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Authors
Dauber, Philip N.
Hoch, Paul
Manning, Robert J.
et al.

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LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

OBSERVATION OF FORWARD PEAKS IN SINGLE-MESON-EXCHANGE FORBIDDEN REACTIONS[*]

Philip M. Dauber, Paul Hoch, Robert J. Manning,
and Daniel M. Siegel[†]

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

and

Maris A. Abolins and Gerald A. Smith

Department of Physics
Michigan State University
East Lansing, Michigan 48823

June 2, 1969

ABSTRACT

We have observed forward peaks of 2 to 150 μb/sr in the differential cross section in Δ (1236), Y^* (1385), and Ξ^* (1530) production reactions which can proceed by single-meson exchange only if $I \geq 3/2$ or $|S| = 2$ mesons exist. The data are in the beam momentum range from 1.8 to 4.2 GeV/c. Interpretations involving interference among s-channel resonances or two-meson exchange are not ruled out.

Several authors[1] have pointed out that forward (meson exchange) peaks in production angular distributions are absent or small (< 1 μb/sr) when charge or strangeness 2 is required in the t channel. Mesons with $I \geq 3/2$ or $|S| \geq 2$ cannot be made out of a quark-antiquark pair; they have not been observed to date.[1] We have observed forward peaks of 2 to 150 μb/sr in four "single-meson-exchange forbidden" reactions which require $I \geq 3/2$ or $|S| = 2$ in the t channel.

The reactions studied were

$\pi^+ n \to \pi^- \Delta^{++}(1236)$ with $S = 0$, $I = 2$, (1)
$\pi^- p \to K^+ Y^{*-}(1385)$ with $S = 1$, $I = 3/2$, (2a)
$\pi^+ n \to K^0 Y^{*+}(1385)$ with $S = 1$, $I = 3/2$, (2b)
$K^- p \to \pi^+ Y^{*-}(1385)$ with $S = 1$, $I = 3/2$, (3)
$K^- p \to K^+ \Xi^{*-}(1530)$ with $S = 2$, $I = 1$, (4b)
$K^- p \to K^0 \Xi^{*0}(1530)$ with $S = 2$, $I = 0$, (4b)

where the values of S and I are respectively the magnitude of strangeness and the lowest isospin in the t channel. Reactions (2a) and (2b) were considered together, since they are charge-symmetric. Except for $\pi^- p \to \pi^+ \Delta^-$ (which is charge-symmetric with reaction 1) and $K^- n \to K^0 \Xi^{*-}$ (which we are studying now), reactions (1) through (4) exhaust the accessible "single-meson-exchange forbidden" reactions of the type 0^- meson + nucleon → 0^- meson + $3/2^+$ decuplet baryon. The common view that no exotic mesons are needed as t-channel mediators is based mainly on the absence of forward peaks in <u>octet</u> production reactions such as $\pi^- p \to K^+ \Sigma^-$, $K^- p \to \pi^+ \Sigma^-$, and $K^- p \to K^+ \Xi^-$.[2] We summarize the data on these reactions later in this paper.

Our data were obtained in exposures of the Berkeley 72-inch bubble chamber to π and K^- beams at momenta of 1.8 to 4.2 GeV/c. The c.m. energies span a region that is densely populated by πN and $\overline{K}N$ resonances. Thus, interfering s-channel resonances with decay modes (not yet established) into channels (1) through (4) can in principle explain the forward peaks. This possibility cannot be ruled out by the data.

Some of the data presented here have been previously reported.[3-5] The data are grouped into beam momentum intervals consisting, in general, of several beam momentum settings. For reaction (2 a, b) the intervals are 1.8 to 2.4 GeV/c, 2.8 to 3.3 GeV/c, and 3.8 to 4.2 GeV/c (labeled 2, 3, and 4 GeV/c). The K^- data were obtained in a run at 2.1 GeV/c and in runs at 2.4 to 2.75 GeV/c (labeled 2.6 GeV/c). The path length was 52 events/μb for pions and 21 events/μb for kaons.

