Double Resonance Production by 2.77-BeV/c π^+ Mesons on Hydrogen*†

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Reactions $\pi^++p\to\pi^++\pi^++\pi^-+p$, $\pi^++p\to\pi^++\pi^++\pi^-+p+\pi^0$ and $\pi^++p\to\pi^++\pi^++\pi^++\pi^-+n$ were studied at an incident π^+ momentum of 2.77 BeV/c. The first reaction is dominated by a quasi-two-body intermediate state $\rho+N^*$. The decay distributions of ρ and N^* are consistent with the predictions of the single-pion-exchange model. The ρ^0 decay distributions show the well-known asymmetry, which may be attributed to an interference with a $T=0$ even-spin background. The second reaction is dominated by a quasi-two-body intermediate state $\omega+N^*$. The decay distributions of ω and N^* are not consistent with the unmodified ρ-exchange model, but could be made to be consistent by including the absorptive effects in the input and output channels. The last reaction shows no prominent resonance production.

INTRODUCTION

RECENT experimental results indicate that many reaction channels proceed through quasi-two-body intermediate states which subsequently decay.[1–6] Several such examples are listed below:

$$K^-+p\to Y_1^{*+}+\pi^-$$
$$K^++p\to K^{*+}+p$$
$$\to K^0+N^{*++}$$
$$\pi^++p\to\rho^++p$$
$$\to\omega+N^{*++}$$
$$\bar{p}+p\to N^{*++}+\bar{N}^{*--}.$$

The decay distributions of some of these resonances from such quasi-two-body states have been investigated to determine the spin and, sometimes, parity of these resonances.[2,7] Once the spin and parity of a given resonance are known, however, quasi-two-body reactions involving it can be used to study the production mechanism for such reactions. Recently much work has been done on various models of peripheral production of quasi-two-body states involving resonances in high-energy meson-nucleon collisions.[8–13] In these models definite predictions are made with respect to the production and decay angular distributions of a resonance based on the nature of the exchanged particle. Some experimental results were in excellent agreement with theoretical predictions as far as the decay distributions were concerned.[5,14,15] But the production distributions were in general more "peripheral" (forward or backward peaked) than predicted by unmodified single-particle exchange models, and a strongly momentum-transfer-dependent form factor was needed to make the theoretical curves fit the experimental data. In order to avoid using such an *ad hoc* form factor, several authors[16–22] have proposed single-particle-exchange models which take into consideration the effects due to absorption in the initial and final state of reaction. In this way low partial waves are absorbed by other competing open channels, and thus produce a desired peaking in the production angular distribution. The absorption will affect the decay distributions in varying degrees. In cases in which definite calculations have been made, agreement between theoretical predictions and experimental data is reasonable.[22]

The present work is carried out in order to investigate the production mechanisms of double resonance production in the reactions $\pi^++p\to N^*+\rho$ and $\pi^++p\to N^*+\omega$.

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[5] G. B. Chadwick *et al.*, Phys. Letters 6, 309 (1963).

[6] T. Ferbel *et al.*, Phys. Rev. Letters 9, 351 (1962). (References 1–6 are just samples of work involving quasi-two-body final states, and are not meant to be complete.)

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[8] J. D. Jackson and M. Pilkuhn, Nuovo Cimento 33, 906 (1964); 34, 1841 (1964).

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[17] A. Dar, M. Kugler, Y. Kothan, and S. Nussinov, Phys. Rev. Letters 12, 82 (1964); A. Dar and W. Tobocman, *ibid.* 12, 511 (1964); A. Dar, *ibid.* 13, 91 (1964).

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[19] M. H. Ross and G. L. Shaw, Phys. Rev. Letters 12, 627 (1964).

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ANALYSIS OF EXPERIMENTAL RESULTS

Since the details of the analysis procedure and experimental set up were given in a previous communication,[23] we will only mention that the beam momentum was 2.77 ± 0.04 BeV/c, and that only the four-prong events are involved in the present work.

