OBSERVATION OF FORWARD PEAKS IN $\pi^+n \rightarrow K^0Y^{*+}(1385)$ AND IN
RELATED SINGLE-MESON-EXCHANGE-FORBIDDEN REACTIONS

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OBSERVATION OF FORWARD PEAKS IN $\pi^+n \rightarrow K^0Y^{*+}(1385)$ AND IN RELATED
SINGLE-MESON-EXCHANGE-FORBIDDEN REACTIONS

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ABSTRACT

We have studied the production of decuplet-baryon resonances [$Y_1^*(1385)$, $\Xi^*(1530)$, and $\Delta(1236)$] in reactions which cannot proceed by the exchange of any single known meson. We have examined these exotic exchange reactions at incident momenta ranging from 1.0 to 4 GeV/c, using data from several bubble chamber exposures. In all but one of the reactions studied, there is significant "forbidden" forward peaking. At roughly 2 to 3 GeV/c, the cross section in the forward direction is 2 to 7 $\mu\text{b/sr}$ for $\pi^-p \rightarrow K^+Y^{*-}$ and $K^-p \rightarrow K^+\Xi^{*-}$, ≈ 20 $\mu\text{b/sr}$ for $K^-p \rightarrow \pi^+Y^{*-}$, and ≈ 100 $\mu\text{b/sr}$ for $\pi^-p \rightarrow \pi^+\Delta^-$; no peak is seen in $K^-p \rightarrow K^0\Xi^{*0}$. A decrease with energy is evident. The data is presented at length, to establish the existence of the forbidden peaking in final states which are dominated by other features; production and decay distributions are given.

Various possible explanations of forbidden peaking are reviewed. We argue that Berger's model does not explain away the peaking as a kinematic reflection. Recent work suggests that two-meson exchange may provide an explanation. We also consider the possible roles of exchange of a single (exotic) meson and of direct-channel resonance formation.

3.1 INTRODUCTION

3.11 GENERAL REMARKS

This report is essentially an expanded version of two published Letters, in which we reported forward peaking in $\pi^+n \rightarrow K^0Y^{*+}$ and in other decuplet-baryon production reactions whose t-channel quantum numbers forbid the exchange of any known (i.e., non-exotic) meson.^{91,92} The data analysis which has been done since those papers were completed has not altered the results. This chapter does present the analysis in considerably more detail, and includes many additional figures. In Section 3.3 we have expanded the discussion of various possible interpretations of the effect, taking note of recently published experimental and theoretical work. Our opinion on the most probable explanation has changed somewhat; two-meson exchange now seems most likely to explain this phenomenon. For a summary of the data presented here, the reader is referred to Section 3.4.

3.12 HISTORICAL BACKGROUND

The one-particle-exchange model has been remarkably successful in describing two-body and quasi-two-body reactions at moderate and high energies. The most prominent feature of many such reactions is a c.m. production cosine distribution that is markedly forward peaked. In naive terms, the one-meson-exchange model suggests that the target or beam emits a virtual meson which is captured by the other particle. The corresponding amplitude has a propagator with a pole where the transferred four-momentum is equal to the mass of the exchanged particle; this leads to peaking in the forward direction (i.e., at small momentum transfer). (Backward peaking can similarly be associated with baryon exchange.)

Especially when modified by absorption corrections, this model has provided a good description of the production distribution of many reactions. Decay correlations of resonances produced by one-particle-exchange (OPE) can be interpreted in terms of the spin and angular momentum information carried by the exchanged particle. The OPE model has been extended to cover the exchange of Regge trajectories, corresponding to families of particles; the properties of the trajectories have been deduced from their exchanges. Duality arguments have allowed the use of exchange models to describe (at least in an average sense)

reactions which appear to be dominated by, and can be described simply in terms of, direct-channel resonances. Finally, we note that one can use extrapolation techniques to extract information on real particle scattering from an exchange-dominated reaction, with the virtual exchanged particle acting as a target.

The simple OPE model is applicable in a negative sense to reactions where the quantum numbers in a crossed channel prohibit the exchange of a single particle. For example, the reaction $\pi^- p \rightarrow K^+ \Sigma^-$ is, in the t-channel, $p \bar{\Sigma}^+ \rightarrow K^+ \pi^+$. Since the exchange process conserves charge, strangeness, and baryon number, one-meson exchange would require a particle or resonance with the quantum numbers of a $K^+ \pi^+$ resonance ($S=1, B=0, Q=2$); none such is known to exist. When we began our study, the reported evidence on such single-meson-exchange-forbidden reactions was essentially confined to reactions, such as this one, where a member of the $J^P = 1/2^+$ baryon octet is produced. Experimentally, forward peaking in such reactions was known to be very small or absent. This was occasionally cited as indirect evidence that the mesons which would have to be exchanged, and had not been observed directly, in fact did not exist.⁹³

We studied the counterpart of the reaction $\pi^- p \rightarrow K^+ \Sigma^-$ with a member of the $3/2^+$ baryon decuplet produced,

$$\pi^- p \rightarrow K^+ \Upsilon^{*-}(1385)$$

and its charge-symmetric equivalent

$$\pi^+ n \rightarrow K^0 \Upsilon^{*+}(1385).$$

We have also studied additional decuplet-production reactions, using data from old Berkeley bubble chamber experiments. Attention had been focused on other, more prominent, features of the final states fed by these reactions, and little consideration had been given to the possibility of forbidden forward peaking.

Since the publication of our results and other experimental studies, it is recognized that, at the very least, the evidence against the exchange of these unknown mesons is weak. There is now quite a bit of interest in exotics. This report attempts to provide an up-to-date (but not necessarily complete) review of recent theoretical models for these forbidden reactions. The experimental situation has been summarized in a review by Rosner.⁹⁴ We note that the reaction $\pi^- p \rightarrow K^+ \Upsilon^{*-}$ has now been studied by other researchers; it and other forbidden decuplet-production reactions have been looked for at energies higher than ours.⁹⁵⁻⁹⁹

3.13 TERMINOLOGY AND DEFINITIONS

If the above-mentioned reactions were to proceed by one-meson exchange, the mesons would have to be members of a multiplet with $S = 1$ and $I = 3/2$. (That is, " K^{*++} ", " K^{*+} ", " K^{*0} ", and " K^{*-} " (not " $\bar{K}^{*-}$ ").) Such mesons are generally referred to as exotic. Since the hypothesized quark q has quantum numbers $I = 1/2$, $S = 0$ or $I = 0$, $S = 1$, this multiplet can not be constructed out of $q\bar{q}$. All established mesonic states can be put into the $\underline{1}$ and $\underline{8}$ representations of $SU(3)$; those are the representations generated by $q\bar{q}$. The states which in this chapter we refer to as exotic would require a larger $SU(3)$ multiplet and would have to be constructed out of $qq\bar{q}\bar{q}$.

Rosner distinguishes two additional types of exotic mesons.⁹⁴ "Type 2 exotics" have J^{PC} which cannot be accounted for by $q\bar{q}$ with orbital angular momentum. "Type 3 exotics" would be "extra" low-mass states with allowed quantum numbers which do not fit into the established multiplets and whose existence would imply non-harmonic $q\bar{q}$ forces. We use "exotic" to mean Type 1.

Rosner's review covers the experimental evidence on all three types of exotics. Since no exotic mesons or baryons have been established in production or formation experiments, we call an exchange process "forbidden" if it is forbidden in the absence of type-1 exotics.

If exotics do exist and are exchanged, the process obviously should be referred to as "exotic meson exchange." However, we will avoid using "exotic exchange" as an abbreviation for this. One may argue that exchange of two known mesons in a reaction whose t -channel quantum numbers are exotic may be referred to as exotic exchange. As we shall see, although two-meson exchange is expected to occur, it is interesting enough so that the label "exotic" is not inappropriate.

We will use the abbreviations OME [OBS, OPE] for one-meson [baryon, particle] exchange, and DME for double-meson (i.e., two-meson) exchange.

Our production cosine will be the cosine of the angle between the beam and the outgoing meson in the overall c.m. frame. Thus, "forward" and "peripheral" correspond to meson-exchange diagrams, and "backward" corresponds to baryon exchange.

Unless otherwise specified, Y^* , Δ (or N^*), and Ξ^* refer to the members of the $3/2^+$ decuplet: $\Sigma(1585)$, $\Delta(1236)$, and $\Xi(1530)$.

3.14 LISTS OF REACTIONS AND FINAL STATES

For convenient reference, we list here all the reactions given more than passing mention in this chapter. First we present *all* OME-forbidden reactions of the form

$$(\pi^\pm \text{ or } K^\mp) + (p \text{ or } n) \rightarrow (0^- \text{ octet meson}) + (3/2^+ \text{ decuplet baryon}).$$

We denote charge-symmetric pairs by (for example) "(1p)" and "(1n)"; references to "Reaction (1)" are to the pair considered together. The t-channel quantum numbers are indicated.

[b N $\rightarrow$ M B*]	S _t	Q _t	I _t	
$\pi^- p \rightarrow K^+ \gamma^{*-}$	1	2	3/2	(1p)
$\pi^+ n \rightarrow K^0 \gamma^{*+}$	1	1	3/2	(1n)
$K^- p \rightarrow \pi^+ \gamma^{*-}$	1	2	3/2	(2)
$K^- p \rightarrow K^+ \Xi^{*-}$	2	2	1	(3)
$K^- p \rightarrow K^0 \Xi^{*0}$	2	1	0,1	(4)
$K^- n \rightarrow K^0 \Xi^{*-}$	2	1	0,1	(5)
$\pi^- p \rightarrow \pi^+ \Delta^-$	0	2	2	(6p)
$\pi^+ n \rightarrow \pi^- \Delta^{++}$	0	2	2	(6n)

We have not studied Reaction (5). We report on data from several LBL bubble chamber experiments for the other reactions.

Next we list the final states for each of the reactions on which we present data. A spectator proton is denoted by "(p)."

Reaction	Final State [M π B]	
(1p)	$\pi^- p \rightarrow K^+ \pi^- \Lambda$	(7)
(1n)	$\pi^+ d \rightarrow (p) K^0 \pi^+ \Lambda$	(8)
(2)	$K^- p \rightarrow \pi^+ \pi^- \Lambda$	(9)
(3)	$K^- p \rightarrow K^+ \pi^0 \Xi^-$	(10)
(3)	$K^- p \rightarrow K^+ \pi^- \Xi^0$	(11)
(4)	$K^- p \rightarrow K^0 \pi^+ \Xi^-$	(12)
(6p)	$\pi^- p \rightarrow \pi^+ \pi^- n$	(13)
(6n)	$\pi^+ d \rightarrow (p) \pi^- \pi^+ p$	(14)

For comparison with our results, we will refer to the octet-baryon reactions corresponding to (1) through (5):

$$\pi^- p \rightarrow K^+ \Sigma^- \quad (15p)$$

$$\pi^+ n \rightarrow K^0 \Sigma^+ \quad (15n)$$

$$K^- p \rightarrow \pi^+ \Sigma^- \quad (16)$$

$$K^- p \rightarrow K^+ \Xi^- \quad (17)$$

$$K^- p \rightarrow K^0 \Xi^0 \quad (18)$$

$$K^- n \rightarrow K^0 \Xi^- \quad (19)$$

Finally, we take this opportunity to point out that there are other classes of accessible OPE-forbidden reactions. (See Ref. 94 for a survey of the data.) For example, these reactions are forbidden both forward (i.e., with the first final-state particle having low momentum transfer from the beam) and backward:

$$\bar{p} p \rightarrow \bar{\Sigma}^+ \Sigma^-, \text{ or } \Xi^+ \Xi^- \quad (20)$$

$$\bar{p} p \rightarrow \bar{\Sigma}^{*+} \Sigma^{*-}, \text{ or } \Xi^{*+} \Xi^{*-}, \text{ or } \bar{\Delta}^+ \Delta^- \quad (21)$$

When our work was published, a small number of events had been reported in these reactions and the possibility of forbidden exchanges had been tentatively raised.¹⁰⁰⁻¹⁰¹

The reaction

$$p n \rightarrow \Delta^- \Delta^{++} \quad (22)$$

is forbidden with the Δ^- forward; in Section 3.3.22 we will comment on a recent study of this reaction.

The reactions

$$K^- p \rightarrow p K^- \quad (23)$$

$$\text{and} \quad \bar{p} p \rightarrow p \bar{p} \quad (24)$$

are dominated by allowed meson exchange mechanisms; however, with the first-written final-state particle going forward, exchange of an exotic baryon would be required.

3.2 DATA

3.21 SUMMARY OF THE BASIC RESULTS

In this section we identify our data samples, show plots establishing the existence of forbidden forward peaking in 4 of the 5 reactions, and present our results for the production angular distributions. In Section 3.22 we discuss in detail the sources of the data and the cuts applied, and explain in each case how we got the shape and normalization for the production distribution. Additional results are presented in Sections 3.23 and 3.24.

Table 3.1 gives the number of events in the uncut data for the 5 reactions we have studied, each at 2 or 3 beam momenta. The precise meaning of the momentum indicated (in GeV/c) for each of the 12 Samples is given in Section 3.22; generally several beam momenta have been combined. Our data comes from several different LBL experiments, all using the 72-inch bubble chamber at the Bevatron. Here we have combined charge-symmetric π^-p and π^+n states, and the two $(\Xi\pi)^-$ states; results from these subsamples separately (which are generally consistent, as expected) are given in Section 3.24.

In order to refer to all the reactions together, we will denote them by " $bN \rightarrow M\pi B$ ", where $B^* \rightarrow B\pi$ is the decuplet baryon resonance and the beam-to-meson production cosine is given by $\cos \theta_{pr} = (\hat{b} \cdot \hat{M})$. We will use "Fig. 3.n⁺" to refer to Figures 3.n through 3.(n+11), corresponding to Sample (1) through Sample (12).

Our basic results are shown in Fig. 3.1⁺ [3.1 through 3.12]. Fig. 1⁺(a) is a plot of the $B\pi$ effective mass against the production cosine. [Such a plot will be referred to as a Chew-Low-like plot. We have chosen to display $m(B\pi)$ rather than $m^2(B\pi)$, and to show $\cos \theta_{pr}$ rather than the corresponding momentum transfer so that when several beam momenta are combined the backward direction lies on a single kinematic boundary.] Fig. 1⁺(b) is the Dalitz plot for forward-produced events ($\cos \theta_{pr} > 0.7$). Fig. 1⁺(c) gives the production angular distribution as obtained from a cut in $m(B\pi)$, with a background subtraction using events in adjacent $m(B\pi)$ bins.

We see that a B^* resonance band is present (for some values of $\cos \theta_{pr}$) in each sample, and that there is some B^* in the forward direction in most cases. The possible exceptions are Sample 9, where there is essentially no forward Ξ^*0 production, and Samples 10 through 12, where Δ production is not readily distinguishable from a broad enhancement which crosses the plot from the region

UNCUT DATA		
Sample	Reaction	Events
1	P~2 $\pi^-p \rightarrow K^+\pi^-\Lambda$ (& $\pi^+n \rightarrow K^0\pi^+\Lambda$)	1958
2	P~3 $\pi^-p \rightarrow K^+\pi^-\Lambda$ (& $\pi^+n \rightarrow K^0\pi^+\Lambda$)	2089
3	P~4 $\pi^-p \rightarrow K^+\pi^-\Lambda$ (& $\pi^+n \rightarrow K^0\pi^+\Lambda$)	930
4	P=2.1 GeV/c $K^-p \rightarrow \pi^+\pi^-\Lambda$	4424
5	P~2.6 GeV/c $K^-p \rightarrow \pi^+\pi^-\Lambda$	6519
6	P=2.1 GeV/c $K^-p \rightarrow K^+\pi^0, -\Sigma^-, 0$	348
7	P~2.6 GeV/c $K^-p \rightarrow K^+\pi^0, -\Sigma^-, 0$	1024
8	P=2.1 GeV/c $K^-p \rightarrow K^0\pi^+\Sigma^-$	379
9	P~2.6 GeV/c $K^-p \rightarrow K^0\pi^+\Sigma^-$	697
10	P<1.8 $\pi^+n \rightarrow \pi^-\pi^+p$	9676
11	P~2.2 $\pi^-p \rightarrow \pi^+\pi^-n$ (& $\pi^+n \rightarrow \pi^-\pi^+p$)	19453
12	P=3.2 $\pi^-p \rightarrow \pi^+\pi^-n$	2545

Number of Events in Samples 1 through 12 (Raw Data)

Table 3.1

$P \sim 2 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 1)

XBL 729-1713

Fig. 3.1

$P \sim 3 \text{ GeV}/c$

$\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$)

(Sample 2)

XNL 729-1714

Fig. 3.2

$P \sim 4 \text{ GeV}/c$

$\pi^- p \rightarrow K^+ \pi^- \Lambda$ ($k \pi^+ n \rightarrow K^0 \pi^+ \Lambda$)

(Sample 3)

XBL 729-1715

Fig. 3.3

$P=2.1 \text{ GeV}/c$

$K^- p \rightarrow \pi^+ \pi^- \Lambda$

(Sample 4)

XBL 729-1716

Fig. 3.4

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow \pi^+ \pi^- \Lambda$

(Sample 5)

XRL 729-1717

Fig. 3.5

$P=2.1 \text{ GeV}/c$ $K^-p \rightarrow K^+\pi^0\pi^- \Xi^{*-0}$ (Sample 6)

XBL 729-1718

Fig. 3.6

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^+ \pi^0 \pi^- \Xi^-$

(Sample 7)

XBL 729-1719

Fig. 3.7

P=2.1 GeV/c

$K^-p \rightarrow K^0 \pi^+ \Xi^-$

(Sample 8)

XBL 729-1720

Fig. 3.8

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^0 \pi^+ \Xi^-$

(Sample 9)

XBL 729-1721

Fig. 3.9

$P < 1.8 \text{ GeV}/c$

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

(Sample 10)

XBL 729-1722

Fig. 3.10

$P \sim 2.2 \text{ GeV}/c$

$\pi^- p \rightarrow \pi^+ \pi^- n$ (& $\pi^+ n \rightarrow \pi^- \pi^+ p$)

(Sample 11)

XBL 729-1723

Fig. 3.11

P=3.2 GeV/c $\pi^-p \rightarrow \pi^+\pi^-\pi^-n$ (Sample 12)

XBL 729-1724

Fig. 3.12

of high $n\pi^-$ mass and $\cos \theta_{pr} \approx -1$ to the low-mass, forward production region. This enhancement is a kinematic reflection of peripheral $\pi\pi$ production; in the forward region it results in broad bands in the Δ region which look quite a bit wider than the Δ . [The Δ band, $(m_0^2 \pm m_0\Gamma)$, is $(1.53 \pm 0.14) \text{ GeV}^2$.] We discuss below (Sections 3.24, 3.321) our claim that there is in fact Δ production on top of this enhancement.

From Fig. 1⁺(a) and (c), we see that the production distribution of events in the B^* band has forward peaking in all cases except Ξ^{*0} production (Samples (8)-(9)), and perhaps Ξ^{*-} production at 2.1 GeV/c (Sample (6)). Note that in Y^* and Ξ^{*-} production there are backward peaks comparable in size to the forward peaks; in Δ production the backward peaks are small; in Ξ^{*0} production there are backward peaks with a pronounced dip in the extreme backward direction.

The forward Dalitz plots show competing M^* production in the $M\pi$ system (that is, ρ or K^*) in most cases. For Samples (1)-(3) and (10)-(12), M^* production in this region is stronger than B^* production; for Samples (4)-(5) it is comparable in size. In Samples (6)-(9), K^* production is OME-forbidden and is not evident in the B^* -forward region. In all cases, Fig. 1⁺(b) shows that the forward B^* production is not predominantly connected with the B^*-M^* overlap region.

In Figures 3.13 and 3.14 we give our best estimates for the shapes and sizes of the production angular distributions. They were obtained in various ways which, we hope, take into account the peculiarities of each sample. The distributions for Samples (1)-(5) come from maximum-likelihood fits for the amount of B^* production made in each region of production cosine. The Ξ^* distributions come from the data with a simple mass cut. There is no distribution shown for Sample (10). Those for Samples (11) and (12) come from an eyeball estimate of the number of Δ events in the $N\pi$ spectrum for each cosine interval. These distributions were normalized to total B^* cross sections obtained from a variety of sources. We feel that the uncertainties in our procedures, especially for $\pi^+N \rightarrow KY^*$ and for Δ production, have given us good estimates for the size of the forward peak rather than careful measurements. Our primary interest was in studying the existence of authentic forward peaking, not in determining its magnitude. The error bars do not include any of the systematic uncertainties in the normalization.

We see that the differential cross section in the forward bin ranges in size from about 1 $\mu\text{b/sr}$ to about 150 $\mu\text{b/sr}$. (The forward cross sections, with normalization uncertainties included, will be summarized in Table 3.12 below.) In

$\pi^- p \rightarrow K^+ \gamma^{*-} \text{ and } \pi^+ n \rightarrow K^0 \gamma^{*+}$

Fig. 3.13

$K^- p \rightarrow \pi^+ \gamma^{*-}$

XBL 729-1791

XBL 729-1792

Fig. 3.14

the cases where we have data above 3 GeV/c, a rapid decrease with energy is apparent.

3.22 DETAILS OF THE BASIC RESULTS

For each reaction in turn, we first identify the source of the data and define the cuts applied. Then we describe how the shape of the B^* production distribution was obtained, and tabulate the numerical results for reference. Finally we discuss our determination of the B^* production cross section, to which the angular distribution was normalized in Fig. 3.13-14.

In Figure 3.15 we give the $E_{c.m.}$ distribution for each sample, with the usual weights and fiducial and spectator cuts (as specified below) applied. For the 4 samples consisting of π^+n and π^-p data, the $E_{c.m.}$ distributions for each subsample are given in Figure 3.16. We have defined 20 subsamples, consisting of charge-symmetric reaction pairs, the two $(\Xi\pi)^-$ states, and odd- or even-pronged proton-spectator events. These subsamples are tallied in Table 3.2.

Table 3.3 lists the resonance masses and widths used to define the resonance bands for cuts. The bands were wide ones, $(m \pm \Gamma)$. We used the masses and widths from the Particle Data Group Compilation,¹⁰² except for the Δ mass (where the peak in our data is slightly lower than the accepted mass) and the Ξ^* width (which is small compared to our resolution).

