A STUDY OF THE REACTIONS $K^-p \rightarrow \Lambda\pi^0, \Lambda\eta, \Lambda\eta'$
AT 8.25 GeV/c INCIDENT K^- MOMENTUM

Birmingham^(*)-CERN-Glasgow^(*)-Michigan State^(**)-Paris^(***) Collaboration

S. Al-Harran¹, M. Baubillier², I.J. Bloodworth¹, G.F. Bossen³,
A. Burns³, J.N. Carney¹, G.F. Cox¹, U. Dore³⁽⁺⁾, Ph. Gavillet³,
J.B. Kinson¹, K. Knudson³, F. Levy², P.F. Loverre³, H. McCann⁴⁽⁺⁺⁾,
M.J. MacDermott¹, P.J. Negus⁴, B. Oh⁵, M. Pratap⁵, E. Quercigh³,
J.M. Scarr⁴, G. Smith⁵, D. Teodoro²⁽⁺⁺⁺⁾, M.F. Votruba¹,
J. Whitmore⁵ and R. Zitoun²

ABSTRACT

Differential cross sections and polarizations are presented for the reactions $K^-p \rightarrow \Lambda\pi^0, \Lambda\eta, \Lambda\eta'$ at 8.25 GeV/c incident K^- momentum. The data, which come from a high statistics experiment in the CERN 2m bubble chamber, are compared with previous experimental results on the same reactions and with current theoretical ideas.

- ¹ Physics Department, University of Birmingham, Birmingham, U.K.
² LPHNE, University of Paris VI, Paris, France.
³ CERN, European Organization for Nuclear Research, Geneva, Switzerland.
⁴ Department of Natural Philosophy, University of Glasgow, Glasgow, U.K.
⁵ Michigan State University, East Lansing, Michigan, U.S.A.

Submitted to Nuclear Physics B

-
- (*) Work supported by the Science Research Council U.K.
(**) Work supported by the National Foundation, U.S.A.
(***) Laboratory associated to IN2P3.
(+) Also Roma University.
(++) Now at Manchester University.
(+++) On leave from Genova University.

1. INTRODUCTION

In this paper we present the result of a high statistics study of the processes

$$K^- p \rightarrow \Lambda \pi^0 \quad (1)$$

$$K^- p \rightarrow \Lambda \eta \quad (2)$$

$$K^- p \rightarrow \Lambda \eta' \quad , \quad (3)$$

at 8.25 GeV/c K^- momentum. The data come from an experiment using the CERN 2m hydrogen bubble chamber and correspond to a sensitivity of ~ 140 events/ μb . The statistics available enable us to study differential cross sections and the Λ polarization. No high statistics results covering the complete angular distribution have previously been published above 4.2 GeV/c, at which momentum the results of the ACNO Collaboration [1] are available.

The paper is organized in the following way: in sect. 2 the experimental procedure is described and sect. 3 is devoted to a discussion of the experimental results. In sect. 4 our results are compared with theoretical predictions and our conclusions are contained in sect. 5.

2. EXPERIMENTAL PROCEDURE

The events used in this analysis were obtained from several exposures of the CERN 2m bubble chamber to an r.f. separated beam of 8.25 GeV/c K^- with a momentum spread of $\sim 1/2\%$. These exposures produced a total of 5.3 million pictures and the data presented here are derived from $\sim 70\%$ of the total, giving a sensitivity of ~ 140 events/ μb . The events have been measured in our five laboratories on different measuring machines and reconstructed via different chains of programs. Results from the various laboratories have been carefully compared and their consistency gives confidence that the data contain no serious biases. Samples of events belonging to reactions (1) to (3) have been obtained from the following channels

$$K^- p \rightarrow \Lambda + \text{neutrals} \quad (23\ 100 \text{ events}) \quad (4)$$

$$\rightarrow \Lambda \pi^+ \pi^- \pi^0 \quad (29\ 400 \text{ events}) \quad (5a)$$

$$\begin{aligned} &\rightarrow \Lambda \pi^+ \pi^- + \text{neutrals} && (87\,400 \text{ events}) && (5b) \\ &\rightarrow \Lambda \pi^+ \pi^- \pi^+ \pi^- \pi^0 && (34\,600 \text{ events}). && (6) \end{aligned}$$

Events in channels (5a) and (6) have 1-constraint kinematic fits.

The following cuts have been applied to select the events used in the analysis:

- (a) The production vertex and the Λ decay vertex are required to be within certain fiducial volumes.
- (b) Events with a beam momentum more than 0.2 GeV/c from the average value have been eliminated.
- (c) A minimum projected length (0.4 cm) for the path of the Λ and a minimum momentum (.025 GeV/c) for the π^- from the Λ decay are required.
- (d) One-constraint fits are required to have a probability greater than 1%.

Weights have been assigned to the accepted events to compensate for these cuts. The average weight is a function of the Λ momentum and reaches a mean value of 1.4 for the highest possible momentum (≈ 8 GeV/c).

The cross section normalization has been determined from the number of observed τ -decays and the results have been corrected for scanning and measuring losses (typically 10%). The overall systematic normalization uncertainty has been estimated to be no more than 5%.

2.1 The reaction $K^- p \rightarrow \Lambda \pi^0$

Data on reaction (1) have been obtained by studying events in channel (4). Analysis of this channel also yields information on reaction (2) where the η decays to neutrals.