The final states analyzed were

$$\pi^+ d \to (p)\, \pi^- \pi^+ p \qquad \text{for reaction (1),}$$

$$\left.\begin{array}{l} \pi^- p \to K^+ \pi^- \Lambda \\ \pi^+ d \to (p)\, K^0 \pi^+ \Lambda \end{array}\right\} \qquad \text{for reaction (2),}$$

$$K^- p \to \pi^+ \pi^- \Lambda \qquad \text{for reaction (3),}$$

$$\left.\begin{array}{l} K^- p \to K^+ \pi^0 \Xi^- \\ K^- p \to K^+ \pi^- \Xi^0 \end{array}\right\} \qquad \text{for reaction (4a),}$$

$$K^- p \to K^0 \pi^+ \Xi^- \qquad \text{for reaction (4b).}$$

For the πd data only events with a spectator proton, (p), were used; the requirement was proton lab momentum < 300 MeV/c. Details of the separation of these final states are presented elsewhere.[3-5]

Figure 1 shows the essential features of the data in typical scatter plots of the cosine of the c. m. meson production angle versus the mass of the outgoing baryon-pion system. A resonance band is observed in each reaction. There is a striking clustering of events in the forward direction within each band.

The broad forward cluster in fig. 1a is partly a kinematic reflection of the fact that the ππ system is produced peripherally. According to Monte Carlo calculations, for the $\cos\theta \equiv \pi^+_{in} \cdot \pi^- > 0.9$ bin the peripherality gives rise to an enhancement in $p\pi^+$ mass that is centered just above the Δ^{++} mass and is several times as wide as the Δ. For $0.8 < \cos\theta < 0.9$, the enhancement is broader and lies significantly higher in $p\pi^+$ mass. The $p\pi^+$ mass spectra in these intervals (fig. 2a, b) show a narrow Δ^{++} peak above the low-mass enhancement.

The Dalitz plot for $\cos\theta > 0.8$ shows that $\approx$ 40% of the events in the forward cluster cannot be confused with ρ. The Δ^{++} peak is relatively enhanced when events in a broad ρ band are removed (shaded histograms).

The Δ^{++} production distribution is given in fig. 2c. The number of Δ events in each $\cos\theta$ interval was estimated by using a hand-drawn background curve (as in fig. 2a, b). The anisotropy of ρ decay and the possibility of ρ-Δ interference add to the uncertainty of this procedure. However, there is little doubt that there is substantial forward Δ^{++} production. We have also analyzed the unpublished data of L. Jacobs[6] on $\pi^-p \rightarrow \pi^+\pi^-n$ from 2.05 to 3.22 GeV/c and have found Δ^- production distributions consistent with fig. 2c at the lower momenta, but with a forward peak that is $\approx$ 30% smaller and somewhat sharper at the higher momenta.

Maximum-likelihood fits to the Dalitz plots have been carried out for the final states fed by reactions (2) and (3). The fits assume a phase-space background and Breit-Wigner amplitudes for the several resonances observed in each final state. The Y^* production angular distributions shown in fig. 2 d–f and 3 a, b were obtained by using this method to determine the number of Y^* events in each angular interval separately. This model does not take into account the distortion of phase space associated with the rather strong and peripheral production of the competing reactions. This effect is less pronounced here than in reaction (1), and (because of the relatively small Y^* width) does not obscure the resonance production as much. To correct for this effect, we have reduced the forward bin in figs. 2 d and 3 a by ≈ 25%. The model also does not take interference effects into account; no obvious interference is apparent in the Dalitz plots.

No background subtraction has been performed for the Ξ^* distributions of fig. 3 c-f; the events were selected by $\Xi\pi$ mass. As indicated by fig. 1 d, the background under the forward peak in Ξ^* production is very small ($\lesssim$ 10%).

Forward peaks are present in all the differential cross sections shown except those for Ξ^{*0} production. It is highly unlikely that final-state contamination can account for any of these peaks.[7] Extensive study of plots such as fig. 1 and Dalitz plots for various cos θ intervals (not shown) has convinced us that the forward peaks are not due to peripheral enhancement of phase space, overlapping resonance bands, or nonresonant background.

The uncertainties in the normalization of the cross sections in figs. 2 and 3 are estimated to be $\lesssim$ 20%. For reactions (2) through (4), the errors shown are statistical only. We wish to emphasize that although the exact shape of the production angular distributions shown is subject to some uncertainty because of the complexity of the final states (which, as described above, are not dominated by the reactions of interest), the existence of significant forward peaking in these single-meson-exchange forbidden reactions is well established.

