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[6] Events in Reaction (4) include those that have failed to fit Reaction (3) for technical reasons, although the Λ decay products are visible. After scanning efficiencies and geometrical corrections are taken into account, the ratio of visible to invisible Λ events in Reactions (3) and (4) is consistent with accepted values of the Λ branching ratio [see N. Barash-Schmidt et al., Rev. Mod. Phys. 41, 109 (1969)]. Our conclusions regarding the properties of resonances in these channels are not significantly altered by the inclusion or exclusion of ambiguous events.

[7] For channels (3) and (4), two $I_z=\frac{1}{2}$ $K\pi$ and $\Xi\pi$ combinations are possible, and both have been included in Figs. 1 (a) and 1 (b).

[8] The $\Xi(1530)$ band is defined as 1.500 GeV $<M(\Xi\pi)<1.570$ GeV; the $K^*(890)$ band is defined as 0.86 GeV $<M(K\pi)<0.92$ GeV.

[9] For kinematic reasons, events with $M(\Xi\pi\pi)\simeq 1.960$ GeV have a high probability of appearing in the $\Xi(1530)$, $K^*(890)$ overlap region. Thus, removal of overlap events unavoidably diminishes the enhancement at $M(\Xi\pi\pi)=1.960$

[10] The total center-of-mass energy of 2.56 GeV does not allow the production of the ρ in these reactions. The two $I=\frac{3}{2}$ combinations, $\Xi^0\pi^+$ and $\Xi^-\pi^-$, show no significant structure.

[11] The fitting programs MASTERFEIT [see B. T. Meadows, Syracuse Technical Report No. T-6901, 1969 (unpublished)] and MURTLEBERT [see J. Friedman, Alvarez Group Programing Note, P-156, 1966 (unpublished)] were used. No significant differences were noted. For full details of the procedure adopted see R. J. Hemingway and B. T. Meadows, Intramural Report No. I11-69, 1969 (unpublished). Noninterfering s-wave Breit-Wigner resonances were always assumed.

[12] In both $K^*(890)$ and $\Xi(1530)$ two charge states are present. For the $\Xi(1530)$ the observed neutral to negative ratio is approximately $\frac{4}{3}$.

[13] We note that in the $M(\Xi\pi\pi)$ and $M(\Xi(1530)\pi)$ distributions, $\frac{1}{3}$ of the contribution to the χ^2 results from a 10-12 event excess in the region of 2030 MeV where a resonance has been reported, e.g., see Ref. 3.

[14] Barash-Schmidt et al., Ref. 6. The experimental resolution was not unfolded from the width.

[15] The uncharged Ξ states were used to determine these ratios. Three-body decay into $\Xi^0\pi^0\pi^0$ was estimated as generously as possible on the assumption that $I=\frac{1}{2}$ for both Ξ's.

[16] See R. Hemingway and H. Whiteside, Maryland Technical Report No. 70-065, 1969 (unpublished) for details regarding these corrections.

[17] The structure at 1630 MeV in Fig. 2b has been discussed in Ref. 5.

STUDY OF THRESHOLD ENHANCEMENTS IN $\rho^0\pi^-$ AND $f^0\pi^-$ SYSTEMS FROM THE REACTION $\pi^-p\to p\pi^+\pi^-\pi^-$ AT 6 GeV/c *

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(Received 29 January 1970)

We have observed, in a high-statistics experiment, well-defined threshold enhancements in the $\rho^0\pi^-$ and $f^0\pi^-$ systems at 1120 and 1645 MeV, respectively. We have searched for other dominant decay modes of these enhancements and found none. The question of whether these objects are threshold enhancements of kinematic origin or resonances is examined.

Broad boson enhancements have been observed at threshold in high-energy quasi-two-body final states recoiling against targetlike nucleons in various reactions: $A_1^{\pm}$ in the $\rho\pi$ system and $A_3^{\pm}$ in the $f\pi$ system from $\pi^{\pm}$ reactions[1]; "$Q^{\pm}$" in the K*(890)π system and $L^{\pm}$ in the K*(1420)π system from K$^{\pm}$ reactions.[2] The question of whether these enhancements are real resonances or effects of kinematic origin has been examined from experimental as well as theoretical points of view.[3] In particular, recent developments in the concept of duality in relating the resonant behavior of the imaginary part of the s-channel amplitudes to the t-channel Regge-pole exchanges[4] further support the resonance interpretation of these low-mass enhancements.