Events in channel (4) have the topology 0 prong plus 1 V^0 , with the V^0 satisfying the Λ hypothesis. The fraction of such events where the V^0 also satisfies the K^0 hypothesis is very small for low momentum Λ 's (< 1 GeV/c) when the ambiguity can be resolved by ionization checks, but is large ($\approx 50\%$) for the highest momentum Λ 's. The effect of this ambiguity is shown in fig. 1 where the angular distribution of the Λ decay is given. In fig. 1(a) and fig. 1(b) the shaded areas of the histograms correspond to ambiguous events and θ^* is the angle between the proton in the Λ rest frame and the Λ line of flight in the laboratory. For $p_\Lambda < 1$ GeV/c (fig. 1(a)) the angular distribution is flat, except for a loss at $\cos\theta^* = +1$ corresponding to the loss of very slow π^- 's in the laboratory system. As already mentioned, this loss has been corrected by the weighting procedure. Fig. 1(b) ($p_\Lambda > 3$ GeV/c) shows that the ambiguous events are concentrated at positive $\cos\theta^*$ and we deduce from the excess of events in this region that a large fraction of them are not Λ events. That indeed these events contain K^0 's is verified by fig. 1(c) where the effective mass of the V^0 with its tracks taken to be π 's, is plotted. A clear peak is seen at the K^0 mass.

To ensure a clean sample of Λ events all ambiguous events have been rejected. Correction factors have been calculated for various intervals of p_Λ by assuming the events with $\cos\theta^* < -0.2$ to be Λ 's and requiring the whole distribution to be flat. These correction factors, depend only on p_Λ and are no greater than 1.4; they have been incorporated in the event weight. It should be noted that subsequently we only attempt to determine the polarization of slow Λ 's and (< 1.5 GeV/c) these are not affected by this correction procedure. Having thus defined the $\Lambda +$ neutrals sample we proceed now in the study of reaction (1). The missing mass (MM) spectrum to the Λ is shown in fig. 2. Peaks are visible corresponding to the π^0 , η , η'/ϕ (not resolved), A_2 and f' . The plot of MM^2 against $|t'|$ for this channel, for $MM^2 < 1$ GeV², (fig. 3), shows that the forward (small $|t'|$) and backward (small $|u'|$) regions are completely separated and that there are practically no events in the intermediate region. Here and in the following, forward and

backward will always refer to the meson direction with respect to the incident K^- in the c.m. system and t' (u') is defined as $t - t_{\text{MIN}}$ ($u - u_{\text{MIN}}$). The values of t_{MIN} for reactions (1) to (3) are given in table 4.

Fig. 4 gives (a) the forward and (b) the backward missing mass squared spectra. In both cases the experimental resolution function (error ideogram) centred at the π^0 mass is shown as a continuous curve. In the backward direction dramatic reductions in both rate and resolution are apparent and no peak is visible in this region.

To avoid biases in the calculation of the t' distribution for reaction (1), owing to the variation of resolution with t' , we do not use events that give a 1-C fit to this reaction (shown by the shaded areas in fig. 4). Instead, we have determined the number of π^0 's by analysing the mass spectra in various t' intervals. For $|t'| < 1.5 \text{ GeV}^2$ the mass spectra have been fitted between -0.2 and 0.8 GeV^2 using a polynomial background and three resolution functions centred at the π^0 , η and ω masses (the latter becomes more important as $|t'|$ increases). The results of these fits are shown as continuous curves in fig. 5 and are summarized numerically in table 1.

No fits have been attempted for the other t' regions owing to the paucity of statistics and poor resolution. Upper limits for the numbers of π^0 events have been obtained from the numbers of events with negative MM^2 . Fig. 6 shows the mass spectra corresponding to the following intervals regions, $|t'| = 1.5 - 7.1 \text{ GeV}^2$ (a), $|u'| = 7.1 - 1 \text{ GeV}^2$ (b) and $|u'| = 1.0 - 0 \text{ GeV}^2$ (c). 7.1 GeV^2 is the $|t'|$ ($|u'|$) value corresponding to a production angle of 90° in the c.m. system.

For $|u'| < 1 \text{ GeV}^2$ a determination of the number of π^0 's has been attempted by assuming a negligible background in the negative MM^2 region and an η contribution normalized to the one observed via the η charged decay mode. The continuous curve in fig. 6(c) shows the sum of the π^0 and η contributions and well represents the data in the π^0 mass region, thus confirming the absence of any other important contributions in this region.

All results, including numbers of events, $d\sigma/dt'$ and integrated cross sections are summarized in table 1.

In table 1 we also give our values of the Λ polarization for various t' intervals in the forward direction. We have used events with MM^2 between -0.2 GeV^2 and $+0.15 \text{ GeV}^2$ because in this region the background is always small and does not change very much with t' . The Λ polarization has been calculated from the formula

$$P_{\Lambda} = \frac{3}{\alpha_{\Lambda}} \langle \cos \zeta \rangle$$

where $\alpha_{\Lambda} = 0.642$ and ζ is the angle between the decay proton in the Λ rest frame and the production plane normal^(*).

2.2 The reaction $K^-p \rightarrow \Lambda\eta$

The numbers of η events given by the fits to the channel (4) missing mass spectra described in the previous section are presented in table 2. We recall that the amount of η production was only fitted in the region $|t'| < 1.5 \text{ GeV}^2$ and no attempt has been made to extract information on non-forward η production from this channel. In table 2 we also give the corresponding values of $d\sigma/dt'$.

Further information on reaction (2) can be obtained by studying channel 5(a) where one observes the charged decay mode $\eta \rightarrow \pi^+\pi^-\pi^0$. We shall show that this channel also contains the decay mode $\eta \rightarrow \pi^+\pi^-\gamma$ so that the mass spectrum is distorted.