A. Cross Sections

The five major categories of these four-prong events are

$$\pi^+ + p \rightarrow \pi^+ + \pi^+ + \pi^- + p \qquad \text{(a)}$$
$$\rightarrow \pi^+ + \pi^+ + \pi^- + p + \pi^0 \qquad \text{(b)}$$
$$\rightarrow \pi^+ + \pi^+ + \pi^+ + \pi^- + n \qquad \text{(c)}$$
$$\rightarrow \pi^+ + \pi^+ + \pi^- + p + \text{missing mass} \qquad \text{(d)}$$
$$\rightarrow \pi^+ + \pi^+ + \pi^+ + \pi^- + \text{missing mass.} \qquad \text{(e)}$$

Table I gives the partial cross sections into the above channels, where reactions (d) and (e) are lumped as missing-mass events. These cross sections are in agreement with those obtained by Alff *et al.*[1] Even after checking the bubble density of ambiguous events, about 15% of the total events had two possible interpretations, and for the partial cross sections they were aportioned out according to the ratios of the unambiguous events. In the following analyses, however, these ambiguous events were not included.

TABLE I. Table of partial cross sections.

Final state	σ in mb
$\pi^+\pi^+\pi^- p$	3.19 ± 0.17
$\pi^+\pi^+\pi^- p\pi^0$	3.87 ± 0.21
$\pi^+\pi^+\pi^+\pi^- n$	0.33 ± 0.03
Missing mass	0.60 ± 0.05

B. Reaction (a)

Figure 1 is a scatter plot of $\pi^+\pi^-$ effective mass versus π^+p effective mass. Each event is represented twice as there are two π^+'s. It is clear from the concentration of events in a region bounded by 644 MeV $< M_{\pi^+\pi^-} < 906$ MeV, and 1120 MeV $< M_{\pi^+p} < 1360$ that ρ^0 and $N_{3,3}^{*++}$ are produced. The concentration of events occurs only in this region and not in bands, thus indicating that these two resonances are produced only in association with each other. Figures 2(a) and 2(b) are the projections of the scatter plot on the $M_{\pi^+\pi^-}$ and M_{π^+p} axes. Both the ρ^0 meson with a mass of 750 MeV and the N^{*++} isobar with a mass of 1238 MeV are clearly seen. An enhancement in the $M_{\pi^+\pi^-}$ distribution around 380 MeV is probably due to a kinematical effect, since it is greatly reduced if the $\pi^+\pi^-$ combinations, in which the π^+ forms an N^* with the proton, are removed from the distribution.

If we define the ρ and N^* masses to be 750 ± 100 and 1238 ± 85 MeV, respectively, about 28% of this reaction goes via an intermediate state $\rho + N^*$. Figure 3

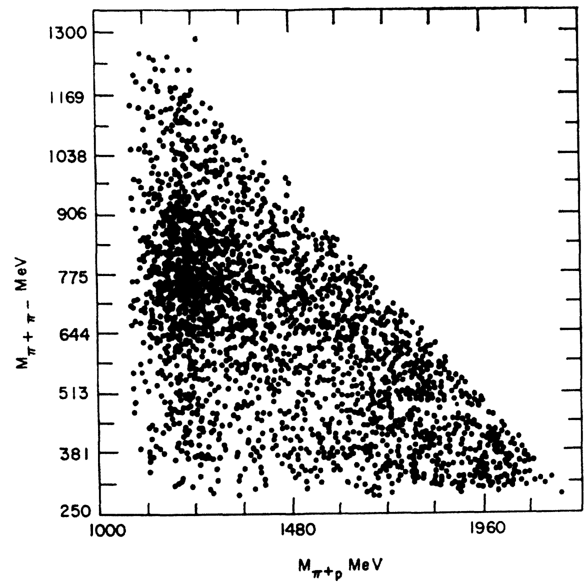

FIG. 1. Scatter plot of $M_{\pi^+\pi^-}$ vs M_{π^+p} from reaction (a).

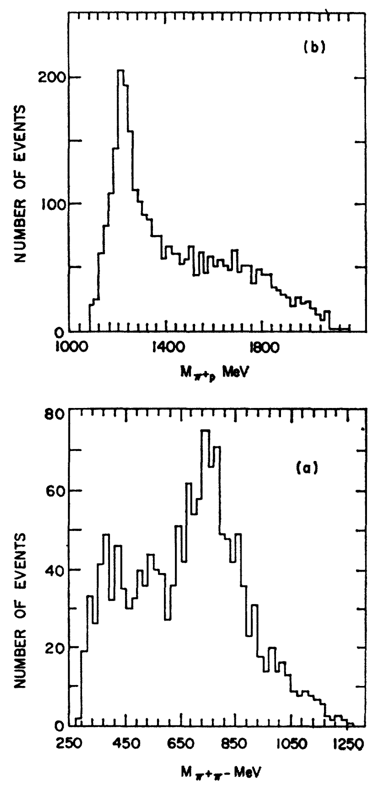

FIG. 2. (a) $M_{\pi^+\pi^-}$ plot from reaction (a). Each column is 20 MeV wide. (b) M_{π^+p} plot from reaction (a). Each column is 20 MeV wide.