The forward peaks are quite steep. In the forward direction, $d\sigma/dt$ (as roughly obtained by a mass cut and exclusion of events in other resonance bands) goes approximately as $\exp(-a|t-t_0|)$, with $3 \lesssim a \lesssim 5$. The peaks in analogous "single-meson-exchange allowed" reactions are 5 to 10 times as large as those presented here for Y^* production,[3,5] but within a factor of ≈ 2 for Δ production.[8] Reactions (1) through (4) can proceed by the exchange of known baryons; backward peaks comparable in size to the forward peaks are generally present.

The forward peaks may be interpreted in several ways, for example:

(1) Single-Meson Exchange. Mesons with the required quantum numbers may exist even though they have not been observed to date. An SU(3) 27-plet could accommodate the mesons needed to account for the peaks observed in reactions (1) through (4a). Exchange of an S = 2, I = 1 meson in Ξ^* production would lead to a ratio of 4 to 1 for the size of the forward peak in $K^- p \rightarrow K^+ \Xi^{*-}$ and $K^0 \Xi^{*0}$, consistent with the data at 2.6 GeV/c.

If the exchanged meson has $J^P = 0^+$ (0^- is ruled out by angular momentum and parity conservation), one might expect the Δ, Y^*, or Ξ^* to be produced in a pure $m = \pm 1/2$ state, resulting in a $1 + 3 \cos^2$ decay distribution in t-channel coordinates. The Ξ^{*-} data (see inserts, fig. 3 c, d) agree with the 0^+ hypothesis when events with production cosine greater than 0.7 are selected. The corresponding distributions of the Treiman-Yang angle (not shown) are flat within the limited statistics. For the other reactions the decay distributions are symmetric, but the background is too large to permit meaningful interpretation.

(2) Two-Meson Exchange. The forward peaks might arise from processes which are well represented by box diagrams with two distinct meson-exchange lines. In Ξ^* production, these lines could be K mesons; the meson vertices might be connected by a member of the 1^- meson octet (ρ, ω, or ϕ) and the baryon vertices by Λ or Σ^0. A model incorporating several box diagrams could conceivably account for our peaks, including the ratio of $\Xi^{*-} K^+$ to $\Xi^{*0} K^0$; we have not attempted a calculation.[9] Double quark scattering[10] may also provide a framework for understanding these peaks.

(3) Baryon Exchange. An "explanation" involving baryon exchange alone is conceivable,[11] but would require a very large change in the relative phases of several exchange amplitudes between small and large u. There would be nearly complete destructive interference at small u [possibly related to the dips in the extreme backward direction in reaction (4a, b)] and constructive interference at maximum u. In Regge-model terms this requires trajectories with radically different shapes.

(4) Resonance Formation. The higher-mass N^*'s and Y^*'s may couple to the quasi-two-body channels under discussion. It is possible to construct interference models involving many s-channel resonances, as well as possible baryon exchange, which could fit the data at all our momenta for each reaction. The presence of a forward peak in $K^+\Xi^{*-}$ and its absence in $K^0\Xi^{*0}$ could be explained by such a model as the result of interference between s-channel resonances of different isospin. A fit including many resonances would be meaningless at present; far more data (as well as much better knowledge of the resonance spectra) would be required to test such an interference model conclusively.

It is instructive to compare our results for reactions (1) through (4) with Σ and Ξ production reactions above 2 GeV/c. In $\pi^- p \rightarrow K^+\Sigma^-$ there is a broad backward peak with only a slight hint of a forward peak ($< 1\ \mu b$) at some momenta.[12] In $K^- p \rightarrow \pi^+\Sigma^-$ near 2 GeV/c there is a $\approx 50\ \mu b/sr$ forward peak[13] which shrinks rapidly with increasing energy to $\approx 5\ \mu b/sr$ at 3 GeV/c[14] and $< 2\ \mu b/sr$ above 3 GeV/c.[15, 16] In $K^- p \rightarrow K^+\Xi^-$ there is no evidence for a sharp forward peak (although there is substantial cross section in the forward hemisphere); at 2.6 GeV/c a 1 μb/sr upper limit can be set for a forward peak.[4] In $K^- p \rightarrow K^0\Xi^0$ at 2.1 GeV/c there is a 6 ± 2-μb/sr forward peak which shrinks to 1.5 ± 1.0 μb/sr at 2.6 GeV/c.[4] The peaks in $K^-p \rightarrow \pi^+\Sigma^-$ and $K^0\Xi^0$ appear to be associated with s-channel resonances; the variation with energy is extremely rapid.[4,13]