We have considered all events with the topology 2 prongs plus 1 ν^0 that fit the kinematical hypothesis $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^0$ with a probability greater than 1% and that are not ambiguous with any competing 4-constraint hypothesis ($\Lambda\pi^+\pi^-$ or ΛK^+K^-). With regard to possible Λ/K^0 ambiguities, we find that in the regions of interest, namely $p_{\Lambda} < 1 \text{ GeV}/c$ (forward η) and $p_{\Lambda} > 8 \text{ GeV}/c$ (backward η), the lambda decay angular distributions are both consistent with being flat so no correction has been

(*) Defined by the vector product of the 3 momenta of the incident proton and the outgoing Λ in the c.m. system.

made. It must be noted that the $\Lambda\pi^+\pi^-\pi^0$ hypothesis is ambiguous with other 2- or 1-constraint hypotheses, namely $\Sigma^0 K^+ K^-$, $\Sigma^0 \pi^+ \pi^-$ and $\Lambda K^+ K^- \pi^0$. We have not tried to resolve these ambiguities but we have checked that events of these types, if misinterpreted as $\Lambda\pi^+\pi^-\pi^0$, give a negligible contribution in the η region. The $\pi^+\pi^-\pi^0$ mass distribution is shown in fig. 7 and peaks due to the η , ω and η'/ϕ are visible. The plot of $\pi^+\pi^-\pi^0$ mass against $|t'|$ is shown in fig. 8 and fig. 9 gives (a) the forward, (b) the backward and (c) the very backward ($|u'| < 1 \text{ GeV}^2$) mass spectra.

We shall now show that we cannot discriminate between a missing π^0 and a missing γ and therefore that we do not distinguish the $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$ decay modes. This point is relevant in the calculation of absolute cross sections. Parts (a), (b) and (c) of fig. 10 show the missing mass spectrum at the production vertex in the η , ω and η' mass regions respectively. We observe that, whereas in the ω region the spectrum is well centred at the π^0 mass, in the η' region there is clearly a component centred at 0 due to the $\rho\gamma$ decay of the η' . We have fitted each of these spectra with a sum of two resolution functions centred at the π^0 and γ masses. The results are shown as continuous curves in fig. 10 and the numbers of γ events in the η , ω and η' regions are respectively, 12 ± 12 , 60 ± 30 and 380 ± 35 . Although the low statistics in the η region do not allow any quantitative conclusion, the number of γ events in the η' region is in good agreement with the number expected from the well-known η' decay branching ratios [2] and our analysis of η' production obtained from the study of channels (5b) and (6) (sect. 2.3). In the forward $\pi^+\pi^-\pi^0$ mass spectrum shown in fig. 11(a) we see a peak due to the η' but shifted, as expected, to a higher mass and merging into the peak due to the decay $\phi \rightarrow \pi^+\pi^-\pi^0$. Using unfitted and therefore undistorted quantities for the same events we obtain, in contrast, an unshifted peak (fig. 11(b)). The continuous curve shows the result of a fit carried out with the ϕ contribution fixed at that expected from our measurement of the reaction $K^- p \rightarrow \Lambda\phi$ with the decay $\phi \rightarrow K^+ K^-$. The number of η' events estimated in this way is consistent with what we expect, but the uncertainty in the background, clearly rising steeply in this region, does not allow any quantitative conclusion. We conclude that an event of the type $K^- p \rightarrow \Lambda\eta$, $\eta \rightarrow \pi^+\pi^-\gamma$, will be fitted in channel (5a) thus distorting the η mass spectrum. If

we look again at the mass spectrum in fig. 9(a) and interpret all the events between 0.5 GeV and 0.65 GeV as η , we obtain a total number of 182 ± 15 . This gives, together with the 488 ± 42 events observed for $\eta \rightarrow$ neutrals in channel (4), a B.R.

$$\frac{\eta \rightarrow \pi^+ \pi^- \pi^0(\gamma)}{\eta \rightarrow \text{neutral}} = .37 \pm .04$$

in agreement with the P.D.G. value [2].

The t' distribution of the events attributed to reaction (2) and the related values of $d\sigma/dt'$ are given in table 2. We see that the data derived from channel (5a) are in good agreement with those derived from channel (4) and we shall use their weighted averages (also given in table 2) for our final results.

Channel (5a) also allows us to study reaction (2) in the non-forward region. From fig. 9(c) we see that in the very backward region ($|u'| < 1 \text{ GeV}^2$) the η peak is still visible although some background may be present. Assuming the linear background shown as a dashed line in fig. 9(c) we obtain the number of backward η 's given in table 2. Finally we have calculated the Λ polarization in the forward direction and the result is also given in the same table.

2.3 The reaction $K^- p \rightarrow \Lambda \eta'$

Data on reaction (3) can be obtained from channels (5b) and (6). Channel (5b) contains events where either the η' decays to $\eta \pi^+ \pi^-$ and the η subsequently decays to neutrals or the η' decays to $\eta \pi^0 \pi^0$ and the η undergoes charged decay. Events in channel (6) have the topology 4 prongs plus 1 V^0 and fit the 1-constraint hypothesis $\Lambda \pi^+ \pi^- \pi^+ \pi^- \pi^0$. In this channel we can observe the decay $\eta' \rightarrow \eta \pi^+ \pi^-$ followed by charged decay of the η .

