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ANALYSIS OF $\pi\rho$ ENHANCEMENTS IN $\pi^- + d$ INTERACTIONS AT 3.2 BeV/c*

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In a study of multipion final states produced in π^+p interactions at 3.65 BeV/c, Goldhaber et al. demonstrated that almost all $\pi^+\pi^+\pi^-p$ events proceed through either the $\rho^0 N^{*++}$ or $\rho^0\pi^+p$ intermediate states.[1] They found that the $\pi^+\rho^0$ effective-mass distribution, $M(\pi^+\rho^0)$, for the $\pi^+\rho^0p$ events contains a broad enhancement (A^+) in the interval 1.0 to 1.4 BeV. Subsequent analyses by other groups have shown that the enhancement in the $\pi^\pm\rho^0$ system consists of two peaks:[2,3] the $A_1(1080)$ with $\Gamma = 80$ to 140 MeV and the $A_2(1310)$ with $\Gamma = 80$ to 100 MeV. The observation by Chung et al. of what may reasonably be interpreted as the decays $A_2 \to K^-K_1$ and $A_2 \to K_1K_1$ suggests that the A_2 enhancement represents a state with well-defined quantum numbers;[3] they conclude that the most likely assignment is $I^GJ^P = 1^-2^+$. In contrast, the structure of the A_1 peak has remained obscure. No related decays have been established; in addition, several possible kinematic origins for the enhancement have been suggested.[4–6]

To compare the production and decay properties of the A_1 and A_2 systems in a variety of final states under similar kinematic conditions, we have analyzed π^-d interactions at 3.2 BeV/c. Thus far, the final states

$$\pi^- + d \rightarrow (p)\, n + \pi^- + \pi^- + \pi^+ \qquad (2881 \text{ events}) \qquad (1a)$$

$$\rightarrow (n)\, p + \pi^- + \pi^- + \pi^+ \qquad (669 \text{ events}) \qquad (1b)$$

and

$$\rightarrow (p)\, p + \pi^- + \pi^- + \pi^0 \qquad (1577 \text{ events}) \qquad (1c)$$

have been studied. Direct comparison of correlations with those observed in $\pi^{\pm}p$ experiments is significant only for events representing interactions on a single nucleon. Consequently, all events with an unobserved proton (i.e., only three visible prongs) were measured;[7] four-prong events were measured only when a clearly identified proton was present. With these criteria, the detection efficiency for (1b) decreases rapidly for events involving protons with laboratory momenta $p_L > 800$ MeV/c. Since the A enhancements in $\pi^{\pm}p$ interactions occur predominantly at low momentum-transfer-squared, $\Delta^2(p)$, this bias does not affect the present conclusions. After fitting, events were assigned to (1a, b, or c) when the nucleon in parentheses had $p_L \leq 220$ MeV/c.[8]

The combined $M(N\pi)$ and $M(\pi\pi)$ distributions for the two $N\pi$ and $\pi\pi$ pairings are shown by the dashed curves in Fig. 1. To distinguish the two $\pi^{+,0}\pi^-$ pairs, we calculated Δ^2 for each. We designate the pair with lower (higher) Δ^2 by $\pi\pi_1 (\pi\pi_2)$; the associated $N\pi$ pair is then $N\pi_2$ $(N\pi_1)$. Distributions for the $N\pi_2$ and $\pi\pi_1$ pairs are shown separately in the solid curves. The $M(N\pi_2)$ distributions for events in which the $\pi\pi_1$ pair lies in the ρ interval (600 to 850 MeV) are represented by the shaded areas in 1a, c, and e; the N^* peaks in these distributions correspond predominantly to the $N^*\rho$ final state. The $M(\pi\pi_1)$ distributions associated with the $N\pi_2$ pairs outside the N^* intervals are shown by the shaded areas in 1b, d, and f. Events in the ρ intervals in these distributions together with those in the $\pi\pi_2$ combinations are used in the final analysis.