3.221 REACTION (1), $\pi N \rightarrow KY^*$

Description of the Data Sample

For reaction (1p), $\pi^-p \rightarrow K^+Y^{*-}$, we have used the data of the PI63 experiment (run in 1963), as described in theses by R. Hess¹⁰³ and L. Hardy.¹⁰⁴ We have denoted by "P~2" the data taken at various beam momenta from 1.6 to 2.2 GeV/c (totaling 13.6 ev/ μ b). "P~3" and "P~4" correspond respectively to 12.8 ev/ μ b at 2.9 to 3.3 GeV/c and 5.6 ev/ μ b at 3.8 to 4.2 GeV/c.¹⁰⁵ We used a final data-summary tape left by the PI63 experimenters, which included some events from an earlier exposure at 1.5 to 2.4 GeV/c in the "P~2" sample. [For unknown reasons, the number of events on this tape did not agree exactly with the numbers given in Ref. 104; however, our results for the fractions of resonance production at all $\cos \theta_{pr}$ were almost all within one standard deviation of the results of a similar fit reported in Ref. 104.] Hardy noted that Y^{*-} was

P~2 $\pi^-p \rightarrow K^+\pi^-\Lambda$ (& $\pi^+n \rightarrow K^0\pi^+\Lambda$)

P~3 $\pi^-p \rightarrow K^-\pi^+\Lambda$ (& $\pi^-n \rightarrow K^0\pi^-\Lambda$)

P~4 $\pi^-p \rightarrow K^+\pi^-\Lambda$ (& $\pi^+n \rightarrow K^0\pi^+\Lambda$)

P=2.1 GeV/c $K^-p \rightarrow \pi^+\pi^-\Lambda$

P~2.8 GeV/c $\pi^-p \rightarrow \pi^+\pi^-\Lambda$

P=2.1 GeV/c $K^-p \rightarrow K^+\pi^0\Xi^-0$

NRL 729-1783

Fig. 3.15 (Page 1)

Fig. 3.15 (Page 2)

Fig. 3.16 (Page 1)

Sample	UNCUT DATA		Events
	Reaction		
13	$P \sim 2$ GeV/c	$\pi^- p \rightarrow K^+ \pi^- \Lambda$	1275
14	$P \sim 3$ GeV/c	$\pi^- p \rightarrow K^+ \pi^- \Lambda$	966
15	$P \sim 4$ GeV/c	$\pi^- p \rightarrow K^+ \pi^- \Lambda$	331
16	$P \sim 2$ GeV/c	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$	683
17	$P \sim 3$ GeV/c	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$	1123
18	$P \sim 4$ GeV/c	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$	599
19	$P = 2.1$ GeV/c	$K^- p \rightarrow K^+ \pi^0 \Sigma^-$	120
20	$P \sim 2.6$ GeV/c	$K^- p \rightarrow K^+ \pi^0 \Sigma^-$	359
21	$P = 2.1$ GeV/c	$K^- p \rightarrow K^+ \pi^- \Sigma^0$	228
22	$P \sim 2.6$ GeV/c	$K^- p \rightarrow K^+ \pi^- \Sigma^0$	665
23	$P \sim 2.2$ GeV/c	$\pi^- p \rightarrow \pi^+ \pi^- n$	5242
24	$P \sim 2.2$ GeV/c	$\pi^+ n \rightarrow \pi^- \pi^+ p$	14211
25	$P \sim 2$	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG	350
26	$P \sim 3$	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG	641
27	$P \sim 4$	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG	341
28	$P \sim 2$	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG	333
29	$P \sim 3$	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG	482
30	$P \sim 4$	$\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG	258
31	$P \sim 2.2$	$\pi^+ n \rightarrow \pi^- \pi^+ p$ EVEN-PRONG	6978
32	$P \sim 2.2$	$\pi^+ n \rightarrow \pi^- \pi^+ p$ ODD-PRONG	7233

Number of Events in Subsamples (Raw Data)

Table 3.2

Resonance	m (MeV)	Γ (MeV)
Υ^{*+}	1382.2	36
Υ^{*-}	1388	38
Ξ^{*0}	1528.9	30 ^(a)
Ξ^{*-}	1533.8	30 ^(a)
$\Delta^{++,-}$	1206 ^(b)	120
K^{*0}	897.7	49.7
K^{*+}	891.4	49.7
ρ^0	764	120

(a) This was used to take our resolution into account. The actual widths are [respectively] ≈ 9 [≈ 16] MeV for the Ξ^{*0} [Ξ^{*-}].

(b) The accepted value of the Δ mass is ≈ 1236 MeV; our Δ peaks were a bit lower.

Parameters Used for Resonance Band Definition

Table 3.3

produced but did not study the production distribution.

The data for reaction $(1n), \pi^+n \rightarrow K^0 Y^{*+}$, was obtained from the LBL Pi66A experiment. The processing of the data from this 72-inch bubble chamber exposure of ≈ 20 ev/ μ b at 3 and 4 GeV/c has been described in Chapter 2 of this thesis.¹⁰⁶ When we did this study of exotic exchange we had processed essentially all the events, but we used a preliminary scheme for the separation of hypotheses.¹⁰⁷ We are confident that our results would be essentially the same with our final data sample. (See Section 3.2.4.)

Around 2 GeV/c, we have examined the π^+n data from the Pi66B exposure.¹⁰⁸ When we did the fits to get $d\sigma/d\Omega$ [Fig. 3.13(a)] these events were not included. However, they are in most of the other figures.

After a preliminary examination showed that the data for the π^+n and π^-p reactions appeared consistent, as predicted by charge symmetry, we did most of our studies using all the events combined.

The number of events in the raw data samples is given in Tables 3.1 and 3.2. We generally applied the usual fiducial-volume cuts, with the corresponding weights, and (in the π^+d exposure) a spectator-momentum cut ($p_{sp} < 300$ MeV/c). For the fits described in the next subsection, we had to exclude a fairly small number of events in the tails of the distribution of effective c.m. energy. (The fitting program could handle only a limited c.m. energy range.) For consistency, this same cut was applied to all the plots in this chapter (except where the raw data was used). Overall, about 70% of the events on the data tapes (i.e., about 5000 events) survived all these cuts. The number of events used in the figures is given in Table 3.14 below.

Shape of the Production Distribution

The combination of small production cross sections and relatively large non- Y^* background (as indicated by Figures 3.1-3.3(a-b)) has made accurate estimation of the angular distributions difficult. The Y^* production angular distributions (Fig. 3.13) were obtained by dividing the events into six intervals in $\Lambda\pi$ production cosine and, for each interval, calculating the number of Y^* events present. This work was done before it became clear to us that one could get a good idea of the distribution by simpler methods (a Y^* mass cut and background subtraction, or an eyeball estimate of the number of Y^* events in each production interval); in view of the complications of this fitting method we emphasize that the existence of the forward peaking is best seen directly in the Chew-Low-like

plots in Fig. 3.1⁺(a).

The fraction of each evident resonance process and of phase space was obtained by using the maximum-likelihood fitting program MURTEBERT.¹⁰⁹ The results of the fits are given in Table 3.4. (In one interval with a small number of events, no fit was found, and an eyeball estimate of the number of Y^* events was used.) We used simple (S-wave) Breit-Wigner forms for the 3 resonant processes, with the indicated "wallet card" resonance parameters. It was assumed that these resonant processes and phase space did not interfere.

We found that the results were not particularly sensitive to the details of the model. In Table 3.5 we present the fits (for all production angles combined) with various changes in the model, and for π^+n (Pi66) and π^-p (Pi63) separately. (We did not repeat the fits for each $\cos \theta_{pr}$ interval in all these cases.) It can be seen that the overall amount of Y^* production is not greatly changed by changing the resonance masses or widths, allowing them to vary, adding a weakly produced resonance, or using non-simple Breit-Wigner shapes.

At 2 and 3 GeV/c, the use of noninterfering processes is justified by the absence of obvious interference effects in the Dalitz plots. (In Section 3.323, we comment on a model which describes the forward peaking in terms of interference effects in the K^*-Y^* crossing region. Such an effect seems to be present, at least at 4 GeV/c; we had not noticed this when we did the fits.)

In general, the fits gave good agreement with the mass projections. In each interval, the number of Y^* events given by the fit was checked for consistency with the $m(\Lambda\pi)$ spectrum. Also, we obtained the angular distributions in a more conventional manner: we looked at events in a wide $[m \pm \Gamma]$ Y^* band, subtracting, as background, events in bands of width Γ on either side of the Y^* band. The resulting production distributions (in six bins, so that they can be compared with Figs. 3.13(a)-(c)) are given in Figs. 3.1-3.3(c). We also tried cutting out events in a wide $K^*(890)$ band; the resulting distributions, similar in shape, are given in Figs. 3.42-3.44(d) below. The qualitative agreement is quite good; certainly the forward peak is present in all cases.

After our results on Y^* production were published,⁹¹ we started working on the other reactions. In the case of Δ production, we paid special attention to the low-mass enhancement in $m(B\pi)$ that results from the strong peripheral production of the dimeson $M\pi$. We then decided that the amount of Y^* production in the forward bin at 2 GeV/c had probably been overestimated by about 20% because of this enhancement. Thus, the forward peak was reduced by this amount

Cos θ Bin ^(a)	Events		Resonance Fractions (%)			Number of Y* Events
	N	ΣWt	Y*	K*(890)	K*(1420)	
			(m, Γ)=(1385,38)	(892,49.2)	(1440,80)	[MeV]

P $\approx$ 2 GeV/c:

1	186	186.7	33.9 $\pm$ 5.3	41.0 $\pm$ 6.0	-	63.3 $\pm$ 10.9
2	152	157.3	38.6 $\pm$ 6.1	46.6 $\pm$ 7.3	-	60.7 $\pm$ 10.7
3	125	123.6	15.6 $\pm$ 6.6	53.3 $\pm$ 8.9	-	19.3 $\pm$ 6.4
4	158	160.0	12.1 $\pm$ 4.9	62.6 $\pm$ 7.6	-	19.4 $\pm$ 7.9
5	171	174.5	19.1 $\pm$ 5.6	54.6 $\pm$ 7.3	-	33.4 $\pm$ 10.0
6	292	291.1	44.9 $\pm$ 5.0	40.3 $\pm$ 5.6	-	130.8 $\pm$ 16.4
All	1084	1093.1	29.3 $\pm$ 2.4	48.8 $\pm$ 3.0	-	[Sum=326.9]

P $\approx$ 3 GeV/c:

1	297	303.6	8.5 $\pm$ 2.8	6.9 $\pm$ 2.9	-	25.9 $\pm$ 8.6
2	162	173.4	-2.9 $\pm$ 2.1	13.8 $\pm$ 4.4	-	-5.0 $\pm$ 3.6
3	108	109.8	-2.2 $\pm$ 2.4	17.3 $\pm$ 6.4	-	-2.5 $\pm$ 2.6
4	144	138.5	0.0 $\pm$ 2.7	40.5 $\pm$ 8.5	-	0.0 $\pm$ 3.8
5	227	238.8	1.9 $\pm$ 2.2	59.0 $\pm$ 5.0	-	4.6 $\pm$ 5.1
6	549	582.4	10.0 $\pm$ 2.1	68.3 $\pm$ 3.0	-	58.5 $\pm$ 12.2
All	1487	1546.5	4.3 $\pm$ 1.1	40.6 $\pm$ 1.9	-	[Sum= 81.5]

P $\approx$ 4 GeV/c:

1	116	128.5	4.9 $\pm$ 3.0	3.8 $\pm$ 3.2	28.8 $\pm$ 7.0	6.3 $\pm$ 3.9
2	65	71.4	-0.2 $\pm$ 2.6	2.9 $\pm$ 3.9	46.7 $\pm$ 10.6	-0.1 $\pm$ 1.9
3	42	46.4	No fit obtained; Estimate:			0 $\pm$ 2
4	43	45.9	-4.4 $\pm$ 6.4	10.2 $\pm$ 7.8	-3.4 $\pm$ 9.0	-2.0 $\pm$ 2.9
5	103	113.7	-0.2 $\pm$ 1.7	55.2 $\pm$ 6.0	19.7 $\pm$ 6.5	-0.2 $\pm$ 2.0
6	324	348.3	8.2 $\pm$ 2.2	72.6 $\pm$ 3.6	1.9 $\pm$ 2.0	28.4 $\pm$ 7.7
All	693	754.2	3.2 $\pm$ 1.3	40.3 $\pm$ 2.7	12.5 $\pm$ 2.6	[Sum= 32.4]

(a) Each bin covers an interval of 0.33 in $\cos \theta_{pr}$ [$\equiv (\hat{\pi}^- \cdot \hat{K}^+)$]; bin 1 is $-1 < \cos \theta_{pr} < -2/3$.

Resonance-Production Fits in $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (and $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$)

Table 3.4

# Features	Note	Y* Fraction (%)		
		P $\approx$ 2	P $\approx$ 3	P $\approx$ 4 GeV/c
1 Basic Fits	(a)	29.3 $\pm$ 2.4	4.3 $\pm$ 1.1	3.2 $\pm$ 1.3
2 $\pi^+\pi^-$ only	-	-	3.8 $\pm$ 1.5	3.6 $\pm$ 1.7
3 $\pi^+\pi^-$ only		[29.3 $\pm$ 2.4]	4.6 $\pm$ 1.9	2.6 $\pm$ 1.7
4 m and Γ varied	(b)	29.7 $\pm$ 2.8	3.7 $\pm$ 0.9	No solution
[Results for m (MeV):]		[1388.9 $\pm$ 2.2]	[1381.1 $\pm$ 4.2]	-
[Results for Γ (MeV):]		[37.8 $\pm$ 4.7]	[16.8 $\pm$ 5.6]	-
5 $\Gamma(Y^*) = 43$ MeV	-	30.5 $\pm$ 2.5	4.4 $\pm$ 1.1	3.3 $\pm$ 1.3
6 With $N^*(1680)$	(c)	-	5.1 $\pm$ 1.6	-
7 Non-simple Breit-Wigners	(d)	30.2 $\pm$ 2.5	4.7 $\pm$ 1.1	3.5 $\pm$ 1.4

Notes:

- (a) These are the fits given in detail in Table 3.4
- (b) In all the fits except #4, the resonances masses and widths were fixed. Since this work was done before we decided what values to use in the final fits, there was some variation. For the Y^* , we used (m, Γ) = (1385 or 1392, 37 or 38), and $\Gamma=43$ for Fit #5; for the $K^*(890)$, we used (m, Γ) = (892.0 or 892.4, 49.2 or 49.8); for the $K^*(1420)$, which was included only at 4 GeV/c, we used (m, Γ) = (1440 or 1418.6, 80 or 89.1).
- (c) For $\pi^+\pi^-$ at 3 GeV/c only, we tried a fit with this N^* , with $\Gamma=130$ MeV; the result was (18 $\pm$ 3)% N^* .
- (d) P-wave dependence included (D-wave for the $K^*(1420)$).

Y* Fraction in Fits with Modifications

Table 3.5

(after the normalization described in the next subsection).

Cross-Section Normalization

As discussed in detail here, we estimated the cross section for $\pi^- p \rightarrow K^+ Y^{*-}, Y^{*-} \rightarrow \Lambda \pi^-$ to be $42.8 [5.5, 3.5] \mu\text{b}$ at 2 [3, 4] GeV/c [respectively]. The production distributions were normalized to these numbers (increased by 11% to take into account the $\Sigma\pi$ decay mode of the Y^*). The result is given in Fig. 3.13 and in Table 3.6. The indicated errors are statistical only. The correction for the low-mass enhancement in the forward bin at 2 GeV/c is a reduction of 19%, corresponding to a decrease of the total Y^* production cross section by 8%.

At 2 GeV/c, we simply used the Pi63 result for the $\Lambda K^+ \pi^-$ cross section, $(42.8 \pm 4.0) \mu\text{b}$.¹¹⁰ At 3 and 4 GeV/c, we have combined the Pi63 result with an estimate of the cross section observed in Pi66. We wanted to take into account the fact that our Pi66 ($\pi^+ n$) data was subject to misassignment problems which had not yet been examined closely. Table 3.7 indicates the rather involved way we got those estimates; the details of the calculation are in the notes.

In Pi66, the $\Lambda K^0 \pi^+$ final state can be detected in 3 ways: with both or either strange particle decaying via a charged mode. The ratio of "all : 2V" should be $(\Lambda + K^0 + \Lambda K^0)/\Lambda K^0 = (4+1+2)/2$. In our (uncut) data, the ratio $R_X = n_{\text{tot}}/[(7/2)n_{2V}]$ is not 1 but 1.4 at 3 GeV/c and 2.1 at 4 GeV/c. We expected that since the 2V state is a 4-production-constraint fit, and the others (being 1C) are more subject to misassignment, we probably had an excess of 1V events and roughly the right number of 2V events. We argued that the excess 1V events would probably not contribute to the Y^* peak if they were not real $\Lambda K^0 \pi^+$ events. If all that were true, it would have been proper to increase the $\Lambda K^0 \pi^+$ cross section according to the 1V excess and hope that the Y^* fraction (from the fit) was compensatingly low. So, we multiplied the "one-vee excess" ratio R_X by the $\Lambda K\pi$ cross section from Pi63, giving the indicated Pi66 $\Lambda K\pi$ cross sections. The $Y^* K$ cross section is then calculated from the Y^* fraction given by our fits, and averaged with the $Y^* K$ cross section found by Pi63.

Now that we have calculated the Pi66 cross sections, it appears that our assumption that we had an excess of one-vee events was in error, and that we have a deficiency of 2V events. Here are the results from Chapter 2 for $\sigma(\Lambda K^0 \pi^+)$ (with the visibility factors for the vees multiplied in):¹¹¹

$\cos \theta_{pr}$ [$\hat{\pi}^-\hat{K}$]	Number of γ^* events	$d\sigma/d\Omega$ ($\mu\text{b}/\text{sr}$)
$P \approx 2 \text{ GeV}/c$:		
-1.00 to -0.67	63.3 ± 10.9	4.40 ± 0.76
-0.67 to -0.33	60.7 ± 10.7	4.22 ± 0.74
-0.33 to 0.00	19.3 ± 8.4	1.34 ± 0.58
0.00 to 0.33	19.4 ± 7.9	1.34 ± 0.55
0.33 to 0.67	33.4 ± 10.0	2.32 ± 0.70
0.67 to 1.00	$[130.8 \pm 16.4]$	$[9.08 \pm 1.14]$
Corrected:	106.0 ± 20.0	7.36 ± 1.39
Totals: $N = 302.2$ [327.0 before correction], $\sigma \pm \Delta\sigma = (44.0 \pm 4.4)$ [47.6 ± 4.4] μb . ($\Delta\sigma/\sigma = 10\%$)		

$P \approx 3 \text{ GeV}/c$:		
-1.00 to -0.67	25.9 ± 8.6	0.93 ± 0.31
-0.67 to -0.33	-5.0 ± 3.6	-0.18 ± 0.13
-0.33 to 0.00	-2.5 ± 2.6	-0.09 ± 0.09
0.00 to 0.33	0.0 ± 3.8	0.00 ± 0.14
0.33 to 0.67	4.6 ± 5.1	0.17 ± 0.18
0.67 to 1.00	58.5 ± 12.2	2.09 ± 0.44
Totals: $N = 81.5$, $\sigma \pm \Delta\sigma = (6.1 \pm 1.7) \mu\text{b}$. [$\Delta\sigma/\sigma = 27\%$]		

$P \approx 4 \text{ GeV}/c$:		
-1.00 to -0.67	6.3 ± 3.9	0.36 ± 0.23
-0.67 to -0.33	-0.1 ± 1.9	-0.01 ± 0.11
-0.33 to 0.00	0.0 ± 2.0	0.00 ± 0.11
0.00 to 0.33	-2.0 ± 2.9	-0.12 ± 0.17
0.33 to 0.67	-0.2 ± 2.0	0.01 ± 0.11
0.67 to 1.00	28.4 ± 7.7	1.63 ± 0.44
Totals: $N = 32.4$, $\sigma \pm \Delta\sigma = (3.9 \pm 2.3) \mu\text{b}$. [$\Delta\sigma/\sigma = 58\%$]		

The normalization uncertainty, $\Delta\sigma/\sigma$, is not included in the errors on $d\sigma/d\Omega$.

Production Distributions for $\pi^-p \rightarrow K^+\gamma^*-$ (and $\pi^+n \rightarrow K^0\gamma^{*+}$)

Table 3.6

			P $\approx$ 3 GeV/c	P $\approx$ 4 GeV/c
From $\pi^-p \rightarrow \Lambda K^+\pi^-$:	(Units)			
(1) $f(Y^*)$			0.05 ± 0.01	0.02 ± 0.02
(2) $\sigma_p(Y^{*-}K^+)$	μb		5.0 ± 1.0	1.9 ± 1.9
(3) $\sigma(\Lambda K^+\pi^-)$	μb		110 ± 20	95 ± 15
From $\pi^+n \rightarrow \Lambda K^0\pi^+$:				
(4) $N(\Lambda_V K^0_V \pi^+)$	ev		265.2 ± 16.3	92.8 ± 9.6
(5) $N_{Tot.}(\Lambda K^0\pi^+)$	ev		1289.1 ± 35.9	677.3 ± 26.0
(6) R_X			1.39 ± 0.09	2.09 ± 0.23
(7) $N_{Cut}(\Lambda K^0\pi^+)$	ev		749.8 ± 27.4	441.7 ± 21.0
(8) " $\sigma(\Lambda K^0\pi^+)$ "	μb		153 ± 30	198 ± 38
(9) $f(Y^*)$			$(3.8 \pm 1.5)\%$	$(3.6 \pm 1.7)\%$
(10) $\sigma_p(Y^{*}K)$	μb		5.81 ± 2.55	7.13 ± 3.64
Net:				
(11) $\sigma_p(Y^{*}K)$	μb		5.5 ± 1.5	3.5 ± 2.0
(12) $\sigma(Y^{*}K)$	μb		6.1 ± 1.7	3.9 ± 2.3

Table 3.7 (Page 1)

Notes:

- (1) Y^* fraction, from fit. From Ref. 104, Table 9.
- (2) Cross section for Y^*K in the $\Lambda K\pi$ final state. From Ref. 104, Table 10. [The value at 4 GeV/c is reported there as $(0 \pm 1.9) \mu\text{b}$; we have changed it to agree with Row (1). There is some Y^* in $m(\Lambda\pi)$ in the π^-p data alone (See Fig. 3.87(a)); our own fit on that data alone gave $(2.6 \pm 1.7)\% Y^*$.]
- (3) Cross section for the final state. [Row (2)/Row (1)]; at 3 GeV/c, we used $(110 \pm 20) \mu\text{b}$ rather than $(100 \pm 20) \mu\text{b}$, to get better agreement with the value of $\sigma(\Lambda K^+\pi^-)$ given in Table 7 and Fig. 9 of Ref. 104.
- (4) Number of events with 2 vees (in the uncut data).
- (6) One-vee-excess ratio. $\{\text{Row (5)}/[\text{Row (4)} \times (7/2)]\}$.
- (7) Number of events used in the fits.
- (8) Effective final-state cross section, $[\text{Row (3)} \times \text{Row (6)}]$.
- (9) Y^* fraction from fit. (Table 3.5, Fit #2)
- (10) $[\text{Row (8)} \times \text{Row (9)}]$
- (11) Average of Row (2) and Row (10). (We used these estimated averages; the weighted averages are respectively $(5.1 \pm 0.9) \mu\text{b}$ and $(3.0 \pm 1.7) \mu\text{b}$.)
- (12) From Row (11), corrected for $Y^* \rightarrow \Sigma\pi$.

Cross-Section Estimates for $\pi^+n \rightarrow K^0Y^{*+}$ (or $\pi^-p \rightarrow K^+Y^{*-}$)

Table 3.7 (Page 2)

	$n_{\text{tot}}/$ [[7/2]* n_{2V}]	Decays: ΛK^0	$\sigma(\Lambda K^0 \pi^+)$ K^0	(μb) Λ	$\sigma(\Lambda K^+ \pi^-)$ From Pi63
P~3	1.27	83.7 ± 7.9	145.4 ± 14.0	105.9 ± 8.0	110 ± 20
P~4	1.99	49.4 ± 8.1	146.3 ± 21.7	92.6 ± 12.4	95 ± 15

Thus, it would appear that we have too few 2V events and too many with a K^0 decay.

At 3 GeV/c, our estimate for $\sigma(Y^*K)$ came out to be consistent with the Pi63 value. The result at 4 GeV/c is perhaps the most important, since the question of the persistence of the forbidden forward peaking with increasing energy is crucial to the interpretation. From Pi66 alone we estimate the Y^* cross section at 4 GeV/c to be $(7.1 \pm 3.6) \mu\text{b}$, compared to the Pi63 result of $(1.9 \text{ [or } 0] \pm 1.9) \mu\text{b}$. This discrepancy reflects the fact that there does seem to be more Y^* production in our data, as well as the high value for $\sigma(\Lambda \pi \pi)$ obtained in Pi66. We decided to use $(3.5 \pm 2.0) \mu\text{b}$; the large error reflects our conclusion that the normalization in Fig. 3.13(c) may be off by $\approx 50\%$ in either direction.

3.222 REACTION (2), $K^-p \rightarrow \pi^+ Y^{*-}$

We used the final data tape from the Berkeley K63 experiment, as processed by Dan Siegel. Our determination of the shape of the production distribution is taken directly from his thesis.¹¹² Here we summarize the relevant information from that report.

The experiment was an exposure of the 72-inch chamber to K^- beams at 5 incident momenta.¹¹³ In our plots, "P=2.1" denotes a 6.6 ev/ μb sample at 2.10 GeV/c, and "P~2.6" denotes the other 4 exposures, from 2.47 to 2.73 GeV/c. [However, Siegel's fit at 2.6 GeV/c, which we used in Fig. 3.13(e), did not include the relatively small sample at 2.47 GeV/c.]

Siegel achieved good separation of the 4-production-constraint $\Lambda \pi^+ \pi^-$ final state, yielding about 11000 events. Weights for the Λ decay were calculated, and a fiducial cutoff was defined. (The data tape did not include any of the events which failed the fiducial test, so what we refer to as our "raw data" consists of the same events as the cut data.)

