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Author

Berger, Edmond L

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Edmond L. Berger

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LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

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EXOTIC EXCHANGE OR KINEMATICAL REFLECTION?*

Edmond L. Berger+

Lawrence Radiation Laboratory
University of California
Berkeley, California

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ABSTRACT

Recently observed peripheral peaks in reactions where single-meson-exchange is forbidden are explained as kinematical reflections. Experimental and theoretical implications are discussed.

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A notable feature of strong interactions is the apparent absence of exotic meson resonances.[1] Recently, however, peripheral forward peaks have been observed in differential cross sections of certain quasi-two-body reactions for which ordinary single-meson-exchange is forbidden.[2] Interpreted naively, these peaks suggest a dynamics involving exchange of meson states with exotic quantum numbers, $I \geq 3/2$ or $|S| = 2$. In this note, a simple alternative explanation is developed. Peripheral peaks of the type observed are shown to be generated as reflections from competing allowed processes. Calculated magnitudes and shapes are consistent with available data.

The mechanism proposed here would not seem subject to duality ambiguities. Strong backward peaks exist at low energy in (stable particle) two-body reactions such as $\pi^+\pi^- \to \pi^+\pi^-$ and $K^-p \to \bar{K}^0 n$.[3] For these, the backward exchange (u) channel is exotic; however, the observed peaks are generally understood as manifestations of prominent resonances in the direct (s) channel. No exotic exchange mechanism, whether dual or not, need be invoked.[4] As will be demonstrated in this paper, the backward peaks associated with these two-body channels propagate to higher multiplicity reactions. Specifically, for $M^{\pm}B \to (M^{\pm}B) + M^{\mp}$ at fairly high energy, the observed (forbidden) peripheral production of decuplet states $(M^{\pm}B)$ is shown here to be a consequence of backward "scattering" in the $M^{+}M^{-}$ (meson-meson) rest frame at relatively small values of $M^{+}M^{-}$ invariant mass.

An experimental suggestion from this analysis is that the search for exotic exchange effects is best confined to reactions (such as $\pi^{-}p \to \Sigma^{-}K^{+}$ or $p\bar{p} \to \Sigma\bar{\Sigma}$) involving particles which are stable with respect to strong interactions. Implications for phenomenology, including $\pi\pi$ scattering, are discussed at the end of the paper.

<u>The model</u> is best illustrated by explicit examples which will be treated in turn:

$$\pi^{+}n \to \pi^{+}\pi^{-}p \quad (\to \pi^{-}\Delta^{++}(1238)) ; \qquad (1)$$

$$\pi^{-}p \to \pi^{-}K^{+}\Lambda \quad (\to K^{+}Y^{*-}(1385)) ; \qquad (2)$$

$$K^{-}p \to \pi^{-}K^{+}\Xi^{0} \quad (\to K^{+}\Xi^{*-}(1530)) . \qquad (3)$$

The pseudo-exotic exchange processes are indicated in parentheses.

Prominent features of the data for Reaction (1) include peripheral production of the ρ^{0} and f^{0} as well as the Δ^{++}. Backward[5] production of Δ^{++} is presumably mediated by baryon exchange; one expects to observe a peak in the center-of-mass differential cross section near $\cos\theta^{cm} = -1$. However, after selecting events for which the invariant mass $m_{\pi^{+}p}$ is in the $\Delta^{++}(1238)$ mass band, one observes a pronounced peak near $\cos\theta^{cm} = +1$, also. As will now be demonstrated, an enhancement in the $\pi^{+}p$ mass spectrum near the Δ position as well as the peak near $\cos\theta^{cm} = +1$

result from decay of $\pi^+\pi^-$ states formed in the peripheral process $\pi^+ n \to (\pi^+ \pi^-)p$.