In this Letter we present an analysis of the $\rho^0\pi^-$ and $f^0\pi^-$ systems near their threshold regions from the reaction $\pi^-p\to p\pi^+\pi^-\pi^-$ at 6 GeV/c with better statistics than any single reported experiment thus far.[1] The effective mass spectrum of three pions from this experiment indicates the existence of well-defined peaks at 1120 and 1645 MeV as well as the A_2. The 1120-MeV enhancement is consistent with a $\rho^0\pi^-$ decay mode whereas the 1645-MeV enhancement is consistent with an all $f^0\pi^-$ decay mode. We have searched for other dominant decay modes for these enhancements and found none. In addition, we have examined the three-pion mass spectrum with $\pi^+\pi^-$ mass outside the ρ^0 and f^0 mass regions, and observe no real three-pion threshold enhancements.

The data were obtained from an exposure of the BNL 80-in. liquid-hydrogen bubble chamber to a 6-GeV/c π^- beam. Approximately 30 000 four-prong events with at least one nonminimum ionized positive outgoing track[5] were measured by the BNL flying-spot digitizer. After imposing relevant cutoffs,[6] we were left with 8158 events of the four-constraint $p\pi^+\pi^-\pi^-$ final state. The two-body effective mass distributions $M(\pi^+p)$, $M(\pi^-p)$, and $M(\pi^+\pi^-)$ are shown in Figs. 1(a)-1(c). The most prominent features are the appearance of the $\Delta^{++}(1238)\rightarrow\pi^+p$ and $\rho^0(760)\rightarrow\pi^+\pi^-$. There are also signals for $f^0(1260)\rightarrow\pi^+\pi^-$ and nucleon resonances such as $\Delta^0(1238)\rightarrow\pi^-p$. For the following analysis we have removed all events in the Δ^{++} mass region (1080-1380).[7] The hatched histogram in Fig. 1(c) is the $\pi^+\pi^-$ mass spectrum after Δ^{++} removal. The smooth curve for the hatched histogram indicates a rough estimation of the f^0 contribution. We shall limit our discussions to the $\rho^0\pi^-$ and $f^0\pi^-$ enhancements near their threshold and the "continuous three-pion threshold enhancements"[8] as follows:

(1) The $\rho^0\pi^-$ threshold enhancement.—The three-pion mass spectrum is shown in Fig. 2. Marked enhancements are seen in the regions corresponding to the previously reported A_1, A_2, and A_3. The A_1 is well separated from the A_2 and peaks at the mass value of 1120 MeV, in agreement with results of high-energy πp experiments.[9] The value of the width can vary from ~100 to 300 MeV since it is extremely dependent on the assumed background. The A_1 signal is strongly peripheral, and only a weak signal remains for events with $|t_{p\rightarrow p}|\geq 0.075$ GeV^2 (see Fig. 2 shaded). In contrast the A_2, which will not be discussed further, is essentially not changed by the same cut.

Events in the A_1 region (1060-1180) were fitted to ~$\exp(bt_{p\rightarrow p})$ and gave a value $b=10\pm2$ GeV^{-2}. This steep distribution has been interpreted to favor A_1 production by Pomeranchukon exchange.[10]