Siegel's maximum-likelihood fits for various resonant processes are presented in his Chapter 5. The number of events and the fraction of $Y^{*-} \pi^+$ in each of 10 intervals of $\cos \theta_{pr}$ [$\equiv \hat{K}^- \cdot \hat{\pi}^+$] are given in his Table 18. From his Table 15, we take the cross section for $K^-p \rightarrow Y^{*-} \pi^+ \rightarrow \Lambda \pi^- \pi^+$ to be $(135 \pm$

$\cos \theta_{pr}$ [$K^- \pi^+$]	Number of Y^{*-} Events	$d\sigma/d\Omega$ ($\mu\text{b}/\text{sr}$)
P=2.1 GeV/c:		
-1.0 to -0.8	74.4 ± 12.8	19.15 ± 3.30
-0.8 to -0.6	73.7 ± 11.6	18.99 ± 2.99
-0.6 to -0.4	28.9 ± 8.7	7.44 ± 2.23
-0.4 to -0.2	35.3 ± 10.8	9.09 ± 2.78
-0.2 to 0.0	30.9 ± 11.1	7.94 ± 2.86
0.0 to 0.2	17.0 ± 9.1	4.38 ± 2.34
0.2 to 0.4	42.9 ± 10.7	11.04 ± 2.75
0.4 to 0.6	-2.9 ± 5.8	-0.75 ± 1.50
0.6 to 0.8	47.4 ± 11.1	12.19 ± 2.85
0.8 to 1.0	$[116.1 \pm 37.5]$	$[29.89 \pm 9.66]$
Corrected:	82.0 ± 30.0	21.11 ± 7.73
Totals: N = 429.6 [463.6 before correction], $\sigma \pm \partial\sigma = (139 \pm 17)$ [150 $\pm$ 17] μb . ($\partial\sigma/\sigma = 12\%$)		

P=2.6 GeV/c:

-1.0 to -0.8	127.6 ± 22.6	17.83 ± 3.16
-0.8 to -0.6	39.3 ± 10.8	5.49 ± 1.51
-0.6 to -0.4	35.0 ± 9.0	4.89 ± 1.26
-0.4 to -0.2	20.5 ± 8.5	2.86 ± 1.19
-0.2 to 0.0	49.1 ± 9.6	6.85 ± 1.35
0.0 to 0.2	22.5 ± 9.3	3.14 ± 1.30
0.2 to 0.4	29.7 ± 8.7	4.16 ± 1.21
0.4 to 0.6	28.4 ± 8.7	3.97 ± 1.22
0.6 to 0.8	28.9 ± 11.3	4.04 ± 1.58
0.8 to 1.0	137.9 ± 17.1	19.27 ± 2.39

Totals: N = 519.0, $\sigma \pm \partial\sigma = (91.1 \pm 10.0) \mu\text{b}$. [$\partial\sigma/\sigma = 11\%$]

The normalization uncertainty, $\partial\sigma/\sigma$, is not included in the errors on $d\sigma/d\Omega$.

Production Distributions for $K^-p \rightarrow \pi^+ Y^{*-}$

Table 3.8

15) μb at 2.1 GeV/c and $(82 \pm 9) \mu\text{b}$ at 2.6 GeV/c. Taking note of the $\Sigma\pi$ decay mode of the Y^* (10%), we have normalized the result of his fits to $\sigma(Y^*-\pi^+) = 150.0 \mu\text{b}$ at 2.1 GeV/c and $91.1 \mu\text{b}$ at 2.6 GeV/c. The results are given in Fig. 3.13(d,e) and Table 3.8

As we did for Y^* production in πN at 2 GeV/c, we have corrected the forward bin at 2.1 GeV/c to take into account the effect of peripheral $\pi\pi$ production. (This problem is discussed in detail in Section 3.32.) After an examination of the $m(\Lambda\pi^-)$ spectrum for $\cos \theta_{pr} > 0.8$, we decreased the number of Y^* events by 29%. However, we did not renormalize, with the result that the total Y^* cross section indicated in Fig. 3.13(d) and Table 3.8 is 7% lower than Siegel's value.

Note that the distributions in Fig. 3.13(d-e) are in qualitative agreement with those obtained from a mass cut with background subtraction [Fig. 3.4(c), 3.5(c)].

3.223 REACTIONS (3) AND (4), Ξ^* PRODUCTION

This data came from the K63 experiment, as did that for reaction (2). Dauber et al. have reported on Ξ production in that exposure.¹¹⁴ We used the final data tapes, reflecting the processing described in Ref. 114. The usual fiducial cuts were applied, removing about 15% of the events. The final state $K^+\Xi^0\pi^-$ was believed to be quite contaminated ($\approx 26\%$); Dauber et al. defined a purified subsample, consisting essentially of unambiguous events, which was believed to be only $\approx 7\%$ contaminated.¹¹⁵ We usually did not apply this purification cut, but did check that it had little effect on the production distribution.

Dauber et al. studied Ξ^* production, obtaining production and decay distributions by mass cuts.¹¹⁶ We repeated that procedure to get the distributions given in Fig. 3.14(a-d). Because of the small background under the Ξ^* , no background subtraction was done. (The distributions with that subtraction are given in Figs. 3.47-3.50(c) below.) We have normalized to the cross sections given in Table 6 of Ref. 114. The results are given in Tables 3.9 and 3.10.

$\cos \theta_{pr}$ [$\hat{K}^- \cdot \hat{K}^+$]	Number of Ξ^{*-} Events	$d\sigma/d\Omega$ ($\mu\text{b/sr}$)
P=2.1 GeV/c:		
-1.0 to -0.9	11.6 ± 3.7	3.61 ± 1.15
-0.9 to -0.8	9.0 ± 3.2	2.80 ± 1.00
-0.8 to -0.7	13.5 ± 4.5	4.20 ± 1.40
-0.7 to -0.6	6.5 ± 2.6	2.01 ± 0.83
-0.6 to -0.5	5.5 ± 2.5	1.72 ± 0.77
-0.5 to -0.4	7.3 ± 2.8	2.29 ± 0.87
-0.4 to -0.3	10.0 ± 3.4	3.12 ± 1.05
-0.3 to -0.2	4.2 ± 2.1	1.32 ± 0.66
-0.2 to -0.1	3.3 ± 1.9	1.02 ± 0.59
-0.1 to 0.0	9.6 ± 3.8	3.00 ± 1.19
0.0 to 0.1	5.4 ± 2.4	1.63 ± 0.76
0.1 to 0.2	3.1 ± 1.8	0.95 ± 0.55
0.2 to 0.3	5.1 ± 2.3	1.60 ± 0.72
0.3 to 0.4	5.4 ± 2.4	1.70 ± 0.76
0.4 to 0.5	6.6 ± 2.7	2.06 ± 0.84
0.5 to 0.6	4.4 ± 2.2	1.36 ± 0.69
0.6 to 0.7	4.3 ± 2.2	1.36 ± 0.68
0.7 to 0.8	8.0 ± 3.1	2.50 ± 0.95
0.8 to 0.9	7.3 ± 3.0	2.27 ± 0.93
0.9 to 1.0	12.8 ± 3.7	3.98 ± 1.16

Totals: $N = 142.9$, $\sigma \pm \partial\sigma = (28 \pm 4) \mu\text{b}$. [$\partial\sigma/\sigma = 14\%$]

The normalization uncertainty, $\partial\sigma/\sigma$, is not included in the errors on $d\sigma/d\Omega$.

Production Distributions for $K^-p \rightarrow K^+\Xi^{*-}$

Table 3.9 ($P_{z_{cm}} = 1$)

$\cos \theta_{pr}$ [$K^- \cdot \bar{K}^+$]	Number of Ξ^{*-} Events	$d\sigma/d\Omega$ ($\mu\text{b/sr}$)
P $\approx$ 2.6 GeV/c:		
-1.0 to -0.9	17.6 $\pm$ 4.6	1.99 $\pm$ 0.52
-0.9 to -0.8	18.8 $\pm$ 5.3	2.12 $\pm$ 0.60
-0.8 to -0.7	28.2 $\pm$ 5.8	3.20 $\pm$ 0.66
-0.7 to -0.6	9.3 $\pm$ 3.3	1.05 $\pm$ 0.37
-0.6 to -0.5	6.5 $\pm$ 2.7	0.74 $\pm$ 0.30
-0.5 to -0.4	3.0 $\pm$ 1.7	0.34 $\pm$ 0.20
-0.4 to -0.3	10.2 $\pm$ 3.4	1.16 $\pm$ 0.39
-0.3 to -0.2	9.2 $\pm$ 3.9	1.04 $\pm$ 0.44
-0.2 to -0.1	7.8 $\pm$ 3.2	0.88 $\pm$ 0.36
-0.1 to 0.0	5.1 $\pm$ 2.6	0.57 $\pm$ 0.29
0.0 to 0.1	8.4 $\pm$ 3.2	0.96 $\pm$ 0.36
0.1 to 0.2	11.5 $\pm$ 4.3	1.30 $\pm$ 0.49
0.2 to 0.3	2.0 $\pm$ 1.4	0.23 $\pm$ 0.16
0.3 to 0.4	2.6 $\pm$ 1.8	0.29 $\pm$ 0.21
0.4 to 0.5	5.4 $\pm$ 2.4	0.62 $\pm$ 0.28
0.5 to 0.6	5.3 $\pm$ 2.4	0.61 $\pm$ 0.27
0.6 to 0.7	9.5 $\pm$ 3.4	1.08 $\pm$ 0.38
0.7 to 0.8	12.7 $\pm$ 3.9	1.44 $\pm$ 0.44
0.8 to 0.9	14.9 $\pm$ 4.2	1.69 $\pm$ 0.47
0.9 to 1.0	36.7 $\pm$ 6.5	4.15 $\pm$ 0.73

Totals: $N = 224.9$, $\sigma \pm \partial\sigma = (16 \pm 3) \mu\text{b}$. [$\partial\sigma/\sigma = 19\%$]

The normalization uncertainty, $\partial\sigma/\sigma$, is not included in the errors on $d\sigma/d\Omega$.

Production Distributions for $K^-p \rightarrow K^+\Xi^{*-}$

Table 3.9 (Page 2)

$\cos \theta_{pr}$ [$\hat{K}^- \cdot \hat{K}^0$]	Number of Ξ^{*0} Events	$d\sigma/d\Omega$ ($\mu\text{b/sr}$)
P=2.1 GeV/c:		
-1.0 to -0.9	12.6 ± 4.4	6.53 ± 2.25
-0.9 to -0.8	8.5 ± 3.7	4.41 ± 1.91
-0.8 to -0.7	22.3 ± 6.2	11.51 ± 3.21
-0.7 to -0.6	30.6 ± 6.7	15.81 ± 3.45
-0.6 to -0.5	16.3 ± 4.5	8.41 ± 2.34
-0.5 to -0.4	16.9 ± 4.7	8.72 ± 2.43
-0.4 to -0.3	16.6 ± 5.4	8.58 ± 2.76
-0.3 to -0.2	10.0 ± 3.6	5.18 ± 1.83
-0.2 to -0.1	15.1 ± 4.4	7.82 ± 2.26
-0.1 to 0.0	7.3 ± 3.0	3.79 ± 1.55
0.0 to 0.1	11.8 ± 3.9	6.09 ± 2.04
0.1 to 0.2	11.6 ± 3.9	5.98 ± 1.99
0.2 to 0.3	9.1 ± 3.4	4.70 ± 1.78
0.3 to 0.4	7.7 ± 3.1	3.95 ± 1.61
0.4 to 0.5	6.5 ± 2.9	3.35 ± 1.50
0.5 to 0.6	7.6 ± 3.1	3.91 ± 1.60
0.6 to 0.7	7.8 ± 3.2	4.00 ± 1.63
0.7 to 0.8	10.0 ± 3.8	5.15 ± 1.96
0.8 to 0.9	6.7 ± 3.0	3.46 ± 1.55
0.9 to 1.0	11.6 ± 4.1	5.97 ± 2.12

Totals: $N = 246.7$, $\sigma \pm \partial\sigma = (80 \pm 11) \mu\text{b}$. [$\partial\sigma/\sigma = 14\%$]

The normalization uncertainty, $\partial\sigma/\sigma$, is not included in the errors on $d\sigma/d\Omega$

Production Distributions for $K^-p \rightarrow K^0\Xi^{*0}$

Table 3.10 (Page 1)

$\cos \theta_{pr}$ [$K^- \bar{K}^0$]	Number of Ξ^{*0} Events	$d\sigma/d\Omega$ ($\mu\text{b/sr}$)
$P \approx 2.6 \text{ GeV/c:}$		
-1.0 to -0.9	16.8 ± 4.7	2.70 ± 0.76
-0.9 to -0.8	18.6 ± 4.8	3.00 ± 0.77
-0.8 to -0.7	40.9 ± 7.4	6.57 ± 1.20
-0.7 to -0.6	15.7 ± 5.3	2.52 ± 0.85
-0.6 to -0.5	12.7 ± 4.0	2.04 ± 0.65
-0.5 to -0.4	14.5 ± 4.4	2.33 ± 0.70
-0.4 to -0.3	6.8 ± 3.1	1.09 ± 0.49
-0.3 to -0.2	3.9 ± 2.2	0.62 ± 0.36
-0.2 to -0.1	11.6 ± 3.9	1.86 ± 0.62
-0.1 to 0.0	7.5 ± 3.1	1.20 ± 0.49
0.0 to 0.1	9.3 ± 3.9	1.49 ± 0.62
0.1 to 0.2	15.4 ± 4.7	2.48 ± 0.76
0.2 to 0.3	8.8 ± 3.3	1.42 ± 0.54
0.3 to 0.4	12.9 ± 4.1	2.07 ± 0.65
0.4 to 0.5	7.8 ± 3.2	1.25 ± 0.51
0.5 to 0.6	8.2 ± 3.4	1.31 ± 0.54
0.6 to 0.7	9.5 ± 3.6	1.53 ± 0.58
0.7 to 0.8	7.3 ± 3.3	1.18 ± 0.53
0.8 to 0.9	4.1 ± 2.3	0.65 ± 0.38
0.9 to 1.0	5.6 ± 2.8	0.90 ± 0.45

Totals: $N = 237.6$, $\sigma \pm \Delta\sigma = (24 \pm 3) \mu\text{b}$. [$\Delta\sigma/\sigma = 12\%$]

The normalization uncertainty, $\Delta\sigma/\sigma$, is not included in the errors on $d\sigma/d\Omega$.

Production Distributions for $K^- p \rightarrow K^0 \Xi^{*0}$

Table 3.10 (Page 2)

3.224 REACTION (6), $\pi N \rightarrow \pi \Delta$

Description of the Data Sample

For the reaction $\pi^+ d \rightarrow (\pi_{sp}) \pi^- \pi^+ p$, we used data from the low momentum (1.1 to 2.4 GeV/c) part of the Pi66 experiment. This final state is discussed in detail in Jerry Manning's thesis.¹¹⁷ We have divided the data into two intervals at an effective c.m. energy (for the $p\pi^+\pi^-$ system, excluding the spectator proton) of 2.05 GeV/c, which corresponds to a beam momentum of 1.75 GeV/c. These intervals are denoted by "P<1.8" and "P~2.2" respectively. In the P<1.8 sample we have only even-pronged events (i.e., those with a visible spectator proton); at P~2.2 we have both even-prongs (from the low-momentum beam settings) and odd-prongs. [The $E_{c.m.}$ spectra are in Fig. 3.15 and (for even- and odd-prongs separately) Fig. 3.16.] The spectator-momentum cut removes 41% of the ≈ 10000 events at 1.8 GeV/c and 15% of the ≈ 14000 events at ≈ 2.2 GeV/c.

The data for the reaction $\pi^- p \rightarrow \pi^+ \pi^- n$ was provided to us by Larry Jacobs. It consists of events from the Pi72 experiment (run in 1962 on the 72-inch chamber) at 2.05, 2.17, and 2.36 GeV/c, and from the Pi63 exposure at 2.60, 2.86, and 3.22 GeV/c. The processing of this data is discussed in Jacobs' thesis.¹¹⁸ The 5 lower momenta were grouped together (along with $\pi^+ n$ data) in the 'P~2.2' sample; the highest-momentum data forms Sample 12. The fiducial cut removes $\approx 10\%$ of the ≈ 8000 events.

Shape of the Production Distribution

Because of the low c.m. energy, we did not take the trouble of making a determination of $d\sigma(\Delta\pi)/d\Omega$ from the data below 1.8 GeV/c. The production distribution obtained from cuts is given in Fig. 3.10; there is a forward peak in the N^* band but it is not immediately apparent how much is due to the broad kinematic enhancement. There is some N^* in the forward region, as shown by Figs. 3.27(b) and 3.63(b) below. [In this interval, $\sigma(\pi^+\pi^-p)$ is about 8 mb and falling rapidly;¹¹⁷ that number corresponds to 2 $\mu\text{b}/\text{ev}$ for the 4003 events in our cut sample.]

When we did our published determination of $d\sigma/d\Omega$ at 2.2 GeV/c, we had only the $\pi^+ n$ data. Here again we faced the problem of disentangling Δ production from the broad low-mass enhancement. We simply estimated the number of Δ events from plots of $m(N\pi)$ in various intervals of $\cos \theta_{pr}$. Unfortunately, in the forward direction the enhancement peaks at just about the same $m(\pi\pi^+)$ as the Δ . In Figs. 3.17(a-b) we give the mass plots for the two most forward bins and our

$\cos \theta_{pr}$ [$\hat{\pi} \cdot \hat{\pi}$]	Number of Δ Events	$d\sigma/d\Omega$ ($\mu\text{b}/\text{sr}$)
P $\approx$ 2.2 GeV/c, $\pi^+n \rightarrow \pi^-\Delta^{++}$ [Note unequal bin widths]:		
-1.0 to -0.9	48 $\pm$ 15	32 $\pm$ 10
-0.9 to -0.8	84 $\pm$ 11	56 $\pm$ 7
-0.8 to -0.7	76 $\pm$ 13	50 $\pm$ 9
-0.7 to -0.5	78 $\pm$ 17	25 $\pm$ 6
-0.5 to -0.3	30 $\pm$ 12	10 $\pm$ 4
-0.3 to -0.1	27 $\pm$ 9	9 $\pm$ 3
-0.1 to 0.1	33 $\pm$ 10	11 $\pm$ 3
0.1 to 0.3	42 $\pm$ 15	14 $\pm$ 5
0.3 to 0.5	36 $\pm$ 12	12 $\pm$ 4
0.5 to 0.7	52 $\pm$ 12	17 $\pm$ 4
0.7 to 0.8	85 $\pm$ 15	57 $\pm$ 10
0.8 to 0.9	126 $\pm$ 25	83 $\pm$ 17
0.9 to 1.0	230 $\pm$ 40	152 $\pm$ 27
Totals: N = 947, $\sigma \pm \partial\sigma = (395 \pm 118) \mu\text{b}$. [$\partial\sigma/\sigma = 30\%$]		

P $\approx$ 3.2 GeV/c, $\pi^-p \rightarrow \pi^+\Delta^-$ [Note unequal bin widths]:		
-1.0 to -0.9	5 $\pm$ 2	9.5 $\pm$ 3.8
-0.9 to -0.8	6 $\pm$ 2	11.4 $\pm$ 3.8
-0.8 to -0.6	3 $\pm$ 1	2.8 $\pm$ 0.9
-0.6 to -0.4	1 $\pm$ 1	0.9 $\pm$ 0.9
-0.4 to -0.2	2 $\pm$ 2	1.9 $\pm$ 1.9
-0.2 to 0.0	3 $\pm$ 3	2.8 $\pm$ 2.8
0.0 to 0.2	0 $\pm$ 1	0.0 $\pm$ 0.9
0.2 to 0.4	0 $\pm$ 1	0.0 $\pm$ 0.9
0.4 to 0.6	1 $\pm$ 1	0.9 $\pm$ 0.9
0.6 to 0.8	0 $\pm$ 1	0.0 $\pm$ 0.9
0.8 to 0.9	3 $\pm$ 1	5.7 $\pm$ 1.9
0.9 to 0.95	10 $\pm$ 5	37.9 $\pm$ 19.0
0.95 to 1.0	28 $\pm$ 6 - 12	106.2 $\pm$ 22.8 - 45.5
Totals: N = 62, $\sigma \pm \partial\sigma = (74 \pm 12) \mu\text{b}$. [$\partial\sigma/\sigma = 17\%$]		

The normalization uncertainty, $\partial\sigma/\sigma$, is not included in the errors on $d\sigma/d\Omega$.

Production Distributions for $\pi^-p \rightarrow \pi^+\Delta^-$ (and $\pi^+n \rightarrow \pi^-\Delta^{++}$)

Table 3.11

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Fig. 3.17

hand-drawn curves from which we got the number of Δ events. When the p band is removed (shaded histograms), the Δ is enhanced a little. The numbers of events (and the results of the normalization to $\sigma(\Delta\pi)$) are given in Table 3.11 and Fig. 3.14(e).

At 3.2 GeV/c, almost all the Δ events have $\cos \theta_{pr} > 0.8$. The $m(n\pi^-)$ spectra for the forward region are given in Fig. 3.17(c-d). There is Δ^- production for $\cos \theta_{pr} > 0.95$, but it is hard to separate from the low-mass kinematic enhancement. For $0.8 < \cos \theta_{pr} < 0.95$, however, the Δ peak stands out more clearly above the background. We estimated the number of Δ events in each production interval from these mass spectra; the results (with the normalization) are given in Fig. 3.14(f) and Table 3.11.

Cross-Section Normalization

In the 2.2 GeV/c interval, we obtained $\sigma(N\pi\pi)$ both by extrapolating Jacobs' values¹¹⁹ and by simply dividing the number of events in our uncut π^+n sample by the exposure size. We obtained [respectively] 5.9 [5.4, 4.2] mb at $P = 1.9$ [2.1, 2.4] GeV/c. We then estimated the Δ fraction by counting events in a plot of $m(N\pi)$ for all production angles, and got Δ production cross sections of 538 [434, 380] μb . Our plot of the production distribution for all these 3 parts of the " $P \sim 2.2$ " sample together is normalized to 395 μb ; we estimate the error to be $\pm 30\%$. This is in fact higher than Jacobs' determination of the Δ production cross section, which ranged from (350 ± 100) μb at $P=2.05$ GeV/c to (100 ± 50) μb at 2.86 GeV/c.¹²⁰ We obtained these values by counting Δ events. Although we feel that our eyeball estimate of the number of Δ events was conservative, we do note the possibility that our forward peak is overestimated by up to a factor of two.

At 3.2 GeV/c, we have normalized to $\sigma(\Delta^-\pi^+) = (74 \pm 12)$ μb . This was obtained from our estimate of (62 ± 10) Δ events at all $\cos \theta_{pr}$, and Jacobs' path length value of $0.839 \text{ ev}/\mu\text{b} \pm 5\%$.¹²¹ (Jacobs' own estimate, apparently also obtained by counting events, was $(0.05 \pm 0.02) \text{ mb}$.¹²⁰)

3.225 CROSS SECTION VALUES

In Table 3.12 we summarize our results for the B^* production cross section at all production angles and in the forward hemisphere, and the differential cross section in the forward bin. The information comes from Tables 3.6 and 3.8-3.11, which have just been discussed. In those tables, and in Figs. 3.13-3.14, we

Sample	Reaction	P_{bm} (GeV/c)	$\sigma(\text{total})$ (μb)	$\sigma(\cos \theta_{pr} > 0)$		Forward Bin	
				(μb)	(a)	$\cos \theta_{pr}(\text{min})$	$d\sigma/d\Omega$ ($\mu\text{b/sr}$) (a)
1	$\pi^- p \rightarrow K^+ \gamma^{*-}$ (b)	≈ 2	44.00 ± 4.44	23.12 ± 4.17		0.67	7.36 ± 1.58
2	"	≈ 3	6.11 ± 1.67	4.74 ± 1.66		0.67	2.09 ± 0.72
3	"	≈ 4	3.88 ± 2.26	3.15 ± 2.10		0.67	1.63 ± 1.05
4	$K^- p \rightarrow \pi^+ \gamma^{*-}$	2.1	139.0 ± 16.7	60.3 ± 13.5		0.8	21.11 ± 8.13
5	"	≈ 2.6	91.1 ± 10.0	43.43 ± 6.56		0.8	19.27 ± 3.19
6	$K^- p \rightarrow K^+ \Xi^{*-}$	2.1	$28. \pm 4.$	12.23 ± 2.39		0.9	3.98 ± 1.29
7	"	≈ 2.6	$16. \pm 3.$	7.77 ± 1.67		0.9	4.15 ± 1.07
8	$K^- p \rightarrow K^0 \Xi^{*0}$	2.1	$80. \pm 11.$	29.26 ± 5.37		0.9	5.97 ± 2.27
9	"	≈ 2.6	$24. \pm 3.$	8.97 ± 1.59		0.9	0.90 ± 0.46
11	$\pi^+ n \rightarrow \pi^- \Delta^{++}$	≈ 2.2	$395. \pm 118.5$	245.3 ± 77.1		0.9	152.0 ± 53.0
12	$\pi^- p \rightarrow \pi^+ \Delta^-$	3.2	$74. \pm 12.$	50.1 ± 12.2		0.95	106.2 ± 28.6 $- 48.7$

(a) From Tables 3.6 and 3.8-3.11, with the error in $\sigma(\text{total})$ folded in.