A qualitative argument will be given first. The diagram of Fig. 1(a) illustrates the effect. The $\pi^+\pi^-$ pair is typically produced with a wide spectrum of invariant masses, but with most of the events in the resonance region below ≈ 1.5 GeV. This peripherally produced $\pi\pi$ system, traveling forward with respect to the incident π^+ beam, decays with an angular distribution in its <u>center-of-mass frame</u> characteristic of the resonant and other low partial waves in the $\pi\pi$ spectrum. This distribution changes with $\pi\pi$ mass, but is generally peaked near both $z = -1$ and $z = +1$, or at least has significant intensity in the backward hemisphere.[6] With substantial probability, therefore, the decay π^+ may proceed backwards, i.e. in the direction of the p. The result is an enhancement near threshold in the $\pi^+ p$ system. Moreover, largely for kinematic reasons, the enhancement is associated with very small values of the invariant-momentum-transfer-squared, $t_{\pi^+\pi^-}$, from incident π^+ to final π^-.

The preceding argument may be made more quantitative. An approximate form for the absolute square of the relevant invariant amplitude (Fig. 1(b)) is

$$\sum |\mathcal{M}|^2 = 2g^2 \frac{-t_{np}}{(t_{np} - m_\pi^2)^2} |A_{\pi^+\pi^-}|^2 \exp[\lambda(t_{np} - m_\pi^2)] \quad (4)$$

$$|A_{\pi^+\pi^-}(s_{\pi^+\pi^-}, z)|^2 = (8\pi)^2 s_{\pi\pi}(d\sigma_{\pi\pi}/d\Omega) . \quad (5)$$

Below $s_{\pi\pi} = 2.9 \text{ (GeV)}^2$, the physical $\pi^+\pi^-$ elastic scattering angular distribution, $d\sigma_{\pi\pi}/d\Omega$, can be represented by actual, nonextrapolated data[7] restricted to values $|t_{np}| < 0.2 \text{ (GeV)}^2$. Above 2.9 (GeV)^2, a smooth Regge pole amplitude is employed; it is constructed using parameters for the P, P', and ρ trajectories obtained through factorization[8] and has no backward peak. The value of λ in Eq. (4) was determined to be 6.0 $(\mathrm{GeV}/c)^{-2}$ by a fit to $d\sigma/dt$ for $\pi^- p \to \rho^0 n$. In Eq. (4) the pion-nucleon coupling constant is $g^2/4\pi = 14.5$; there are no free parameters.

Results are shown in Fig. 2; to facilitate comparison with the data,[2] the ρ mass band was excluded from the integrations. As will be noted, the decaying $\pi^+\pi^-$ system generates a sizeable reflection near threshold in the π^+p mass spectrum. Moreover, the effect is produced very peripherally: for $m_{\pi^+p} < 1.36$ GeV, $d\sigma/dt_{\pi^+\pi^-} \propto \exp(7t_{\pi^+\pi^-})$ at 2.0 GeV/c and $\propto \exp(11t_{\pi^+\pi^-})$ at 6.0 GeV/c. Because of the more restricted phase space, the two peaks shown in Fig. 2(a) are not resolved at 2.0 GeV/c; the near threshold enhancement appears as a shoulder only. At 6.0 GeV/c, the center-of-mass production angular distribution is qualitatively similar to Fig. 2(b), but considerably more forward peaked, as indicated by the dashed line in Fig. 2(a).

A comparison with sizes of analogous peaks in reactions for which single meson exchange is allowed demonstrates that the magnitude of the calculated effect is indeed large. For example, the observed forward peak in $d\sigma/d\Omega$ for $\pi^+p \to \pi^0\Delta^{++}$ is only a factor of 2-3 larger.[9] At 2, 4, 6, and 10 GeV/c, with $\Delta^{++} \equiv m_{\pi^+p} < 1.36$ GeV and ρ restored, $\sigma(\pi^+n \to \pi^-\Delta^{++})$ is 0.50, 0.18, 0.07, and 0.02 mb, respectively.

Except, perhaps, for the full width of the mass enchancement, these results are in agreement with the available data.[2,10] The width issue will be discussed after the next example is treated.

