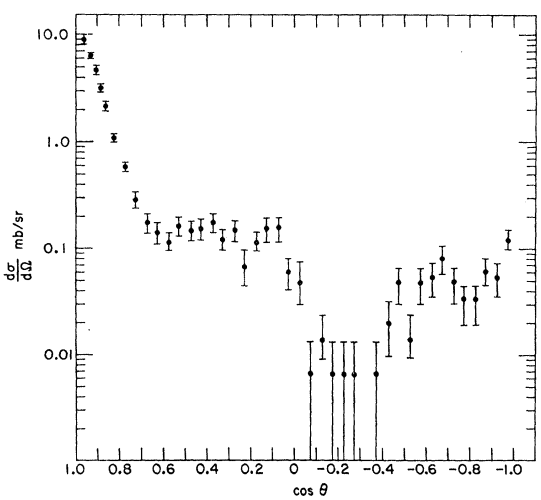

FIG. 1. Angular distribution of π^+ from the final state $\pi^+ + p$.

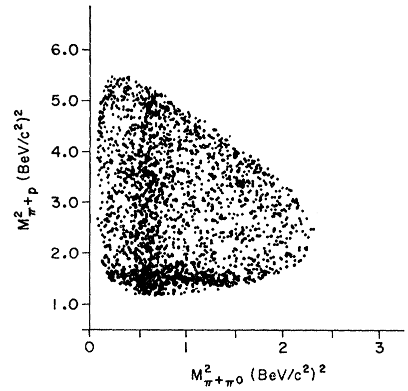

FIG. 2. Dalitz plot of $M_{\pi^+\pi^0}{}^2$ for the final state $\pi^+ + p + \pi^0$.

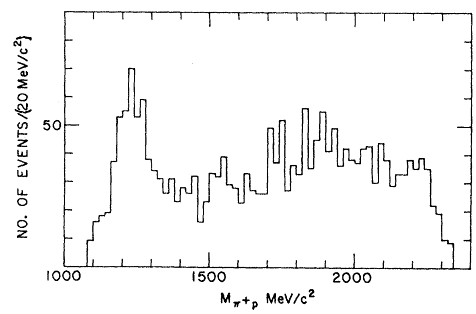

FIG. 3. Histogram of M_{π^+p} from the final state $\pi^+ + p + \pi^0$.

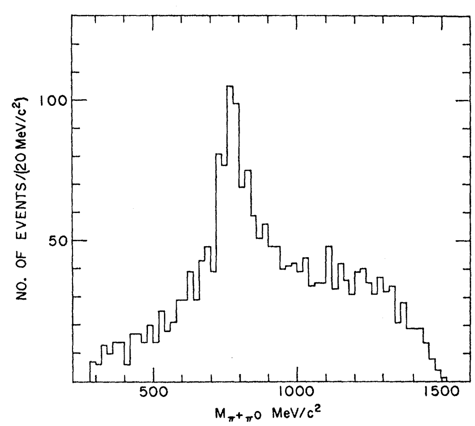

FIG. 4. Histogram of $M_{\pi^+\pi^0}$ from the final state $\pi^+ + p + \pi^0$.

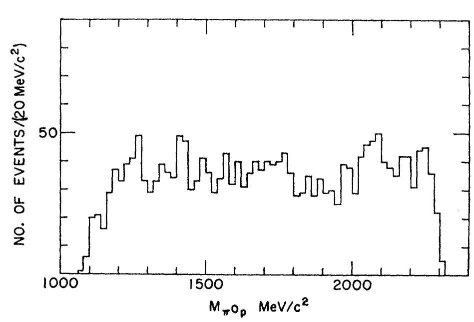

FIG. 5. Histogram of M_{π^0p} from the final state $\pi^+ + p + \pi^0$.