(b) Includes data from the charge-symmetric reaction.

Summary of Forward Cross Sections

Table 3.12

presented the shape of the production distribution and gave only the error (statistical or estimated) on the number of events in each interval. In Table 3.12, however, we have included the normalization uncertainties in the error estimates.

3.23 ADDITIONAL FEATURES OF THE DATA

First we show some figures designed to convince the skeptical reader that there really are forbidden forward peaks. We point out other features of the final states, in many cases stronger than the processes of interest; they do not obscure the forward peaking. To do this we look at Dalitz plots and their projections for various regions in $\cos \theta_{pr}$, and at production distributions obtained by mass cuts with various degrees of refinement. We examine the degree to which the forward peaking is associated with the competing meson resonance (M^*) production process.

Then we look at other features of the forward peaking: decay distributions, slopes in momentum transfer, and energy dependence.

We usually made each of these plots for all 12 data samples. To avoid confusion and preserve an adequate record we present all of the plots systematically here.¹²² We comment only on the plots of special interest. We have not indicated the number of events in each figure; tallies containing this information are presented below (Table 3.14).

Forward-Production Dalitz Plots

In Fig. 3.18⁺ [i.e., 3.18-3.29 for Samples (1)-(12)] we repeat the Dalitz plot for the forward production region, this time with all its projections. As is the case in all plots unless "raw data" is specified, we have made the usual cuts on fiducial volume and spectator momentum, and applied the fiducial weights in the histograms.

Strong M^* production is evident in the $m(M\pi)$ spectrum, Fig. 3.18⁺(c), in most cases. The strong peripheral $M\pi$ production results in a low-mass enhancement in $m(B\pi)$ [Fig. 3.18⁺(b)]. (In this interval of $\cos \theta_{pr}$, it also gives a high-mass enhancement in $m(BM)$ [Fig. 3.18⁺(d)].) The forbidden peaking is seen as a relatively narrow peak in the region of this enhancement in $m(B\pi)$. In Fig. 3.19 and 3.20, the narrow Y^* peak is evident; assuming that the resolution is not worse at lower beam momentum, one can see Y^* production in Fig. 3.18(b). (Recall

that for this sample we reduced the value given by the fit for the number of forward Y^* events.)

In Figs. 3.21 and 3.22, there is Y^* production both in (d), where it is not forbidden, and in (b); the fact that the peaks are comparable in width suggests that the one of interest [in (b)] is not an artifact.

In the $\Xi K\pi$ final states, the Ξ^* peak is particularly clean, and there is little competing K^* production.

In Figs. 3.27 - 3.29, ρ production and the corresponding enhancement are very strong. Since the peak of the enhancement is approximately at the Δ mass, one could not claim forward Δ production from these plots alone unless the exact shape of the enhancement was known.

Non-Forward-Production Dalitz Plots

Fig. 3.30⁺(a) and (b) are the Dalitz plots for the central and backward production intervals respectively. They supplement the production distributions already presented, typically showing little B^* production in the central region, and backward peaking in many cases. The backward B^* events, where present, are not substantially associated with production of other resonances. Fig. 3.30⁺(c) and (d) are the Dalitz plot for all production angles and its $m(B\pi)$ projection. There is a clear B^* peak in all cases, even Samples 10-12, where there is some non-forward (i.e., non-forbidden) B^* production not obscured by the enhancement. When the peaks in Figs. 3.39-3.41(d) are compared (in position and width) with those in Figs. 3.27-3.29(b), the impression that there is forward Δ production is strengthened.

Production Distributions from Cuts

In Fig. 3.42⁺, we give the production distributions as obtained by 4 different cuts. The shapes of these 4 distributions for each sample may be compared with each other, and with our best estimates (Figs. 3.13-3.14). The main point to be made is that these successive cuts do not grossly change the shape and do not make the forbidden peaks go away.

In each case, we have plotted events in a B^* band defined by $(m_0 - \Gamma) < m(B\pi) < (m_0 + \Gamma)$, where m_0 and Γ are the resonance parameters given in Table 3.3. In Fig. 3.42⁺(a) no other cuts have been applied. In Fig. 3.42⁺(b), we have used the usual spectator and fiducial cuts, and the fiducial weights. In Fig. 3.42⁺(c) we have in addition made a background subtraction: events in the two adjacent

$m(B\pi)$ bands, each with width Γ , have been included with weights equal to the negative of the fiducial weights. (This has resulted in negative contents for some bins.) To the degree that the number of non- B^* events and their production distribution do not change with $m(B\pi)$, this is an adequate way to remove the background contribution to the shape of the distribution. This assumption was not checked for each final state, and can not be expected to hold perfectly. Note that Fig. 3.42⁺(c) is the same as Fig. 3.1⁺(c), except for the number of bins, which was chosen in the latter case to allow comparison with Figs. 3.13-3.14. Finally, in Fig. 3.42⁺(d), we have also excluded (from the B^* and the adjacent bands) events in the M^* resonance band. This cut shows that the forward peaking is not primarily associated with M^* production; however, as we have noted, the main problem is competition with peripheral $M\pi$ production whether or not an M^* is involved.

Dalitz Plots for the Near-Forward Direction

In Fig. 3.54⁺(a-b) we see the Dalitz plot and $m(B\pi)$ for $0.7 < \cos \theta_{pr} < 0.9$. The most interesting plots are those for Samples (10-12), especially Fig. 3.64 (Sample 11). From the Chew-Low-like plot (Fig. 3.11(a)), it appeared that a Δ band extended back further from the forward direction than the enhancement. In Fig. 3.64(b) there is a rather clean Δ signal, about 120 MeV wide. This plot is our principal proof of forbidden Δ production.

Going up to 3.2 GeV/c, we see that almost all the events have $\cos \theta_{pr} > 0.9$, but among the not-quite-forward events shown there may be a small Δ signal. The interval which most clearly shows Δ production is $0.8 < \cos \theta_{pr} < 0.95$; the $m(n\pi^-)$ spectrum was presented in Fig. 3.17(d).

In the low-momentum interval (Fig. 3.63), there is no clean Δ peak separated from background; compared with Fig. 3.27(b), the spectrum has just about the same shape in the Δ region. However, the events around $m(n\pi^-) = 1.5$ GeV suggest a slightly lower non- Δ background when events with $\cos \theta_{pr} > 0.9$ are excluded.

Correlation between Forward B^* Production and M^* Production

In Fig. 3.54⁺(c-d) we have plotted $m(B\pi)$ for only forward-produced events, both with the M^* band cut out and with only M^* events. (That is, the sum of (c) and (d) is Fig. 3.18⁺(b).) From the production distributions with M^* removed, we have already seen that B^* production is not primarily associated with M^*

production. We now note that what correlation exists tends to be negative:

Below 3 GeV/c, Figs. 3.54⁺(c) and (d) are quite similar. However, above 3 GeV/c (in Figs. 3.55, 3.56, and 3.65), there is essentially no B^* production in the M^* band. In all three cases the statistics are not good, but in Fig. 3.56, $\pi^-p \rightarrow K^+\pi^-\Lambda$ at 4 GeV/c, the effect is quite striking. The absence of B^*M^* events is also clear in the Dalitz plot, Fig. 3.20(a). This effect is the basis of a model proposed by Sivars and Von Hippel, which will be discussed in Section 3.323. We did not notice this depletion until we learned of the work of Sivars and Von Hippel, who saw a similar (but even stronger) effect in the data of Crennell *et al.* for the same reaction at 4.5 GeV/c. As noted earlier, this does raise a little doubt about the fits we did to get the Y^* production distribution, for which we assumed no interference.

We now turn to plots showing additional properties of the forward-produced B^* events.

Decay Angular Distributions

It would be quite difficult to disentangle the B^* decay distributions from the effects of strong M^* production. (The B^* decay cosine is linearly related to $m^2(M\pi)$.) We have not tried to do this in any sophisticated way. For forward-produced ($\cos \theta_{pr} > 0.7$) events in the B^* band, we have looked at the decay angular distributions using the same 4 successive cuts as for the production distributions. In Fig. 3.66⁺ are the results for the raw data and for the cut and weighted data with a background-band subtraction.

The angles are the conventional decay angles in the Jackson frame appropriate for meson exchange. (That frame is the $B\pi$ rest frame with the y axis defined as the production normal [$\hat{y} \propto (\hat{N} \times (\hat{B}\hat{\pi}))$ in the overall c.m.], and the z axis defined as the target nucleon N in the $B\pi$ rest frame. That is, $-\hat{z}$ is the $\bar{p} \rightarrow M$ momentum transfer.) Thus, $\cos \theta_{decay} = (\hat{B} \cdot \hat{N})$, the angle between the outgoing and target baryons, and $\phi_{decay} = \tan^{-1}[(\hat{B} \cdot \hat{y})/(\hat{B} \cdot \hat{x})]$. [We put ϕ_{decay} in the appropriate quadrant between 0 and 360°. The "±" in the definition of ϕ reflects the fact that we do not know whether the data tapes we used from the old experiments had been converted from the left-handed internal chamber coordinate system to a right-handed system. This is of course of no concern as long as we are dealing with strong-interaction effects, and may fold the ϕ distributions around 180°.]

Most of these decay distributions are subject to considerable uncertainty, because of the presence of background. For the parity-conserving decay of a single J^P state (e.g., a pure $3/2^+$ resonance), the decay cosine distribution should be symmetric. The M^* band (which is at rather low $m(M\pi)$) shows up as an excess of events at $\cos \theta_{\text{decay}} \approx +1$, e.g. in Fig. 3.76-77(a). The crude background subtraction we have used cannot be expected to help much; nonetheless, the subtracted distributions of $\cos \theta_{\text{decay}}$ are more or less symmetric.

Here again, Ξ^* production is an exceptional case: we have some confidence in the result, since there is no problem with background. The Ξ^{*-} distributions will be compared with two model predictions in Sections 3.34 and 3.38.

We note that several of the ϕ distributions show hints of structure, in particular a dip at $\phi = 180^\circ$. We have not investigated the possibility that this may result from a scanning bias.

Momentum Transfer Distributions

For 6 of the 12 samples, we have plotted in Fig. 3.78 the number of events in the B^* band as a function of $-t'$ ($\equiv |t - t_{\text{min}}|$, where t_{min} is the kinematic limit corresponding to $\cos \theta_{\text{pr}} = +1$). The B^* is defined by the usual mass cut, with weights but not M^* band exclusion. [In (f), the "purified" (unambiguous) Ξ^0 sample was used.] The indicated slopes are eyeball estimates; the lines with those slopes have been drawn through the first point in each case.

We see that these distributions are characterized by roughly exponential behavior, with slopes from 2.2 to 5.4 $(\text{GeV}/c)^{-2}$. The other Ξ^* reactions do not show this behavior; the Δ data has not been plotted since the observed exponential dropoff is almost certainly a property of the kinematic enhancement and not of Δ production. In Table 3.13 we have tabulated our estimates of the slopes, and (for reference) the range in t' corresponding to $-1 < \cos \theta_{\text{pr}} < 1$.

Variation with C.m. Energy

Fig. 3.79 consists of plots of $\cos \theta_{\text{pr}}$ vs. center-of-mass energy, for events in the B^* band. The deuterium data spans the c.m. energy range rather smoothly, and there as well as in the hydrogen data we noticed no rapid fluctuations. However, our data do not sample enough energies to rule out the rapid variation that would be expected if s-channel effects dominated, as discussed in Section 3.36.

The Δ production distribution apparently gets quite a bit sharper with

$P \sim 2 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 1)

XBL 729-1725

Fig. 3.18

$P \sim 3 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 2)

XBL 729-1726

Fig. 3.19

$P \sim 4 \text{ GeV}/c$

$\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$)

(Sample 3)

XBL 729-1727

Fig. 3.20

P=2.1 GeV/c

$K^-p \rightarrow \pi^+\pi^-\Lambda$

(Sample 4)

XBL 729-1728

Fig. 3.21

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow \pi^+ \pi^- \Lambda$

(Sample 5)

XBL 729-1729

Fig. 3.22

P=2.1 GeV/c

$K^-p \rightarrow K^+\pi^0\pi^-\pi^0$

(Sample 6)

XBL 729-1730

Fig. 3.23

$P \sim 2.6 \text{ GeV}/c$ $K^- p \rightarrow K^+ \pi^0 \pi^- \pi^0$ (Sample 7)

XBL 729-1-51

Fig. 3.24

P=2.1 GeV/c

$K^-p \rightarrow K^0\pi^+\Xi^-$

(Sample 8)

XBL 729-1732

Fig. 3.25

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^0 \pi^+ \Xi^-$

(Sample 9)

XBL 729-1733

Fig. 3.26

$P < 1.8 \text{ GeV}/c$

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

(Sample 10)

XBL 729-1734

Fig. 3.2'

$P \sim 2.2 \text{ GeV}/c$

$\pi^- p \rightarrow \pi^+ \pi^- n$ (& $\pi^+ n \rightarrow \pi^- \pi^+ p$)

(Sample 11)

XBL 729-1735

Fig. 3.28

P=3.2 GeV/c

$\pi^-p \rightarrow \pi^+\pi^-\pi^0$

(Sample 12)

XBL 729-1736

Fig. 3.29

$P \sim 2 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 1)

XBL 729-1737

Fig. 3.30

$P \sim 3 \text{ GeV}/c$

$\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$)

(Sample 2)

XBL 729-1738

Fig. 3.31

$P \sim 4 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 3)

XBL 729-1739

Fig. 3.32

P=2.1 GeV/c

$K^- p \rightarrow \pi^+ \pi^- \Lambda$

(Sample 4)

XBL 729-1740

Fig. 3.33

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow \pi^+ \pi^- \Lambda$

(Sample 5)

XBL 72⁹-1741

Fig. 3.34

$P=2.1 \text{ GeV}/c$ $K^-p \rightarrow K^+\pi^0\Xi^-0$ (Sample 6)

XBL 729-1741

Fig. 3.35

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^+ \pi^0 \pi^- \pi^0$

(Sample 7)

XBL 729-1743

Fig. 3.36

P=2.1 GeV/c

$K^-p \rightarrow K^0\pi^+\pi^-$

(Sample 8)

XBL 729-1744

Fig. 3.37

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^0 \pi^+ \Xi^-$

(Sample 9)

XBL 729-1745

Fig. 3.38

$P < 1.8 \text{ GeV}/c$

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

(Sample 10)

XBL 729-1746

Fig. 3.39

$P \sim 2.2 \text{ GeV}/c$ $\pi^- p \rightarrow \pi^+ \pi^- n$ (& $\pi^+ n \rightarrow \pi^- \pi^+ p$) (Sample 11)

XBL 729-1747

Fig. 3.40

$P=3.2 \text{ GeV}/c \quad \pi^- p \rightarrow \pi^+ \pi^- n \quad (\text{Sample 12})$

XBL 729-1748

Fig. 3.41

$p \sim 2 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 1)

XBL 729-1701

Fig. 3.42

$P \sim 3 \text{ GeV/c}$

$\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$)

(Sample 2)

XBL 729-1702

Fig. 3.43

$P \sim 4 \text{ GeV}/c \quad \pi^- p \rightarrow K^+ \pi^- \Lambda \quad (\& \quad \pi^+ n \rightarrow K^0 \pi^- \Lambda) \quad (\text{Sample 3})$

XBL 729-1703

Fig. 3.44

P=2.1 GeV/c

$K^-p \rightarrow \pi^+\pi^-\Lambda$

(Sample 4)

LBL 200-1704

Fig. 3.45

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow \pi^+ \pi^- \Lambda$

(Sample 5)

XBL 729-1705

Fig. 3.46

P=2.1 GeV/c

 $K^-p \rightarrow K^+\pi^0\pi^-\pi^0$

(Sample 6)

Fig. 3.47

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^+ \pi^0 \bar{\Xi}^-$

(Sample 7)

XBL 729-1707

Fig. 3.48

$P=2.1 \text{ GeV}/c$

$K^-p \rightarrow K^0 \pi^+ \bar{p}$

(Sample 8)

NBL 229-1700

Fig. 3.49

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^0 \pi^+ \Xi^-$

(Sample 9)

XBL 729-1709

Fig. 3.50

$P < 1.8 \text{ GeV}/c \quad \pi^+ n \rightarrow \pi^- \pi^+ p \quad (\text{Sample } 10)$

Fig. 3.51

$P \sim 2.2 \text{ GeV}/c$ $\pi^- p \rightarrow \pi^+ \pi^- n$ (& $\pi^+ n \rightarrow \pi^- \pi^+ p$) (Sample 11)

XBL 729 1711

Fig. 3.52

$P=3.2 \text{ GeV}/c \quad \pi^- p \rightarrow \pi^+ \pi^- n \quad (\text{Sample 12})$

Fig. 3.53

$P \sim 2 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 1)

XBL 729-1749

$P \sim 3 \text{ GeV}/c$

$\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$)

(Sample 2)

XBL 729-1750

Fig. 3.55

$P \sim 4 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 3)

XBL 729-1751

Fig. 3.56

P=2.1 GeV/c

$K^-p \rightarrow \pi^+\pi^-\Lambda$

(Sample 4)

XBL 729-1752

Fig. 3.57

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow \pi^+ \pi^- \Lambda$

(Sample 5)

XBL 729-1753

Fig. 3.58

$P=2.1 \text{ GeV}/c$ $K^-p \rightarrow K^+\pi^0\Xi^-$ (Sample 6)

XBL 729-1754

Fig. 3.59

P~2.6 GeV/c

$K^-p \rightarrow K^+\pi^0\Xi^- \bar{\Xi}^0$

(Sample 7)

$0.7 < (\hat{K}^- \cdot \hat{K}^+) < 0.9$ $M^2(\Xi^- \pi^0 \bar{\Xi}^-)$ (GeV²)

$0.7 < (\hat{K}^- \cdot \hat{K}^+) < 0.9$ $M(\Xi^- \pi^0 \bar{\Xi}^-)$ (GeV)

(K* Band Out) $M(\Xi^- \pi^0 \bar{\Xi}^-)$ (GeV)

(K* Band Only) $M(\Xi^- \pi^0 \bar{\Xi}^-)$ (GeV)

XBL 729-1755

Fig. 3.60

P=2.1 GeV/c

$K^-p \rightarrow K^0 \pi^+ \Xi^-$

(Sample 8)

XBL 729-1756

Fig. 3.61

$P \sim 2.6 \text{ GeV}/c$

$K^- p \rightarrow K^0 \pi^+ \Xi^-$

(Sample 9)

XBL 729-1757

Fig. 3.62

$P < 1.8 \text{ GeV}/c$

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

(Sample 10)

XBL 729-1736

Fig. 5.63

$P \sim 2.2 \text{ GeV}/c$

$\pi^- p \rightarrow \pi^+ \pi^- n$ (& $\pi^+ n \rightarrow \pi^- \pi^+ p$)

(Sample 11)

XBL 729-1759

Fig. 3.64

P=3.2 GeV/c

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

(Sample 12)

XBL 729-1760

Fig. 3.65

$P \sim 2 \text{ GeV}/c \quad \pi^- p \rightarrow K^+ \pi^- \Lambda \text{ (\& } \pi^+ n \rightarrow K^0 \pi^+ \Lambda) \text{ (Sample 1)}$

$\ln \gamma^* \text{ Band} \quad \cos \theta_{\text{prod}} > 0.7$

Fig. 3.66

XBL 729-1761

$P \sim 3 \text{ GeV}/c$ $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 2)

In Y^{*-} Band $\cos \theta_{\text{prod}} > 0.7$

XBL 729-1762

Fig. 3.67

$P \sim 4$ GeV/c $\pi^- p \rightarrow K^+ \pi^- \Lambda$ (& $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$) (Sample 3)
 In Y^{*-} Band $\cos \theta_{\text{prod}} > 0.7$

Fig. 3.68

P=2.1 GeV/c $K^-p \rightarrow \pi^+\pi^-A$ (Sample 4)

In Υ^{*-} Band $\cos \theta_{\text{prod}} > 0.7$

$P \sim 2.6 \text{ GeV}/c \quad K^- p \rightarrow \pi^+ \pi^- \Lambda \quad (\text{Sample 5})$

$\ln \gamma^+ \text{ Band} \quad \cos \theta_{\text{prod}} > 0.7$

Fig. 3.70

$P=2.1 \text{ GeV}/c$ $K^-p \rightarrow K^+\pi^0 \Xi^{*-0}$ (Sample 6)

In Ξ^{*-} Band $\cos \theta_{\text{prod}} > 0.7$

XBL 729-1766

Fig. 3.71

$P \sim 2.6 \text{ GeV}/c$ $K^- p \rightarrow K^+ \pi^0 \Xi^- \Xi^-$ (Sample 7)

In Ξ^- Band $\cos \theta_{pred} > 0.7$

Fig. 3.72

$P=2.1 \text{ GeV}/c \quad K^-p \rightarrow K^0 \pi^+ \Xi^- \quad (\text{Sample 8})$

In Ξ^{*0} Band $\cos \theta_{\text{prod}} > 0.7$

Fig. 3.73

$P \sim 2.6 \text{ GeV}/c$ $K^- p \rightarrow K^0 \pi^+ \Xi^-$ (Sample 9)

In Ξ^{*0} Band $\cos \theta_{\text{prod}} > 0.7$

XBL 729-1769

Fig. 3.74

$P < 1.8 \text{ GeV/c}$ $\pi^+ n \rightarrow \pi^- \pi^+ p$ (Sample 10)
 In N^{*++} Band $\cos \theta_{\text{prod}} > 0.7$

$P \sim 2.2 \text{ GeV/c}$ $\pi^- p \rightarrow \pi^+ \pi^- n$ (& $\pi^+ n \rightarrow \pi^- \pi^+ p$) (Sample 11)

In N^+ Band $\cos \theta_{\text{prod}} > 0.7$

Fig. 3.76

XBL 729-1771

$P=3.2 \text{ GeV}/c$ $\pi^-p \rightarrow \pi^+\pi^-n$ (Sample 12)

In N^{*-} Band $\cos \theta_{\text{prod}} > 0.7$

XBL 729-1772

Fig. 3.77

NOL 778-1373

Reaction	P_{beam} (GeV/c)	Slope in $t' \equiv t-t _{\text{min}}$ (GeV/c) ⁻²	(Note)
$\pi^- p \rightarrow K^+ Y^{*-} \quad (\pi^+ n \rightarrow K^0 Y^{*+})$	≈ 2	3.2 ± 0.8	(a)
"	≈ 3	4 ± 1	(a)
"	≈ 4	5.4 ± 2.0	(a)
$K^- p \rightarrow \pi^+ Y^{*-}$	2.1	2.2 ± 0.8	(b)
"	≈ 2.6	3 ± 1	(c)
$K^- p \rightarrow K^+ \Xi^{*-}$	≈ 2.6	5 ± 1	(d)
$\pi^- p \rightarrow \pi^+ \Delta^- \quad (\pi^+ n \rightarrow \pi^- \Delta^{++})$	≈ 2.4	5 ± 1	(e)

Notes:

These slopes are from eyeball estimates. The Ξ^{*-} samples not listed here did not show exponential falloff; the other Δ data was not examined.