2.3.1 Channel (5b)

The missing mass spectrum to the Λ for all events compatible with the hypothesis $\Lambda\pi^+\pi^- + \text{neutrals}$ is shown in fig. 12 and a clear peak is visible at the η' mass. Fig. 13 shows the forward spectrum in the region of the η' and fitting this spectrum gives 582 ± 40 for the number of η' events. Selecting events with a missing mass squared at the production vertex between 0.25 GeV^2 and 0.35 GeV^2 (η selection) gives rise to the shaded histogram in fig. 13. The η' peak is still strong as expected from the fact that the major fraction of the η' events in this channel are due to the decay $\eta' \rightarrow \eta\pi^+\pi^-$ followed by neutral decay of the η . With the η selection there is now practically no background under the η' peak and so we use this sample to calculate $d\sigma/dt'$ and the polarization. The integrated forward cross section is normalized to the number of events found in the mass plot fit described above. It should be noted that the reduction in the number of events due to the missing η selection is in good agreement with what would be expected, taking into account the truncation of the η mass spectrum and the fact that the $3\pi^0$ system arising from the decay $\eta' \rightarrow \eta\pi^0\pi^0$ followed by $\eta \rightarrow \pi^+\pi^-\pi^0$, can lie in this mass region.

All the relevant data for this channel are given in table 3.

2.3.2 Channel (6)

Events fitting the $\Lambda\pi^+\pi^-\pi^+\pi^-\pi^0$ hypothesis with a probability greater than 1% have been considered. In the case of kinematical ambiguities we have used the procedures followed in the treatment of channel $\Lambda\pi^+\pi^-\pi^0$ (par. 2.2). Fig. 14 shows the total 5π mass spectrum, fig. 15 shows the plot of the 5π mass against $|t'|$ and the forward and backward mass spectra in the η' region are shown in fig. 16. In the forward spectrum we can see (as in the case of the η) a tail of events on the right of the η' peak corresponding to misfitted events where the η decays to $\pi^+\pi^-\gamma$. We shall assume that all events below 1.06 GeV are η' events. The numbers of η' events in various t' intervals, $d\sigma/dt'$ and the polarization are given in table 3. It must be noted that we find no event with $|t'| > 2 \text{ GeV}^2$. These data are in very good agreement with those derived from channel (5b) as described in the previous sub-section. In table 3 we also give as our final values the weighted averages of the two determinations.

3. DISCUSSION OF EXPERIMENTAL RESULTS

All of our results on reactions (1) to (3) are summarized in tables 1-3. The differential cross sections are presented in figs 17-19 with inserts to show the small $|t'|$ behaviour on an enlarged scale.

Figs 17-19 and the scatter plots for the three reactions given in figs 3, 8 and 15 show that the forward and backward parts of these reactions are completely separated with no events in the intermediate region. Thus, either a t -channel or u -channel interpretation of these processes is fully justified. We shall now comment on the various characteristics of these reactions.

3.1 Forward cross sections

From figs 17-19 we see that for $|t'| < 0.5 \text{ GeV}^2$ the differential cross sections can be well described by an exponential behaviour of the form

$$\frac{d\sigma}{dt'} = a' e^{-b|t'|} . \quad (7)$$

Values of a' and b have been obtained from least-squares fits to the interval $0 < |t'| < 0.5 \text{ GeV}^2$ and are given in table 4. The results of these fits are the straight lines in figs 17-19. In table 4 we also give the values of $t_{\min}$ and the intercepts at $t = 0$ (denoted a). Finally we quote in this table the analogous quantities for the related reaction

$$\pi^- p \rightarrow K K^0 \quad (8)$$

at 8 GeV/c, as given in [3].

It can be seen that eq. (7) provides an adequate representation of the differential cross sections in the π^0 and η' reactions out to $|t'| \approx 1 \text{ GeV}^2$. However, in the case of the η reaction, after falling more steeply from $t' = 0$, $d\sigma/dt'$ exhibits a minimum near $|t'| = 0.5 \text{ GeV}^2$ followed by a maximum near $|t'| = 0.8 \text{ GeV}^2$. This "dip/bump" structure has already been observed in the 4.2 GeV/c experiment [1] and has been interpreted in t -channel Regge trajectory language as being due to the dominance of K^{*} exchange (in general, K^{**} exchange also features in the meson exchange part of these processes).

The slope parameters we have found are very similar to those that can be extracted from the differential cross sections for $|t'| < 0.3 \text{ GeV}^2$ at 4.2 GeV/c [1].

In terms of an effective Regge trajectory $\alpha_{\text{eff}}(t)$, defined by the relation $\frac{d\sigma}{dt} \sim s^{2\alpha_{\text{eff}}(t)-2}$, the above similarity can be expressed by saying that for $|t| < 0.3 \text{ GeV}^2$ $\alpha_{\text{eff}}(t)$ is practically independent of t (no shrinkage). Using the 4.2 GeV/c data [1] and our own we obtain $\alpha_{\text{eff}}(0 < |t| < 0.3 \text{ GeV}^2) = .20 \pm .05, .35 \pm .05, .30 \pm .05$ for the reactions $\Lambda\pi^0$, $\Lambda\eta$ and $\Lambda\eta'$ respectively.

At higher values of $|t|$ shrinkage is however present and, for example, in the interval $0.3 < |t| < 1.0 \text{ GeV}^2$ we obtain the following values of $\alpha_{\text{eff}}(t)$: $-.35 \pm .07, -.40 \pm .15, -.05 \pm .10$. All these conclusions are supported by the differential cross sections data at 14.3 GeV/c [6(f)] although the statistical significance of the latter is not very great. We observe that the behaviour of $\alpha_{\text{eff}}(t)$ is very similar to that found in the line reversed reaction $\pi^- p \rightarrow K^0 \Lambda$ [4].