The structure in the $(p)n\pi^-\pi^-\pi^+$ final state is similar to that observed in the charge-symmetric state $p\pi^+\pi^+\pi^-$.[1] The Δ^2 selection in Figs. 1a and b provides a remarkably clean separation of the $N^{*-}\rho^0$ events. Some N^{*-} and ρ^0 production occurs in the $n\pi^-_1$ and $\pi^+\pi^-_2$ pairs; however, the scatter plot shows no additional enhancement in the overlapping $N^{*-}\rho^0$ bands for these pairs. Correlations in the $(n)p\pi^-\pi^-\pi^+$ events are similar to those reported for the analogous final state produced in π^-p interactions at 3.2 BeV/c.[3] Although the $N^{*0}\rho^0$ final state is observed, the inset in 1c indicates that N^{*++} is stronger. Most π^+'s associated with the N^{*++} interval combine with π^-_1 to form ρ^0's; consequently, no unambiguous separation into $N^{*0}\rho^0$ events is possible. Some ρ^0 production occurs in both the $\pi^+\pi^-_1$ and $\pi^+\pi^-_2$ pairs outside the N^{*++} interval. Structure observed in the $(p)p\pi^-\pi^-\pi^0$ final state consists predominantly of $N^{*0}\rho^-$ formation in the $p\pi^-_2$ and $\pi^0\pi^-_1$ pairs; negligible ρ^- production occurs outside the N^{*0} interval. Some uncorrelated N^{*0} and ρ^- formation is present in the $p\pi^-_1$ and $\pi^0\pi^-_2$ pairs.

To compare the structure in $\pi\rho$ systems produced in reactions (1a, b, and c), we plot $\Delta^2(\pi\rho)$ against $M^2(\pi\rho)$ in Fig. 2 for each final state. Events with either $n\pi^-$ pair (1a), the $p\pi^+$ pair (1b), or either $p\pi^-$ pair (1c) in the N^* interval (1120 to 1320 MeV) have been rejected. The $M^2(\pi\rho)$ distribution for reaction (1a) agrees qualitatively with that observed by Goldhaber et al.;[1] although a broad enhancement occurs in the region 1.0 to 2.0 $(\text{BeV})^2$, no clear separation of the A_1 and A_2 peaks is achieved. Alternatively, for reaction (1b), a well-defined peak is observed at $M^2(\pi\rho) \sim 1.72\ (\text{BeV})^2$ for events with $0.15 < \Delta^2(p) \leq 0.7\ (\text{BeV/c})^2$; this is consistent with the results of Chung et al.[9] Almost all events whose assignment is ambiguous ($p_L \leq 220$ MeV/c for both nucleons) fall in the A_1 region; when the projections in Figs. 2d and e are added and ambiguous events used only once, the relative intensities in the A_1 and A_2 enhancements tend toward those observed in the $\pi^{\pm}p$ experiments.

It is important to note that the strong A_1 enhancements in both $\pi^-\rho^0$ plots are confined to events with $\Delta^2(\pi\rho) \leq 0.15$ (BeV/c)^2. In contrast, no analogous effect is observed when similar criteria are used to select $\pi^-\rho^-$ combinations;[10] within statistics, the $\pi^-\rho^-$ plot suggests a uniform density for $\Delta^2(\pi\rho) < 1$ (BeV/c)^2. Since the π^-d data reproduce the essential features of the corresponding $\pi^{\pm}p$ experiments, this difference probably cannot be attributed to the presence of the additional nucleon in the final state.

Three diagrams which may contribute significantly to $N\pi\pi\pi$ final states are shown in Fig. 3. In (3a), exchange of a $G = -1$ system is allowed; when the exchanged particle is a pion (OPE) this diagram contributes strongly to ρN^* events.[11] The presence of the pion propagator implies that with increasing c.m. energy, the OPE contribution tends to concentrate in the $N\pi_2$ and $\pi\pi_1$ pairs; this effect is particularly clear in the $(p)n\pi^-\pi^-\pi^+$ final state. In (3b), the exchanged system must have $G = +1$; at low $\Delta^2(N)$, this diagram dominates in the production of resonant systems whose decay into 3π is strong. Diagram (3c) represents a mechanism suggested by Nauenberg and Pais for generation of peaks in 3π systems.[4] For real particles, π-Y_c scattering would show a peak in the mass region where the decay pion from Y_c can combine with the incident π to form Y_c'; enhancements associated with this mechanism would result from the sequence $\pi + \rho \rightarrow \pi + \pi + \pi \rightarrow \rho' + \pi'$.[12]