- (a) With the K^* band cut out, the slopes appear consistent.
- (b) With the ρ band cut out, slope = 3.6 ± 1.5 .
- (c) With the ρ band cut out, slope = 3.6 ± 1.2 .
- (d) Estimated slope unchanged when ambiguous events are removed.
- (e) Data for $E_{\text{c.m.}} > 2.25$ GeV only.

Kinematic Range [$\Delta t(-1 < \cos \theta < 1) \equiv 4p_{\text{in}}p_{\text{out}}$]

Reaction	P_{beam} (GeV/c)	Δt (GeV/c) ²	Reaction	P_{beam} (GeV/c)	Δt (GeV/c) ²
$\pi N \rightarrow KY^*$	2.0	1.67	$KN \rightarrow K\Xi^*$	2.1	1.59
"	3.0	3.57	"	2.6	2.52
"	4.0	5.43	$\pi N \rightarrow \pi \Delta$	1.8	2.14
$KN \rightarrow KY^*$	2.1	2.44	"	2.2	2.85
"	2.6	3.31	"	3.22	4.69

Slopes in Momentum Transfer

Table 3.13

XBL 728-1380

Fig. 3.79

increasing energy, but again this is probably a property of the dominant kinematic reflection of peripheral $\pi\pi$ production.

Since our data span a rather small range in s , we did not attempt to measure the energy dependence. Of course, this is important in deciding between alternative explanations. The energy dependence has been studied by Crennell *et al.*; Fig. 3.80 is Fig. 3 of their paper.⁹⁶ The total forward cross section for $\pi^-p \rightarrow K^+\gamma^*{}^-$ is shown in (a); the data in (b) and (c) are for related allowed reactions. The 3 low-energy points are from our data.

Tallies

Table 3.14 consists of tallies for Samples (1)-(12), with various cuts. The number of events for any of Figs. 3.1-3.12, 3.15-3.16, and 3.18-3.77 can be found here. (The other figures were made long ago, and the number of events may not correspond exactly to what is given in the table.) In the tallies for production and decay angles, (A) through (D) correspond to the successive cuts used in parts (a) through (d) of the figures. The last 4 tallies, which apply to Fig. 3.55⁺, are designated "miscellaneous": (E) and (F) are for $0.7 < \cos \theta_{pr} < 0.9$, with the usual cut, and respectively without and with weights. (G) and (H) are forward-produced, cut, and weighted events, respectively not in the M^* band and in it.

3.24 AUTHENTICITY OF THE FORWARD PEAKS

Here we concern ourselves with two different problems: competition from the enhancement which reflects peripheral $M\pi$ production, and possible systematic effects due to problems in the preparation of our data samples.

We have already noted the existence of a low-mass $B\pi$ enhancement, which we have asserted is the result of peripheral $M\pi$ production. This effect is most prominent in the reaction $\pi^-p \rightarrow \pi^+\pi^-n$. It is our claim that Δ production can be seen on top of that enhancement. We feel that examination of the Chew-Low-like plots (Fig. 3.11-3.12(a)) does reveal a forward Δ band, extending further back in $\cos \theta_{pr}$ than the enhancement. As we have noted, the Δ stands out more clearly in the forward mass spectra when the extreme forward region ($\cos \theta_{pr} > 0.9$ or 0.95) is excluded.

We have made Monte-Carlo studies, generating events with a p produced

Fig. 3.80

HISTOGRAMS OF DECAY ANGLES

Sample	(A)	(B)	(C)	(D)
1	185	150.4	84.3	56.7
2	112	78.1	23.0	31.2
3	40	35.1	19.5	24.9
4	111	134.0	83.2	33.0
5	139	170.4	77.4	50.1
6	28	28.0	20.0	10.9
7	68	64.4	53.2	43.1
8	27	28.3	26.8	24.0
9	16	17.0	13.1	4.8
10	1121	753.0	569.0	185.0
11	1842	1700.0	1101.0	463.0
12	175	153.0	81.0	56.0

MISCELLANEOUS FALLIES

Sample	(A)	(B)	(C)	(D)
1	202	227.4	188.6	184.7
2	777	313.0	243.0	287.1
3	83	194.2	180.2	183.1
4	392	271.4	46.2	39.9
5	84	467.8	612.4	442.2
6	28	30.3	32.6	22.9
7	100	113.6	120.5	61.8
8	21	28.4	30.9	12.0
9	28	38.2	41.7	20.7
10	728	724.0	487.0	601.0
11	2116	2116.0	1910.0	2199.0
12	226	226.0	314.0	234.0

(A) : Raw Data
 (B) : Weighted
 (C) : Subtracted
 (D) : M^2 Band Out
 (E) : $0.7 < \cos \theta < 0.9$, No Weight
 (F) : $0.7 < \cos \theta < 0.9$, Weighted
 (G) : $\cos \theta > 0.7$, Outside M^2 Band
 (H) : $\cos \theta > 0.7$, In M^2 Band

XBL 729-1822

INTERVALS OF π (π Cos θ_{prod}) $\pi < \Delta\pi$ $\pi > \Delta\pi$ All π

Sample	$\pi < \Delta\pi$	$\pi > \Delta\pi$	All π
1	330	822	204
2	478	638	250
3	282	108	863
4	618	2831	4424
5	863	4338	6519
6	48	180	508
7	82	434	214
8	37	225	321
9	45	348	174
10	1158	3657	587
11	4109	10633	857
12	548	1278	5672

INTERVALS OF π (π Cos θ_{prod}) $\pi < \Delta\pi$ $\pi > \Delta\pi$ All π

Sample	$\pi < \Delta\pi$	$\pi > \Delta\pi$	All π
1	373.3	906.0	274.8
2	542.9	773.3	260.2
3	333.3	748.9	122.0
4	753.6	3819.0	754.2
5	1084.7	5714.8	9277.5
6	25.6	116.3	1581.1
7	103.1	443.8	285.4
8	50.9	280.4	1093.4
9	47.4	488.5	86.2
10	1158.0	3457.0	438.7
11	4109.0	10633.0	788.4
12	548.0	1278.0	857.0

HISTOGRAMS OF PRODUCTION CORNER

Sample	(A)	(B)	(C)	(D)
1	871	530.8	273.1	184.2
2	70	170.5	61.4	53.5
3	469	51.8	32.6	30.6
4	469	877.8	314.5	182.5
5	508	874.0	400.6	281.6
6	137	142.8	82.3	74.7
7	207	224.8	137.0	92.2
8	215	246.7	168.2	163.7
9	215	237.6	165.5	114.4
10	4383	2779.0	1232.0	580.0
11	3645	3071.0	1571.0	614.0
12	267	228.0	85.0	82.0

Tallies For Histograms of
 Samples 1 through 12
 Table 3.14

with an $\exp(-a|t|)$ distribution, with various reasonable decay distributions (e.g., flat, $\cos^2 \theta$). Although we did not systematically examine the sensitivity of the results to the choice of the slope parameter and the ρ decay distribution, we found that there was quite generally a broad low-mass enhancement in $m(n\pi^-)$, peaking at about the Δ mass. Away from the forward direction, the enhancement becomes broader and higher in mass.

An example is given in Fig. 3.81, for the reaction $\pi^-p \rightarrow \pi^+\pi^-n$ at 3.22 GeV/c, with the $\pi\pi$ system produced as a ρ according to $\exp(-\theta|t| \text{ (GeV/c)}^{-2})$ and decaying isotropically in the ρ rest frame. The broad enhancement in $m(n\pi^-)$ thus generated resembles what we see in the corresponding real data, Fig. 3.12. (Also, compare Fig. 3.10-3.11, the lower-momentum data.)

We now look at the final state to see the overall effects of the dominance of peripheral $\pi\pi$ production. It is illustrative to examine the Chew-Low-like plots for the other two ways of treating the 3-particle final state as a diparticle plus a bachelor particle. All 3 plots and their mass projections are given in Fig. 3.82 for the real data at $P \approx 2.2$ GeV/c. Fig. 3.82(a) is the appropriate plot for the study of the dominant process: peripheral production of $\pi\pi$, largely as ρ . The plots in (c) and (e) correspond to the processes $\pi^-p \rightarrow \pi^+(n\pi^-)$ and $\pi^-p \rightarrow \pi^-(\bar{n}\pi^+)$, which are respectively OME-forbidden and OME-allowed.

To the extent that the $\pi\pi$ interaction is symmetric (or, for ρ production, that the ρ decay is symmetric), the enhancement produced by the reflection of $\pi\pi$ production is the same in these two processes. The data does, in fact, include similar broad enhancement bands in the two cases. However, the $m(N\pi)$ spectrum is much more shifted towards lower mass in the OME-allowed case (Fig. 3.82(e,f)).

The reaction $\pi^-p \rightarrow \pi^-\Delta^+$ can proceed by either meson or baryon exchange, but little Δ^+ production is seen in Fig. 3.82(e,f). In Fig. 3.82(d) the Δ^- corresponding to baryon exchange is clear, and not obscured by any enhancement.

So far, we have treated the enhancement as a process competing with exotic exchange. In Section 3.32, we will consider it again, in the context of a model in which the peripheral $M\pi$ production is the cause of the forbidden peaking.

We made a lengthy study of possible systematic effects in the first reaction we studied, $\pi^+n \rightarrow K^0\pi^+\Lambda$. As noted in Section 3.221, the data sample was obtained using a preliminary disambiguation scheme. [Essentially, the events used were those assigned to the $\Lambda K^0\pi^+$ final state on the basis of kinematic χ^2 ,

FAKE DATA $\pi^-p \rightarrow n\pi^+\pi^-$ 3.2 GeV/c

Fig. 3.81

$P \approx 2.2 \text{ GeV}/c$

$\pi^- p \rightarrow \pi^+ \pi^- n$ (& $\pi^+ n \rightarrow \pi^- \pi^+ p$)

(Sample 11)

XBL 729-1787

Fig. 3.82

with a bias of 15 favoring a hypothesis with 4 kinematic constraints (4 C) at the production vertex over one with 1 C, a bias of 5 favoring 1 C over a missing-mass hypothesis, and a bias of 10 favoring Λ over K^0 for each vee.] Since most of the events were fitted with just one constraint (at the production vertex), and many had an invisible spectator proton, we had good reason to worry about the possibility that the forward peaking was not a real effect in Y^* production.

Our primary concern was seeing if the forward peak really existed, rather than finding its exact size and shape. Therefore we concentrated on convincing ourselves that the peak was not an artifact rather than on getting a pure final-state sample. To do this, we made plots like those given above (primarily Chew-Low-like and Dalitz plots) with various cuts applied to the data. Because of the rather meager statistics, we were generally not in a position to detect subtle changes in the angular distributions. We did satisfy ourselves that the existence of the peaking did not depend on which secondary decays were seen, on the inclusion of ambiguous events, or on possible mishandling of the spectator.

In connection with the first of these points, we examined separately the cases where both the Λ and the K^0 or either one is seen to decay. Figure 3.83 is the Chew-Low-like plots for these 3 cases, and for the charge-symmetric reaction. (All beam momenta have been combined.) The forward peaking is visible in all cases, including the highly-constrained 2-vee topology (which is believed to be essentially uncontaminated by misassigned events). Even at 4 GeV/c, where the peak is most questionable, the small sample of 2-vee events (Fig. 3.84(a)) looks like the entire sample (Fig. 3.3(a)), where some Y^* production can be seen.

The final choice of parameters for the assignment of ambiguous events resulted in only a small change in the number of events assigned to this hypothesis.¹²³ (Where only the Λ is seen to decay, the number of events decreased by 25%; the change was <2% in the other two cases and 16% in the overall sample.) Since we saw no strong dependence on the secondary decay, we are confident that our results would not be altered if we used the final separation scheme.

Fig. 3.84(c-d) are the Chew-Low-like plots for $\pi^+n \rightarrow K^0\pi^+\Lambda$, separately for unambiguous and ambiguous events. (Here "ambiguous" means not just that there is a second passing fit, but that it is close in χ^2 to the best fit.) Evidently the forbidden peaking is not strongly correlated with ambiguity; in fact, the ambiguous events seem to have less peaking. That is what one would expect

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Fig. 3.83

Fig. 3.84

If they are more contaminated and the effect is real.

In Δ production in $\pi^+d \rightarrow (p)p\pi^+\pi^-$, we searched for spectator-dependent effects by making a stringent cut on spectator momentum (150 rather than 300 MeV/c); this eliminated almost all events with no true spectator or ambiguity in the identification of the spectator. We also looked for forward Δ production in the $m[(p)\pi^+]$ spectrum - that is, pairing the π^+ with the proton which was called the spectator rather than with the target. In Fig. 3.84(b), we have plotted the production cosine for events in the Δ band against the spectator momentum; it is clear that the forward peaking is not associated with the suspicious fast-spectator events.

We also checked for systematic effects by separating the data into the 20 subsamples listed in Table 3.2. In Figs. 3.85 through 3.94, we present the basic figures (Chew-Low-like plot, forward Dalitz plot, and production distribution via a mass cut) for each of the 10 pairs. The pairs correspond to π^+n vs π^-p , $\pi^0\Xi^-$ vs $\pi^-\Xi^0$, and even-prongs vs odd-prongs. In the first case, we have combined charge-symmetric data from different experiments, with various possibilities for systematic biases. It is encouraging that the separate results are quite consistent. In the second case, we have combined distinct final states, but the Ξ^* should have the same production distribution in both of them. The third pairing gives us additional confidence that our handling of the spectator proton did not somehow generate artificial forbidden peaking.

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Fig. 3.85

$P \sim 3$ GeV/c $\pi^- p \rightarrow K^+ \pi^- \Lambda$

$P \sim 3$ GeV/c $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$

$P \sim 3$ GeV/c $\pi^- p \rightarrow K^+ \pi^- \Lambda$

$P \sim 3$ GeV/c $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$

$P \sim 3$ GeV/c $\pi^- p \rightarrow K^+ \pi^- \Lambda$

$P \sim 3$ GeV/c $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$

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Fig. 3.86

$P \sim 4$ GeV/c $\pi^- p \rightarrow K^+ \pi^- \Lambda$

$P \sim 4$ GeV/c $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$

$P \sim 4$ GeV/c $\pi^- p \rightarrow K^+ \pi^- \Lambda$

$P \sim 4$ GeV/c $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$

$P \sim 4$ GeV/c $\pi^- p \rightarrow K^+ \pi^- \Lambda$

$P \sim 4$ GeV/c $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$

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Fig. 3.87

XBL 729-1776

Fig. 3.88

XBL 729-1777

Fig. 3.89

XBL 729-1778

Fig. 3.90

$P \sim 2$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG

$P \sim 2$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG

$P \sim 2$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG

$P \sim 2$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG

$P \sim 2$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG

$P \sim 2$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG

XBL 729-1779

Fig. 3.91

P $\sim$ 3 $\pi^+n \rightarrow K^0\pi^+\Lambda$ EVEN-PRONG

P $\sim$ 3 $\pi^+n \rightarrow K^0\pi^+\Lambda$ ODD-PRONG

P $\sim$ 3 $\pi^+n \rightarrow K^0\pi^+\Lambda$ EVEN-PRONG

P $\sim$ 3 $\pi^+n \rightarrow K^0\pi^+\Lambda$ ODD-PRONG

P $\sim$ 3 $\pi^+n \rightarrow K^0\pi^+\Lambda$ EVEN-PRONG

P $\sim$ 3 $\pi^+n \rightarrow K^0\pi^+\Lambda$ ODD-PRONG

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Fig. 3.92

$P \sim 4$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG

$P \sim 4$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG

$P \sim 4$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG

$P \sim 4$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG

$P \sim 4$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ EVEN-PRONG

$P \sim 4$ $\pi^+ n \rightarrow K^0 \pi^+ \Lambda$ ODD-PRONG

XBL 729-1781

Fig. 3.93

P~2.2 $\pi^+n \rightarrow \pi^- \pi^+ p$ EVEN-PRONG

P~2.2 $\pi^+n \rightarrow \pi^- \pi^+ p$ ODD-PRONG

P~2.2 $\pi^+n \rightarrow \pi^- \pi^+ p$ EVEN-PRONG

P~2.2 $\pi^+n \rightarrow \pi^- \pi^+ p$ ODD-PRONG

P~2.2 $\pi^+n \rightarrow \pi^- \pi^+ p$ EVEN-PRONG

P~2.2 $\pi^+n \rightarrow \pi^- \pi^+ p$ ODD-PRONG

Fig. 3.94

3.3 INTERPRETATION

3.31 HOW MANY EXPLANATIONS ARE NEEDED?

Before considering various models for OME-forbidden reactions, we make one cautionary comment which is relevant to all of the discussion. We will treat all the decuplet-production reactions (1) - (6) as a class, since the forbidden peak is seen in all but one of those we have studied. (Later we will focus on the differences from the octet-baryon-production class.) In exact SU(3), all the decuplet reactions would have similar behavior. However, despite the general validity of broken SU(3), different explanations may be relevant for the different reactions in each class. There certainly are differences that should be taken into account. For example, separating resonance production from kinematic reflections is more of a problem for the wide Δ than for the relatively narrow Y^* and Ξ^* . Another distinguishing factor is that production of a dimeson state via meson exchange is a competing process for all but Ξ^* production.

In Fig. 3.13-3.14 and Table 3.12 we have summarized our results on the size of the forward and total cross sections. At first glance the wide range of values appears inconsistent with simple SU(3). In particular, the large cross section for Δ production looks suspicious, in light of the experimental difficulties we encountered in that case.

However, we note that similar differences in the cross sections of four of these reactions at lower energies have been reconciled to SU(3) by Trilling.¹²⁴ The Clebsch-Gordan coefficients for unbroken SU(3) predict $\sigma_6/3 = \sigma_1 = \sigma_2 = \sigma_3$, where the subscripts are the reaction numbers. Since the low-lying SU(3) multiplets are strongly split in mass, the question arises of how to make the comparison. Trilling has suggested comparing cross sections at the same lab beam momenta, incorporating a barrier factor corresponding to an effective angular momentum. Up to about 2 GeV/c, $l=1$ works surprisingly well; see Fig. 3.95, which is from Ref. 124. (The curves in (b) are from the one drawn in (a); the data is the same in both graphs.) We have not applied Trilling's scheme to our results, but it appears that the observed sizes are not grossly out of line.

Crudely put, duality reminds us that the amplitude for any reaction can be expanded in terms of either t-channel (or u-channel) exchanges or s-channel resonances; it may be that neither or both descriptions are "simple." Although a dual interpretation of our results is unlikely in light of the low total energies involved, we should keep in mind that duality does remove some of the burden of

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finding a single best explanation.

3.32 REFLECTION AND FINAL-STATE-INTERACTION MODELS

3.321 BERGER'S KINEMATIC REFLECTION MODEL:

APPLICATION TO OUR DATA

First we consider a description of our results which purports to explain them away. Berger claims to have explained the observed peaks as kinematic reflections;¹²⁵ we feel that he has not.

Here we follow his article in examining first reaction $(6n), \pi^+n \rightarrow \pi^-\Delta^{++}$. Berger's description of the final state $p\pi^+$ is based on the fact that it is dominated by peripheral production of the $\pi\pi$ system via π exchange. The dipion mass spectrum and "decay" angular distribution are determined by $\pi^+\pi^-$ elastic scattering. The basic diagram is given in Fig. 3.96.

The "blob" at the upper vertex represents $\pi\pi$ scattering at an energy given by the $\pi\pi$ mass. That mass ranges from threshold up to $(E_{c.m.} - m_p)$. At these relatively low energies, $\pi^+\pi^-$ elastic scattering is dominated by s-channel resonances, and of course may have a large backward cross section. (The backward scattering is CME-forbidden.) In fact, where a single resonance, such as the ρ , dominates the $\pi\pi$ system, the angular distribution must be forward-backward symmetric. (These angles are the production angles for $\pi\pi$ scattering, but would be considered the dipion decay angles in the overall reaction.) Berger's basic result is that this low-energy backward $\pi\pi$ scattering, combined with peripheral production of the $\pi\pi$ system, results in a low-mass, forward-peaked enhancement in the $p\pi^+$ mass spectrum.

Berger's calculations were done with a pion propagator and $\pi^+\pi^-$ cross sections determined elsewhere. He found that the enhancement produced by reflection is in the Δ region, but quite a bit wider than the $\Delta(1236)$. This problem is even more evident in the case of production of the $Y^*(1385)$, which has a width of only 36 MeV. The calculated enhancement in $m(\Lambda\pi)$ in $\pi^-p \rightarrow K^+\pi^-\Lambda$ at 6 GeV/c is sharply peaked, but is a couple of hundred MeV wide. (See Fig. 3a of Ref. 125.)

Berger presented a qualitative resolution of this problem:

"As they stand, the full widths of [the] mass enhancements... 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

Fig. 3.96

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Fig. 3.97

Fig. 3.96-3.97

characteristic of these resonant states. Moreover, partial-wave analysis of the amplitudes [used] shows that at low invariant masses the p-wave component in the π^+p and $\pi^-\Lambda$ rest frames is substantial. 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 $J^P = (3/2)^+$ component of the amplitudes by a Breit-Wigner form. 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 the effect."

Berger concluded that his results are in agreement with the available Δ data. That includes agreement in the size of the cross section for events in the Δ band, which was fixed in his calculation by known coupling constants; this is a strong point in favor of this model as a description of the final state "before rescattering."

In an appraisal of Berger's model, the rescattering required to shape the broad enhancement into a narrow resonance is of crucial significance. He pointed out that "once final-state interactions are included (e.g. to shape a final-state mass distribution), the topology of the overall scattering diagram is that of a box" [two-meson exchange diagram]. (This correspondence is indicated schematically in Fig. 3.97; we will discuss explicit two-meson-exchange diagrams in Section 3.33.) Berger's scheme is equivalent to summing over all possible intermediate states in $\pi\pi$ scattering ("X" in Figure 3.97); the typical DME calculation puts only one or two resonances here. As Berger pointed out, the energy dependence at intermediate energies can be quite different in these two cases. However, once rescattering is included, it does not seem appropriate to consider Berger's scheme to be simply kinematic reflection. The two-meson-exchange model to which it is equivalent is an interesting non-kinematic process in itself. (In this case it involves the exchange of exotic quantum numbers overall, although no exotic resonance is invoked.)

Furthermore, nothing in Berger's argument precludes the presence of an additional mechanism producing real forward Δ (e.g. via s-channel resonances); we are making no claim that any of his calculations are invalid. His article did not discuss our interpretation of the data as Δ added to a kinematic enhancement. Therefore, the dichotomy suggested by the title of Berger's letter, "exotic exchange or kinematical reflection," and by his choice of the latter as the correct explanation, seems too strong.

We cannot deny that our claim to see forward Δ production on top of the

enhancement may have been influenced by the unequivocal presence of analogous peaks in the Y^* data. For Y^* production, Berger's model works essentially the same way, producing an enhancement that is a bit narrower than in the Δ case but still too broad to be considered a Y^* unless rescattering is invoked. In $\pi^-p \rightarrow K^+Y^{*-}$ and $K^-p \rightarrow \pi^+Y^{*-}$, there are suggestions that the enhancement is present, but the forbidden forward peaking is not obscured by it. After having become aware of this problem in the Δ data, we did re-examine the Y^* results; as already noted, we reduced the values given by our simple fit for the amount of resonance production in the forward bins at $P \approx 2$ and $P = 2.1$ GeV/c.

The final states for Ξ^* production are quite different from those for Δ and Y^* production, since the meson system ($K\pi$) cannot be produced from the incident K^- by nonexotic exchange. Therefore, Berger's model can not be trivially extended to this case. Berger suggested that a two-step process is involved: "First, in $K^-p \rightarrow K^+K^-\Lambda$, 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 $K^-\Lambda \rightarrow \Xi^{*-}(1530) \rightarrow \pi^-\Xi^0$." Since I am not familiar with the theoretical or experimental status of such exothermic rescattering, this argument strikes me as a bit *ad hoc*.¹²⁶ We note that since this mechanism involves rescattering which changes not only the relative momentum of the particles but their identity, it certainly seems proper to consider it a modified box diagram and not a kinematic effect.

The preceding comments relate primarily to the interpretation of Berger's work as explaining our data away. We now mention a specific point where his predictions appear to disagree with the data.