[23] S. S. Yamamoto, L. Bertanza, G. C. Moneti, D. C. Rahm, and I. O. Skillicorn, Phys. Rev. 134, B383 (1964).

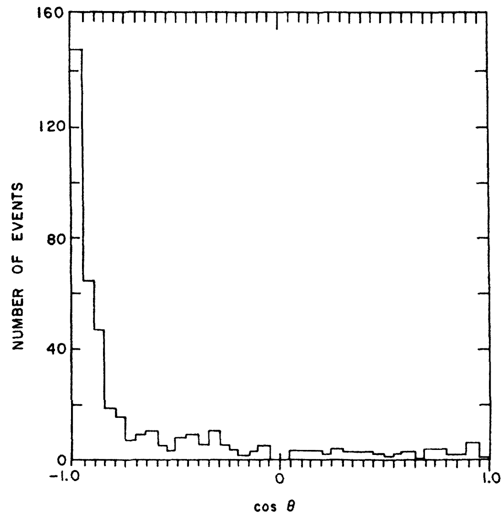

FIG. 3. Center-of-mass production angular distribution of N^* from the $\rho+N^*$ events.

shows the center-of-mass production angular distribution of the N^* from the $\rho+N^*$ events. The sharp backward peaking is characteristic of the peripheral nature of this interaction.

In order to study the exchange mechanism of the production of quasi-two-body states we used a method of analysis suggested by Gottfried and Jackson.[9] In this method the angular correlation of the decay of a resonance in a quasi-two-body final state is given in terms of the elements of the helicity density matrix of the resonance, and angles θ and ϕ. These angles are defined in the resonance center of mass, and the incident beam direction is taken as the axis of quantization. θ is the angle which one of the decay products of the resonance makes with the axis, and ϕ is its azimuthal angle. The angle ϕ is the same as the Treiman-Yang angle[24] as shown by Jackson.[10]

The decay distribution $w(\theta,\phi)$ for a $J=1$ resonance is given as

$$w(\theta,\phi)=(3/4\pi)\{\rho_{11}\sin^2\theta+\rho_{00}\cos^2\theta -\rho_{1,-1}\sin^2\theta\cos2\phi -\sqrt{2}\,\mathrm{Re}\rho_{10}\sin2\theta\cos\phi\} \quad (1)$$

and for a $J=\frac{3}{2}$ resonance

$$w(\theta,\phi)=(3/4\pi)\left\{\rho_{33}\sin^2\theta+\rho_{11}(\tfrac{1}{3}+\cos^2\theta) -\frac{2}{\sqrt{3}}\mathrm{Re}\rho_{3,-1}\sin^2\theta\cos2\phi -\frac{2}{\sqrt{3}}\mathrm{Re}\rho_{31}\sin2\theta\cos\phi\right\}, \quad (2)$$

where the $\rho_{mm'}$'s are the elements of the helicity density matrix connecting helicity states m and m'. In the case of Eq. (2) the subscripts m and m' represent 2 times the actual values of the helicity states. The requirement that the trace of the matrix should be 1 gives the following relations:

$$\rho_{11}=(1-\rho_{00})/2, \quad (3)$$

$$\rho_{33}=\tfrac{1}{2}-\rho_{11}. \quad (4)$$

Integrating (1) and (2) over θ and ϕ separately, we get the following distributions:

for $J=1$,

$$w(\theta)\propto\rho_{11}+(1-3\rho_{11})\cos^2\theta,$$

$$w(\phi)\propto 1-2\rho_{1,-1}\cos2\phi;$$

for $J=\frac{3}{2}$,

$$w(\theta)\propto 1+4\rho_{33}+3(1-4\rho_{33})\cos^2\theta,$$

$$w(\phi)\propto 1-(4/\sqrt{3})\,\mathrm{Re}\rho_{3,-1}\cos2\phi.$$

Also averaging $\sin2\theta\cos\phi$ over the entire distribution yields

$$\mathrm{Re}\rho_{10}=(-5/4\sqrt{2})\langle\sin2\theta\cos\phi\rangle$$

$$\mathrm{Re}\rho_{31}=(-5\sqrt{3})/8\langle\sin2\theta\cos\phi\rangle.$$

The choice of the coordinate system is such that the incident beam particle and the exchanged particle travel in opposite directions, and therefore the angular momentum between the beam particle and the exchanged particle cannot contribute to the substates of the resonance spin, if the axis of quantization is taken to be the beam direction as in our case. Thus for the case of a vector meson such as ρ produced by a π^++p reaction, only ρ_{00} in Eq. (1) can be nonzero, if a pseudoscalar meson is exchanged. Similarly, only ρ_{11} can be nonzero for the N^* production for pseudoscalar meson exchange.

Figures 4(a), 4(b), and 4(c) are the distributions of $\cos\theta$ for ρ events for which the cosine of the c.m. N^* production angle is (a) less than -0.85, (b) less than 0.9, and (c) less than -0.95, respectively. These cutoffs correspond to Δ^2 of 0.34 $(\mathrm{BeV}/c)^2$, 0.265 $(\mathrm{BeV}/c)^2$, and

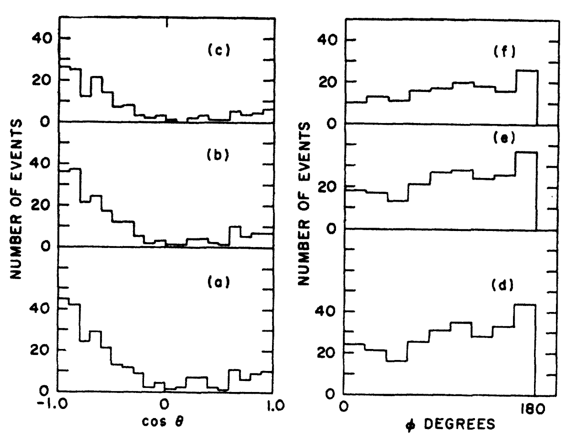

FIG. 4. Cosθ distributions of ρ from the $\rho+N^*$ events for which the cosine of the c.m. N^* production angle is (a) less than -0.85, (b) less than -0.9, and (c) less than -0.95; (d), (e), and (f) are the ϕ distributions of ρ with the same angular cutoffs in the same order as above.

[24] S. Treiman and C. Yang, Phys. Rev. Letters 8, 140 (1962).

0.19 (BeV/c)^2. We used the π^- from the ρ as the decay product in computing θ. The large asymmetry in these distributions is characteristic of the neutral ρ meson. Because of this asymmetry a fit to the form $A+B\cos^2\theta$ is not applicable. The general shape of these distributions is, however, consistent with $\rho_{00}\gg\rho_{11}$ indicating pseudoscalar meson exchange. Figures 4(d), 4(e), and 4(f) are the ϕ distributions for ρ's from the $\rho+N^*$ events using the same c.m. N^* production angular cutoffs as before. Again some asymmetry is observed in these distributions.

The observed asymmetry in the ρ^0 decay distributions can be attributed to an interference of the resonant amplitude with an S or D wave $T=0$ background.[25,26] Recently Durand and Chiu suggested the possible existence of a $T=0$, 0^+ or 2^+ di-pion resonance designated as ϵ^0 which could account for the observed asymmetry in the ρ^0 decays. They were able to fit the data from the compilation of the 2.75 BeV/c,[3] and 3 BeV/c,[25] $\pi^-+p\rightarrow\rho^0+N$ events by using the single-pion-exchange model with absorption in the initial and final state for the production of ρ^0 and ϵ^0. The observed decay distributions shown in Ref. 27 are very similar to those shown in Figs. 4(a) through 4(f). Even though the nucleon vertex involves the N^* in the present case rather than a nucleon as in Ref. 27, the ρ^0 decay distributions averaged over the N^* decay distributions are not expected to differ greatly from the ρ^0 decay distributions from the $\rho+N$ events. Therefore the present results do not seem inconsistent with the production mechanism described by Durand and Chiu.