The observed $\pi\rho$ structure may be compared with predictions for the diagrams in Fig. 3. We note first that a low mass $\pi\rho$ enhancement corresponds to a strongly peaked angular distribution in the πN c.m. Deck has pointed out that diagram 3 a leads to this configuration if the Δ^2 dependence for virtual πN scattering at vertex I a is similar to that for the free πN system.[5,13] This mechanism also accounts naturally for the observed concentration of A_1^- events at $\Delta^2(\pi^- \rho^0) \leq 0.15$ (BeV/c)^2. Since vertex Ia represents $\pi^0 + n \rightarrow \pi^- + p$ for the (p) $p\pi^-\pi^-\pi^0$ final state, the absence of a significant A_1^{--} enhancement may be attributed to the small charge-exchange cross section for energies above the N^* region.

In diagram 3b, we assume that the $\pi\rho$ enhancements result from decay of resonant states with $I = 1$ or 2. If we neglect absorptive effects, the relative production rates of the observed decay modes for reactions (1 a, b, and c) are 1 : 1 : 0; and 1 : 1 : 8 for $I = 1$ and 2, respectively. The distributions in Fig. 2 are consistent with the $I = 1$ assignment for the A_1 or A_2; there is no possibility for interpretation of either enhancement as an $I = 2$ resonant state. However, it is important to note that the concentration of A_1 events at $\Delta^2(\pi\rho) \leq 0.15$ (BeV/c)^2 is not expected for production of a resonant state through ρ exchange. For example, in a study of the reaction $\pi^+ + n(p) \rightarrow \omega + p$ (p) at 3.25 BeV/c, Cohn et al.[14] find significant production of ω in the Δ^2 interval 0 to 0.6 (BeV/c)^2. In contrast to the distribution of $\Delta^2(\pi\rho)$ for the A_1 events, that for A_2 is similar to the distribution observed in ω production.[1-3]

If we assume that Y_c and Y_c' are ρ's, relative production rates through diagram 3 c are 1 : 1 : 2. Since no A_1^{--} enhancement is observed, and the A_2 is almost certainly a state with $I^G J^P = 1^- 2^+$, this mechanism may be rejected.

An alternative kinematic origin for the A_1 enhancement has been proposed by Chang.[6] Since each final state contains two identical pions, symmetrization results in a production amplitude of the approximate form $M_P = M_0(D_{13} + D_{23})$, where D_{ij} is the ρ propagator leading to $\pi_i\pi_j$. He notes that constructive interference can occur only for both $D_{12} \neq 0$ and $D_{23} \neq 0$, i.e., in the c.m. energy region where both $\pi\pi$ combinations may form ρ's. Since the dominant ρ production amplitudes for interference presumably result from diagram 3a, no direct test for distinguishing the two kinematic mechanisms is available.

We conclude that the absence of any significant $\pi^-\rho^-$ enhancements precludes the interpretation of either the A_1 or A_2 as an $I = 2$ resonant state. The observed $\pi\rho$ enhancements in the A_1 region are in qualitative agreement with predictions for the kinematic mechanism proposed by Deck. Alternatively, the A_1 may represent a broad resonance with $I = 1$. The data agree with the $I = 1$ assignment for the A_2.[15]

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FOOTNOTES AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

†Visiting scientist from Princeton University.