3.2 Λ polarization

The Λ polarization in the π^0 reaction is given in table 1 as a function of t' out to $|t'| = 1 \text{ GeV}^2$. Its average value in the forward direction is 0.40 ± 0.06 . Owing to the poor statistics we are unable to measure the polarization in the backward direction. For the η and η' reactions we are only able to measure the average polarization in the forward direction; the values found are 0.45 ± 0.20 and -0.01 ± 0.10 respectively.

3.3 Backward meson production

Owing to the poor resolution and low statistics, our data in the backward region are less significant but some interesting conclusions can still be drawn.

We shall denote the cross sections for $|u'| < 1 \text{ GeV}^2$ by σ_B (they practically coincide with the total backward cross sections). We recall that we can measure σ_B for the η reaction but can only give an

upper limit for the η' reaction (no event observed). In the case of the π^0 reaction we can only determine σ_B by making an assumption about the background (sub-sect. 2.1), for this reason we also quote an assumption-free upper limit for the π^0 . These data are summarized in table 5 together with the results of the 4.2 GeV/c experiment and those of two counter experiments, one at 6.0 GeV [5] in which the π^0 and η reactions are observed, and another at 5.0 GeV/c [6] measuring only the π^0 reaction. The variation of σ_B with P_{lab} is shown for the three reactions in fig. 20.

The following observations can be made:

- (a) $\sigma_B(\pi^0)$ and $\sigma_B(\eta)$ follow the trend indicated by the lower momentum experiments.
- (b) The behaviour of σ_B as a function of P_{lab} is by no means the same for the three reactions. If we assume σ_B varies as P_{lab}^{-n} we find $n = 2.7 \pm 1.0$ for the π^0 , $n = 0.75 \pm 0.40$ for the η and $n > 2.5$ for the η' . Owing to the uncertainty of our results, $n(\pi^0)$ has been determined from the points at 4.2, 5 and 6 GeV/c only. The value of $n(\eta)$ has been obtained from a fit to all three available points and the lower limit for $n(\eta')$ has been obtained from the point at 4.2 GeV/c and our upper limit. We note that the value of $n(\eta)$ is smaller than what would be expected if the reaction were interpreted in terms of baryon exchange.

3.4 Total cross section

Fig. 21 shows the variation of the three total cross sections with P_{lab} for $P_{lab} > 4$ GeV/c. Our results are indicated by arrows. The straight lines correspond to a parametrization $\sigma_T \propto P_{lab}^{-n}$ and have been obtained using only our results and those of the 4.2 GeV/c experiment. We obtain the following values: $n(\pi^0) = 2.1 \pm 0.2$, $n(\eta) = 1.6 \pm 0.2$ and $n(\eta') = 1.6 \pm 0.2$. All the other data [7] shown in fig. 21 are consistent with these straight lines, allowing for their larger errors. The values of n agree with what would be expected considering that the bulk of the cross sections is provided by the forward parts, i.e. by strange meson exchange.

4. COMPARISON WITH THEORETICAL PREDICTIONS

4.1 Equality of line reverse reactions

Reactions (1) and (8) are related by line-reversal. Regge models predict that if the dominant t-channel trajectories (K^* and K^{**}) are exchange degenerate then

$$2 \frac{d\sigma}{dt} (K^- p \rightarrow \Lambda \pi^0) = \frac{d\sigma}{dt} (\pi^- p \rightarrow \Lambda K^0) \quad (11)$$

where the factor of 2 arises from isospin factors. This rule has been found to be satisfied at 14 GeV/c [7(b)] but is known to be violated at lower momenta. Using the π^- data of [3] at 8.0 GeV/c, correcting for $t_{\min}$ effects and integrating out to $|t'| = 1 \text{ GeV}^2$ we find

$$\text{LHS of (11)} = (34 \pm 2) \mu\text{b}$$

$$\text{RHS of (11)} = (23 \pm 2) \mu\text{b}.$$

Clearly this rule is far from being satisfied near 8 GeV/c. The fact that (11) is not satisfied can also be deduced, independently of possible normalization errors, from the difference in the slopes of $d\sigma/dt$ (table 4).

4.2 Quark model sum rules

It is well known [1,7(b)] that the quark model sum rule for pseudoscalar mesons

$$\frac{d\sigma}{dt} (K^- p \rightarrow \Lambda \pi^0) + \frac{d\sigma}{dt} (\pi^- p \rightarrow \Lambda K^0) = \frac{d\sigma}{dt} (K^- p \rightarrow \Lambda \eta) + \frac{d\sigma}{dt} (K^- p \rightarrow \Lambda \eta') \quad (12)$$

is badly violated. This is also true at our momentum where using again the results of [3] on $\pi^- p \rightarrow \Lambda K^0$, and integrating the cross sections out to $|t'| = 1 \text{ GeV}^2$, we obtain

$$\text{LHS of (12)} - \text{RHS of (12)} = (13 \pm 3) \mu\text{b}.$$

in a recent paper [8] Cohen and Lipkin discuss a new type of $\eta - \eta'$ mixing, taking into account the orbital excitations of the quark wave functions. This leads to a modified sum rule of the form