Figures 5(a), 5(b), and 5(c) are the $\cos\theta$ distributions of the N^* from the $N^*+\rho$ events for which the cosine of the c.m. N^* production angle is less than -0.85, -0.9, and -0.95, respectively. The π^+ from the N^* was used as the decay particle to compute the angle θ. Figures 5(d), 5(e), and 5(f) are the ϕ distributions of the N^* with the same angular cutoffs.

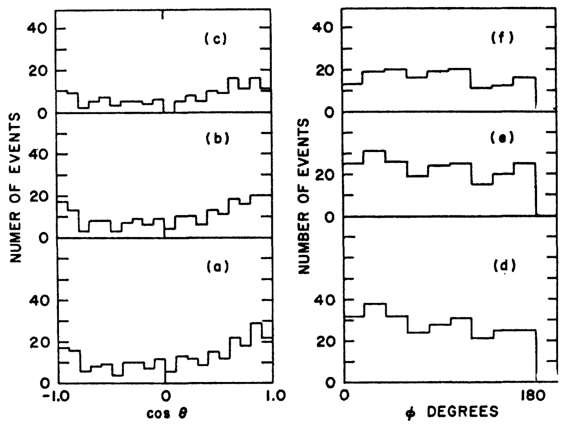

FIG. 5. Cosθ distributions of N^* from the $\rho+N^*$ events for which the cosine of the c.m. N^* production angle is (a) less than -0.85, (b) less than -0.9, and (c) less than -0.95; (d), (e), and (f) are the ϕ distributions of N^* with the same angular cutoffs in the same order as above.

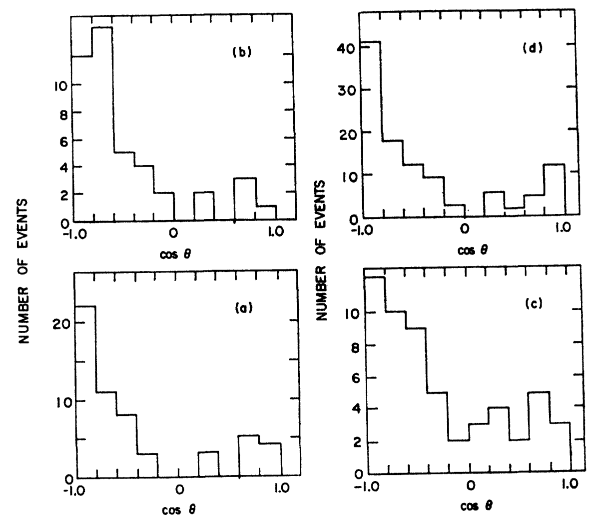

FIG. 6. Cosθ distributions of ρ from the $\rho+N^*$ events for which the cosine of the c.m. N^* production angle is less than -0.85, and the cosθ of the N^* decay distribution lies between (a) -1.0 and -0.5, (b) -0.5 and 0, (c) 0 and 0.5, and (d) 0.5 and 1.0.

Figures 6(a), 6(b), 6(c), and 6(d) are the $\cos\theta$ distributions of the ρ for which the cosine of the c.m. N^* production angle is less than -0.85, and the $\cos\theta$ of the N^* decay distribution lies between (a) -1.0 and -0.5, (b) -0.5 and 0.0, (c) 0.0 and 0.5, and (d) 0.5 and 1.0. The similarity of these distributions indicates the absence of correlations between the ρ and N^* decays, which is as it should be, if the exchanged particle carries no spin.

In conclusion, then, our data seem to be consistent with the single-pion-exchange model including the effects of absorption, and possibly of the existence of an even spin-parity $T=0$ resonance, or background amplitude.

C. Reaction (b)

Figure 7 is a scattergram of the $\pi^+\pi^-\pi^0$ effective mass against the π^+p effective mass. Each event is represented twice. It is clear that the production of a quasi-two-body final state $N^*+\omega$ is copious. Figures 8(a) and 8(b) are the projections on the two axes of Fig. 7. In addition to the ω there is some indication of η production in the $\pi^+\pi^-\pi^0$ effective mass.

Defining the ω mass to be 800±35 MeV, and the N^* mass to be 1238±95 MeV, we selected about 30% of the events in this reaction as belonging to the $N^*+\omega$ quasi-two-body state. In the following discussion we shall deal only with these events.