1. G. Goldhaber, J. L. Brown, S. Goldhaber, J. A. Kadyk, B. C. Shen, and G. H. Trilling, Phys. Rev. Letters 12, 336 (1964).
2. Aachen-Birmingham-Bonn-Hamburg-London-München Collaboration, Phys. Letters 6, 62 (1963).
3. S-U. Chung, O. I. Dahl, L. M. Hardy, R. I. Hess, G. R. Kalbfleisch, J. Kirz, D. H. Miller, and G. A. Smith, Phys. Rev. Letters 12, 621 (1964).
4. M. Nauenberg and A. Pais, Phys. Rev. Letters 8, 82 (1962).
5. R. T. Deck, Phys. Rev. Letters 13, 169 (1964).
6. N. P. Chang, Phys. Rev. Letters 14, 806 (1965).
7. Approximately 65% of the events measured had only three visible prongs; these correspond to a projected length less than 1.5 mm for the low momentum recoil. The fitting program treated the unseen proton as a measured track with momentum components equal to zero but having appropriate errors in the x, y, and z directions. For the four-constraint final state, $pp\pi^-\pi^-$, the resulting momentum distribution for the lower-momentum proton is consistent with the Hulthén distribution. With the weaker constraints in reactions 1, the momentum distribution for unmeasured protons tends to peak at zero; the distribution for measured protons ($p_L \gtrsim 80$ MeV/c) is consistent with the Hulthén distribution.

   This distortion has no significant effect on $M(\pi^-\pi^-\pi^+)$ because the three pions are measured. It is difficult to estimate the effect on $M(\pi^-\pi^-\pi^0)$, although the poorer resolution is probably reflected in the observed width of the ρ^0 (140 MeV) and of the ρ^- (180 MeV).

8. An additional 700 events contained no nucleon with $p_L \leq 220$ MeV/c; in 167 events both the neutron and proton had $p_L \leq 220$ MeV/c. Since the assignment of events is obscured when both nucleons have low momentum, alternate selections were tried. For the present analysis, 30 "double-spectator" events are used in Fig. 2d only, 46 in 2e only, and 23 in both. The second selection in which each event is assigned only to the final state corresponding to the lower-momentum nucleon, led to similar conclusions.

9. Although Chung et al.[3] observed the A_1 and A_2 peaks for $\Delta^2(p) < 0.65$ (BeV/c)^2, they find that, after deletion of events with $\Delta^2(p) < 0.15$, there is a similar emphasis of the A_2 peak with respect to the A_1. Private communication.

10. When events with $M(N\pi_2)$ in the N^* interval are not removed, all final states contain a strong $\pi\rho$ enhancement throughout the A_1 region at $\Delta^2(\pi\rho) < 0.15$ (BeV/c)^2.

11. M. Abolins, R. L. Lander, W. A. Mehlhop, Ng. h. Xuong, and P. M. Yager, Phys. Rev. Letters 11, 381 (1963).

12. See C. Goebel, Phys. Rev. Letters 13, 143 (1964) in which a further analysis of this mechanism demonstrates that it cannot produce an enhancement in the $\pi\rho$ system by virtual ρ exchange.

13. Alternatively, a genuine $\pi\rho$ enhancement at low mass may erroneously lead to the conclusion that virtual πN scattering is similar to that for the free πN system. Abolins et al. (Proc. Second Athens Topical Conference on Resonant Particles, 1965, to be published) have described a test for the mechanism proposed by Deck. In the πN c.m., events are divided into those in which the nucleon goes forward or backward with respect to the incident beam direction. They find that the low-mass $\pi\rho$ enhancement occurs only in the forward events. However, this is no more than a restatement of the fact that the A_1 enhancement occurs at low Δ^2.

