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INCLUSIVE PRODUCTION OF γ , K^n , Λ^0 AND $\bar{\Lambda}^0$ IN K^-p INTERACTIONS AT 110 GeV/c

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ABSTRACT

Results on inclusive production of γ , K^n , Λ^0 and $\bar{\Lambda}^0$ in K^-p interactions at 110 GeV/c are presented. Total cross sections, and differential cross sections in terms of Feynman x , rapidity and p_T^2 are given. It is found that about 40% of K^n s are produced together with a strange particle pair, and that 80% of Λ^0 s are produced together with a $K\bar{K}$ pair. These Λ^0 s are produced predominantly in the backward direction. Fits to the form $(1 - |x|)^n$ to the x_F distributions of K^n and Λ^0 in the fragmentation regions are found to be in general agreement with quark counting rule predictions.

1. INTRODUCTION

In this paper we present results on the inclusive processes:

$$K^- p \rightarrow \gamma + X \quad (1)$$

$$K^- p \rightarrow K^n + X \quad (2)$$

$$K^- p \rightarrow \Lambda^0 + X \quad (3)$$

$$K^- p \rightarrow \bar{\Lambda}^0 + X \quad (4)$$

and the double inclusive processes:

$$K^- p \rightarrow K^n K^n + X \quad (5)$$

$$K^- p \rightarrow \Lambda^0 K^n + X \quad (6)$$

at an incident K^- momentum of 110 GeV/c. In this context K^n denotes both K^0 and $\bar{K}^0$; Λ^0 denotes both prompt Λ^0 's and those produced via the electromagnetic decay $\Sigma^0 \rightarrow \Lambda^0 \gamma$. The events were observed in the 3.7 m hydrogen bubble chamber, BEBC, which provides 4π acceptance for all types of events, and good neutral particle detection efficiency, even at this high momentum. Most neutral particles decaying to charged particles in the chamber are identified by kinematic fitting; those that remain ambiguous can be treated in a systematic, bias-free manner.

The paper is organised as follows: sect. 2 describes the experimental procedure and data processing. Sect. 3 presents the inclusive cross section for γ production, makes an estimate of the inclusive π^0 production cross section, and discusses the energy dependence of these results. Sect. 4 presents the inclusive cross sections for reactions (2)-(6) and discusses the energy dependences observed. In sect. 5 some inclusive differential distributions for K^n , Λ^0 , and $\bar{\Lambda}^0$ production are given and compared to lower energy data. In sect. 6 the quark counting rule fits to the fragmentation regions of the Feynman x distributions of K^n and Λ^0 are presented and the results obtained compared with theoretical predictions. The results are summarized in sect. 7.

2. EXPERIMENTAL PROCEDURE

The data for this analysis were obtained from exposures of BEBC to the RF separated K^- beam tuned to a momentum of 110 GeV/c. As the separation is not complete at this momentum (the beam composition being $\sim 85\% K^-$, 10% π/μ and 5% $\bar{p}$) a beam-tagging system consisting of two coded scintillator hodoscopes and two threshold Cerenkov counters [1] was used during the runs. Using the information from this system, an essentially pure sample of K^- induced reactions was obtained.

All of the film taken ($\sim 110,000$ pictures) has been scanned twice for events on kaon tagged beam tracks in a fiducial region 290 cm long, with a combined scanning efficiency of $> 99\%$, except for two-prong events where the efficiency was $\sim 90\%$. For frames with an identified kaon induced event, the entire visible volume of the chamber was scanned for γ conversions and V^0 decays associated to the event. The scanning efficiency obtained for γ s was $80 \pm 5\%$, that for V^0 s was $90 \pm 5\%$.

Results are presented here on 12,600 of the $\sim 20,000$ events found in the scanning. These events have been measured and processed through the HYDRA Geometry program [2,3]. As an indication of the quality of the data only 2.5% of all tracks either fail completely in geometry or have a momentum error, $\Delta P/P$, of $> 50\%$. A measure of the mass resolution of the bubble chamber can be obtained from the distribution of the measured K^n mass. The distribution is centred within $1 \text{ MeV}/c^2$ of the nominal K^n mass [4], with a FWHM which is a strong function of the K^n momentum, being $6.2 \text{ MeV}/c^2$ for K^n 's of momentum less than 6 GeV/c, and rising to $\sim 15 \text{ MeV}/c^2$ for K^n 's of momentum $> 20 \text{ GeV}/c$.

The output from the Geometry program after removing events outside the fiducial volume, and those with badly defined or "off-beam" beam tracks constitutes the sample of 10,883 good events on which this analysis has been performed. In order to obtain the microbarn equivalent of one event, this number is normalised to the total K^-p cross section of 20.5 mb at 110 GeV/c [7], with a suitable correction for the loss of two-prong events. This results in the value of $1.78 \mu\text{b}/\text{event}$.

In order to identify the γ s, K^n s, Λ^0 s and $\bar{\Lambda}^0$ s associated to the primary events, and to obtain their track parameters at the primary vertices, the geometry output data were passed through a kinematic fitting program, which fits the usual hypotheses $\gamma \rightarrow e^+ e^-$, $K^n \rightarrow \pi^+ \pi^-$, $\Lambda^0 \rightarrow p \pi^-$, $\bar{\Lambda}^0 \rightarrow \pi^+ \bar{p}$ at each V^0/γ vertex. This program is a specially modified version of the standard HYDRA kinematics program [5], optimised for V^0/γ fitting. Details of the modifications and of the optimisation process may be found in ref. [6]. The passing rate for all types of V^0/γ through this program has been estimated to be $90 \pm 5\%$.