The present data on reactions (1) through (4) do not sample enough energies to rule out the rapid variation that one would associate with an s-channel mechanism. In any case, the contrast between $\pi^-p \rightarrow K^+\Sigma^-$ and K^+Y^{*-} (or $K^-p \rightarrow K^+\Xi^-$ and $K^+\Xi^{*-}$) is striking.[17] The consistent presence of a forward peak in reactions (1) through (4a) is remarkable if there is no meson-exchange-like mechanism. We speculate that either the required mesons exist (and couple more strongly to the baryon decuplet than to the octet)[18] or there are some unknown symmetries among the couplings of the higher-mass N^* and Y^* resonances with the decuplet and octet baryons which produce constructive interference in the forward direction only in certain reactions. Finally, we note that complicated exchange models and s-channel models need not be mutually exclusive, and that different explanations may apply to the various channels.

More data on reactions (1) through (4) would be useful, particularly above 4 GeV/c. A direct search for S = 2 mesons is under way at LRL using a large H_2 bubble chamber exposure of 12-GeV/c K^+. The possibility of a rarely produced, stable ($\tau \approx 10^{-8}$ sec) S = 2, I = 1 meson with a mass $< 2\,m_K$ is particularly intriguing.

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FOOTNOTES AND REFERENCES

[*] Work supported by the U. S. Atomic Energy Commission.

[†] Present address: Yale University, New Haven, Connecticut.

1. For recent reviews on the subject of mesons with $I \geq 3/2$ or $|S| = 2$ see the articles by A. H. Rosenfeld, in Meson Spectroscopy (W. A. Benjamin, Inc., New York, 1968), p. 455; and G. Goldhaber, in Proceedings of the Second Hawaii Topical Conference in Particle Physics, 1967 (University of Hawaii Press, Honolulu, 1968), p. 165.

2. The reactions $\bar{p}p \rightarrow \overline{\Sigma^-}\Sigma^-, \overline{\Xi^-}\Xi^-$ have cross sections of several μb at 3 to 4 GeV/c with some suggestion of forward peaking. See B. Musgrave et al., Nuovo Cimento 35 (1965) 735 and C. Baltay et al., Phys. Rev. 140B (1965) 1027.

3. M. A. Abolins, O. I. Dahl, J. Danburg, D. Davies, P. Hoch, D. H. Miller, R. Rader, and J. Kirz, Phys. Rev. Letters 22 (1969) 427.

4. P. M. Dauber, J. P. Berge, J. R. Hubbard, D. W. Merrill, and R. A. Muller, Phys. Rev. 179 (1969).

5. Daniel M. Siegel (Ph. D. Thesis), Lawrence Radiation Laboratory Report UCRL-18041, 1967 (unpublished).

6. L. D. Jacobs (Ph. D. Thesis), Lawrence Radiation Laboratory Report UCRL-16877, 1966 (unpublished). At 4 GeV/c [(Aachen-Birmingham-Bonn-Hamburg-London (I. C.)-München Collaboration, Nuovo Cimento 31 (1965) 729] there is a 90 ± 30-μb cross section for the reaction charge-symmetric to (1), $\pi^- p \rightarrow \pi^+ \Delta^-$, with about half the events peaked forward; the Δ^- peak is not clearly resolved.