14. H. O. Cohn, W. M. Bugg, and G. T. Condo, Phys. Letters 15, 344 (1965).

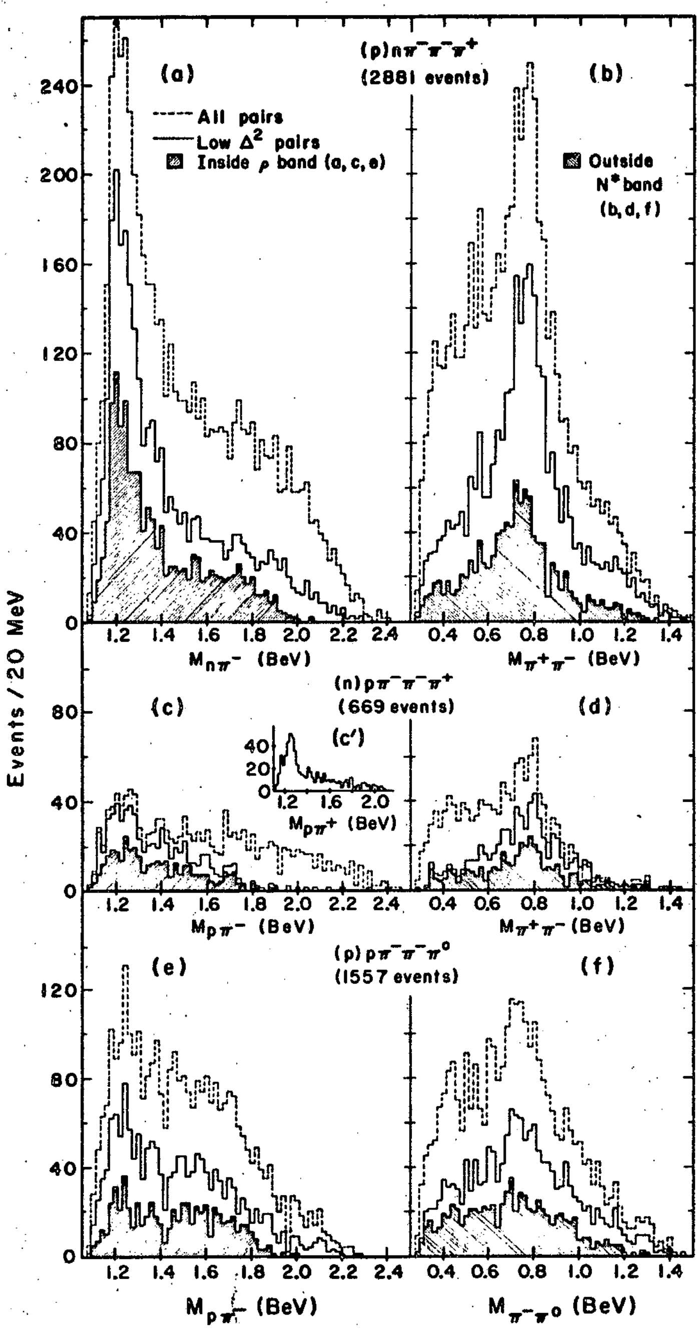
15. Similar conclusions have been reached by the La Jolla group in a study of $\pi^- + d$ interactions at 3.7 BeV/c, (N. Xuong and R. Lander, University of California, La Jolla, private communication.)

FIGURE LEGENDS

Fig. 1. Distributions of the invariant mass of $N\pi$ and $\pi\pi$ pairs. The dotted lines represent two combinations per event. The one combination per event for which $\Delta^2(\pi\pi)$ is the lower is represented by the solid lines.

Fig. 2. (a), (b), and (c) Chew-Low plots of the $\pi\rho$ systems in reactions 1a, b, and c, respectively. (d), (e), (f), (g), (h), and (i) Projections of mass-squared ($\pi\rho$) for the same reactions. In all plots, events were excluded if neither $\pi^{+,0}\pi^-$ pair was in the ρ interval (600 to 850 MeV). Events with either $n\pi^-$ pair (a), the $p\pi^+$ pair (b), or either $p\pi^-$ pair (c) in the N^* interval (1120 to 1320 MeV) were excluded.

Fig. 3. Diagrams considered in the production of $\pi\rho$ enhancements.



(p)nπ⁻π⁻π⁺
(2881 events)
(a)
(b)
All pairs
Low Δ² pairs
Inside ρ band (a, c, e)
Outside N* band (b, d, f)
Events / 20 MeV
M nπ⁻ (BeV)
M π⁺π⁻ (BeV)
(n)pπ⁻π⁻π⁺
(669 events)
(c)
(c′)
(d)
M pπ⁺ (BeV)
M pπ⁻ (BeV)
M π⁺π⁻ (BeV)
(p)pπ⁻π⁻π⁰
(1557 events)
(e)
(f)
M pπ⁻ (BeV)
M π⁻π⁰ (BeV)