$$0.9 \frac{d\sigma}{dt} (K^- p \rightarrow \Lambda \pi^0) + 1.1 \frac{d\sigma}{dt} (\pi^- p \rightarrow \Lambda K^0) = \frac{d\sigma}{dt} (K^- p \rightarrow \Lambda \eta) + A \frac{d\sigma}{dt} (K^- p \rightarrow \Lambda \eta') \quad (13)$$

where the factor $A (> 1)$ takes into account the reduction of the η' cross section due to the large component of radial excitations in this particle. Using the 4.2 GeV/c forward cross sections (not corrected for $t_{\min}$ effects) Cohen and Lipkin find that the data are in good agreement with (13) if $A = 2$. Good agreement, with the same value of A , is also found at 16 GeV/c [7(b)] although the large errors make the comparison less significant. At 8.25 GeV/c we find (using $A = 2$)

$$\text{RHS of (13)} = (46.1 \pm 2.1) \mu\text{b}$$

$$\text{LHS of (13)} = (40.2 \pm 2.6) \mu\text{b}.$$

The agreement can be considered satisfactory taking into account the normalization uncertainties (5% in our experiment and 10% for the data of [3]).

5. CONCLUSIONS

We can summarize the results of our study of reactions (1)-(3) as follows:

- (a) Our cross section measurements significantly improve the data available above 4 GeV/c. They indicate that the total cross sections vary approximately as P_{lab}^{-2} .
- (b) In the forward direction the variation of $d\sigma/dt$ can be represented by an exponential form out to $|t'| = 0.5 \text{ GeV}^2$. The slope for the η is much greater than for the π^0 or η' .
- (c) In reaction (1) the average polarization of the Λ in the forward direction is quite large (≈ 0.4) and positive. A similar value is found for reaction (2) but the much increased error makes the conclusion less certain. For reaction (3) the polarization is consistent with 0.
- (d) The backward cross section for the η seems to indicate an s dependence that is less steep than would be expected for a baryon exchange process.

- (e) The modified sum rule of [8] is reasonably well satisfied by our forward cross sections.

We want to thank Dr. A. Irving for fruitful discussion. We also wish to thank the operating crews of the CERN PS and 2m HBC, the constructor of the r.f. separated beam and the scanning, measuring and computing staffs at our laboratories.

REFERENCES

- [1] F. Marzano et al., Nucl. Phys. B123 (1977) 203.
- [2] Review of Particle properties, Phys. Lett. 75B (1978) 1.
- [3] K.J. Foley et al., Phys. Rev. D8 (1973) 27.
- [4] A.C. Irving et al., Nuovo Cimento 16A (1973) 573.
- [5] H. Becker et al., Nucl. Phys. B167 (1980) 292.
- [6] J. Gallivan et al., Nucl. Phys. B117 (1976) 269.
- [7] (a) M. Aguilar Benitez et al., Phys. Rev. D6 (1972) 19;
(b) P. Girtler et al., Nucl. Phys. B159 (1979) 397;
(c) D.C. Colley et al., Nuovo Cimento 53A (1968) 522;
(d) C. Loueduc et al., Nuovo Cimento 41A (1977) 166;
(e) J. Mott et al., Phys. Rev. 177 (1969) 1966;
(f) B. Chaurand et al., Nucl. Phys. B117 (1976) 1.
(g) R. Davis et al., Phys. Lett. 27B (1968) 532.
- [8] J. Cohen and H. Lipkin, Nucl. Phys. B151 (1979) 16.

TABLE CAPTIONS

Table 1 Results on the reaction $K^- p \rightarrow \Lambda \pi^0$.

Table 2 Results on the reaction $K^- p \rightarrow \Lambda \eta$.

Table 3 Results on the reaction $K^- p \rightarrow \Lambda \eta'$.

Table 4 Parameters of the exponential representation of small $|t'|$ differential cross sections.

Table 5 Backward ($u' < 1 \text{ GeV}^2$) cross section for reactions (1) to (3).

TABLE 1

	No. of events	$d\sigma/dt'(\mu\text{b}/\text{GeV}^2)$
$ t' $ interval (GeV^2)		
0 - .05	351 ± 28	84.5 ± 6.7
.05 - .15	467 ± 26	56.2 ± 3.2
.15 - .30	385 ± 23	30.9 ± 1.8
.30 - .60	239 ± 19	$9.6 \pm .8$
.60 - 1.0	80 ± 14	$2.4 \pm .4$
1.0 - 1.5	29 ± 7	$.7 \pm .2$
1.5 - 7.1	$< 10^{(a)}$	$< .02$
Total forward	1551 ± 53	
$ u' $ interval (GeV^2)		
7.0 - 1.0	< 32	$< .06$
1.0 - 0.	$< 92^{(b)}$	< 1.1
	$60 \pm 16^{(c)}$	0.7 ± 0.2
Integrated cross sections (μb)		
Forward cross section	(18 ± 1)	
Backward cross section	< 1.3	
$\sigma_B(u' < 1 \text{ GeV}/c^2)$	$< 1.1^{(b)}$	
	$.7 \pm 2^{(c)}$	
Total cross section	$18^{+1.4}_{-1.0}$	
Λ polarization		
$ t' $ interval (GeV^2)	Polarization	
0 - .05	$.05 \pm 14$	
.05 - .15	$.59 \pm .10$	
.15 - .50	$.24 \pm .10$	
.5 - 1.0	$.73 \pm .24$	
.0 - 1.5	$.37 \pm .06$	

(a) All upper limits at 90% confidence level.

(b) Assumption-free upper limit.

(c) Obtained with the assumption explained in the text.