7. The contamination in the $\pi^- p \rightarrow K^+ \pi^- \Lambda$, $K^- p \rightarrow \pi^+ \pi^- \Lambda$, $K^+ \pi^0 \Xi^-$, and $K^0 \pi^+ \Xi^-$ samples is believed to be $\leq 1\%$. The $\pi^+ d \rightarrow (p) \pi^- \pi^+ p$ sample is $< 5\%$

contaminated. The $\pi^+d \to (p) K^0 \pi^+ \Lambda$ and $K^-p \to K^+\pi^-\Xi^0$ samples are more heavily contaminated ($\lesssim$ 30%), but study of highly purified subsamples has shown that the results described here are not affected by this contamination. In addition, the results obtained from the charge-symmetric reactions (2a) and (2b) are consistent, as are those from the two different final states for reaction (4a). In reaction (1), the results were not changed by a more stringent momentum cutoff (150 MeV/c) on the slower proton, which eliminated almost all the contamination due to events with no spectator (impulse approximation not valid) or with ambiguity in the choice of the spectator.

8. Based on unpublished data for $\pi^+n \to \pi^+\Delta^0$ and on data presented in the compilation by I. Ohba and T. Kobayashi, Prog. Theor. Phys. Suppl. 41 (1967) 90.

9. Few calculations of such diagrams have been published; see, e. g., C. P. Singh and B. K. Agarwal, Phys. Rev. 177 (1969) 2350.

10. N. W. Dean, Nucl. Phys. B7 (1968) 311. The simple Glauber scattering model proposed by Dean explains neither the sharpness of the observed peaks nor the inequality of the Ξ^{*-} and Ξ^{*0} cross sections.

11. See J. T. Donohue (Ph. D. Thesis), University of Illinois, 1967 (unpublished). Donohue's calculation (one-particle exchange with absorption) yields a cross section due to Λ exchange which is substantial in the forward direction.

12. O. I. Dahl et al., Phys. Rev. 163 (1967) 1430.

13. P. M. Dauber et al., Phys. Letters 23 (1966) 154.

14. J. Badier et al., Possible Baryon Exchange Mechanism in 3-GeV/c K^-p Interactions, in Proceedings of the International Conference on Elementary Particles, Oxford, September 1965. See also the 2.24-GeV/c data of G. W. London et al., Phys. Rev. 143 (1966) 1034.

15. Data of the Amsterdam-Bologna-Ecole Polytechnique-Rehovoth-Saclay collaboration at 3.5 GeV/c presented by M. Derrick at the CERN Conference on Hadron Collisions at High Energy, January 1968, ANL/HEP 6802.

16. J. S. Loos, U. E. Kruse, and E. L. Goldwasser, Phys. Rev. 173 (1968) 1330.

17. Octet and decuplet production at the same c. m. energy may not be strictly comparable. If exchange mechanisms become important at a certain c. m. momentum, the corresponding beam momentum is somewhat higher ($\lesssim 1/2$ GeV/c) for production of the more massive decuplet baryons.

18. For example, in exact SU(3) a 35-plet of mesons would couple to the $10 \otimes 8$ baryon-antibaryon system, but not to the $8 \otimes 8$.

FIGURE CAPTIONS

Fig. 1. Cosine of the c. m. meson production angle versus the mass of the baryon-pion system in channels fed by "single-meson-exchange forbidden" reactions. Plots (a) through (d) correspond to reactions (1), (2a, b), (3), and (4a) of the text. No mass selections have been made.

Fig. 2. Effective mass of $p\pi^+$ in reaction (1) for (a) $\cos\theta \equiv \pi^+_{in} \cdot \pi^- > 0.9$; (b) $0.9 > \cos\theta > 0.8$. Shaded histograms have the ρ^0 band [$644 < m(\pi^+\pi^-) < 884$ MeV/c^2] excluded. The curves are hand-drawn estimates of background. Plots (c) - (f): Differential cross sections for reactions (1) and (2a, b). For reaction (2), the errors shown are statistical only. Background subtractions have been performed as described in the text.

Fig. 3. Differential cross sections for reactions (3), (4a), and (4b). The inserts in plots (c) and (d) show the Ξ^{*-} decay alignment with the target proton direction for events in the forward peak, $\hat{K}^- \cdot \hat{K}^+ > 0.7$. The curves correspond to an aligned Ξ^* spin state, $m = \pm 1/2$. Errors shown are statistical only.