We have noted that the Δ is produced quite a bit less peripherally than the enhancement. This appears to be true for the Y^* also; see Figs. 3.1-3.5(a). Berger pointed out that for $\pi^-p \rightarrow K^+\Lambda\pi^-$, "the $\ell=1$ and higher components in the $\pi^-\Lambda$ system are ... produced more peripherally than is the overall enhancement. For example, for $\ell=1$, $d\sigma/dt(\pi^- \rightarrow K^+) \propto \exp(20t)$ at 6 GeV/c lab momentum."¹²⁷ This is, of course, the partial wave in which the Y^* occurs. To the extent that Berger's model is primarily kinematic, the same is true in Δ production - the higher waves are more peripheral. It would be interesting to deduce from Berger's model how much of the P-wave required to make the resonance is available as a function of angle - specifically, in the not-quite-forward direction, where we see Δ production most clearly. Perhaps some variant of the

rescattering hypothesis can be invoked to explain this, e.g. by changing the relative angular momentum as well as linear momentum of the two particles in the resonance. Failing that, however, it would appear that Berger's model disagrees significantly with our data on this point.

We can reformulate this argument in quantitative (but not thereby stronger) terms. Berger used an exponential slope derived from real data to describe the dominant process; the reflected processes turned out to have similar exponential behavior. (That is, they were exponential in the exotic momentum transfer; e.g., $t_{\pi^-K^+}$ in $\pi^-p \rightarrow K^+\gamma^* \pi^-$.) The numerical results he cited all have slopes of 7 (GeV/c)^{-2} and greater:

Reaction	Mass selection (GeV)	P_{lab} (GeV/c)	"a" in $\exp(-a t)$ (GeV/c) $^{-2}$
$\pi^+n \rightarrow \pi^-(p\pi^+)$	$m(p\pi^+) < 1.36$	2	7
"	"	6	11
$\pi^-p \rightarrow K^+(\Lambda\pi^-)$	$m(\Lambda\pi^-) = 1.4$	2	10
"	"	6	13
"	"	10	16

As noted above, it is difficult to extract such information from our data, but the slopes we found (Table 3.13) were in the range of 2 to 5 $(\text{GeV/c})^{-2}$, in disagreement with Berger's results for the energy range of 2 to 4 GeV/c.

We conclude, in summary, that Berger's model does describe a process that is significant in our final state. When the necessary rescattering is included, it should not be considered a purely kinematic alternative to exotic exchange. Contrary to the prediction of the model, we see resonance production which is less peripheral than the enhancement.

3.322 BERGER'S MODEL APPLIED TO $pn \rightarrow \Delta^-\Delta^{++}$

At this point we digress to comment on an exchange of Letters on the OME-forbidden reaction $pn \rightarrow \Delta^-\Delta^{++}$. Using the model just discussed, Berger and Morrow have explained the observed forward peaking, apparently quite well. We wish to point out the differences between this reaction and ours. We feel that Berger's success in understanding this reaction is not independent confirmation of his case for a kinematic explanation of our data and does not remove our objections to it.

Yekutieli *et al.* studied $pd \rightarrow (p_{sp})pn\pi^+\pi^-$ at 6.98 GeV/c.¹²⁸ Looking at 1900 events with forward n and backward p , they saw in the triangle plot a prominent excess of events in the Δ regions. By fitting the mass spectra to various resonant processes plus phase space, they found $(8 \pm 3)\%$ $\Delta^-\Delta^{++}$ production. Events in the $\Delta\Delta$ region show very strong forward peaking. (That is, almost all have $(\hat{p}\cdot\hat{\Delta}^-) > 0.9$.)

In rebuttal, Berger and Morrow provided a "nonexotic, kinematic" interpretation of this result, calculating both the shapes and sizes of the published distributions.¹²⁹ As was the case with our data, the basic mechanism is the promotion of low-energy scattering to high energy in the overall reaction. The diagrams (Fig. 1(a-b) from Ref. 129) are reproduced in Fig. 3.98. Berger and Morrow calculated the cross section using previously evaluated descriptions of the $\pi N \rightarrow \pi\Delta$ scattering.

As discussed in the previous section, in our reaction ($\pi^+n \rightarrow \pi^-\pi^+p$) Berger's model certainly does generate a broad low-mass enhancement in the Δ region. Our mass spectra indicated either Δ or an enhancement above threshold, and we had to look at Dalitz plots for various cuts in production cosine to establish Δ production. In the four-body state this sort of study is much more complicated. Yekutieli *et al.* show convincing evidence for $\Delta \rightarrow N\pi$ in their $\Delta N\pi$ Dalitz plot and projections, but there are many background events in the Δ band selected. Berger suggested that their estimate for the contribution of $pn \rightarrow \Delta^-\Delta^{++}$ was inadequate, and that they saw only $\Delta^-\pi^+$ and $\Delta^{++}n\pi^-$ imitating $\Delta\Delta$ production. As Berger noted, the quoted 8% for $\Delta\Delta$ production seems to be close to just the fraction of events in both Δ bands.

That is, Yekutieli *et al.* may not have been able to take into account the kinematic reflection of allowed processes like that which we know to be present in our data. However, it appears to us that this criticism by Berger and Morrow is not essential to their proposed interpretation, for two reasons. First, forward Δ^- production in $pn \rightarrow \Delta^-\pi^+$ and backward Δ^{++} production in $pn \rightarrow n\pi^-\Delta^{++}$ are in themselves exotic effects. Second, Berger and Morrow presumably could invoke $N\pi$ rescattering in the $\Delta N\pi$ state to get $\Delta\Delta$, just as Berger invoked it in our $\pi N\pi$ final state to get $\pi\Delta$; however, they did not do so.

The problem of width-narrowing by rescattering does not arise for another reason: each of Berger's diagrams does include the production of real Δ . So, upon looking for $\Delta\Delta$ production (in the $\Delta N\pi$ state defined by a mass cut on one $N\pi$ pair), we see an authentic peak in the (other) $m(N\pi)$ spectrum generated by this

(a)

(b)

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Fig. 3.98

real Δ . [Specifically, Fig. 3.98(a) has real Δ^- and a broad low-mass $p\pi^+$ enhancement, so a cut on $m(n\pi^-)$ to define a Δ^- gives just a broad enhancement in $m(p\pi^+)$.¹³⁰ Similarly, the diagram in Fig. 3.98(b) gives no Δ^- peak, just a broad enhancement in $m(n\pi^-)$, but the $m(p\pi^+)$ spectrum in the $\Delta^-p\pi^+$ state includes the real Δ^{++} peak.] In other words, taking the sum of these two diagrams avoids the need for $N\pi$ rescattering to get a narrow peak in the $\Delta N\pi$ final state.

It is worth noting another way in which Berger's calculations here are different from those compared to our data. There, the low-energy OME-forbidden process which was promoted to high overall energy ($\pi^+\pi^- \rightarrow \pi^-\pi^+$) was described by real data which has backward scattering attributable to s-channel effects in the produced meson system. The backward (OME-forbidden) scattering is what generates the forbidden forward peaking in the overall reaction. The Regge parametrization used for $\pi^+\pi^-$ scattering at higher energies (above $s_{\pi\pi}=2.9 \text{ GeV}^2$) did not have that backward peak. In the case of $pn \rightarrow \Delta^-\Delta^{++}$, Berger used real data for the component exotic reaction $\pi^-p \rightarrow \pi^+\Delta^-$ only below $\sqrt{s_{\pi p}}=1.8 \text{ GeV}$, which is $p_{\pi} = 1.24 \text{ GeV}/c$; above that he used a representation obtained from the theoretical model which he had applied to our data. That is, he used a theoretical representation which does show forbidden peaking at lab momenta of several GeV/c , just like the data with which it generally agrees.

In other words, the results of Yekutieli *et al.* can originate either from the double promotion of low-energy $\pi^+\pi^-$ elastic scattering, or from the single promotion of the intermediate reaction $\pi^-p \rightarrow \pi^+\Delta^-$, produced by any non-kinematic mechanism. Since there is no question that kinematic reflections like that described by Berger do occur, the success he has had with the data of Yekutieli *et al.* does not imply that his model is the proper explanation of our data on $\pi^-p \rightarrow \pi^+\Delta^-$.

3.323 THE FINAL-STATE INTERACTION MODEL OF SIVERS AND VON HIPPEL

Sivers and Von Hippel have presented a calculation of reaction $(1p), \pi^- p \rightarrow K^+ Y^{*-}$, in which a $\Lambda\pi^-$ final state interaction is fed by production of $K^*(890)$ and $K^*(1420)$.¹³¹ The key to this model is the resonant $\Lambda\pi^-$ interaction which occurs when the Λ and the π^- have the effective mass and J^P of a Y^* ; this interaction takes events from the K^* band in the region of $m(\Lambda\pi^-)=m(Y^*)$ and creates a Y^* band away from the K^* band.

This model is related to a multiple scattering model based on two successive nonexotic exchanges. (It involves keeping only the on-mass-shell part of the pole term for the second exchange, which is responsible for the reaction $K^{*0}\Lambda \rightarrow K^+ Y^{*-}$.) For an unusually readable discussion of this model, its relation to other models for exotic exchange, and its possible broader applications, see Ref. 131.

Like Berger's model, it seems to be in some sense equivalent to a two-meson-exchange picture. We discuss it at this point because, like Berger's model, it relies upon the modification, via rescattering, of a prominent exchange process in the same final state. In other words, in both of these models it is crucial that a 3-body final state is involved; a straightforward two-meson-exchange diagram does not take the Y^* decay into account, and can be written as well for a two-body final state (e.g., ΣK rather than $Y^* K \rightarrow \Lambda\pi K$).

With considerable success, Sivers and Von Hippel have compared the results of their calculation with the data of Crennell *et al.* at 4.5 GeV/c. The feature of the data that makes this success possible is the presence of significant Y^* only if the K^* bands are excluded. The forward Dalitz plot of Crennell *et al.* shows a very striking hole in the $Y^* K^*(890)$ region; in the $Y^* K^*(1420)$ overlap region the depletion is less prominent but apparently present. (In my opinion there are a few Y^* events in the uncut $m(\Lambda\pi^-)$ spectrum, but of course a small amount of another mechanism could be added to the Sivers-Von Hippel description.)

Similarly, our data at 4 GeV/c for $\cos\theta_{pr} > 0.7$ shows essentially no Y^* in the $K^*(890)$ band (Figs. 3.20(a), 3.56(d)). Although the Y^* signal is stronger with the $K^*(890)$ band removed (Fig. 3.56(c)), we definitely do see Y^* without this cut (Fig. 3.20(b)). [In addition, we see no sign of a depletion in the $Y^* K^*(1420)$ region; we have very few events there, but if anything there is constructive interference. Note that the $K^*(1420)$ (and, analogously, the f^0) are not cut out in Fig. 3.54⁺(c).] Thus, it appears that the Sivers-Von Hippel model may be substantially relevant to our 4 GeV/c data, but cannot explain it entirely.

As noted above (Section 3.23), for all our data above 3 GeV/c the $M^* B^*$

overlap region seems to be depleted; below 3 GeV/c, it is not.

3.33 DOUBLE-PARTICLE-EXCHANGE MODELS

Recent Results on Double-Particle Exchange in General

In our second Letter,⁹² we discussed various alternative explanations for the observed forward peaking and speculated that either the required exotic mesons did in fact exist, or a complicated s-channel mechanism with interfering resonances was at work. We now share the opinion of several authors who have recently reviewed the subject (e.g. Rosner⁹⁴ and Barloutaud¹³²) that two-particle exchange is the most likely source of a relatively simple explanation. (Some typical DME diagrams are given in Fig. 3.103 below; note that often there will be several possible particles on the intermediate lines.)

In a sense, two-meson-exchange diagrams are built into the basic peripheral model; the OPE diagram is only the leading term of the t-channel expansion. Harari has studied the various terms systematically, examining a hierarchy of decreasing strengths.¹³³ The strongest amplitudes are those for Pomeron exchange (where no internal quantum numbers are exchanged). Next in strength is ordinary one-particle exchange; in Regge language, this is one-pole exchange. Harari pointed out that the data for various reactions calls for the exchange of a particle and a Pomeron. (A double-exchange diagram corresponds to a cut, rather than a pole.) These cuts are typically comparable in strength to the OPE amplitudes. One step weaker are the cuts generated by the exchange of two (non-Pomeron) poles. Harari examined data for some reactions where DPE amplitudes should be seen interfering with Pomeron- or ordinary-particle exchange, as well as for some OME-forbidden reactions (but not any of the octet or decuplet production reactions (1)-(6) or (15)-(19)). He concluded that "Several clues indicate that the ratio between a DPE amplitude and a single-particle exchange amplitude at any given energy is roughly the same as the ratio between the single-particle-exchange term and the Pomeron-exchange amplitude at the same energy. This ratio is typically $0.2 - 0.3$ at $p_L \approx 5$ BeV [$/c$?]."

It was pointed out some time ago that OME-forbidden reactions are an easy and natural place to study DPE.¹³⁴ Harari noted, however, that typically a nonexotic DPE amplitude can be expected to be larger than an exotic one. Henyey *et al.* have made specific calculations which lead to the same conclusion.¹³⁵ They use a previously developed strong-absorption model, with parameters all taken

from fits to OPE-allowed reactions. Their somewhat surprising result is that "spin effects, variations in coupling values, and unavoidable cancellations result in a cross-section range of $\pm 10^5$ for different forward reactions, in good agreement with existing data. Reactions with exotic-quantum-number exchange are small because of spin and symmetry coupling properties of particles, while some nonexotic double-particle exchanges are quite large."

The systematic weakness of nonstrange exotic exchange is related to the fact that a t-channel isospin $I \geq 3/2$ requires that at least one $I=1$ trajectory be exchanged; the high-lying $I=1$ trajectories (ρ , A_2 , and ω) are mainly helicity flip at the baryonic vertex. Henyey et al. have found that, other things being equal, amplitudes involving only spin-flip are strongly suppressed. They further point out that the weakness of exotic cuts can be related to the absence of exotic resonances.

Henyey et al. have tested their model on several OME-allowed and OME-forbidden reactions, with general success. In particular, they claim to understand the smallness of the cross section for reaction (15), $\pi^- p \rightarrow K^+ Z^-$. They did not discuss any decuplet-production reactions, but did indicate that they were continuing to study OPE-forbidden reactions. The weakness of reaction (15) depends on sensitive cancellations, and on the values of the coupling constants. Thus it seems quite possible that our results might be understood in this model.

It is not clear to me whether any of our data is high enough in energy to be comfortably treated by such models. Quigg has suggested that for $\pi^- p \rightarrow K^+ Z^-$ DPE begins to dominate at about 5 GeV/c over whatever mechanism is responsible for the reaction at lower energy.¹³⁶ It appears that Regge theories may be inappropriate below ≈ 5 GeV/c.¹³⁷

The papers cited here (especially Ref. 136) provide references on the historical development of DPE models. In the next subsection we just mention a couple of previous studies which are, perhaps, completely superseded by the work we have just discussed; we refer to them since they do make DPE predictions that have been or could be applied to our data.

Old Studies Applicable to Our Data

Dean has used the quark model and the Glauber formalism for multiple scattering to derive simple relationships between OME-forbidden reactions and allowed ones.¹³⁸ The forbidden reaction can be considered in terms of two inelastic scatterings of the component quarks, with each scattering being responsible by itself for a related allowed reaction. Dean has derived simple predictions for the size and slope of the forward cross sections (assuming an exponential in the momentum transfer t). (E.g., if the component allowed reactions $K^+p \rightarrow \bar{K}^0 n$ and $K^-p \rightarrow \pi^- \Sigma^+$ have slopes a and b , the forbidden reaction $K^-p \rightarrow \pi^+ \Sigma^-$ has slope c , given by $1/c = 1/a + 1/b$.) Dean found rather good agreement, within the large errors, with the limited data available on the octet-production reactions (15) - (17). There is even less data available on decuplet production and we have not attempted to check his predictions against our data.

Singh and Agarwal have applied a specific DPE model to a number of reactions, including some of the forbidden decuplet-production ones reported on here. They use a box diagram (DPE diagram) with only a single pair of exchanged particles and a single pair of intermediate states in each case; they evaluate the amplitude using a "coincident pole" method that is obscure to me. Once the coupling constants are fixed, their model has no free parameters. They claim to have reproduced the shape and magnitude of our production distributions for $\pi^+ n \rightarrow \pi^- \Delta^{++}$ and $K^- p \rightarrow \pi^+ Y^{*-}$,¹³⁹ and the shape of $\pi^- p \rightarrow K^+ Y^{*-}$.¹⁴⁰ I am not in a position to evaluate their theoretical work or to compare it with other DPE models; however, they have also claimed that two-meson exchange reproduces the *backward* peak in $K^- p \rightarrow \pi^- \Sigma^+$.¹⁴¹ (They studied this reaction since it cannot come from the exchange of a stable baryon; however, Δ exchange is allowed.) Their fit for $\pi^- p \rightarrow K^+ Y^{*-}$ includes a large broad backward peak as well as a forward peak. Also, by using only a single DPE diagram in each case they disallow the cancellations which Henyey *et al.* have found to be crucial in several cases.

3.34 EXCHANGE OF A SINGLE EXOTIC MESON

It seems a remote possibility that the mesons required to account for the forward peaking in terms of OME really do exist, but have not been observed directly. We suggest that OME should be invoked only if DME fails to explain the data. No such strong failure is presently apparent. The flexibility of DME makes it difficult to distinguish from OME.

The experimental situation for reaction (1), $\pi^- p \rightarrow K^+ Y^{*-}$, has been discussed in detail by Crennell *et al.*, using our data at 2 to 4 GeV/c, theirs at 4.5 GeV/c, and their upper limit at 6 GeV/c.⁹⁶ The energy dependence is reasonably well fitted by an effective Regge trajectory with intercept $\alpha_0 = -0.9 \pm 0.2$. This would not be an unreasonable value for a single exotic trajectory.

Crennell *et al.* note that simple DPE predicts the same form for the energy dependence, with $(\alpha_0 - 1)$ replaced by $(\alpha_0^1 - 1) + (\alpha_0^2 - 1)$, the sum of the values for the two exchanged trajectories. The effective α_0 is about -1.25 for π -and-K exchange, and about -0.4 for ρ -and- K^* exchange, bracketing the observed value. Allowing some combination of these DPE's would give a range of values for the effective α_0 .

Crennell *et al.* also noted that the slope in t they observed, $(2 \pm 1) (\text{GeV}/c)^{-2}$, is reasonably consistent with the predictions of ρ -and- K^* exchange, but smaller than that of π -and-K exchange.

OME without absorption makes simple predictions about the density matrix elements of the resonance produced. However, the greater freedom of DPE models makes it seem unlikely that any useful differentiation could be made here either.

Thus, we agree with Crennell *et al.* that, at least with the kind of data presently available, OME and DME are hard to distinguish experimentally. Hopefully, additional data and continuing work on the model of Kenyey *et al.* will clarify the situation.

Nevertheless, since our study was motivated in part by the idea of ruling out or detecting exotic mesons via exchange reactions, it is appropriate to consider the possibility of one-meson exchange further here. The simplest exotic SU(3) multiplets would be $\underline{10}$, $\underline{27}$, and $\underline{35}$. All the mesons required to produce peaks in reactions (1) through (6) could be accommodated by a $\underline{27}$ or a $\underline{35}$; the $\underline{10}$ does not include $S = 2$ or $I = 2$ mesons (required for reactions (3) and (6) respectively).

Since $0^- \rightarrow 0^- + 0^-$ is forbidden by conservation of angular momentum and

$\cos \theta_{\text{prod}} > 0.7$

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Fig. 3.99

parity, the simplest case for the J^P of an exchanged meson in our reactions would be 0^+ . Such an exchange would populate only the $m = \pm 1/2$ states (in the Jackson frame) of the $3/2^+$ baryon. In the absence of absorption corrections, this would give a decay distribution of $(1 + \cos^2\theta)$, flat in the Treiman-Yang angle ϕ . The Ξ^{*-} data (for production cosine > 0.7) is given in Fig. 3.99, along with this decay distribution (the solid curves in (a) and (b) and the dotted lines in (c) and (d)). There are too few events to allow a conclusion to be drawn. For the other reactions, the background is too great to allow such a comparison.

Rosner has summarized the spectroscopic evidence on exotic mesons. He has noted that not only has no new direct evidence come up in the past few years, but "the candidate states, never in very good health, seem to be declining further."⁹⁴ (There are no established exotic baryons either, but the controversial Z^* 's are rather persistent.) Theoretical arguments have been set forth by Chiu and Hwa¹⁴² and by Rosner¹⁴³ in favor of exotic meson enhancements which would couple primarily to the baryon-antibaryon system and not to mesons. Here we add only that the direct search mentioned in our second Letter⁹² has been completed. If an $S = 2$, $Q = 2$ meson had mass $< 2m_K$, it would be stable against strong decay and would leave a track in the bubble chamber with ionization at least four times minimum; Dauber found no such particles in a study of some K^+p film at 12 GeV/c.¹⁴⁴

3.35 THE ROLE OF BARYON EXCHANGE

Effects in all 3 channels (s, t, and u) may appear in our final states. For completeness, we remark here on the possible role of u-channel (baryon exchange) amplitudes in the forward-production region of the OME-forbidden reactions. (In the next section, we comment on the ability of baryon exchange to generally explain the allowed backward peaks, both in these reactions and in related final states.)

As we noted in Ref. 92, to explain the forward peaks as the tails of backward peaks would require great variation with u of the relative phases between several exchange amplitudes. There would have to be nearly complete destructive interference at small $|u|$ and constructive interference at maximum $|u|$ to give backward and forward peaks of comparable size. The observed dip in the extreme backward direction in reactions (3) and (4) might conceivably be a manifestation of such destructive interference.¹⁴⁵ In terms of Regge models,

this hypothesis requires trajectories with radically different shapes.

This hypothesis also requires baryon exchange amplitudes which do not fall off too quickly with u . In our Letter⁹² we commented on one calculation of Λ exchange with absorption which gave a cross section at 2 GeV/c for $K^-p \rightarrow K^+\Xi^-$ which is substantial in the forward direction.¹⁴⁶ Of course, one hesitates to take any exchange calculation seriously too far from the backward direction. We note that for $K^-p \rightarrow K^+\Xi^*$, the physical region spans a range in u (or in t) of 1.6 (GeV/c)^2 at $P_{\text{beam}} = 2 \text{ GeV/c}$. Any baryon-exchange pole is at least $\approx 1 \text{ (GeV/c)}^2$ from the $|u| = |u|_{\text{min}}$ end of the physical region; thus the other end of the physical region is only a couple of times as far from the pole at our lowest c.m. energies. (In non- Ξ^* reactions the range of u is somewhat larger; see Table 3.13.) As we go to higher energies, however, it rapidly becomes less reasonable to extend a baryon-exchange model to the forward direction.

Yodh has attempted to describe reaction (4), $K^-p \rightarrow K^0\Xi^*0$, with u -channel amplitudes. This is the one reaction in which we do not see a forward peak; there is, however, a substantial cross section spread over the forward hemisphere. Yodh reportedly has obtained a good fit up to 2.8 GeV/c.¹⁴⁷ Although we see a prominent forward peak in reaction (3) ($K^-p \rightarrow K^+\Xi^{*-}$) at 2.6 GeV/c, and a definite peak at 2.1 GeV/c, the production distribution is not grossly different from that for reaction (4) (especially at 2.1 GeV/c). Thus, it would be interesting to try Yodh's u -channel model in reaction (3). However, our data for Υ^* and Δ production is more suggestive of well separated forward and backward peaks than the Ξ^* data, so it would be very surprising indeed if any reasonably simple u -channel model could give a good fit. We conclude only that it is not unreasonable to consider the contribution of baryon exchange in the forward direction for the lower-energy parts of our data.

3.36 S-CHANNEL MODELS: EXCHANGE PROCESSES IN RELATED REACTIONS

We now consider the possibility that the observed forward peaks are the consequence of resonance production in the direct channel. We have not attempted to generate a specific s -channel model to fit our data; the lack of detailed information about the resonances which would play a part, and the limited nature of our data, made such an undertaking seem unprofitable. We can anticipate that with enough work we could get a reasonably good description of the data. We restrict ourselves to general observations about the applicability of

s-channel models (as opposed to exchange models).