TABLE 2

	$\eta \rightarrow \text{neutrals}$		$\eta \rightarrow \pi^+ \pi^- \pi^0$		Average
	No. of events	$d\sigma/dt'$ ($\mu\text{b}/\text{GeV}^2$)	No. of events	$d\sigma/dt'$ ($\mu\text{b}/\text{GeV}^2$)	$d\sigma/dt'$ ($\mu\text{b}/\text{GeV}^2$)
$ t' $ interval (GeV^2)					
0 - .05	220 ± 21	74.4 ± 7.1	64.8 ± 9.0	55.9 ± 7.9	65.8 ± 5.3
.05 - .15	157 ± 18	26.5 ± 3.0	64.0 ± 9.0	27.6 ± 3.8	26.9 ± 2.4
.15 - .30	61 ± 13	6.9 ± 1.5	31.5 ± 6.0	9.1 ± 1.7	7.9 ± 1.1
.30 - .60	9 ± 7	$.51 \pm .40$	4.9 ± 3.0	$.70 \pm .35$	$.61 \pm .25$
.60 - 1.0	17 ± 16	$.72 \pm .68$	11.7 ± 4.0	$1.26 \pm .40$	$1.12 \pm .34$
1.0 - 1.5	24 ± 6	$.81 \pm .20$	4.8 ± 2.0	$.41 \pm .20$	$.61 \pm .15$
1.5 - 3.0			8.1 ± 3.0	$.23 \pm .08$	$.23 \pm .08$
3.0 - 7.0			1.6 ± 1.6	$.02 \pm .02$	$.02 \pm .02$
Total forward	488 ± 42		182 ± 15		
$ u' $ interval (GeV^2)					
7.0 - 1.0			3.0 ± 2	$.02 \pm .03$	$.02 \pm .03$
1.0 - 0.			11.0 ± 6	$.60 \pm .30$	$.60 \pm .30$
Integrated cross sections (μb)					
σ forward	$8.6 \pm .7$		$8.2 \pm .7$		$8.5 \pm .5$
σ backward			$.70 \pm .30$		$.70 \pm .30$
$\sigma_B (u' < 1 \text{ GeV}^2)^2$			$.60 \pm .30$		$.60 \pm .30$
Total cross section					$9.2 \pm .6$
Λ polarization forward region			0.45 ± 0.20		$.45 \pm 0.20$

TABLE 3

	$\eta' \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0$		$\eta' \rightarrow \pi^+ \pi^-$ neutrals		Average
	No. of events	$d\sigma/dt'$	No. of events	$d\sigma/dt'$ ($\mu\text{b}/\text{GeV}^2$)	$d\sigma/dt'$ ($\mu\text{b}/\text{GeV}^2$)
$ t' $ interval (GeV^2)					
0.0 - .05	47.5 ± 8	95.9 ± 16	112.6 ± 12	97.3 ± 13.9	96.7 ± 10.7
.05 - .15	64.8 ± 9	65.4 ± 9.1	134.0 ± 13	58.1 ± 7.9	61.2 ± 6.0
.15 - .30	45.0 ± 7	30.3 ± 4.7	122.3 ± 12	35.1 ± 4.8	32.6 ± 3.2
.30 - .60	27.6 ± 6	9.2 ± 1.9	50.6 ± 8	7.3 ± 1.3	7.9 ± 1.1
.60 - 1.0	4.4 ± 2.2	$1.1 \pm .6$	$10.5 \pm .25$	$1.1 \pm .4$	$1.1 \pm .3$
1.0 - 2.0	1.3 ± 1.3	$.12 \pm 0.12$	5.5 ± 2.5	$.24 \pm .11$	$.20 \pm .10$
2.0 - 6.7	0	$< .05^{(a)}$			$< .05$
Total forward	189 ± 15		435.5 ± 25		
$ u' $ interval (GeV^2)					
6.7 - 1.0	0	$< .04$			$< .04$
1.0 - 0.0	0	$< .25$			$< .25$
Integrated cross sections (μb)					
Forward cross section	19.0 ± 1.4		18.6 ± 1.3		$18.8 \pm .8$
Backward cross section	$< .25$				$< .25$
σ_B ($ u' < 1(\text{GeV}^2)$)	$< .25$				$< .25$
Total cross section					$18.8^{+1.}_{-.8}$
Λ polarization forward region	$.29 \pm .20$		$-.14 \pm .13$		$-0.1 \pm .10$

(a) All upper limits at 90% C.L.

TABLE 4

Process	t_{MIN} (GeV) ²	a (μb)	a' (μb)	b (GeV ⁻²)
$\text{K}^- \text{p} \rightarrow \Lambda \pi^0$	.005	$92.2 \pm 3.$	94.6 ± 2.8	$5.1 \pm .1$
$\text{K}^- \text{p} \rightarrow \Lambda \eta$	-.0015	$85.0 \pm 5.$	$83.7 \pm 5.$	$10.8 \pm .4$
$\text{K}^- \text{p} \rightarrow \Lambda \eta'$	-.019	$128.6 \pm 9.$	$114.8 \pm 8.$	$6.0 \pm .3$
$\pi^- \text{p} \rightarrow \Lambda \text{K}^0(\text{a})$	-.006	$164.9 \pm 5.$	$158 \pm 4.$	$7.17 \pm .23$

(a) From ref. [3] valid for $|t'| < 0.4$ (GeV²)

TABLE 5

Process	p_{K^-} (GeV/c)			
	4.2 ^(a)	5.0 ^(b)	6.0 ^(c)	8.25
$\text{K}^- \text{p} \rightarrow \Lambda \pi^0$	5.3 ± 0.5	2.0 ± 0.3	2.20 ± 0.25	< 1.1 (90% C.L.) $.7 \pm .2^{(d)}$
$\text{K}^- \text{p} \rightarrow \Lambda \eta$	1.1 ± 0.1		$.94 \pm .19$	$.60 \pm .30$
$\text{K}^- \text{p} \rightarrow \Lambda \eta'$	2.0 ± 0.7			$< .25$ (90% C.L.)