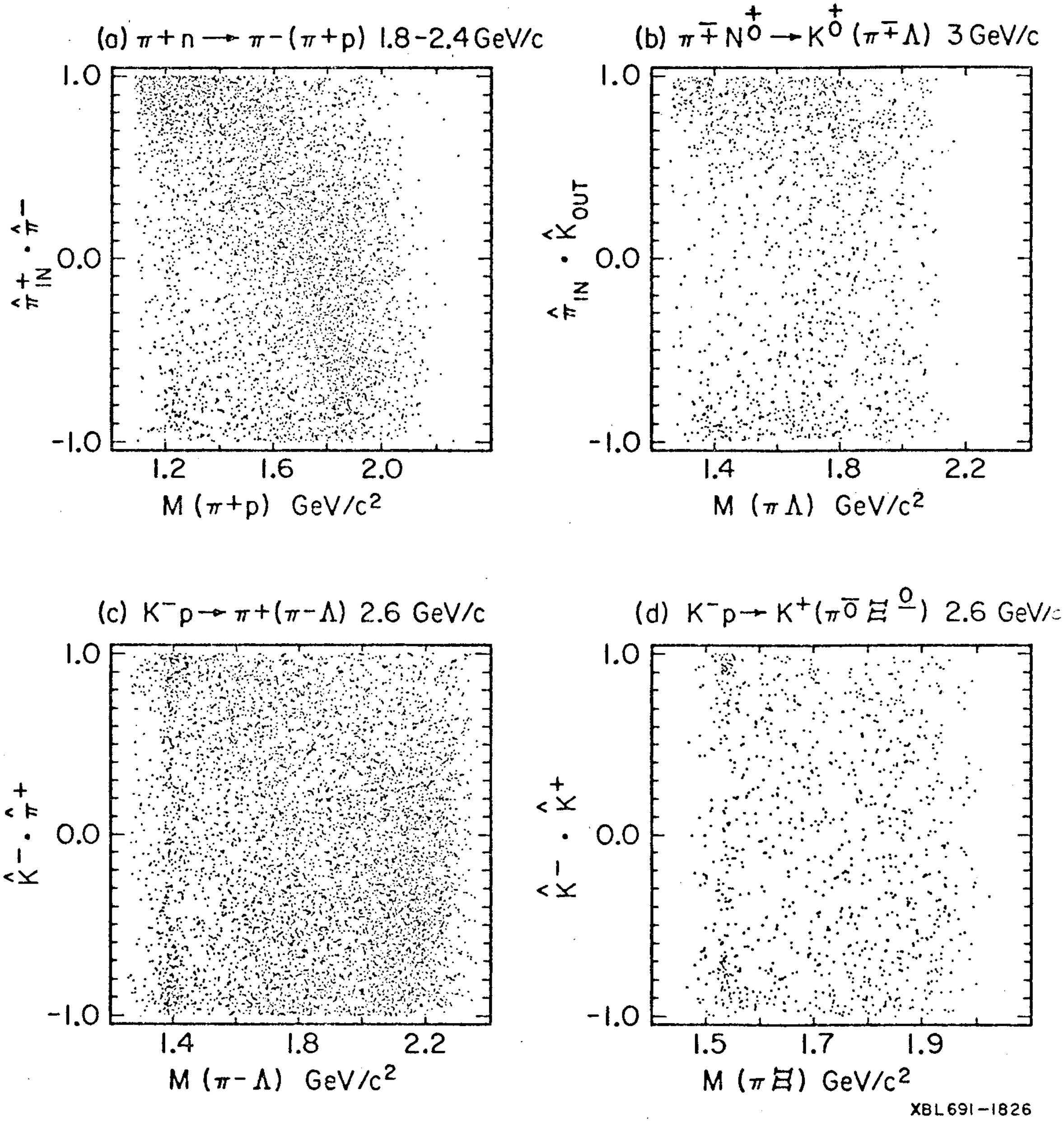