The main reason for expecting that a relatively simple s-channel model might be the best way to describe our results is the relatively low c.m. energies involved. Ordinarily 2 to 4 GeV/c would be considered to be in the resonance region, below the energies where exchange models are expected to apply (although dual interpretations have removed much of the distinction). For πN scattering, 2, 3, and 4 GeV/c correspond respectively to $E_{c.m.} = 2159, 2560, \text{ and } 2900 \text{ MeV}$. The current Particle Data Group listing includes two Δ and three N^* resonances with masses in that range.¹⁴⁸ (No decay fractions into $\Delta\pi$ or Y^*K are listed, so a model calculation would have to leave these as free parameters.) For K^-p , 2.1 and 2.6 GeV/c correspond to 2274 and 2468 MeV; there is one known Y_0^* and two Y_1^* 's which could be formed.

As noted in Section 3.22, we did not observe the rapid fluctuations with c.m. energy that would be expected from a mechanism dominated by resonances which are narrow compared to the c.m. energy range covered. However, our data does not sample enough energies to rule out a simple s-channel mechanism on these grounds.

S-channel models have been applied to various πp and Kp reactions up to several GeV/c with considerable success. If these final states were s-channel dominated, that dominance would be reflected in features other than the forbidden B^* production and in related final states. However, various features of our data and that for related reactions can easily be understood in terms of exchange models, as we shall now see. This does not prove that the forbidden peaking is not an s-channel effect; it is quite possible for different features of a single final state to be produced by exchange and direct-channel mechanisms.

The simplest s-channel models make predictions that are generally not satisfied by the data. We now consider both these predictions and the exchange interpretation of features other than the forbidden forward peaking: (1) backward peaking in the same reaction; (2) production of other charge states of the same decuplet resonance and 0^- meson, with either the same or different total charge; (3) production of other resonances in these final states.

Not surprisingly, since the OME-forbidden processes do not dominate the final states, other processes in the data we used have already been studied rather extensively. Here we merely summarize such work to indicate the kind of arguments that can be made in favor of exchange dominance; this is not a systematic survey of the data. (It appears that generally s-channel mechanisms

were not rejected, but just not examined in detail.)

All of reactions (1) through (6) can proceed by baryon exchange. All of our production distributions (Fig. 3.13-3.14) show backward B^* production.

One fact that is suggestive of an s-channel mechanism is that the forward and backward peaks are comparable in size. A single s-channel resonance, of course, gives a production distribution that is forward-backward symmetric. We further note that in the Ξ^* production reactions there is a substantial cross section in the region around zero in production cosine, which does not suggest an exchange mechanism.

The backward scattering in reaction (6n), $\pi^+ n \rightarrow \pi^- \Delta^{++}$, has been studied in detail by Manning.¹⁴⁹ He found Δ decay distributions inconsistent with simple unmodified nucleon exchange, and he associated the dip in the extreme backward direction with strong helicity-3/2 amplitudes.

Neither the forward nor the backward peaking in reactions (1p), (2), and (6p) was discussed in the original reports on the data we have used.¹⁵⁰⁻¹⁵²

A single dominant s-channel resonance will decay into various charge states with identical angular distributions and cross sections related by Clebsch-Gordan coefficients. For example, reactions (3) and (4) ($K^- p \rightarrow K^+ \Xi^{*-}$ and $K^- p \rightarrow K^0 \Xi^{*0}$) are so related. The differences in the data argue against a simple s-channel effect. In other cases, however, the related reactions are not OME-forbidden. We mention some of the data here.

An s-channel N^* or Δ in reaction (1) would have two Y^*K decay modes:

$$\pi^- p \rightarrow K^+ Y^{*-} \quad (1p)$$

$$\pi^- p \rightarrow K^0 Y^{*0} \quad (25p)$$

The charge-symmetric reactions are

$$\pi^+ n \rightarrow K^0 Y^{*+} \quad (1n)$$

$$\pi^+ n \rightarrow K^+ Y^{*0} \quad (25n)$$

We have studied reaction (25) in the final states

$$\pi^- p \rightarrow K^0 \Lambda \pi^0$$

$$\pi^+ d \rightarrow (p) K^+ \Lambda \pi^0$$

in the same way as we studied reaction (1). (There are two minor differences in procedure; we did not use data for (25n) at 2 GeV/c, and we did not see if any correction for peripheral $K\pi$ production was required in the forward bins.) The resulting Y^* production distributions are given in Fig. 3.100. We present in Appendix D the final-state tallies, the factors for converting Fig. 3.100 to $\mu\text{b/sr}$, the results of the fits to the amounts of resonant processes, the Dalitz

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Fig. 3.100

plots for all angles and for forward production, and the plots of $m(\Lambda\pi)$ against production cosine.

Parity conservation in the decay of a single s-channel resonance would require forward-backward symmetry in the production distributions for both reactions (1) and (25). The asymmetry in the forbidden reaction (1) is not strong enough to rule this out. However, reaction (25) is quite asymmetric. Thus, an s-channel explanation of the forbidden peak requires at least two significant interfering amplitudes. In favor of an s-channel effect is the fact that the allowed and forbidden reactions are comparable in size. However, the allowed reaction seems to be falling off less quickly with energy; see Fig. 3.80.

Dahl et al. analyzed reaction (25p) in terms of K^* exchange down to threshold, using the SU(3)-generalized version of the Stodolsky-Sakurai p-photon analogy.¹⁵³ The model predicts decay correlations in reasonable agreement with the data, but the predicted zeros in the production angular distribution at $\cos \theta = \pm 1$ were not clearly observed.

S-channel dominance in reaction (2) would relate the three reactions

$$K^- p \rightarrow \pi^+ Y^{*-} \quad (2)$$

$$K^- p \rightarrow \pi^0 Y^{*0} \quad (26)$$

$$K^- p \rightarrow \pi^- Y^{*+} \quad (27)$$

Reaction (26) is unobservable in a bubble chamber (except via the small $\Sigma^\pm \pi^\mp$ decay mode of the Y^{*0}); reaction (27) has been studied in the same final state as reaction (2). The production distributions show very strong forward peaking; they are quite different in size and shape from those for reaction (2). (The distributions are given in Fig. 3.101, which is from Figs. 37-38 of Ref. 112; note that meson exchange corresponds to the left side of these figures.) Siegel obtained an adequate fit to the production and decay distributions using K^* exchange with a form factor. Baryon exchange is forbidden, and no backward peak is seen.¹⁵⁴

The data for reactions (3) and (4) have been presented in detail by Dauber et al.¹⁵⁵ The pronounced dip in the extreme backward direction rules out simple $J^P = 1/2^+$ baryon exchange. The authors did consider s-channel contributions. The difference in the data between reactions (3) and (4), $K^- p \rightarrow K^+ \Xi^{*-}$ and $\rightarrow K^0 \Xi^{*0}$, is discussed in the next section.

Reaction (6) has two counterparts, one of which is not accessible in bubble chamber studies:

$$\pi^+ n \rightarrow \pi^- \Delta^{++} \quad (6n)$$

Fig. 3.101

Reactions (6n) and (29n) both could appear in the $p\pi^+\pi^-$ final state. Manning noted that there is no statistically significant Δ^0 production at any energy in the Pi66B data. He attributed this to weakness of $I = 3/2$ baryon exchange. He considered an s-channel explanation of this large difference between backward production in reactions (6) and (29) unlikely, since he noted no rapid variation with c.m. energy.¹⁵⁶ On the other hand, an s-channel explanation of this reaction at 2.15 GeV/c was suggested by Anthony *et al.*¹⁵⁷

It may be relevant to a consideration of $(KY^*)^0$ production in reactions (1) and (25) to note that $(KY^*)^{++}$ production can be understood in terms of a simple exchange mechanism. Davies has studied the reaction

down to threshold. He found a rather good fit to the simple K^* -exchange model which also applied to reaction (25p).¹⁵⁸ Note that in s-channel terms reactions (25) and (30) are quite different, the latter having $I_s = 3/2$ only.

We have not attempted to extend Davies' work above 2.4 GeV/c. He noted that K^* exchange starts to fail as the baryon exchange peak (which is present at 2 and 3 GeV/c) appears. In Fig. 3.102 we present the production distributions obtained from our analysis of Davies' data at 2 GeV/c and ours at 3 and 4 GeV/c. The treatment was the same as for reactions (1p) and (25p); additional information is given in Appendix D.

Finally we comment on the production of other resonances in the same final states as the OME-forbidden reactions. The production and decay of $K^*(890)$, which competes strongly with reaction (1p) in final state (7), has been studied by Dahl *et al.* in terms of K^* exchange with absorption; the production is very peripheral but the decay distributions were not very well understood in their model.¹⁵⁹

In the $\Lambda\pi^+\pi^-$ final state, p production is present but does not dominate over $K^-\pi \rightarrow \pi^+\pi^-\Lambda$. Siegel did not study the p production in his data.¹⁶⁰

There is some K^* production in the $\Xi K\pi$ final states (10) - (12); Dauber *et al.* did not study it in detail.¹⁶¹ Forward-peaked K^* production is OME-forbidden and not seen; backward peaking is allowed and is observed at 2.6 GeV/c.

The final state (14), $(p)p\pi^+\pi^-$, is strongly dominated by p production; Manning studied the $\pi\pi$ interaction (making a cut on momentum transfer and assuming π exchange).¹⁶² Jacobs studied p production via π exchange in the

Fig. 3.102

charge-symmetric final state (13).¹⁶³

In summary, it appears that the prominent features of our and related final states are understood at least qualitatively in terms of exchange models. Also, the production distributions are not consistent with a dominant single s-channel resonance. (This is a very weak statement, since a single-resonance amplitude is very simple indeed; an s-channel mechanism with background and several other resonances would still be considered simple enough if it fit the data.) We conclude that it would be surprising if an s-channel explanation were the simplest one for these OME-forbidden reactions.

3.37 INTERPRETATION OF THE Ξ^* PRODUCTION DATA

Now that we have examined several different explanations for the observed forward peaking, we will consider briefly how each of them might account for the Ξ^* production data - that is, for the fact that at 2.6 GeV/c we see a forward peak in reaction (3) ($K^-p \rightarrow K^+\Xi^{*-}$) but not in reaction (4) ($K^-p \rightarrow K^0\Xi^{*0}$). (At 2.1 GeV/c, the forward cross section is about 4 to 6 $\mu\text{b/sr}$ in both cases, with no prominent forward peaking.)

If reaction (3) proceeds by single meson exchange, that meson would have to have $S=2$ and $I=1$. The Clebsch-Gordan coefficients for such an exchange lead to the prediction that the forward peak is 4 times as big in reaction (3) as in reaction (4). The data at 2.6 GeV/c is consistent with this ratio. Evidently OME (plus a little background) could account for the difference between the two Ξ^* reactions.

In terms of an s-channel model, one can make the same arguments comparing reactions (3) and (4) as were made in the previous section for the forbidden and allowed Y^* production reactions. Dominance by a single s-channel resonance requires forward-backward symmetry in both reactions, and also that the production distributions be the same in the two cases. However, $I_S = 0$ and $I_S = 1$ contribute to reactions (3) and (4) with equal strengths but opposite signs. Thus interference between amplitudes of different I-spin could easily allow a forward peak in (3) but not in (4).

In Fig. 3.103 we indicate the simplest DME diagrams for these reactions. Each of the 4 diagrams indicated in (a) has the same Clebsch-Gordan coefficients as the corresponding diagram in (b). Thus, any single one of these box diagrams gives equal amplitudes for the two reactions. Clearly, however, interference

Fig. 3.103

(XBL729-4004)

Fig. 3.104

among several DME amplitudes could give a wide range of results, presumably including a forward peak in (3) but not in (4).

As noted above, it would be interesting to see if Yodh's baryon-exchange model for reaction (4) might also fit the peak in reaction (3).

We now consider whether a primarily kinematic model can account for this difference. (Rosner has expressed the opinion that Berger's arguments "do not apply" to any of the Ξ^* reactions.¹⁶⁴) In Fig. 3.104 we give the diagrams for Berger's model; the blob on the right represents the rescattering that not only changes the identity of the particles but is exothermic. (That is, the $\Xi^*(1530)$ is below $\Lambda\bar{K}$ or $\Sigma\bar{K}$ threshold.) Perhaps interference between diagrams (c) and (a) [and between (d) and (b)] could be invoked to account for the observed difference. From (a) and (b) alone, the difference would have to come from a difference between low-energy backward elastic K^+K^- scattering and the backward charge-exchange process $K^+K^- \rightarrow \bar{K}^0K^0$. Recalling that Berger's model with rescattering is equivalent to a sum of DME (box) diagrams, we feel that the difference between reactions (3) and (4) argues against a mechanism that can properly be called kinematic.

3.38 CONTRAST WITH OCTET-BARYON PRODUCTION

Data and Interpretation for the Octet Reactions

In our consideration of various mechanisms for the observed forbidden forward peaks, it is instructive to turn for comparison to OME-forbidden reactions which differ in having the decuplet (spin 3/2) baryon replaced by the corresponding member of the (spin 1/2) baryon octet. These are reactions (15) through (19), listed above; of course, there is no octet reaction corresponding to Δ production. At energies comparable to ours, these reactions show no forward peaking suggestive of meson exchange; there is either no peaking or a rapid energy dependence which indicates an s-channel mechanism.

For reaction (15p), $\pi^-p \rightarrow K^+\Sigma^-$, the production distributions have been presented by Dahl et al. at 2 to 4 GeV/c.¹⁶⁵ There is a broad backward peak, with only a slight hint of forward peaking (1 μ b or less) at some momenta. Akerlof et al. have studied this reaction at 2.75 and 5 GeV/c; the forward differential cross section ($d\sigma/dt$ at $t=0$) was measured in a counter experiment and found to be $\leq 1 \mu\text{b}/(\text{GeV}/c)^2$, decreasing with energy.¹⁶⁶ Bashian et al. have looked at higher energies, reporting an upper limit for the forward cross section

ranging from $11.5 \mu\text{b}/(\text{GeV}/c)^2$ at $2.75 \text{ GeV}/c$ to $0.2 \mu\text{b}/(\text{GeV}/c)^2$ at $10 \text{ GeV}/c$.⁹⁷

Akerlof has compiled the forward cross section data and noted a rapid decrease with energy, roughly as s^{-9} . This is quite a bit faster than the falloff of the decuplet reaction. Akerlof noted that such an energy dependence over a wide momentum range can be fairly well approximated by the contribution of the $\Delta(1950)$ alone.¹⁶⁷ In addition, the size of the $\Delta(1950)$ contribution, calculated from known resonance parameters, is quite close to the observed forward cross section. (Of all the N^* and Δ resonances listed in the Particle Data Group compilation, this is the only one with a branching fraction into ΣK listed.) Akerlof noted that this agreement might well be fortuitous, but that in any case it does point out the possibly substantial contributions of s-channel resonances whose decay properties are not fully known.

Bashian et al. have noted that this reaction is unusual among OME-forbidden reactions in that the cross section is small even below $3 \text{ GeV}/c$, well into the resonance region.⁹⁷ This requires either that the branching ratios of N^* 's and Δ 's into ΣK are small, or that there is a systematic cancellation between the two isospin amplitudes involved.

In reaction (16), $K^-p \rightarrow \pi^+\Sigma^-$, there is a forward peak of about $50 \mu\text{b}/\text{sr}$ near $2 \text{ GeV}/c$ which decreases rapidly with increasing energy to about $5 \mu\text{b}/\text{sr}$ at $3 \text{ GeV}/c$ and less than $2 \mu\text{b}/\text{sr}$ above $3 \text{ GeV}/c$.¹⁶⁸ Akerlof et al. have similarly reported a forward cross section of about $30 \mu\text{b}/(\text{GeV}/c)^2$ around $3 \text{ GeV}/c$, and have compiled the data for this reaction.¹⁶⁶ Here too they find an energy falloff consistent with s^{-9} . However, the cross section is larger by about a factor of 50 than that for $\pi^-p \rightarrow K^+\Sigma^-$. Akerlof et al. have suggested that this too can be understood in terms of s-channel dominance; that is, only for reaction (16) are there known to be s-channel resonances which couple strongly to both the initial and final states. They suggested that the ratio of cross sections is hard to understand in terms of exchange models, in which the reactions are related by crossing. (They also suggested that there is a connection between the relatively large exchange-forbidden cross sections in $\bar{p}p$ reactions and the presence of a strong s-channel effect, annihilation.) We noted in Ref. 92 that the variation with energy in reaction (16) is quite rapid, indicating an s-channel effect.

Reactions (17) through (19) have been studied in detail by Muller.¹⁶⁹ Reactions (17) and (19), Ξ^- production, have a strong backward peak and little or no forward peaking. Reaction (18), Ξ^0 production, has a smaller cross section, with rapid variation with energy and a strong forward peak below $2.1 \text{ GeV}/c$.

Muller performed a partial wave analysis from 1.2 to 2.7 GeV/c. A multiparameter fit to all 3 reactions together was done, including baryon exchange and direct-channel resonances. (Muller argued that duality presented no problems of double counting at these energies.) He concluded that the data can be explained in terms of $I=0$ baryon exchange, with small but important contributions from $I=1$ baryon exchange and s-channel resonances. In reaction (18), where $I=0$ exchange is forbidden, the small cross section and rapid fluctuations are attributed respectively to the small $I=1$ exchange amplitude and the s-channel resonances. Above 2.1 GeV/c, the fit had to include a number of unestablished resonances to account for the higher Legendre coefficients; it is not clear to me to what extent these coefficients are associated with the forward peaks. Although the forward peaks apparently can be understood in terms of s-channel effects, the success of this fit does not establish conclusively that this is the simplest explanation, since baryon exchange appears to be the dominant process at these energies.

Interpretation of the Octet-Decuplet Difference

In this section we discuss how some of the models for forbidden peaking might account for the octet-decuplet difference; that is, for the absence of significant forward peaks in the case of octet-baryon production. First, however, we mention a relationship that has been predicted by a simple quark model.

For all these reactions, Biafas has written amplitudes which involve successive absorption and emission of a meson by a baryon, with a propagator.¹⁷⁰ This appears to be an s-channel model with only the quark content of the direct-channel state considered. From the fact that the octet-production amplitudes are "nearly" zero (and various theoretical assumptions), he predicted that the decuplet baryons are produced only in the transversity-3/2 states.

Biafas' result means that the decuplet resonance decay distribution is simply $\sin^2(\theta)$ with respect to the production normal. We have not looked at this distribution, but we can transform to the Jackson frame. Ignoring the θ - ϕ correlation, the prediction becomes $W(\theta) = (1 + \cos^2\theta)$ and $W(\phi) = (2 + \cos(2\phi))$. As noted above, the only decay distribution in which we have any confidence is that for reaction (3), Ξ^{*-} production; unfortunately the number of events is very small. As seen in Fig. 3.99 (solid curves), the decay cosine distribution is consistent with $(1+\cos^2\theta)$, (which is also the prediction of $J^P=0^+$ exchange), but

the azimuthal distributions do not appear to follow Biafas' predictions.

As we noted in Ref. 92, in terms of an s-channel mechanism the octet-decuplet difference might result from some unknown symmetries among the couplings of the higher-mass N^* , Δ , and Y^* resonances with the produced baryons, leading to constructive interference in the forward direction only in certain reactions. We note that reaction (1) cannot be explained by the $\Delta(1950)$, which fits reaction (15) so well. The branching fractions for the $\Delta(1950)$ into Y^*K and ΣK are quite close (1.4% and $\approx 2\%$ respectively); however, the forward cross section is several times larger for Y^* production. More significantly, Y^* production seems to be falling off much less rapidly than Σ production (roughly s^{-4} vs s^{-9}).

Another possible explanation that we noted in Ref. 92 is that the required exotic mesons exist and couple more strongly to the decuplet than to the octet baryons. Recall (Section 3.34) that the exotic mesons required for exchange in reactions (1) through (6) are included in the 27 and 35 representations of $SU(3)$, but not in the 10 . Note the following $SU(3)$ expansions:

$$B\bar{B} = M\bar{M} = 8 \otimes 8 = 1 + 8 + 8 + 10 + 10^* + 27$$

$$D\bar{B} = 10 \otimes 8 = 8 + 10 + 27 + 35$$

Thus, in the exact- $SU(3)$ limit, a member of the 35 would couple to $D\bar{B}$ but not to $B\bar{B}$ or $M\bar{M}$. Therefore, the reactions involving 35 exchange would be forbidden by $SU(3)$ coupling at both vertices for octet-baryon production, but only at one vertex for decuplet production. This presumably would give a greater cross section in the latter case, other things being equal. However, since the quark-antiquark pair $q\bar{q}$ contains only 1 and 8 , we see from the above expansions that the 35 is not found in $q\bar{q}$, but would require the very exotic $qqq\bar{q}\bar{q}$ state; that makes this argument very implausible. (We have presented it here mainly because it was mentioned in our published Letter.)

Rosner has noted that the ratio of $SU(6)$ couplings with an exchanged exotic meson is $4\sqrt{2}$ for $(\pi^- p \rightarrow K^+ Y^{*-}) / (\pi^- p \rightarrow K^+ \Sigma^-)$. 171

In terms of kinematic-reflection explanations, the relevant difference is that the decuplet-production reactions are observed in 3-particle final states, while octet production is studied in 2-particle final states, where no such mechanism can occur.

As noted in Section 3.33, Henyey et al. found strong spin-dependent effects in their double-particle-exchange calculations. They did not discuss any decuplet-production reactions, but did note that they were studying additional

cases. The possibility that this difference might be easily understood in terms of the spin properties is especially intriguing.

3.4 SUMMARY

[Please refer to previous sections for the arguments, assumptions, and qualifications behind the results summarized here, for explanation of the figures and tables, and for other details.]

A basic prediction of the one-particle-exchange model is the absence of forward peaks when the t-channel is exotic - that is, when the t-channel quantum numbers forbid the exchange of one of the known singlet or octet mesons. The absence of forbidden forward peaking in octet-baryon-production reactions was noted as weak evidence against the existence of exotic mesons.

We have studied most of the accessible one-meson-exchange forbidden reactions where a $3/2^+$ baryon is produced:

$$\pi^- p \rightarrow K^+ Y^{*-} \quad (1)$$

$$K^- p \rightarrow \pi^+ Y^{*-} \quad (2)$$

$$K^- p \rightarrow K^+ \Xi^{*-} \quad (3)$$

$$K^- p \rightarrow K^0 \Xi^{*0} \quad (4)$$

$$\pi^- p \rightarrow \pi^+ \Delta^- \quad (6)$$

[We denote each of these reactions by $bN \rightarrow MB^*$.] We have examined each of them in the 3-body final state $MB\pi$, resulting from the decay $B^* \rightarrow B\pi$.

Reactions (1) and (6) have also been examined in the charge-symmetric π^+d reactions with a spectator proton. Data from several exposures of the Berkeley 72-inch bubble chamber has been examined; the beam momenta range from 2 to 4 GeV/c. Table 3.1 gives the number of events in each data sample. We have combined the charge-symmetric states, and the two $(\Xi\pi)^-$ states.

We see forbidden forward peaking in all but Ξ^{*0} production. The production angular distributions are summarized in Fig. 3.13-3.14 and Table 3.12. The shape of the distribution was obtained variously from maximum-likelihood fits for the number of B^* events in each interval of $\cos \theta_{pr}$, from cuts on $B\pi$ mass, and from estimates of the number of B^* events in the $m(B\pi)$ spectra. Each distribution was normalized to the cross section for B^* production, obtained as described in Section 3.22.

Key features of the data are apparent in plots of $\cos \theta_{pr}$ vs $m(B\pi)$ and in Dalitz plots for the forward production region (Fig. 3.1-3.12). Forward B^* production is not concentrated in the region of overlap with M^{**} production (i.e., K^* and p). Most of the final states (except for Ξ^* production) are dominated by

peripheral production of the dimeson ($M\pi$) system. This results in a low-mass enhancement in $m(B\pi)$, as we confirmed by a Monte-Carlo simulation. Where this kinematic reflection is strong, primarily in the $N\pi\pi$ final states, forward Δ production is obscured. However, we can see forward Δ production quite clearly if we exclude the extreme forward direction (Fig. 3.17).

For each of the samples, we present Dalitz plots for various production intervals (Fig. 3.18⁺, 3.30⁺, 3.54(a)⁺) and B^* decay distributions (Fig. 3.66⁺). The slopes in momentum transfer (Fig. 3.78) are estimated to range from 2 to 5 $(\text{GeV}/c)^{-2}$.