A complete treatment of Reaction (2) requires consideration of both pseudo-scalar (K) and vector (K^*) exchange components, known to be present in peripheral production of the $K^*(890)$ and $K^*(1420)$.[11] For simplicity, only pseudo-scalar is retained here; however, the effect obtained is qualitatively similar with K^* exchange included. For $\pi^- p \to (K^+\pi^-)\Lambda$, via K exchange,

$$\sum |\mathcal{M}|^2 = g_\Lambda^{\,2} \frac{(m_\Lambda - m_p)^2 - t_{p\Lambda}}{(t_{p\Lambda} - m_K^{\,2})^2} |A_{K\pi}|^2 \exp\left[2(t_{p\Lambda} - m_K^{\,2})\log s\right] . \quad (6)$$

The elastic $K^+\pi^-$ amplitude, $A_{K\pi}$, was represented as a sum of Breit-Wigner expressions for the $K^*(890)$ and $K^*(1420)$, with spin $J = 1$ and 2, respectively, and width having energy dependence $(q/q_{res})^{2J+1}$. In the calculations, the $Kp\Lambda$ coupling constant has been chosen to be $(g_\Lambda^{\,2}/4\pi) = 14$; other choices will scale the results proportionately. An additional t dependence of Regge type $(s^{2\alpha_K})$ has been included;[12] away from the dip at the forward direction, the differential cross section for Λ production integrated over all $K\pi$ masses, is $\propto \exp(4t_{p\Lambda})$.

The resulting peripheral enhancement in the $\pi^-\Lambda$ mass spectrum is shown in Fig. 3. Also illustrated is the direct association of the backward hemisphere in $\pi^-K^+ \to \pi^-K^+$ with low-mass structure in the $\pi^-\Lambda$ system. When the appropriate proportion of K^* exchange is included, the valley between the two peaks of Fig. 3(a) is filled-in somewhat, and the low mass peak moves to 1.5 GeV. For $m_{\pi\Lambda} = 1.4$ GeV, at 2, 6, and 10 GeV/c, $d\sigma/dt(\pi_{in}^- \to K^+) \propto \exp(bt)$, with $b = 10, 13, 16\ (\text{GeV/c})^{-2}$, respectively. The slope b decreases as $m_{\pi\Lambda}$ is increased, a characteristic feature of doubly peripheral processes.[13]

Forward production of $Y_1^{*-}(1385)$ in kaon induced reactions may be similarly explained. Consider $K^-p \to \pi^+\pi^-\Lambda$. Here, also, an appreciable fraction of the peripherally produced $\pi^+\pi^-$ system will decay in such a manner that the π^- travels backwards and "catches-up" with the Λ.

As they stand, the full widths of mass enhancements shown in Figs. 2(a) and 3(a) are too broad for direct identification with the $\Delta^{++}(1238)$ and $Y_1^*(1385)$, respectively. However, the curves do indicate a large probability for the π^+ and p (or π^- and Λ) to have relative momentum characteristic of these resonant states. Moreover, partial wave analysis of the amplitudes in Eqs. (4) and (6) shows that at low invariant masses the p-wave component in the $\pi^+ p$ and $\pi^-\Lambda$ rest frames is substantial.[14] Inasmuch as strong resonant effects are known to be present in those partial waves, it appears that final-state rescattering effects will be important in reshaping final mass-peaks. Indeed, the approximate effect of final-state interaction is to multiply the $J^P = \frac{3}{2}^+$ component of the amplitudes by a Breit-Wigner form.[15] Unfortunately, the multiplicative scale factor associated with final-state rescattering is not determinable unless explicit models are introduced; however, the usual result of an additional attractive interaction is to augment an effect.

The final-state mechanism may be invoked to explain production of Ξ^{*-} in Reaction (3). A two-step process is involved. First, in $K^-p \to K^+K^-\Lambda$, values of the $K^-\Lambda$ invariant mass near threshold are enhanced as a reflection of backward scattering at low energies in the K^-K^+ system. An established $\bar{K}\Lambda$ state above threshold is the $\Xi^*(1815)$, but exothermic rescattering may transform $K^-\Lambda \to \Xi^{*-}(1530) \to \pi^-\Xi^0$.

In addition to the question of exotic states, other consequences of reflections should be noted. (1) The analysis given here generally emphasizes again the need for better understanding of interference effects among competing two-body channels in a three-body final state reaction. In fact, the discussion can be reversed: the backward peak for $\pi^+\pi^- \to \pi^+\pi^-$, extracted rom data on $\pi^- p \to \pi^+\pi^- n$, for example, may be severely biased by the presence of peripherally produced N^{*-} states. This effect has important bearing for current research on $\pi\pi$ and $K\pi$ phase shifts.