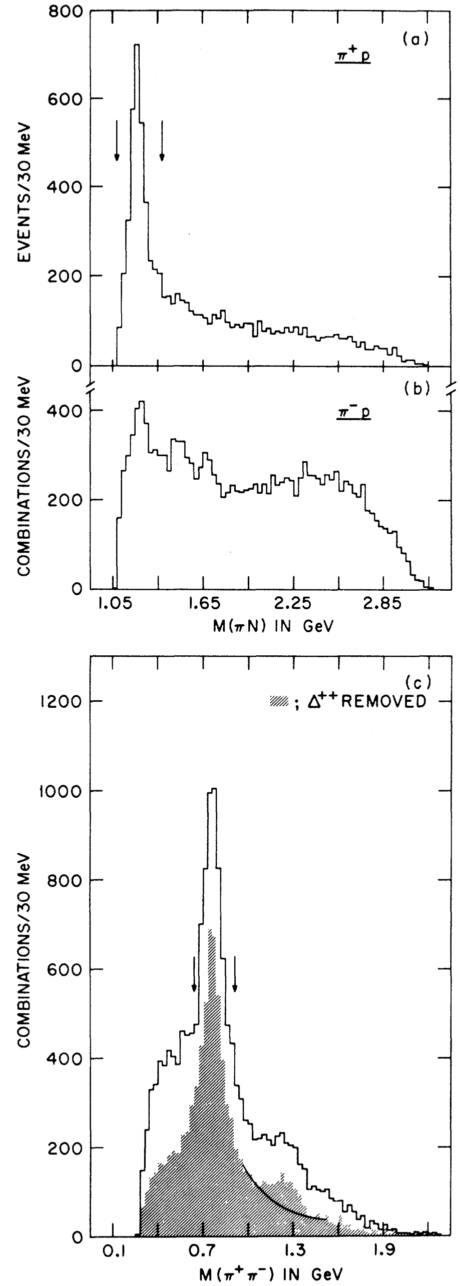

FIG. 1. (a)-(c) Two-body effective mass distributions.

The constant cross section, another feature of Pomeranchukon exchange, is not well established for the A_1 produced in πp reactions because of the difficulty of background estimation.[11]

The entire three-pion Dalitz plot for the A_1 mass region has been fitted to a Bose symmetric $J^P=1^+$ amplitude together with an incoherent phase space background. The fit allows a mixture of longitudinal and transverse ρ^0's[9] and determines g_1/g_0, the ratio of the complex coupling

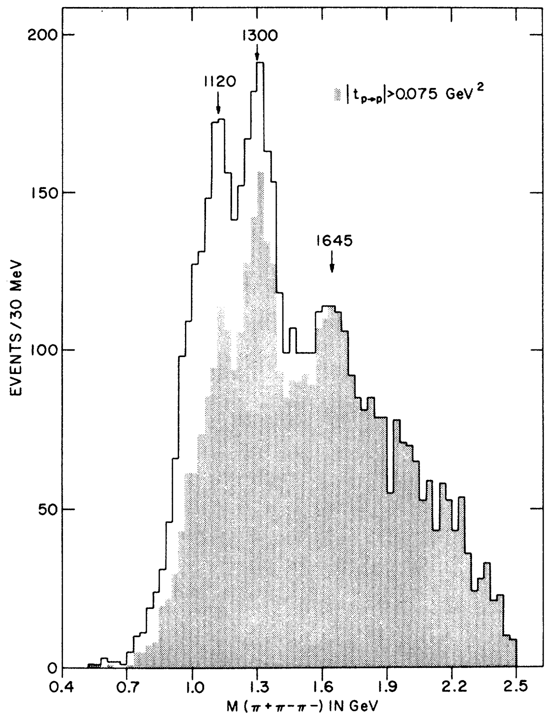

FIG. 2. Three-pion effective mass distribution with events in the $\Delta^{++}(1238)$ region removed.

constants related to the ρ^0 helicity distribution (before Bose symmetrization) by $W(\cos\alpha) = |g_1|^2 \times \sin^2\alpha + |g_0|^2 \cos^2\alpha$. This is equivalent to an arbitrary ratio of s- and d-wave decay; for s-wave $g_1 = g_0$ and for d-wave $g_1 = -0.5g_0$. The best fit to our data gives $g_1/g_0 = (0.89^{+0.07}_{-0.06})\, e^{-i(1.0 \pm 0.6)}$ with a χ^2 probability for the distribution of events in the ρ^0 band of 20%. For comparison, pure s-wave and d-wave fits to the whole Dalitz plot give χ^2 probabilities of 15% and 10^{-7}, respectively, for events in the ρ^0 bands. The value obtained for g_1/g_0 in our data is insensitive to the exact choice of either the A_1 mass region or to the Δ^{++} cut. Dalitz-plot fits to the ρ^0 band regions alone give similar results. We conclude that the decay of A_1 into the $\rho^0\pi^-$ mode is dominantly s wave for the $J^P = 1^+$ assignment. Our value of g_1/g_0 is different from previously reported results on the A_1.[9] We have also examined the possibility of the $J^P = 2^-$ assignment for the A_1. Satisfactory fits to the entire Dalitz plot are obtained and the best fit gives $g_1/g_0 = (0.74 \pm 0.06)\, e^{-i(-1.5 \pm 0.9)}$, where the condition for a pure p wave is $g_1 = 0.866g_0$.

Although the mass spectrum (see Fig. 2) suggests a well-defined $\rho^0\pi^-$ signal at 1120 MeV with a width of ~100 MeV above a broad $\rho^0\pi^-$ enhancement (the Deck effect),[4,12] it is difficult to judge the significance of these values since the complete $\rho^0\pi^-$ spectrum in the A_1 region can be fitted by a single spin and parity. No evidence for the $A_{1.5}$[1] enhancement is seen in this experiment.