Fig. 1

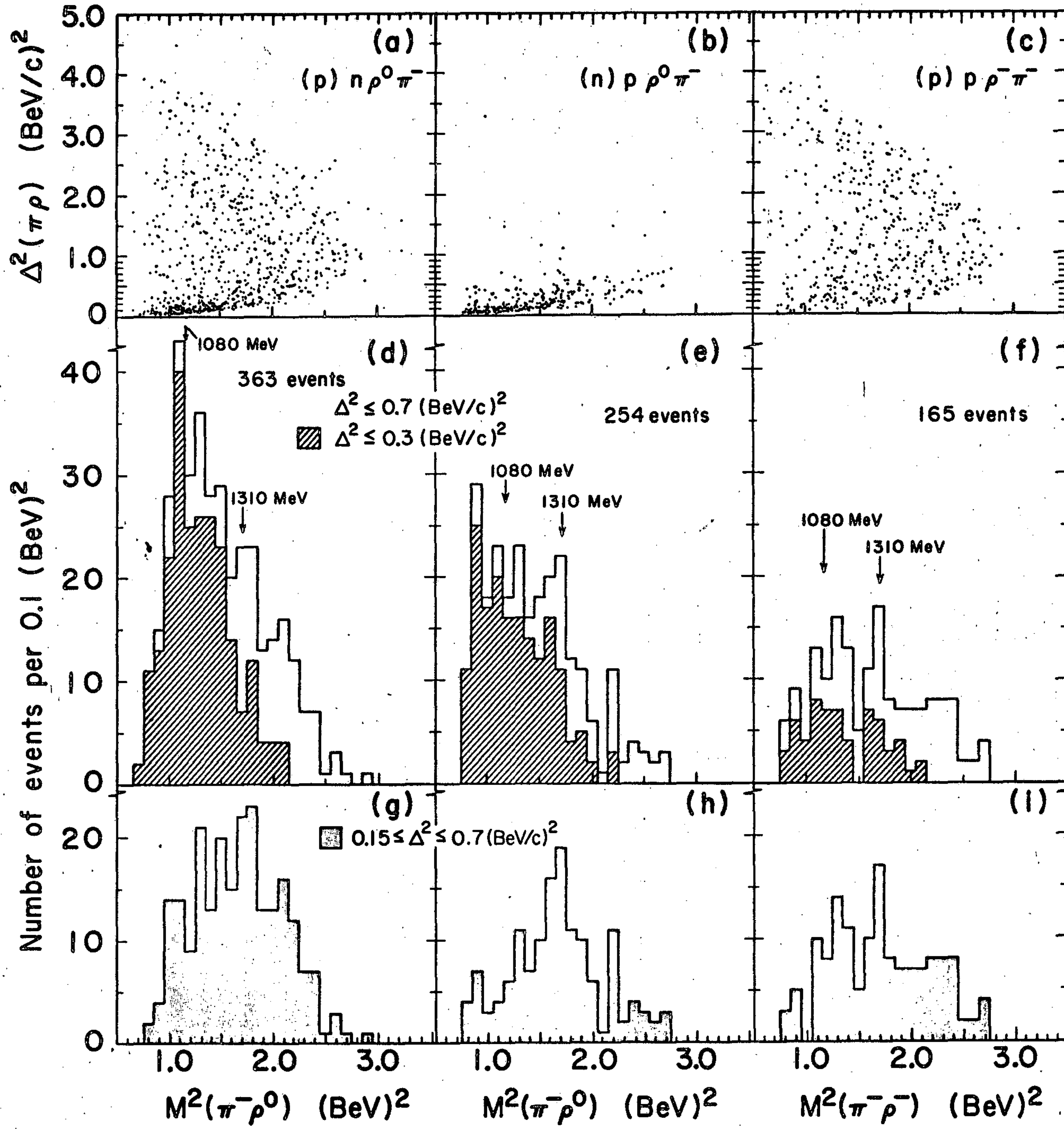

(a)
(p) $n\rho^0\pi^-$
(b)
(n) $p\rho^0\pi^-$
(c)
(p) $p\rho^-\pi^-$
$\Delta^2(\pi\rho)$ $(BeV/c)^2$
0
1.0
2.0
3.0
4.0
5.0
(d)
1080 MeV
363 events
$\Delta^2 \leq 0.7$ $(BeV/c)^2$
$\Delta^2 \leq 0.3$ $(BeV/c)^2$
1310 MeV
(e)
254 events
1080 MeV
1310 MeV
(f)
165 events
1080 MeV
1310 MeV
Number of events per 0.1 (BeV)^2