(a) Derived from the results of ref. [1].

(b) From ref. [6].

(c) From ref. [5].

(d) The upper limit makes no assumption about the background. The cross section assumes no background in the negative MM^2 region.

FIGURE CAPTIONS

- Fig. 1 Angular distribution of the proton from the Λ decay for (a) $p_{\Lambda} < 1$ GeV/c and (b) $p_{\Lambda} > 3$ GeV/c for the $\Lambda +$ neutrals final state. The shaded area corresponds to the ambiguous events. (c) Effective mass spectrum of the V^0 products considered as π 's for the same channel ($p_{\Lambda} > 3$ GeV/c).
- Fig. 2 Missing mass squared spectrum in $K^-p \rightarrow \Lambda +$ neutrals.
- Fig. 3 Plot of MM^2 against $|t'|$ for $K^-p \rightarrow \Lambda +$ neutrals.
- Fig. 4 MM^2 spectra in $K^-p \rightarrow \Lambda +$ neutrals:
(a) in the forward region,
(b) in the backward region.
- In each case the continuous curve shows the resolution function centred at the π^0 mass and the shaded part of the histogram represents events that fit the reaction $K^-p \rightarrow \Lambda\pi^0$.
- Fig. 5 MM^2 spectra in $K^-p \rightarrow \Lambda +$ neutrals for various $|t'|$ intervals. The curves show the results of the fits described in the text.
- Fig. 6 MM^2 spectra in $K^-p \rightarrow \Lambda +$ neutrals for various $|t'|$ and $|u'|$ intervals. The curve in (c) represents the sum of the π^0 and η contributions assuming no background for $MM^2 < 0$.
- Fig. 7 The $\pi^+\pi^-\pi^0$ mass distribution in $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^0$.
- Fig. 8 Plot of $\pi^+\pi^-\pi^0$ mass against $|t'|$ in $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^0$.

FIGURE CAPTIONS (Cont'd)

Fig. 9 The $\pi^+\pi^-\pi^0$ mass distribution is $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^0$.

- (a) in the forward region,
- (b) in the backward region,
- (c) for $|u'| < 1 \text{ GeV}^2$.

Fig. 10 Distribution of MM^2 at the production vertex for events fitting $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^0$ for η , ω and η' . The continuous lines are the results of the fits described in the text.

Fig. 11 (a) Forward distribution of $M(\pi^+\pi^-\pi^0)$ up to 1.2 GeV in $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^0$.

- (b) Missing mass spectrum to the Λ using unfitted quantities for the same events.

The continuous line is the result of the fit described in the text.

Fig. 12 Distribution of missing mass to the Λ in $K^-p \rightarrow \Lambda\pi^+\pi^- +$ neutrals.

Fig. 13 Distribution of missing mass to the Λ in $K^-p \rightarrow \Lambda\pi^+\pi^- +$ neutrals in the forward η' region. The shaded area shows events with missing mass squared at the production vertex between 0.25 GeV^2 and 0.35 GeV^2 (η selection). The continuous curves show fits to these distributions.

Fig. 14 The $\pi^+\pi^-\pi^+\pi^-\pi^0$ mass distribution in $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^+\pi^-\pi^0$.

Fig. 15 Plot of $\pi^+\pi^-\pi^+\pi^-\pi^0$ mass against $|t'|$ in $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^+\pi^-\pi^0$.

FIGURE CAPTIONS (Cont'd)

- Fig. 16 The η' region of the 5π mass distribution in $K^-p \rightarrow \Lambda\pi^+\pi^-\pi^+\pi^-\pi^0$:
 (a) forward,
 (b) backward.
- Fig. 17 $d\sigma/dt'$ for the reaction $K^-p \rightarrow \Lambda\pi^0$. The insert shows the small $|t'|$ region on an enlarged scale. The lines correspond to the exponential fit described in the text.
- Fig. 18 $d\sigma/dt'$ for the reaction $K^-p \rightarrow \Lambda\eta$. The insert shows the small $|t'|$ region on an enlarged scale. The lines correspond to the exponential fits described in the text.
- Fig. 19 $d\sigma/dt'$ for the reaction $K^-p \rightarrow \Lambda\eta'$. The insert shows the small $|t'|$ region on an enlarged scale. The lines correspond to the exponential fits described in the text.
- Fig. 20 Backward cross sections ($|u'| < 1 \text{ GeV}^2$) for the reactions $K^-p \rightarrow \Lambda\pi^0$, $\Lambda\eta$ and $\Lambda\eta'$. The lines represent the P_{lab}^n parametrization described in the text.
- Fig. 21 Total cross sections vs P_{lab} for
 (a) $K^-p \rightarrow \Lambda\pi^0$,
 (b) $K^-p \rightarrow \Lambda\eta$,
 (c) $K^-p \rightarrow \Lambda\eta'$.

The lines are obtained by joining the data at 4.2 GeV/c and 8.25 GeV/c.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig.16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21