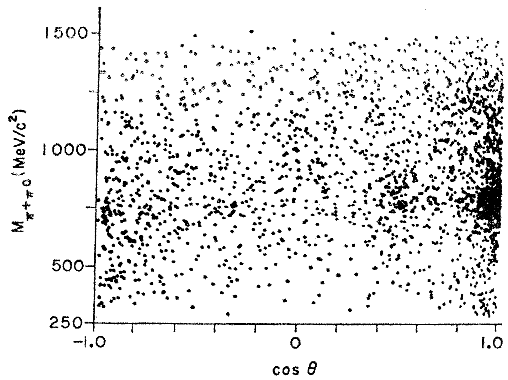

FIG. 6. Scatter plot of $M_{\pi^+\pi^0}$ versus cosine of the dipion production angle from the final state $\pi^+ + p + \pi^0$.

scanner. As will be shown in the next section, we fitted the forward diffraction peak of the elastic scattering to an exponential and extrapolated the fit to zero-degree scattering to get an estimate of the number of events lost in scanning. The total number of elastic events actually found by scanning is then increased by the amount which were missing by scanning (this is *not* the scanning efficiency). The corrected number of events scanned were then corrected for the scanning efficiency, which was 98%.

The results in Table I are in good agreement with those obtained by Alff *et al.*[3,14]

ELASTIC SCATTERING

Figure 1 shows the c.m. angular distribution of the scattered π^+ with repsect to the incoming beam. It shows clearly the diffraction peak which obeys an exponential law and the first and second diffraction minima at about $\cos\theta = 0.6$ and $\cos\theta = -0.2$. The positions of these minima and the over-all shape of the angular distribution are in excellent agreement with data obtained by several authors.[15,16] We have fitted our forward

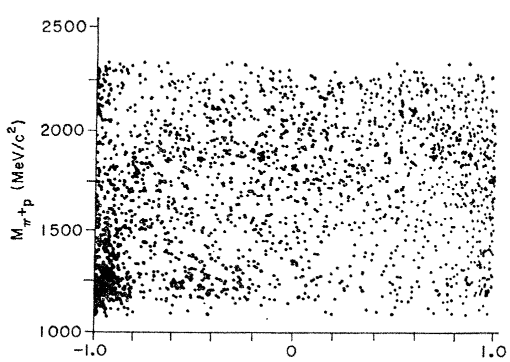

FIG. 7. Scatter plot of M_{π^+p} versus cosine of the M_{π^+p} production angle from the final state $\pi^+ + p + \pi^0$.

[14] C. Alff *et al.*, Phys. Rev. Letters **9**, 322 (1962).
[15] C. T. Coffin *et al.*, Phys. Rev. Letters **15**, 838 (1965).
[16] C. Coffin *et al.*, Phys. Rev. Letters **17**, 458 (1966); M. L. Perl *et al.*, Phys. Rev. **132**, 1252 (1963).

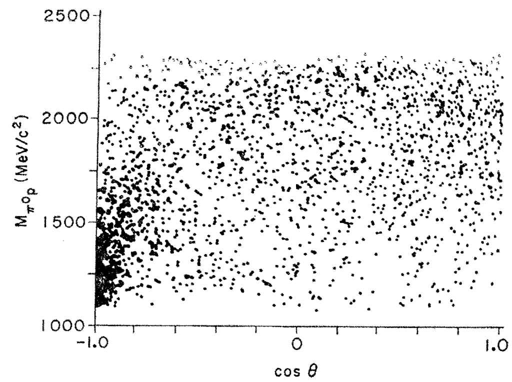

FIG. 8. Scatter plot of M_{π^0p} versus cosine of the M_{π^0p} production angle from the final state $\pi^+ + p + \pi^0$.

peak to a form

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{t=0} e^{+\beta t}.$$

A least-squares analysis gives a value of $\beta = +6.16 \pm 1.51$ $(\text{BeV}/c)^{-2}$. This value of β is in good agreement with values found in other experiments in this momentum region.[3,16,17]

REACTIONS $\pi^+ + p \to \pi^+ + p + \pi^0$

Figure 2 shows the Dalitz plot for $M_{\pi^+p}{}^2$ versus $M_{\pi^+\pi^0}{}^2$. Formation of ρ^+(760 MeV/c^2) and N^{*++}(1238 MeV/c^2) is clear. Figures 3–5 show, respectively, the effective-mass distributions for M_{π^+p}, $M_{\pi^+\pi^0}$, and M_{π^0p}. Figure 5 shows the formation of N^{*+}(1238 MeV/c^2), which is not so clear in the Dalitz plot shown in Fig. 2. The ratio of N^{*++} to N^{*+} should be 3 to 2, and our data are consistent with this ratio. We defined the ρ and N^* masses to be $680 \leq M_\rho \leq 880$ MeV/c^2 and $1140 \leq M_{N^*} \leq 1320$ MeV/c^2, respectively, and selected the following