0
10
20
30
40
(g)
$0.15 \leq \Delta^2 \leq 0.7$ $(BeV/c)^2$
(h)
(i)
1.0
2.0
3.0
$M^2(\pi^-\rho^0)$ $(BeV)^2$
$M^2(\pi^-\rho^0)$ $(BeV)^2$
$M^2(\pi^-\rho^-)$ $(BeV)^2$

Fig. 2

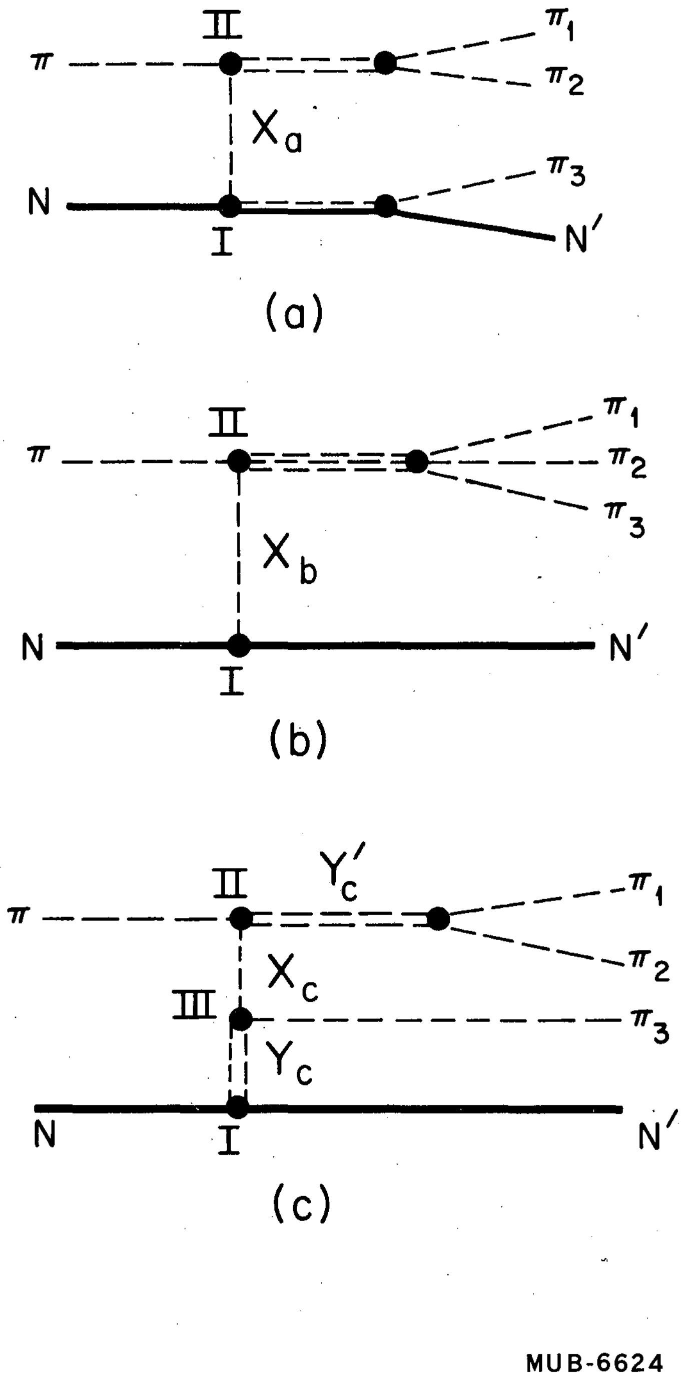

II
π
π_1
π_2
X_a
π_3
N
I
N′
(a)
II
π
π_1
π_2
π_3
X_b
N
I
N′
(b)
II
Y_c'
π
π_1
π_2
X_c
III
π_3
Y_c
N
I
N′
(c)
MUB-6624

Fig. 3