II. The $f^0\pi^-$ threshold enhancement. — We have obtained the following values for the three-pion enhancement at 1645 MeV shown in Fig. 2: $M = 1645 \pm 10$ MeV and $\Gamma = 130 \pm 30$ MeV. These values are consistent with previous results for the $A_3^{\pm}$.[1] The $t_{p\to p}$ distribution for the A_3 signal using a background-subtraction method yields the value $b = 5 \pm 1$ GeV^2 for the slope. This value is markedly different from the value obtained for events in the "A_1" region ($b = 10 \pm 2$ GeV^2).[13]

An examination of the three-pion Dalitz plot (not shown) in the A_3 region shows a concentration of events in the ρ^0 and f^0 bands. Furthermore the distribution of events in the ρ^0 and f^0 bands (outside the overlap region) seems to be isotropic. We, therefore, made an attempt to estimate the $f^0\pi^-$, $\rho^0\pi^-$, and $\pi^+\pi^-\pi^-$ intensities in the three-pion mass spectrum in the A_3 mass region by assuming uniform noninterfering ρ^0 and f^0 bands and making a direct fit to the Dalitz plot. Figure 3 shows the results of this attempt. It seems to suggest that the A_3 effect can be described completely by a $f^0\pi^-$ enhancement with little or no contribution from either $\rho^0\pi^-$ or $\pi^+\pi^-\pi^-$. This procedure does give an adequate description of events in the A_3 region but it is by no means unique. An alternative fit using a mixture of $1^+(s)$, 1^-, and 2^+ in the $\rho^0\pi^-$, and an s-wave $f^0\pi^-$ system, and neglecting the interference between f^0 and ρ^0, gives a result consistent with the above fit. Neither fit is able to produce a peak in the $\rho^0\pi^-$ intensity distribution in the A_3 mass region. To check the self-consistency of this argument, we use the parameters (M and Γ) of the A_3 obtained from the three-pion spectrum (Fig. 2) to fit the $f^0\pi^-$ intensity distribution. The solid lines are the resonance fit plus an assumed $f^0\pi^-$ background as shown in Fig. 3(a), and the overall agreement is good.

We have made a systematic search for other decay modes of the A_3 in systems such as $\pi^-\eta$, $\pi^+\pi^-\pi^+\pi^-\pi^-$, K^-K^0, and $(K^*\bar{K})^-$, and found no strong signal for the first two modes with upper limits for relative branching ratios with respect to $f^0\pi^-$ to be <10% for each. A 1630-MeV enhancement in the $(K\bar{K})^-$[14] and, possibly $(K^*\bar{K})^-$ may be due to the g meson since the G parity of a $K\bar{K}$ or $K^*\bar{K}$ system is not unique. The lack of a $K_1^0K_1^0$ enhancement in this region may indicate that, at least, the $K\bar{K}$ effect is not correlated to

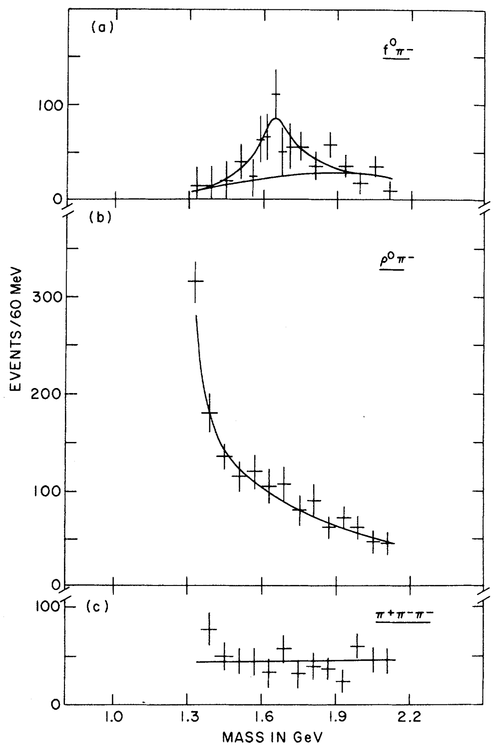

FIG. 3. (a)-(c) Intensity distributions deduced from the three-pion effective mass distribution (Fig. 2). See text for details.

the A_3 phenomena. We therefore conclude that $f^0\pi^-$ is the only strong decay mode for the A_3 in our data.