(2) In phenomenological analyses based on a multiperipheral approach, events are often assigned to specific diagrams based on an ordering of momentum transfer, longitudinal momenta, or related scattering angle variables. When subenergy values are small, the analysis of this note demonstrates that these ordering schemes are likely to be misleading.[16]

(3) Consider $\pi^+ p \to \pi^+\pi^o p$. There are no exotic channels, and the peripheral quasi two-body final state $\pi^o\Delta^{++}$ is presumably mediated by ρ exchange.[9] However, here again, the competing channel, $\pi^+ p \to (\pi^o\pi^+)p$, complicates the problem by generating a sizeable reflection which looks like $\pi^o\Delta^{++}$, is peripheral, and must be treated coherently.

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REFERENCES AND FOOTNOTES

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+ On leave from Dartmouth College, Hanover, N. H.

1. An exotic meson is one whose quantum numbers cannot be generated via the quark model as $(\bar{q}q)$. For a review of the experimental status, see A. H. Rosenfeld, Meson Spectroscopy (W. A. Benjamin, Inc., New York, 1968), p. 455

2. M. A. Abolins et al., Phys. Rev. Letters 22, 427 (1969); P. M. Dauber et al., UCRL-18789 Rev., submitted to Phys. Letters, 1969; A. Bashian et al., SUNY-Stony Brook-Wisconsin preprint, submitted to Lund Conference, 1969.

3. R. Armenteros et al., Nucl. Phys. B8, 235 (1968).

4. See, e.g., J. Shapiro, Phys. Rev. 179, 1345 (1969) for a discussion of $\pi\pi$ scattering in a dual, crossing symmetric model.

5. Direction is specified by following the baryon through the reaction; in meson-meson processes, charge can be followed.

6. In the final state $\pi^-\pi^+$ rest frame, z is the cos of the scattering angle from incident to final π^+. It is not necessary that there be a backward peak, per se; the relative size of the reflection effect is inversely proportional to the ratio $(F - B)/(F + B)$, averaged over the low energy $\pi\pi$ spectrum. For a compilation, see J. J. Veillet, Proc. XIII High Energy Conference, Berkeley, Calif. (1966), p. 130.

7. P. B. Johnson et al., Phys. Rev. 176, 1651 (1968); J. A. Poirier et al., Phys. Rev. 163, 1462 (1967); D. J. Crennel et al., Phys. Letters 28B, 136 (1968).

8. E. L. Berger and G. C. Fox, Pion-Nucleon and Kaon-Nucleon Scattering in the Veneziano Model, UCRL-18886, May, 1969, submitted to Phys. Rev. Factorization gives the parameters of the P and P'; exact exchange degeneracy of the ρ and P' was invoked to obtain the ρ parameters from those of the P'.

9. R. D. Mathews, Nucl. Phys. B11, 339 (1969).

10. Recall that the data do have backward Δ^{++} production produced by baryon exchange, in addition.

11. D. J. Crennel et al., BNL-10462R (1966); $\pi^-p \to K^*(890)\Lambda$ is in fact dominated by vector exchange at 6.0 GeV/c so that the angular distribution in the K^* rest frame is fairly flat. However, $\pi^-p \to K^*(1420)\Lambda$ shows strong forward and backward peaking in cos θ. The $K^*(1420)$ mass region is also more effective in generating the reflection effect discussed here.

12. The Regge form is not essential. Note that it depends on total s, not on a subenergy variable. None of the effects discussed depend critically on its presence.

13. E. L. Berger, Phys. Rev. 179, 1567 (1969); see Sec. V-A.

14. The $\ell = 1$ and higher components in the $\pi^-\Lambda$ system are also produced more peripherally than is the overall enhancement. For example, for $\ell = 1$, $d\sigma/dt(\pi^- \to K^+) \propto \exp(20t)$ at 6 GeV/c lab momentum.

15. J. D. Jackson, Nuovo Cimento 25, 1038 (1962).

16. Uncritical application of the longitudinal momentum scheme by W. Ochs (Nucl. Phys. B10, 453 (1969)) indicated the need for exotic exchange.