Figure 9 is the c.m. production angular distribution of the N^*. The backward peak is considerably broader than the case for the $N^*+\rho$ production, even though

[25] V. Hagopian and W. Selove, Phys. Rev. Letters **10**, 533 (1963).
[26] M. Abolins, R. L. Lander, W. A. Mehlhop, N. H. Xuong, and R. M. Yager, Phys. Rev. Letters **11**, 381 (1963).
[27] L. Durand, III, and Y. T. Chiu, Phys. Rev. Letters **14**, 329 (1965).

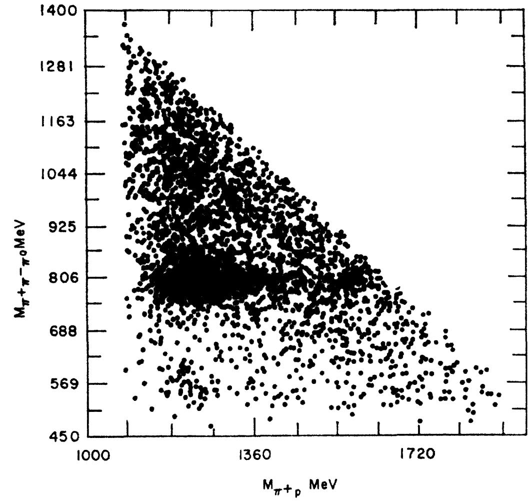

FIG. 7. Scatter plot of $M_{\pi^+\pi^-\pi^0}$ versus M_{π^+p} from reaction (b).

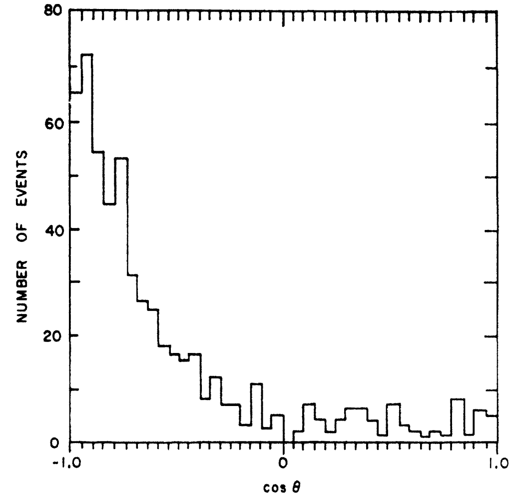

FIG. 9. Center-of-mass production angular distribution of N^* from the $\omega+N^*$ events.

the spin and parity of the particles involved are the same, and the masses are nearly the same (except for the G parity of the ρ and ω, of course). The analysis of Gottfried and Jackson is still applicable in this case, if we take θ of the ω to be the angle which the normal to the decay plane of the ω makes with the incident beam, all evaluated in the ω center of mass.[12] Figures 10(a), 10(b), and 10(c) are the $\cos\theta$ distribution of ω for which the cosine of the c.m. N^* production angle is (a) less than -0.6 $[\Delta^2<0.713\ (\text{BeV}/c)^2]$; (b) less than -0.9 $[\Delta^2<0.271\ (\text{BeV}/c)^2]$, and (c) less than -0.95 $[\Delta^2<0.197\ (\text{BeV}/c)^2]$, respectively. The solid curves are the least-squares fits to the form $A+B\cos^2\theta$. Figures 10(d), 10(e), and 10(f) are the ϕ distributions of ω with the same angular cutoffs. Figures 11(a), 11(b), 11(c), 11(d), 11(e), and 11(f) are the $\cos\theta$ and ϕ distributions of N^* with the same angular cutoffs as in the ω distributions, and again the solid curves are the least-squares fits to the form $A+B\cos^2\theta$. For each angular cutoff the average value of $\sin2\theta\cos\phi$ was calculated both for ω and N^*. Table II lists the values of the coefficients A and B, the χ^2 of the fit, the average value of $\sin2\theta\cos\phi$, and the values of the density-matrix elements derived from these values for ω and N^* for each angular cutoff region. Note that we assumed that the ϕ distributions are all consistent with isotropy, and the errors quoted are statistical. The values of the density-matrix elements obtained here are in general agreement with the values obtained by the Anglo-German collaboration experiment,[4] and similar over-all