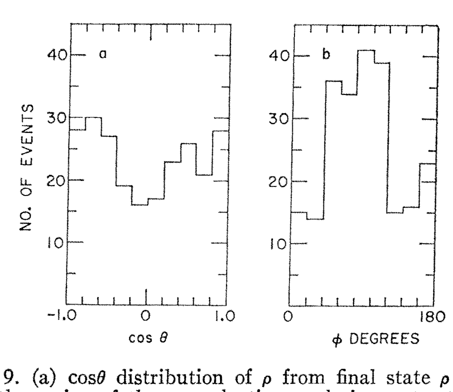

FIG. 9. (a) $\cos\theta$ distribution of ρ from final state $\rho^+ + p$ for which the cosine of the ρ production angle is greater than 0.8. (b) Treiman-Yang angular distribution of ρ from the final state $\rho^+ + p$ with the same angular cut as in (a).

[17] Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I.C.)-München Collaboration, Phys. Letters **10**, 248 (1964).

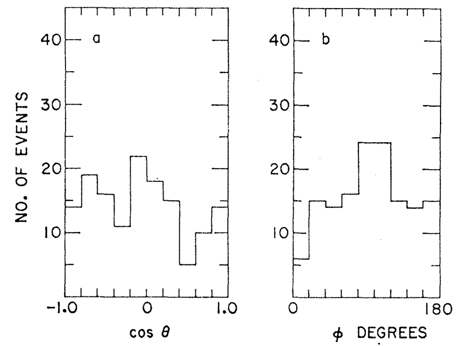

FIG. 10. (a) $\cos\theta$ distribution of N^{*++} from the final state $N^{*++}+\pi^0$ for which the cosine of the N^{*++} production angle is less than -0.8. (b) Treiman-Yang angular distribution of N^{*++} from the final state $N^{*++}+\pi^0$ with the same angular cut as in (a).

quasi two-body final states:

$$\pi^+ + p \to \rho^+ + p \quad (6)$$

$$\to \pi^0 + N^{*++} \quad (7)$$

$$\to \pi^+ + N^{*+}. \quad (8)$$

We made certain in the above selections that no single particle was "shared" by two resonances (such as π^+ between ρ^+ and N^{*++}). The ratio of reaction (6) to (7) to (8) was about 5:3:2. About 50% of the total events were nonresonant using the above mass cuts.

Figures 6–8 show, respectively, the scatter diagrams of $M_{\pi^+\pi^0}$ versus the cosine of the dipion production angle in the reaction c.m. system, M_{π^+p} versus the cosine of the π^+-proton-system production angle, and M_{π^0p} versus the cosine of the π^0-proton-system production angle. It is clear from these diagrams that the ρ^+, N^{*++}, and N^{*+} are produced peripherally. Because of this peripheral nature of the interactions, we obtained the angular correlations of the decay of the ρ^+, N^{*++}, and N^{*+} which might be pertinent to the analysis of these quasi two-body states in terms of a single-particle-exchange model. The two most common correlation angles are (a) $\cos\theta$ defined by Gottfried and Jackson as the cosine of the angle between the incident-beam

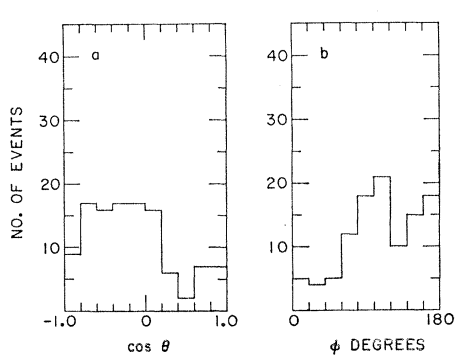

FIG. 11. (a) $\cos\theta$ distribution of N^{*+} from the final state $N^{*+}+\pi^+$ for which the cosine of the N^{*+} production angle is less than -0.8. (b) Treiman-Yang angular distribution of N^{*+} from the final state $N^{*+}+\pi^+$ with the same angular cut as in (a).