FIGURE CAPTIONS

1. Diagrams illustrating the process. In (a), only the final state particles are shown; ρ and f represent, more generally, the peripherally produced $\pi\pi$ system. In (b), the "blob" stands for the complete $\pi\pi$ amplitude.

2. Distributions obtained from Eq. (4) for (a) invariant mass of π^+p and (b) cosine of the π^+(in) to π^-(out) scattering angle <u>in the overall c.m. frame.</u> The ρ band $(0.64 < m_{\pi^+\pi^-} < 0.88)$ was excluded. Other cuts are indicated; $\hat{\pi}$ denotes the unit vector three momentum of a pion in the overall c.m. frame.

3. Distributions calculated from Eq. (6). Cuts are indicated; the dot-dashed curve in (a) was obtained after setting $P_J(z) = P_J(0)$ for $z < 0$ in expressions for the $K^*(890)$ and $K^*(1420)$. Symbols $\hat{\pi}$ and $\hat{K}$ denote unit-vector three-momenta of π and K, respectively, in the overall c.m. frame.

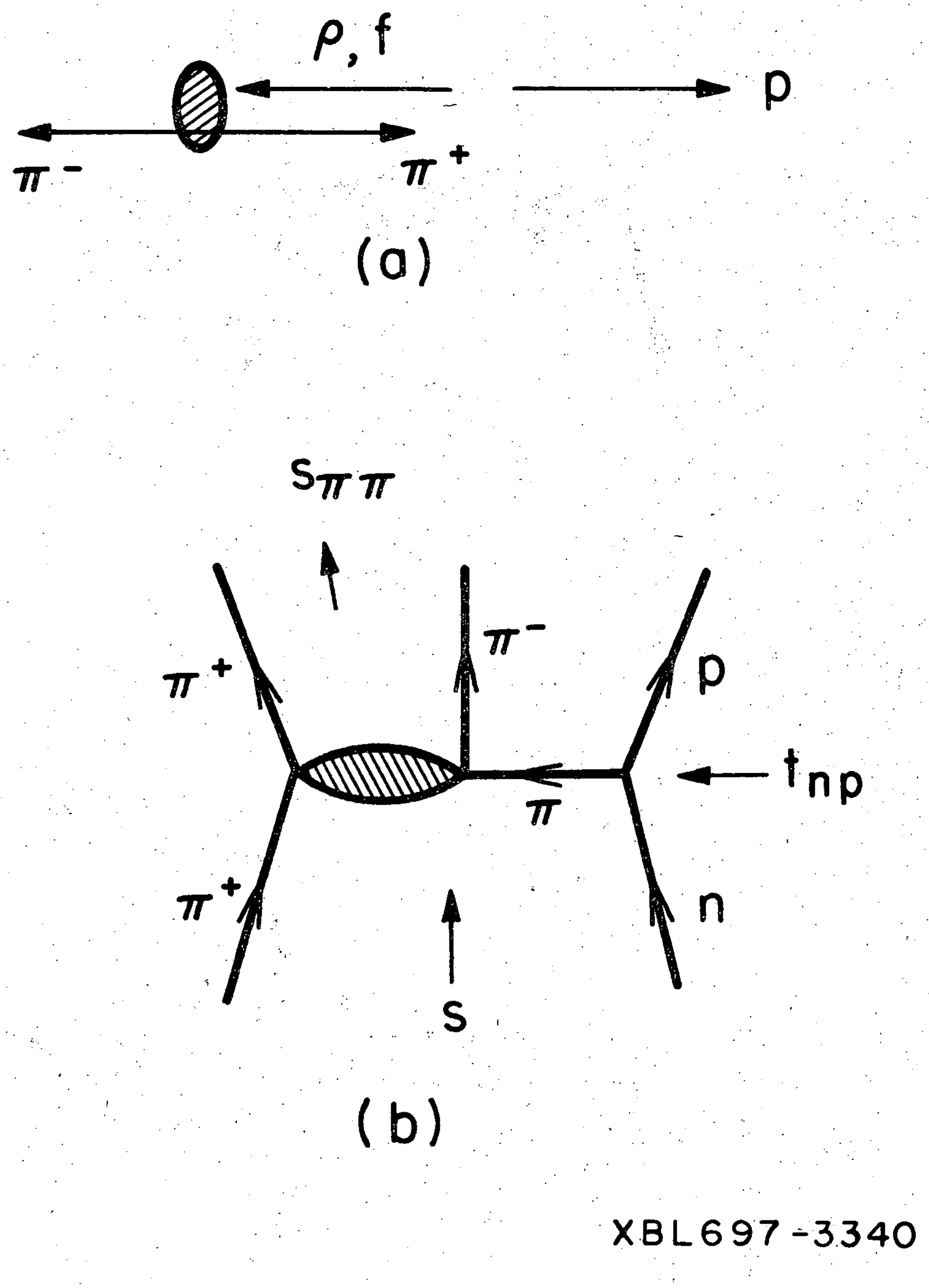
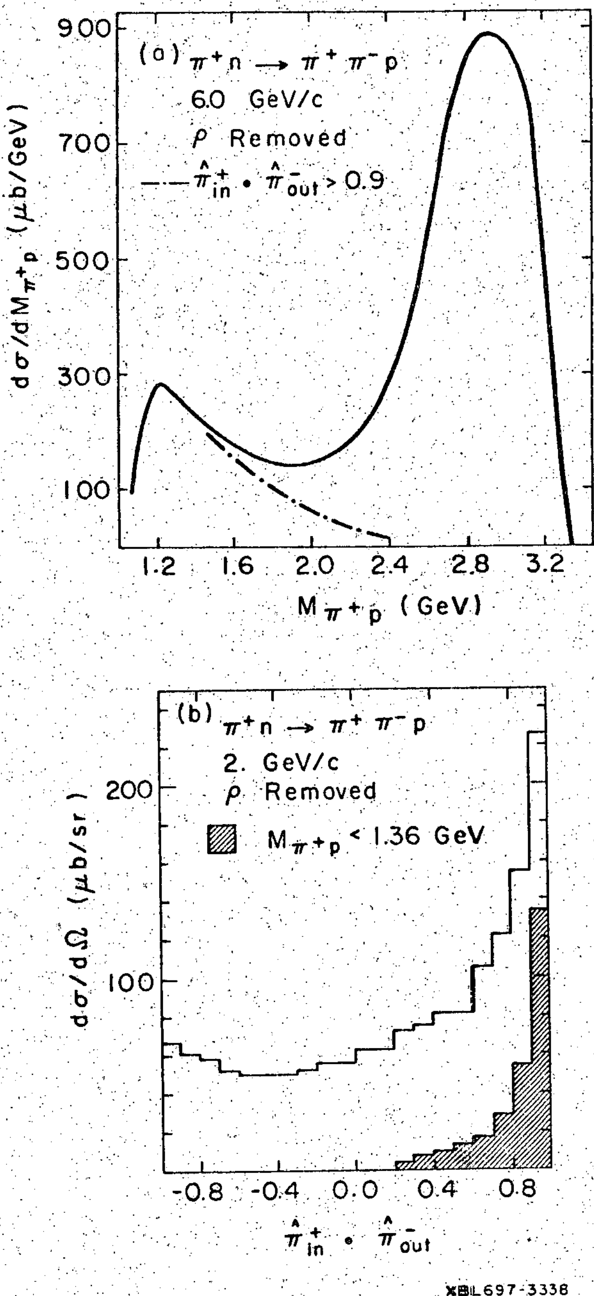


Fig. 1



(a) $\pi^+ n \rightarrow \pi^+ \pi^- p$
6.0 GeV/c
ρ Removed
$\hat{\pi}^+_{in} \cdot \hat{\pi}^-_{out} > 0.9$
$d\sigma/dM_{\pi^+p}$ (μb/GeV)
900
700
500
300
100
1.2
1.6
2.0
2.4
2.8
3.2
M_{π^+p} (GeV)
(b) $\pi^+ n \rightarrow \pi^+ \pi^- p$
2. GeV/c
ρ Removed
$M_{\pi^+p} < 1.36$ GeV
$d\sigma/d\Omega$ (μb/sr)
200
100
-0.8
-0.4
0.0
0.4
0.8
$\hat{\pi}^+_{in} \cdot \hat{\pi}^-_{out}$
XBL697-3338