III. Continuous three-pion threshold enhancements.—Both the 1120- and 1645-MeV enhancements are close to the respective $\rho^0\pi^-$ and $f^0\pi^-$ thresholds. The three-pion spectra for di-pion ($\pi^+\pi^-$) mass intervals in addition to the ρ^0 and f^0 regions have also been examined to see if threshold effects are a general feature of the data.[8] Five di-pion mass intervals of 240 MeV width [indicated in Fig. 4(a)] have been used; the resulting three-pion spectra are shown in Figs. 4(b)-4(f). However, because of the dominance of ρ^0 production, the reflection effects arising from the existence of two $\pi^+\pi^-$ combinations must be considered. Consequently, all events with one $\pi^+\pi^-$ combination in the ρ^0 region (640-880 MeV) are assumed to be mainly ρ^0 events. The other $\pi^+\pi^-$ combinations should be removed, and are shown shaded in Figs. 4(b) and 4(d)-4(f). Three-pion enhancements are not seen in the unshaded areas in Figs. 4(b), 4(d), and 4(f) where ρ^0 is not present. It is evident that real threshold enhancements are only apparent in Figs. 4(c) and 4(e) (with di-pion mass in the ρ^0 and f^0 region, respectively). The small A_3 signal in 4(e) re-

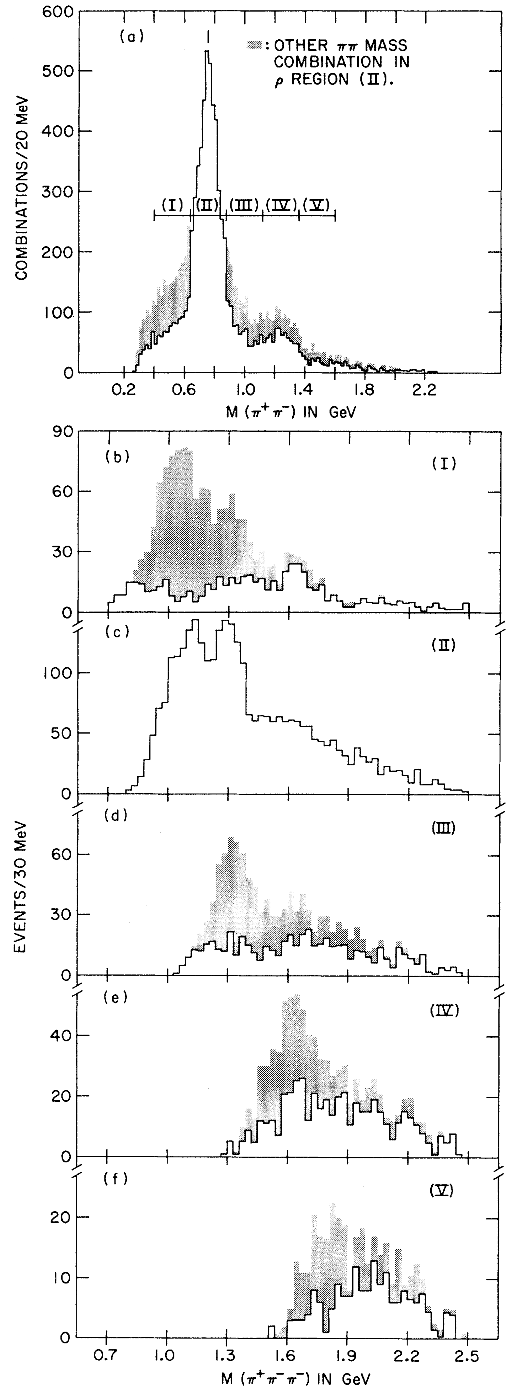

FIG. 4. (a) Di-pion mass distribution with events in the $\Delta^{++}(1238)$ region removed. Five di-pion mass subregions starting at 400 MeV with 240 MeV in each region as shown. (b)-(f) Three-pion effective mass distributions with di-pion mass regions corresponding to regions indicated in (a). The shaded contributions are due to the reflections of ρ events. See text for details.

sults from removal of some events in the f^0 region when the ρ^0 cut is imposed. It should also be noted that reflections of events in the f^0 region have not been removed, hence a small A_3 effect is seen in Fig. 4(b).