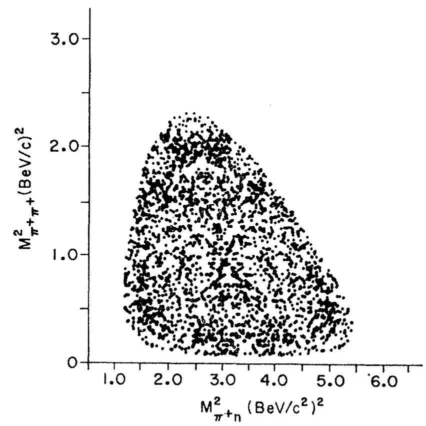

FIG. 12. Dalitz plot of $M_{\pi^+\pi^+}{}^2$ versus $M_{\pi^+n}{}^2$ from the final state $\pi^+ + \pi^+ + n$.

direction and the direction of one of the decay products (e.g., π^+ from ρ^+) evaluated in the resonance c.m. system and (b) the Treiman-Yang angle[18] or, equivalently, the angle ϕ defined by Gottfried and Jackson. Figure 9(a) shows the $\cos\theta$ distribution for the π^+ from the decay of ρ^+ from reaction (6) with a cut such that only those events with the cosine of the ρ^+ production angle greater than $+0.8$ were included. A least-squares fit of the form $A+B\cos^2\theta$ was made to this distribution with $A=37.83\pm5.58$ and $B=26.32\pm13.91$. We also examined the $\cos\theta$ distributions for the following intervals of the cosine of the ρ^+ production angle: (a) $0.85\geq\cos\theta\geq0.8$, (b) $0.9\geq\cos\theta\geq0.85$, (c) $0.95\geq\cos\theta\geq0.9$, and (d) $1.0\geq\cos\theta\geq0.95$. Because of the limited statistics, we were unable to obtain any meaningful fits to these distributions. The over-all shape of

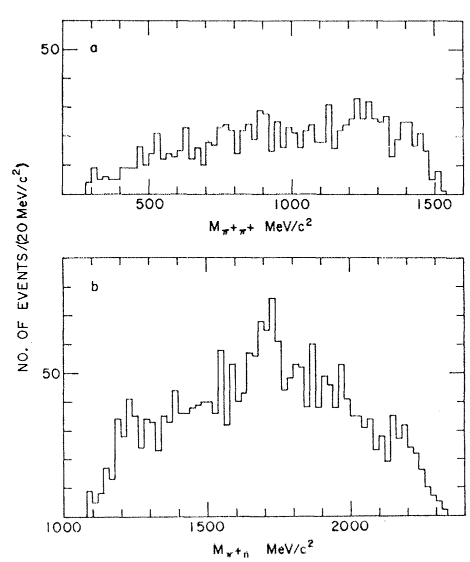

FIG. 13. (a) Histogram of $M_{\pi^+\pi^+}$ from the final state $\pi^+ + \pi^+ + n$. (b) Histogram of M_{π^+n} (two combinations) from the final state $\pi^+ + \pi^+ + n$.

[18] S. Trieman and C. N. Yang, Phys. Rev. Letters 8, 140 (1962).

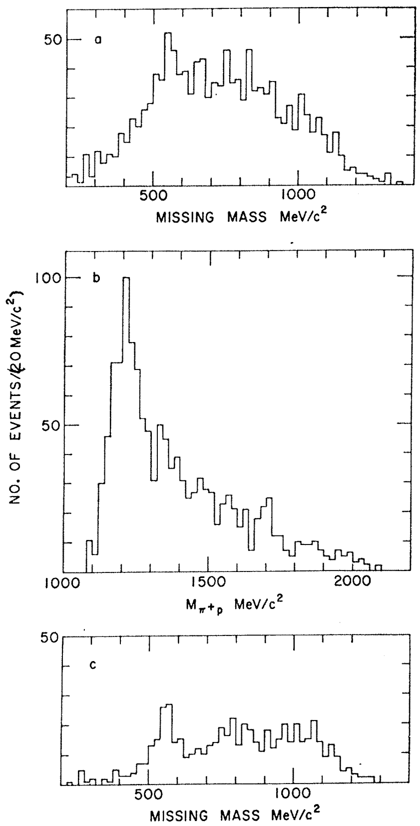

FIG. 14. (a) Histogram of missing mass from the final state $\pi^+ + p^+ +$MM. (b) Histogram of M_{π^+p} from the final state $\pi^+ + p^+ +$MM. (c) Histogram of missing mass recoiling against $M_{\pi^+p}(1140 \leq M_{\pi^+p} \leq 1320$ MeV$/c^2)$ from the final state $\pi^+ + p^+ +$MM.

the distribution in Fig. 9(a), however, is consistent with that predicted by a single-pion exchange.