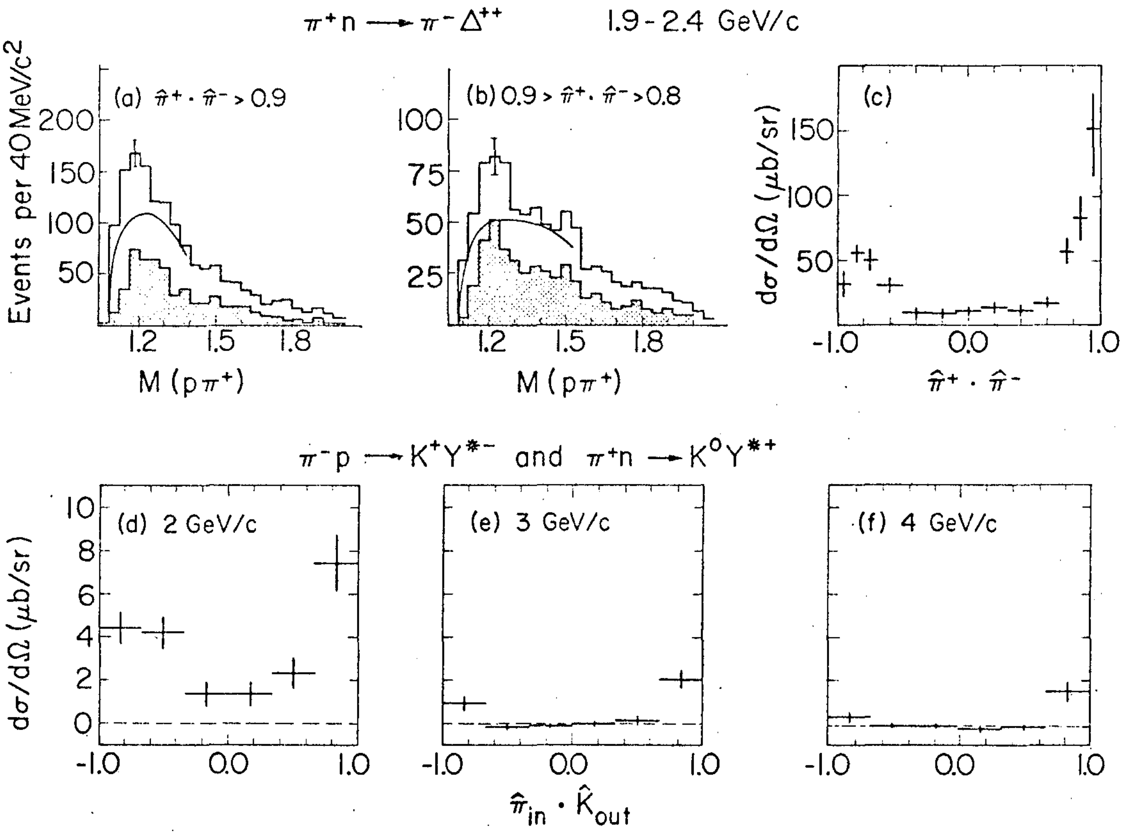