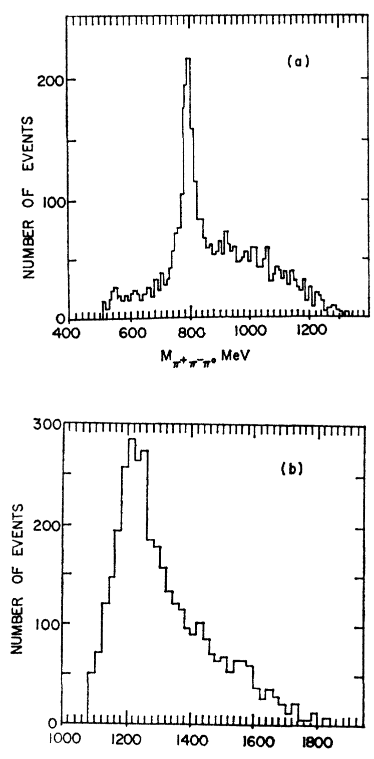

FIG. 8. (a) $M_{\pi^+\pi^-\pi^0}$ plot from reaction (b). Each column is 10 MeV wide. (b) M_{π^+p} plot from reaction (b). Each column is 20 MeV wide.

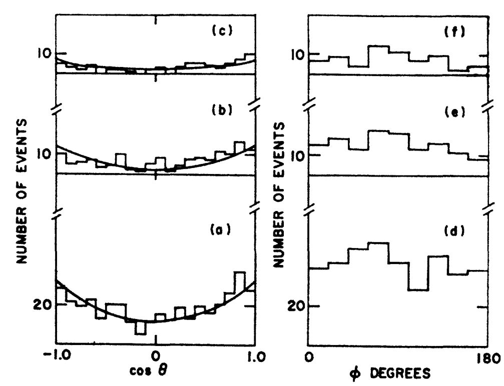

FIG. 10. $\cos\theta$ distributions of ω from the $\omega+N^*$ events for which the cosine of the c.m. N^* production angle is (a) less than -0.6, (b) less than -0.9, and (c) less than -0.95; (d), (e), and (f) are the ϕ distributions of ω with the same angular cutoffs in the same order as above.

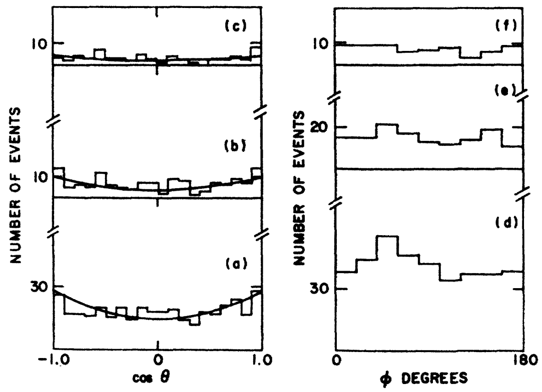

FIG. 11. Cosθ distributions of N^* from the $\omega+N^*$ events for which the cosine of the c.m. N^* production angle is (a) less than -0.6, (b) less than -0.9, and (c) less than -0.95; (d), (e), and (f) are the ϕ distributions of ω with the same angular cutoffs in the same order as above.

features were observed in the ω and N^* decay distributions by Shen *et al.*[28]

The experimental values of the density matrix elements indicate that single-pion exchange dominates this production process, but this is forbidden by G-parity conservation. The only physical particle which can be exchanged is then a ρ meson, but such an exchange with no modification predicts a $\sin^2\theta$ distribution in the ω decay, and $(1-\frac{3}{5}\cos^2\theta)$ distribution in the N^* decay. Therefore, the observed decay distributions are in strong disagreement with the predictions of the simple unmodified ρ-exchange model of Gottfried and Jackson. This apparent discrepancy may be accounted for by taking into consideration the effects of absorption.[29]

TABLE II. Values of A and B, χ^2, average value of $\sin 2\theta\cos\phi$, and values of density-matrix elements for ω and N^* for each angular cutoff region.