Fig. 2

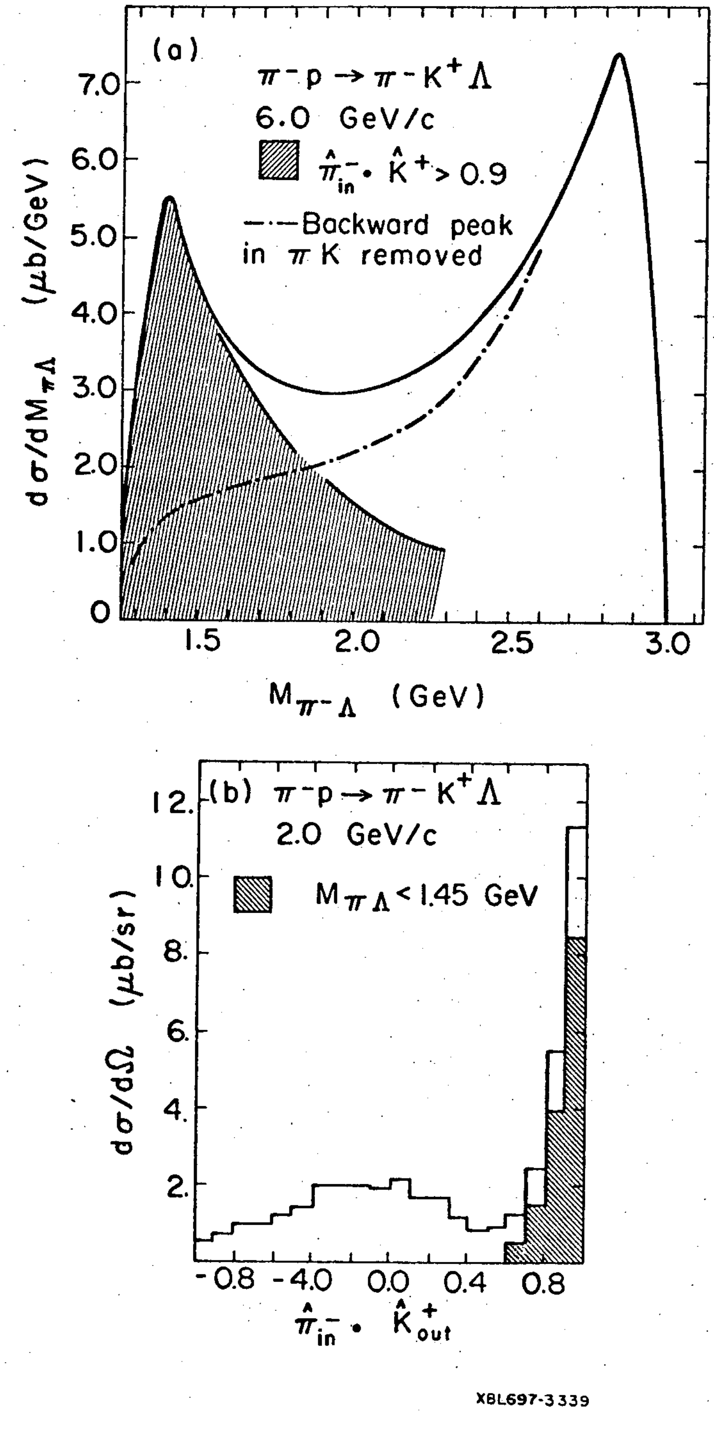

(a)
$\pi^- p \to \pi^- K^+ \Lambda$
6.0 GeV/c
$\hat{\pi}^-_{in} \cdot \hat{K}^+ > 0.9$
Backward peak in πK removed
$d\sigma/dM_{\pi\Lambda}$ (μb/GeV)
$M_{\pi^-\Lambda}$ (GeV)
(b) $\pi^- p \to \pi^- K^+ \Lambda$
2.0 GeV/c
$M_{\pi\Lambda} < 1.45$ GeV
$d\sigma/d\Omega$ (μb/sr)
$\hat{\pi}^-_{in} \cdot \hat{K}^+_{out}$
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Fig. 3

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