(a) π+n → π−(π+p) 1.8-2.4 GeV/c
π̂⁺IN · π̂⁻
1.0
0.0
-1.0
1.2
1.6
2.0
M (π+p) GeV/c²
(b) π∓N± 0 → K±0 (π∓Λ) 3 GeV/c
π̂IN · K̂OUT
1.0
0.0
-1.0
1.4
1.8
2.2
M (πΛ) GeV/c²
(c) K⁻p → π+(π−Λ) 2.6 GeV/c
K̂⁻ · π̂⁺
1.0
0.0
-1.0
1.4
1.8
2.2
M (π−Λ) GeV/c²
(d) K⁻p → K⁺(π0 Ξ 0 −) 2.6 GeV/c
K̂⁻ · K̂⁺
1.0
0.0
-1.0
1.5
1.7
1.9
M (πΞ) GeV/c²
XBL691-1826

Fig. 1



XBL696-2924

Fig. 2

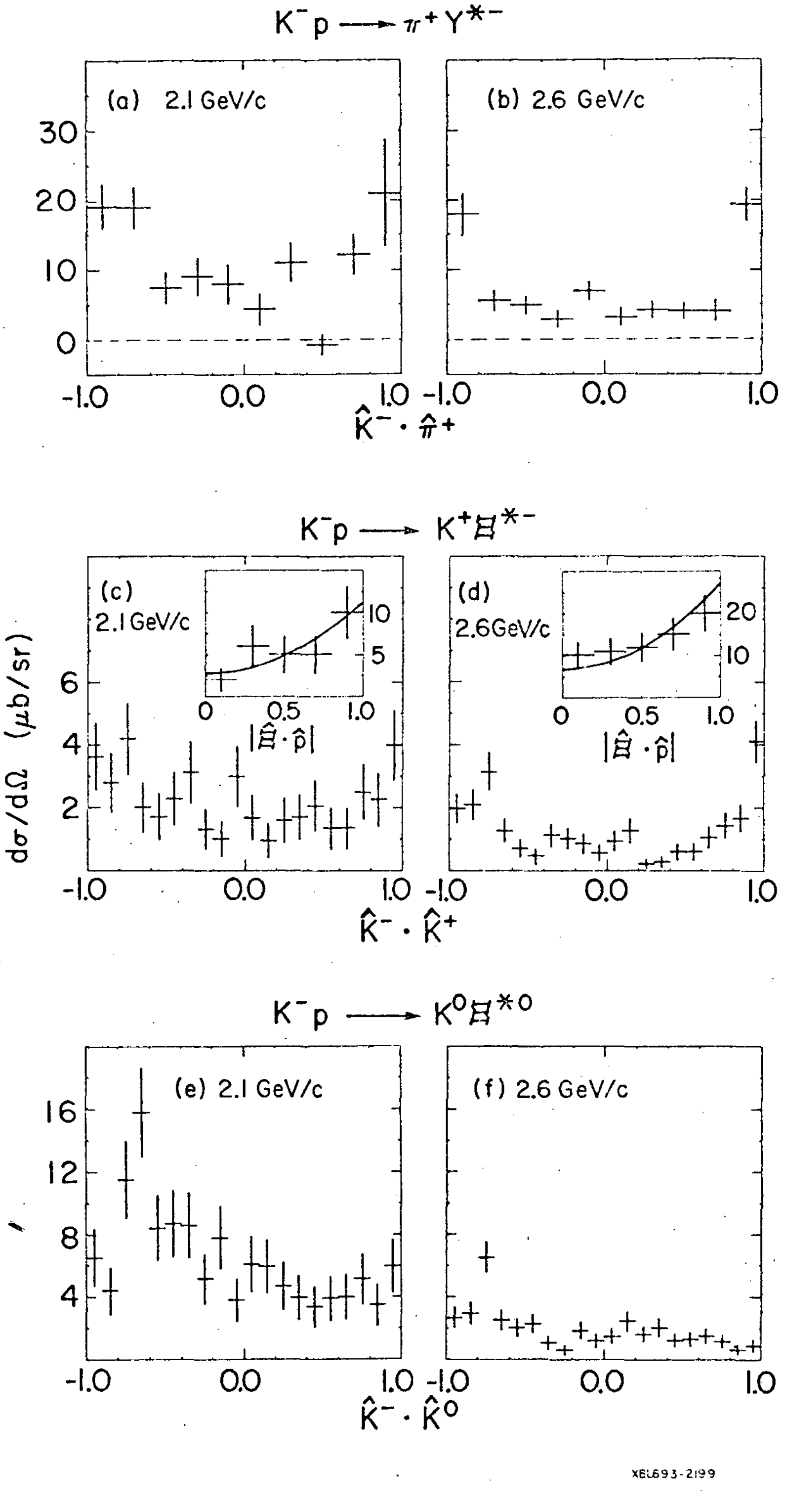

$K^-p \longrightarrow \pi^+ Y^{*-}$
(a) 2.1 GeV/c
(b) 2.6 GeV/c
30
20
10
0
-1.0
0.0
1.0
$\hat{K}^- \cdot \hat{\pi}^+$
$K^-p \longrightarrow K^+ \Xi^{*-}$
(c) 2.1 GeV/c
(d) 2.6GeV/c
$d\sigma/d\Omega$ (μb/sr)
6
4
2
10
5
20
0
0.5
1.0
$|\hat{\Xi} \cdot \hat{p}|$
$\hat{K}^- \cdot \hat{K}^+$
$K^-p \longrightarrow K^0 \Xi^{*0}$
(e) 2.1 GeV/c
(f) 2.6 GeV/c
16
12
8
4
$\hat{K}^- \cdot \hat{K}^0$
XBL693-2199

Fig. 3

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