	$\cos\theta_{N^*}<-0.6.$		
N^*	$A=15.1\pm1.6$	$\rho_{33}=0.14\pm0.02$	$\chi^2=13.3$
	$B=12.3\pm2.5$	$\rho_{11}=0.36\pm0.05$	
	$\langle\sin 2\theta\cos\phi\rangle=-0.060$	$\mathrm{Re}\rho_{31}=+0.065\pm0.004$	
ω	$A=11.6\pm1.3$	$\rho_{11}=0.21\pm0.02$	$\chi^2=18.0$
	$B=20.0\pm3.5$	$\rho_{00}=0.58\pm0.04$	
	$\langle\sin 2\theta\cos\phi\rangle=0.107$	$\mathrm{Re}\rho_{10}=-0.095\pm0.005$	
	$\cos\theta_{N^*}<-0.9$		
N^*	$A=4.31\pm0.99$	$\rho_{33}=0.11\pm0.06$	$\chi^2=31.4$
	$B=5.21\pm2.65$	$\rho_{11}=0.39\pm0.21$	
	$\langle\sin 2\theta\cos\phi\rangle=-0.028$	$\mathrm{Re}\rho_{31}=+0.030\pm0.003$	
ω	$A=2.18\pm0.85$	$\rho_{11}=0.12\pm0.03$	$\chi^2=50.0$
	$B=11.4\pm2.8$	$\rho_{00}=0.76\pm0.22$	
	$\langle\sin 2\theta\cos\phi\rangle=0.104$	$\mathrm{Re}\rho_{10}=-0.092\pm0.008$	
	$\cos\theta_{N^*}<-0.95$		
N^*	$A=2.18\pm0.54$	$\rho_{33}=0.13\pm0.06$	$\chi^2=21.6$
	$B=2.00\pm1.39$	$\rho_{11}=0.37\pm0.18$	
	$\langle\sin 2\theta\cos\phi\rangle=0.051$	$\mathrm{Re}\rho_{31}=0.055\pm0.007$	
ω	$A=2.02\pm0.41$	$\rho_{11}=0.20\pm0.09$	$\chi^2=19.1$
	$B=3.81\pm1.08$	$\rho_{00}=0.60\pm0.28$	
	$\langle\sin 2\theta\cos\phi\rangle=0.081$	$\mathrm{Re}\rho_{10}=-0.072\pm0.009$	

[28] B. Shen, J. Brown, G. Goldhaber, S. Goldhaber, J. Kadyk, and G. Trilling, Bull. Am. Phys. Soc. 9, 722 (1964), Abstract N7.
[29] B. E. Y. Svensson, CERN report TH-451 (unpublished).

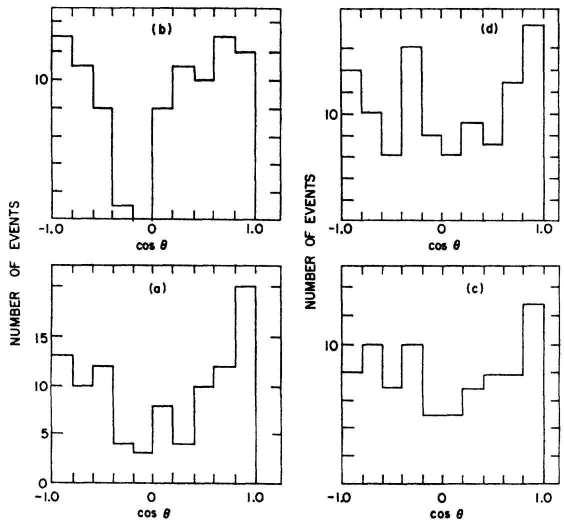

FIG. 12. Cosθ distributions of ω for which the cosine of the c.m. N^* production angle is less than -0.6, and the cosθ of the N^* decay distributions lies between (a) -1.0 and -0.5, (b) -0.5 and 0, (c) 0 and 0.5, and (d) 0.5 and 1.0.

In view of some theoretical reservations concerning the applicability of the absorption mechanism to this reaction[29] the "true" production mechanism of this reaction may involve not only ρ exchange with absorption, but also exchanges of states involving different spins and parities,[9] and in addition nonperipheral mechanisms.

Figures 12(a), 12(b), 12(c), and 12(d) show the cosθ distributions of the ω for which the cosine of the c.m. N^* production angle is less than -0.6, and the cosθ of the N^* lies (a) between -1.0 and -0.5, (b) between -0.5 and 0., (c) between 0.0 and 0.5, and (d) between 0.5 and 1.0. Since all the distributions are similar, there seems to be no significant correlation between the decay distributions of the two resonances.

D. Reaction (c)

The only resonance clearly seen in this reaction was $N^{*-}\to\pi^-+n$. Because of three mass combinations in any effective mass involving a π^+ it would be difficult to detect any resonance if its effect is small.

E. Missing-Mass Events

No work has been done on these events.

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