The preceding argument is not crucially dependent on the exact limits one chooses for the ρ^0 mass region. This observation suggests that the three-pion threshold enhancement only occurs when the di-pion system is dominated by a definite state (or partial wave), such as is the case for $\pi+\rho^0$ (p-wave) and $\pi+f^0$ (d-wave) and not $\pi+\pi\pi$ (no definite partial wave). From the duality point of view,[4] these threshold enhancements are resonances. This approach, when applied to the A_1 and the A_3, gives rise to the question: Why is there no other significant decay mode, in particular, for the case of A_3, since it can, in principle, also decay into a system such as $\rho\pi$ with no known selection rule or Q-value problem[15]?

To summarize, we have observed $\rho^0\pi^-$ and $f^0\pi^-$ enhancements at masses of 1120 and 1645 MeV, respectively. Both $\rho^0\pi^-$ and $f^0\pi^-$ enhancements can be adequately described by an s-wave interaction between π and ρ^0 and π and f^0, respectively. No other significant decay modes have been found for these effects in this experiment. We observed no real three-pion threshold enhancements for di-pion masses outside the known dipion resonances, ρ^0 and f^0.

It is our pleasure to acknowledge the assistance in data reduction from the personnel of the BNL bubble chamber group. We also wish to thank Dr. Ian O. Skillicorn for his participation at early stages of the experiment, Dr. Jack Donohue, Dr. S. Nussinov, Dr. Bing-Lin Young, and Dr. Y. Zarmi for their interest in our data, and finally Dr. Ralph P. Shutt for his continued support and encouragement.

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

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[1]For a review see B. French, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September 1968, edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), pp. 106, 120.

[2]See for example, A. Barbaro-Galtieri et al., Phys. Rev. Letters 22, 1207 (1969).

[3]For a recent analysis see M. Ross and Y. Yam, Phys. Rev. Letters 19, 546 (1967); E. L. Berger, Phys. Rev. 179, 1567 (1969).

[4]R. Dolen, D. Horn, and C. Schmid, Phys. Rev. 166, 1768 (1968); G. F. Chew and A. Pignotti, Phys. Rev. Letters 20, 1078 (1968).

[5]The scanning restriction was checked and found to have no effect on the results presented in this Letter.

[6]The probability of the kinematical fit was required to be greater than 1%. The momentum of the recoiling proton in the laboratory system was required to be less than 1.5 GeV/c.

[7]An examination of the $\rho^0\pi^-p$ Dalitz plots (not shown) indicates no essential difference in the $\rho^0\pi^-$ and $f^0\pi^-$ mass distributions for events in the $\Delta^0(1238)$, $N^0(1520)$ and $N^0(1688)$ bands compared with the region of $M^2(\pi^-p)$ greater than 3.2 GeV^2. GeV^2.

[8]Threshold enhancements in the $K^+\pi^+\pi^-$ system (from the reaction $K^+p\rightarrow K^+\pi^+\pi^-p$ at 12 GeV/c) are observed for $K^+\pi^-$ events outside of, as well as in, the $K^*(890)$ and $K^{**}(1420)$ mass region. See Barbaro-Galtieri et al. (Ref. 2).

[9]See for example, J. Ballam et al., Phys. Rev. Letters 21, 934 (1968), and Phys. Rev. D (to be published).

[10]However, the reaction $\pi^-p\rightarrow\eta\pi^0$ in which only the ρ trajectory can be exchanged has a comparable slope ($b\sim 11$ GeV^{-2}). See for example A. V. Stirling et al., Phys. Rev. Letters 14, 763 (1965).

[11]Despite the experimental compilation by D. R. O. Morrison [Phys. Rev. 165, 1699 (1968)], we note that the cross sections for the A_1 reported by various experiments are strongly biased by the assumptions of the background in the A_1 region.

[12]R. T. Deck, Phys. Rev. Letters 13, 169 (1964), and Ref. 3.

[13]This difference may indicate that f^0 trajectory exchange is important here. We note that the value for b is 5 ± 1 GeV^{-2} for the reaction $\pi^-p\rightarrow n\eta(550)$, where only the A_2 trajectory exchange is allowed [see, for example, O. Guisan et al., Phys. Letters 18, 200 (1965)]. This similarity between the A_3 and the η production from πN interactions may be due to the fact that both f^0 and A_2 are in the same $J^P=2^+$ multiplet.

[14]D. J. Crennell et al., Phys. Rev. Letters 18, 323 (1967), and Phys. Letters 28B, 136 (1968).

[15]Cancelations of amplitudes among all other decay modes would be necessary to explain the "one-decay mode observation" but it is an unlikely explanation for this phenomenon.