Figures 3.83-3.84 confirm that the forbidden peaking is not associated with ambiguous (i.e., contaminated) events, with any single topology of the $AK^0\pi^+$ final state in $\pi^+n \rightarrow K^0Y^{*+}$, or with invisible or high-momentum spectator protons.

We have surveyed recent experimental and theoretical studies of exotic exchange. Although different explanations may apply to our several reactions, they are simply related in SU(3); although the cross sections vary greatly, similar variations have been reconciled to SU(3) by Trilling. Although the energies are low, a dual interpretation (in which both exchange and direct-channel models describe the data simply) may be relevant.

We have given special attention to Berger's claim that these peaks reflect not exotic exchange but a kinematic reflection - that is, the enhancement at low $m(B\pi)$ caused by peripheral $M\pi$ production. Berger's model may be considered as the promotion to high energy of low-energy scattering in a reaction which is exotic in the t channel; at the low energies involved it proceeds via s -channel resonances. Since final-state rescattering is invoked to narrow the peak, this model is (as Berger has noted) equivalent to a two-meson-exchange diagram and is not strictly kinematic. We note that, contrary to Berger's prediction, the Δ production which we see is *less* peripheral than the kinematic enhancement.

Berger has extended his model to describe $pn \rightarrow \Delta^-\Delta^{++}$ at 7 GeV/c. Here $\pi^-p \rightarrow \pi^+\Delta^-$ is promoted to high total energy, but the forward peaking in this component reaction itself may come from some mechanism other than kinematic enhancement. That is, Berger's success here is not additional evidence in favor of his description of our data. In addition, the four-body nature of the $\Delta\Delta$ final state reduces the problem of narrowing the enhancement via rescattering.

Sivers and Von Hippel have proposed a final-state-interaction model in which events are removed from the B^*M^* overlap region of the forward-production Dalitz plot to form a B^* band away from the M^* , but with no

B^* peak in the overall $m(B\pi)$ spectrum. Above 3 GeV/c, we do see some depletion of the B^*M^* region, but there is B^* in the total spectrum. Thus, this model may be relevant to our data, but cannot explain all of it.

The most promising source of an explanation of forbidden peaking seems to be two-particle exchange. Recent studies by Harari and by Henyey *et al.* have predicted strong double-particle exchange effects in some reactions. They have been observed in non-forbidden reactions, and their smallness in exotic exchange reactions may be understood. We also comment on the older double-particle-exchange model of Singh and Agarwal, which they applied to our data.

Crennell *et al.* have studied $\pi^-p \rightarrow K^+\Sigma^-$; they have noted that with available information on the t -dependence and the energy dependence (which they extracted from their data and ours), it is not possible to distinguish two-meson exchange from one-meson exchange. It is possible that exotic mesons exist and are exchanged in our reactions, although they have not been observed.

It is quite unlikely that the observed forward peaks are the tails of baryon exchange; except at our lowest energies, the forward region is quite far from the baryon-exchange poles. Ξ^{*0} production, where we see no forward peaking, has been studied in terms of baryon exchange.

Our energies are low enough for s -channel effects to be significant. They are not dominant, since other features of our final states (backward peaking, production of other resonances) can be described in exchange terms. A single resonance (the simplest s -channel model) would give forward-backward symmetry in $\cos \theta_{pr}$, and would also decay with the same distribution into other charge states of B^*M . Since our forward and backward peaks are comparable in size, and the s -channel resonances in this region are not well known, an s -channel model could probably be made to fit.

The presence of forward peaking in Ξ^{*-} but not Ξ^{*0} production can be understood in any of the above dynamic models, if interfering amplitudes are invoked. However, a purely kinematic explanation will not produce this difference.

In contrast to the reactions we report on, production of $1/2^+$ baryons in OME-forbidden reactions has small or nonexistent forward peaking, with rapid energy variation. S -channel effects appear dominant. Our low-statistics decay distribution for forward-produced Ξ^{*-} (Fig. 3.99) does not favor the prediction of Blafas, based on the weakness of forbidden octet-baryon production. Although the $\Delta(1950)$ seems to dominate $\pi^-p \rightarrow K^+\Sigma^-$, that is not the case for $\pi^-p \rightarrow$

K^+Y^{*-} ; an s-channel explanation of the decuplet-octet difference would require symmetries among the couplings of several resonances. It may be that the required exotic mesons couple more strongly to the decuplet than to the octet. Since Henyey *et al.* found strong spin-dependent effects in their study of two-meson exchange, there is a strong possibility that the difference might be understood in those terms.

APPENDIX D

DATA FOR THE REACTIONS $\pi^+d \rightarrow (p)\Lambda K^+\pi^0$ AND $\pi^+d \rightarrow (n)\Lambda K^+\pi^+$

In Section 3.36, we considered the possibility of an s-channel description of the OME-forbidden reaction $\pi^-p \rightarrow K^+Y^{*-}$ (Reaction 1p). We noted that a direct-channel resonance would show up, via a second decay mode, in $\pi^-p \rightarrow K^0Y^{*0}$ (Reaction 25p). We also noted that up to 2.4 GeV/c, the reaction $\pi^+p \rightarrow K^+Y^{*+}$ (Reaction 30) can be described by a simple exchange model.

The production distributions for these two reactions were presented in Figs. 3.100 and 3.102. Here we tabulate the results of the fits from which we obtained those distributions, and show some plots to summarize our data.

Table D.1 gives the number of events at each of the 3 beam momenta (2, 3, and 4 GeV/c). (Note that for Reaction (25) at 2 GeV/c, we have not used the data from Pi66B.) From the cross sections found in Pi63¹⁷² and in this experiment,¹⁷³ we have calculated the factor for conversion of the production distributions to $d\sigma/d\Omega$.

Like for Reaction (1), we did a maximum-likelihood fit to the final state using noninterfering resonances with fixed masses and widths. The results are given in Tables D.2 and D.3, for Reactions (25) and (30) respectively. (Compare Table 3.4 for Reaction 1.)

The data for $\pi^-p \rightarrow K^0\pi^0\Lambda$ (and for its charge-symmetric counterpart, $\pi^+n \rightarrow K^+\pi^0\Lambda$) is shown in Figs. D.1 through D.3. We present the Chew-Low-like plot corresponding to Y^{*0} production [(a)], the overall Dalitz plot [(d)], and the overall $m(\Lambda\pi)$ spectrum [(c)]. The forward Dalitz plot is also shown [(b)], although (since Y^* production in this region is OME-allowed) it is of no great interest. At the higher momenta, strong K^* production, as well as Y^* production, is present.

In Figs. D.4 through D.6, we present the same information for $\pi^+p \rightarrow K^+\pi^+\Lambda$. Here, of course, no K^* can be produced.

P _{beam} (GeV/c)	Expo- sure	Events		$\sigma(\Lambda K\pi)$ (μb)	$\sigma(Y^*K)$ (Note) (μb) (e)	K [$\equiv 1$] ($\mu\text{b}/\text{sr}/(\text{ev}/\text{bin})$) (f)
		Raw	Cut			
		N	N	$\Sigma(Wt)$		
$\pi^- p \rightarrow \Lambda K^0 \pi^0$ (and $\pi^+ n \rightarrow \Lambda K^+ \pi^0$):						
≈ 2	$\pi^- p$	554	466	481.8	132.1 $\pm$ 7.6	(a) 58.3 $\pm$ 7.1
≈ 3	$\pi^+ d$	862	572	646.1	99.4 $\pm$ 7.9	(b)
"	"	306	257	247.3	94.3 $\pm$ 8.3	(a)
"	Both	1168	829	893.4	97.0 $\pm$ 5.7	(c) 22.7 $\pm$ 2.6
≈ 4	$\pi^+ d$	458	336	385.1	90.8 $\pm$ 12.2	(b)
"	"	94	84	91.4	78.1 $\pm$ 14.2	(a)
"	Both	552	420	476.5	85.4 $\pm$ 9.3	(c) 12.8 $\pm$ 2.7
$\pi^+ p \rightarrow \Lambda K^+ \pi^+$:						
≈ 2	$\pi^+ d$	453	321	357.6	109.8 $\pm$ 12.4	(d) 70.3 $\pm$ 9.4
≈ 3	$\pi^+ d$	708	469	522.9	79.5 $\pm$ 6.5	(b) 25.5 $\pm$ 3.1
≈ 4	$\pi^+ d$	427	271	303.5	65.8 $\pm$ 9.1	(b) 13.0 $\pm$ 2.7

Table D.1 (Page 1)

Notes:

- (a) From Ref. 150, Table 7. These values are the averages of 4 points at 1.94 to 2.14 GeV/c, 5 points at 2.61 to 3.21 GeV/c, and 2 points around 4 GeV/c. At 2 and 4 GeV/c, $d\sigma$ has been scaled up by $\sqrt{[X^2/(N-1)]}$.
- (b) From Ch. 2 of this report (Ref. 106); systematic errors have not been folded in.
- (c) Weighted average of the two preceding values.
- (d) From Ref. 108, Table 2; weighted average of the 4 highest-momentum points.
- (e) $\sigma(Y^*K) = f(Y^*) \times \sigma(\Lambda K\pi) / R$, where f is the Y^* fraction from the fit at all angles (see Tables D.2 and D.3), and R is 0.89, the $\Lambda\pi$ branching fraction for the $Y^*(1385)$.
- (f) Scale conversion factor from events/bin in Figs. 3.100 and 3.102 to $d\sigma/d\Omega$. $K = \sigma(Y^*K)/[N(Y^*)(4\pi/6)]$, where $N(Y^*)$ is the number of events in each Figure ("Sum" in Tables D.2 and D.3) and 6 is the number of bins.

Event Tally and Cross Sections for the Allowed Y^* Production Reactions

Table D.1 (Page 2)

Cos θ	Events	Resonance Fractions (%)			Number of	
Bin ^(a)	N	ΣWt	Υ^*	$K^*(890)$	$K^*(1420)$	Υ^* Events
			(m, Γ)=(1385,38)	(892,49.2)	(1440,80)	[MeV]

P $\approx$ 2 GeV/c:

1	44	46.7	37.1 ± 17.6	31.8 ± 19.8	-	17.3 ± 8.6
2	37	39.5	30.7 ± 13.4	56.3 ± 17.4	-	12.1 ± 5.6
3	46	49.6	35.6 ± 15.5	5.2 ± 15.6	-	17.7 ± 8.1
4	88	92.1	26.6 ± 10.3	24.8 ± 11.7	-	24.5 ± 9.8
5	119	118.9	42.1 ± 9.3	12.4 ± 9.2	-	50.1 ± 11.9
6	132	135.0	48.2 ± 7.7	19.6 ± 8.5	-	65.1 ± 11.8
All	466	481.8	39.3 ± 4.2	21.6 ± 4.6	-	[Sum=186.8]

P $\approx$ 3 GeV/c:

1	89	94.2	9.2 ± 4.8	6.9 ± 7.1	-	8.6 ± 4.6
2	52	54.7	-9.6 ± 5.1	11.0 ± 8.6	-	-5.3 ± 2.9
3	69	74.2	4.3 ± 4.4	8.2 ± 6.7	-	3.2 ± 3.3
4	89	100.2	2.8 ± 4.2	13.7 ± 7.3	-	2.8 ± 4.2
5	149	159.3	13.1 ± 4.3	35.5 ± 6.4	-	20.9 ± 7.1
6	381	410.9	42.7 ± 3.6	21.8 ± 3.3	-	175.5 ± 17.3
All	829	893.4	20.8 ± 2.0	20.5 ± 2.3	-	[Sum=205.7]

P $\approx$ 4 GeV/c:

1	55	59.5	7.5 ± 6.8	-0.5 ± 4.2	8.0 ± 11.4	4.5 ± 4.1
2	27	29.5	No fit obtained; Estimate:			0 ± 1
3	30	35.7	-0.3 ± 7.0	10.3 ± 7.4	35.1 ± 14.0	-0.1 ± 2.5
4	42	48.1	-15.7 ± 3.2	-0.4 ± 5.5	-11.6 ± 6.1	-7.5 ± 1.9
5	55	62.8	3.9 ± 4.5	20.0 ± 7.8	8.3 ± 7.5	2.4 ± 2.8
6	211	241.0	28.2 ± 4.4	24.7 ± 4.4	-2.4 ± 2.9	68.0 ± 11.5
All	420	476.5	13.4 ± 2.4	15.1 ± 2.6	1.9 ± 2.6	[Sum= 67.3]

(a) Each bin covers an interval of 0.33 in $\cos \theta_{pr} \equiv (\hat{\pi}^- \cdot \hat{R}^0)$; bin 1 is $-1 < \cos \theta_{pr} < -2/3$.

Resonance-Production Fits in $\pi^-p \rightarrow K^0\pi^0\Lambda$ (and $\pi^+n \rightarrow K^+\pi^0\Lambda$)

Table D.2

Cos θ Bin ^(a)	Events		Percentage of γ^* [(m, Γ)=(1385,38) MeV]	Number of γ^* Events
N	ΣWt			
P $\approx$ 2 GeV/c:				
1	46	50.0	62.4 ± 9.5	31.2 ± 6.5
2	50	54.6	48.8 ± 10.5	26.6 ± 6.8
3	49	55.1	34.7 ± 10.5	19.1 ± 6.3
4	40	45.6	54.0 ± 11.2	24.6 ± 6.3
5	78	86.8	63.0 ± 8.5	54.7 ± 9.4
6	58	65.6	75.9 ± 11.3	49.8 ± 9.6
All	321	357.6	57.0 ± 4.2	[Sum=206.0]
P $\approx$ 3 GeV/c:				
1	76	82.3	19.5 ± 6.4	16.0 ± 5.5
2	57	63.5	3.1 ± 4.9	2.0 ± 3.1
3	60	66.1	0.5 ± 3.9	0.3 ± 2.6
4	55	62.5	12.9 ± 6.7	8.0 ± 4.3
5	74	82.0	46.0 ± 7.2	37.7 ± 7.2
6	147	166.6	54.9 ± 5.2	91.4 ± 11.1
All	469	522.9	28.5 ± 2.7	[Sum=155.4]
P $\approx$ 4 GeV/c:				
1	45	49.5	-13.4 ± 2.5	-6.6 ± 1.6
2	35	38.2	No fit obtained; Estimate:	0 ± 1
3	25	28.0	8.9 ± 7.1	2.5 ± 2.0
4	25	28.6	No fit obtained; Estimate:	0 ± 1
5	40	44.2	13.2 ± 6.8	5.8 ± 3.1
6	101	115.0	50.2 ± 6.0	57.7 ± 8.8
All	271	303.5	17.6 ± 2.8	[Sum= 59.4]

(a) Each bin covers an interval of 0.33 in Cos θ_{pr} [$\equiv(\hat{\pi}^+ \cdot \hat{K}^+)$]; bin 1 is $-1 < \text{Cos } \theta_{pr} < -2/3$.

Resonance-Production Fits in $\pi^+p \rightarrow K^+\pi^+\Lambda$

Table D.3

Fig. D1

XBL 728-1375

Fig. D2

XBL 728-1376

Fig. D3

Fig. D4

XBL 728-1378

Fig. D5

XBL 728-1379

Fig. D6

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- 174-180. These numbers were not used.

FIGURE AND TABLE CAPTIONS

Note: "Fig. 3.n⁺" denotes Fig. 3.n through Fig. 3.(n+11), corresponding respectively to Sample (1) through Sample (12) of our data for various exotic-exchange reactions of the form $bN \rightarrow MB^* \rightarrow M\pi B$. See Table 3.1 for specification of these samples.

Fig. 3.1⁺ [Fig. 3.1 through 3.12] (Pp. 8-19)
(a): Chew-Low-like plot [$m(B\pi)$ vs $\cos \theta_{\text{prod}}$]; (b): Dalitz plot for forward-produced events; (c): B^* production distribution, obtained from a mass cut and background subtraction.

Fig. 3.13 and 3.14 (Pp. 21-22)
Production distributions ($d\sigma/d\Omega$), obtained as indicated in the text.

Fig. 3.15 (Pp. 24-25)
Effective center-of-mass energy (excluding the spectator, if any) for each sample.

Fig. 3.16 (Pp. 26-27)
C.m. energy distributions, separately for π^-p data, π^+n even-pronged events, and π^+n odd-pronged events.

Fig. 3.17 (Page 47)
For the reaction $\pi^+n \rightarrow \pi^- \pi^+ p$ [$\pi^- p \rightarrow \pi^+ \pi^- n$], $m(p\pi^+)$ [$m(n\pi^-)$] in the forward and nearly-forward intervals of production cosine. Shaded histograms: ρ^0 band removed.

Fig. 3.18⁺ [Fig. 3.18 through 3.29] (Pp. 55-66)
Dalitz plot of forward-produced events, and the projected mass spectra.

Fig. 3.30⁺ [Fig. 3.30 through 3.41] (Pp. 67-78)
Dalitz plots for (a): the central region of production cosine; (b): backward production; (c): all $\cos \theta_{\text{prod}}$; (d): $m(B\pi)$ for all $\cos \theta_{\text{prod}}$.

Fig. 3.42⁺ [Fig. 3.42 through 3.53] (Pp. 79-90)

B^* production distributions, obtained by a cut on $B\pi$ mass, with additional successive cuts as described in the text.

Fig. 3.54⁺ [Fig. 3.54 through 3.65] (Pp. 91-102)

(a)-(b): Dalitz plot for the not-quite-forward region of production cosine and its $m(B\pi)$ projection; (c)-(d): $m(B\pi)$ for forward-produced events, respectively outside and inside the $M^* \rightarrow M\pi$ band.

Fig. 3.66⁺ [Fig. 3.66 through 3.77] (Pp. 103-114)

Decay cosine and azimuth, in the Jackson meson-exchange frame, for forward-produced events in the B^* band.

Fig. 3.78 (Page 115)

Distributions in momentum transfer for selected samples. See text.

Fig. 3.79 (Page 117)

Production distributions as a function of c.m. energy.

Fig. 3.80 (Page 119)

(a): Energy dependence of the integrated forward cross section for $\pi^-p \rightarrow K^+\bar{Y}^{*-}$; (b): the backward cross section for this reaction; (c): the octet-baryon-production reaction corresponding to (a). This figure is from Crennell et al., Ref. 96; the 3 lowest-energy points are from our data.

Fig. 3.81 (Page 122)

Chew-Low-like plot corresponding to Δ^- production, for fake events generated as $\pi^-p \rightarrow p^0n$ with an $\exp(-8|t|(\text{GeV}/c)^{-2})$ distribution. See text.

Fig. 3.82 (Page 123)

Chew-Low-like plots, and their mass projections, corresponding to each of the three momentum transfers in $\pi^-p \rightarrow \pi^+\pi^-n$ at 2.2 GeV/c.

Fig. 3.83 (Page 125)

Chew-Low like plots for $\pi^+n \rightarrow K^0\pi^+\Lambda$, separately according to the secondary decay(s), and for the charge-symmetric reaction.

Fig. 3.84 (Page 126)

Chew-Low-like plots for $\pi^+n \rightarrow K^0\pi^+\Lambda$, (a): for the highly-constrained 2-vee sample at 4 GeV/c; (c) and (d): for unambiguous and ambiguous events respectively. (b): Production distribution as a function of spectator momentum for Δ^{++} production.

Fig. 3.85 through 3.94 (Pp. 128-137)

For each of the 10 pairs of subsamples listed in Table 3.2, the same distributions as in Fig. 3.1⁺: (a,b): Chew-Low-like plot; (c,d): forward Dalitz plot; (e,f): production cosine distribution.

Fig. 3.95 (Page 139)

Cross sections for 4 OME-forbidden reactions. These figures are from Ref. 124; our results are not included. The curves are from Trilling's prescription for the SU(3) comparison of these reactions. (The curves in (b) come from the one in (a); the data is the same in both graphs.)

Fig. 3.96 (Page 141)

Basic diagram for Berger's kinematic reflection model.

Fig. 3.97 (Page 141)

Schematic representation of the relation between Berger's reflection model and two-meson exchange.

Fig. 3.98 (Page 146)

Kinematic-reflection-model diagrams for $pn \rightarrow \Delta^-\Delta^{++} \rightarrow pn\pi^+\pi^-$.

Fig. 3.99 (Page 153)

Folded decay distributions for forward-produced Ξ^{*-} events in the Jackson frame, with the predictions of $J^P=0^+$ meson exchange (solid lines in (a,b); dotted lines in (c,d)) and of Biaľas' quark model (solid lines).

Fig. 3.100 (Page 158)

Production distributions for the non-forbidden reaction $\pi^- p \rightarrow K^0 \gamma^* \pi^0$.

Fig. 3.101 (Page 160)

Production distributions for the non-forbidden reaction $K^- p \rightarrow \pi^- \gamma^* \pi^+$.

Fig. 3.102 (Page 162)

Production distributions for the non-forbidden reaction $\pi^+ p \rightarrow K^+ \gamma^* \pi^+$.

Fig. 3.103 (Page 164)

Two-meson-exchange diagrams for Ξ^* production.

Fig. 3.104 (Page 164)

Kinematic-reflection diagrams for Ξ^* production.

Fig. D1 (Page 179)

For the non-forbidden reaction $\pi^- p \rightarrow \Lambda K^0 \pi^+$ at $P \approx 2$ GeV/c, (a): Chew-Low-like plot corresponding to $\gamma^* \pi^0$ production; (b): Dalitz plot of the forward-produced events; (c)-(d): $m(\Lambda \pi^0)$ and the Dalitz plot for all production angles.

Fig. D2 and D3 (Pp. 180-181)

Same as Fig. D1, except at $P \approx 3$ and $P \approx 4$ GeV/c respectively; data for the charge-symmetric reaction is included.

Fig. D4 through D6 (Pp. 182-184)

For the non-forbidden reaction $\pi^+ p \rightarrow \Lambda K^+ \pi^+$, respectively at $P \approx 2$, ≈ 3 , and ≈ 4 GeV/c, (a): Chew-Low-like plot corresponding to $\gamma^* \pi^+$ production; (b): Dalitz plot of the forward-produced events; (c-d): $m(\Lambda \pi^+)$ and the Dalitz plot for all production angles.

Table 3.1 (Page 7)

Number of Events in Samples 1 Through 12 (Raw Data)

Table 3.2	(Page 29)
Number of Events in Subsamples (Raw Data)	
Table 3.3	(Page 29)
Parameters Used for Resonance Band Definition	
Table 3.4	(Page 32)
Resonance-Production Fits in $\pi^-p \rightarrow K^+\pi^-\Lambda$ (and $\pi^+n \rightarrow K^0\pi^+\Lambda$)	
Table 3.5	(Page 33)
γ^* Fraction in Fits with Modifications	
Table 3.6	(Page 35)
Production Distributions for $\pi^-p \rightarrow K^+\gamma^*{}^-$ (and $\pi^+n \rightarrow K^0\gamma^*{}^+$)	
Table 3.7	(Pp. 36-37)
Cross-Section Estimates for $\pi^+n \rightarrow K^0\gamma^*{}^+$ (or $\pi^-p \rightarrow K^+\gamma^*{}^-$)	
Table 3.8	(Page 39)
Production Distributions for $K^-p \rightarrow \pi^+\gamma^*{}^-$	
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Production Distributions for $K^-p \rightarrow K^+\Xi^*{}^-$	
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Production Distributions for $K^-p \rightarrow K^0\Xi^*{}^0$	
Table 3.11	(Page 46)
Production Distributions for $\pi^-p \rightarrow \pi^+\Delta^-$ (and $\pi^+n \rightarrow \pi^-\Delta^+{}^+$)	
Table 3.12	(Page 49)
Summary of Forward Cross Sections	
Table 3.13	(Page 116)
Slopes in Momentum Transfer	

Table 3.14

(Page 120)

Tallies for Histograms of Samples 1 through 12

Table D.1

(Pp. 175-176)

Event Tally and Cross Sections for the Allowed Y^* Production Reactions

Table D.2

(Page 177)

Resonance-Production Fits in $\pi^-p \rightarrow K^0\pi^0\Lambda$ (and $\pi^+n \rightarrow K^+\pi^0\Lambda$)

Table D.3

(Page 178)

Resonance-Production Fits in $\pi^+p \rightarrow K^+\pi^+\Lambda$