On the other hand, the Treiman-Yang angular distribution shown in Fig. 9(b) for the same events as those in Fig. 9(a) is clearly anisotropic, while an isotropic distribution is expected if single-pion exchange is the dominant mechanism in ρ^+ production. This apparent discrepancy may be attributed to the fact that the final state $\pi^+ + p + \pi^0$ involves three resonance states (6), (7), and (8) as well as nonresonant background, all of which can interfere in a complex way. Thus a clean separation of the final states may not be possible. A similar argument holds true for the reactions (7) and (8).

Figures 10(a) and 10(b) show the $\cos\theta$ and Treiman-Yang angular distributions for reaction (7), excluding those events which have the cosine of the N^{*++} production angle greater than -0.8. Both $\cos\theta$ and Treiman-Yang angles were measured in terms of the π^+ from the decay of the N^{*++}. Figure 11(a) and 11(b) are the $\cos\theta$ and Treiman-Yang angular distributions from reaction (8) with the same N^{*+}-production-angle cut. The two angles are measured in terms of the π^0 from the decay of the N^{*+}.

REACTION $\pi^+ + p \rightarrow \pi^+ + \pi^+ + n$

Figure 12 shows the Dalitz plot of $M_{\pi^+\pi^+}{}^2$ versus $m_{\pi^+n}{}^2$. Figure 13(a) shows the $\pi^+ + \pi^+$ effective-mass distribution. No significant enhancement is observed. Figure 13(b) is the π^+n effective-mass distribution. $N^{*+}(1238$ MeV$/c^2)$ is produced. There may be some evidence for the production of $N^*(1700$ MeV$/c^2)$ and $N^*(2190$ MeV$/c^2)$. A second $\pi^+\pi^+$ effective-mass plot was made after removing events in the three N^* mass regions, and again no significant enhancement was observed.

REACTION $\pi^+ + p \rightarrow \pi^+ + p +$MISSING MASS

Figure 14(a) is the missing-mass distribution from the above reaction. It shows $\eta(550$ MeV$/c^2)$ production. The cross section for reaction $\pi^+ + p \rightarrow \pi^+ + p + \eta$ (neutral decay) is calculated to be 0.19 ± 0.07 mb. Taking the ratio $\eta(\pi^+\pi^-\pi^0)/\eta$(neutral decay)$=0.33$,[19] the expected number of η's decaying into $\pi^+\pi^-\pi^0$ produced in the reaction $\pi^+ + p \rightarrow \pi^+ + \pi^- + \pi^0 + p$ is 38 ± 12, which is in good agreement with the observed number of 33 ± 13.[2] The total cross section for $\eta + \pi^+ + p$ production is 0.27 ± 0.08 mb. This cross section for the $\eta\pi^+p$ final state is somewhat lower than that obtained by Alff *et al.* in this momentum range.[3,14]

Very slight enhancements in the mass regions of $\omega(783$ MeV$/c^2)$ and $\phi(1019$ MeV$/c^2)$ are consistent with the numbers observed in the reactions $\pi^+ + p \rightarrow \pi^+ + \pi^+ + \pi^- + \pi^0 + p^2$ and $\pi^+ + p \rightarrow \pi^+ + p + k_1{}^0 + k_2{}^0$.[9]

Figure 14(b) shows the π^+p effective-mass distribution. The $N^{*++}(1238$ MeV$/c^2)$ formation is evident. Figure 14(c) is a missing-mass spectrum recoiling against the N^{*++} (the N^{*++} mass region was taken to be between 1140 and 1320 MeV$/c^2$). The η peak is strongly enhanced relative to background, indicating that essentially all the η's are produced in the quasi two-body final state $N^{*++} + \eta$.

REACTION $\pi^+ + p \rightarrow \pi^+ + \pi^+ +$MISSING MASS

Aside from the formation of $N^{*0}(1238$ MeV$/c^2)$, no significant enhancements were observed in the missing-mass spectrum from the above reaction. The $\pi^+\pi^+$ effective mass also showed no significant enhancement.

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[19] A. H. Rosenfeld *et al.*, Rev. Mod. Phys. **40**, 77 (1968).