All V^0/γ vertices are subjected to a fiducial volume cut that imposes a minimum length of 20 cm on the charged tracks coming from the V^0/γ decays. This is sufficient to obtain satisfactory reconstruction in nearly all cases. Two additional selections are also made at this stage. One selection, which is implicit in the kinematics program, is the requirement that the observed lifetime of connected V^0 s is less than 9 mean lifetimes. This cut considerably reduces the number of slow Λ^0/γ ambiguous fits, by removing the Λ^0 fit. The other selection is a cut on the χ^2 -probability of all fits at 1%. This cut significantly reduces the number of ambiguities by removing one of the hypotheses. Table 1 shows the numbers of unique γ , K^n , Λ^0 and $\bar{\Lambda}^0$ fits, and the number of ambiguous fit combinations found after these selections. The ambiguities that remain after the selections are treated in the following ways:

- (a) γ/V^0 ambiguities are resolved by taking the γ hypothesis as the correct one, except for V^0 s faster than 25 GeV/c, where the fit with the best probability was taken. There are various justifications for this procedure, for example the number of γ/Λ^0 ambiguities is similar to the number of $\gamma/\bar{\Lambda}^0$ ambiguities; if these were true Λ^0 or $\bar{\Lambda}^0$ these numbers should be in the ratio of the Λ^0 cross section to the $\bar{\Lambda}^0$ cross section, i.e. 5 : 1. In addition, the decay angle distributions for K^n , Λ^0 and $\bar{\Lambda}^0$ show no depletion at $\cos(\theta^*) = \pm 1$ due to this cut, where θ^* is the angle between the positive decay track and the V^0 line of flight, in the V^0 centre of mass.

- (b) All K^n/Λ^0 and $K/\bar{\Lambda}^0$ ambiguous fits are rejected; the remaining unique K^n , Λ^0 and $\bar{\Lambda}^0$ are weighted to compensate for this cut, as will be described in sect. 4.

These selections and assignments yield a sample of 5277 γ 's, 1174 K^n 's, 370 Λ^0 's and 71 $\bar{\Lambda}^0$'s before any corrections or weights are applied.

3. INCLUSIVE γ AND π^0 PRODUCTION

In order to compute the cross section for $K^-p \rightarrow \gamma + X$, several corrections were applied to the γ sample. The first is the correction for those γ s that did not convert in the fiducial volume. A minimum projected length cut of 10 cm in the x-y plane is also applied to correct for those γ s converting close to the primary vertex that are lost due to confusion with charged primary tracks. A further correction is made for Compton scattering, which forms a significant part of the cross section for $p_\gamma < 0.5$ GeV/c. The mean potential weight for γ s was found to be 8.5; the average γ has only a 12% chance of converting in the fiducial volume.

A correction is also applied for the loss of asymmetric γ s, that is γ s with one track slower than 20 MeV/c; such γ s tend to have a low passing rate through kinematics. All γ s with either charged track slower than 20 MeV/c are rejected and a compensating weight, based on the QED prediction of the distribution of the ratio $P_e^\pm/P_\gamma$, is applied to the remaining sample [6]. A consequence of using this procedure is a cut on P_γ of 40 MeV/c, which must be allowed for when computing physical quantities.

In order to correct for this loss of slow γ s we make use of the following relationship, which holds for the decay $\pi^0 \rightarrow \gamma\gamma$:

$$\int_0^{\frac{M_{\pi^0}}{2}} n(P_\gamma) dP_\gamma = \int_{\frac{M_{\pi^0}}{2}}^{\infty} \frac{M_{\pi^0}^2}{4P_\gamma} n(P_\gamma) dP_\gamma \quad (7)$$

for any π^0 momentum, i.e. the cross section for γ s with momentum $P_\gamma < m_{\pi^0}/2$ (67.5 MeV/c) is equal to the cross section for γ s with $P_\gamma > m_{\pi^0}/2$, weighted by the factor $m_{\pi^0}^2/4P_\gamma$. Thus, given a complete sample of γ s with $P_\gamma > 67.5$ MeV/c, the total cross section down to $P_\gamma = 0$ may be easily obtained.

Applying the corrections discussed above, together with corrections for scanning efficiency, passing rate, and the probability cut, and normalising with the microbarn equivalent of 1.78 $\mu\text{b}/\text{event}$, results in the laboratory momentum distribution for γ s shown in fig. 1. The points below $P_\gamma = 67.5$ MeV/c have been calculated from the symmetry relation of eq. (7). The integral of the momentum distribution corresponds to the total inclusive γ production cross section and is

$$\sigma(K^- p \rightarrow \gamma + X) = 137 \pm 10 \text{ mb.}$$

The inclusive cross section for π^0 production (including π^0 's from the decay of η^0 , ω^0 , etc.) can be estimated from the inclusive γ cross section, corrected for the contribution from $\Sigma^0 \rightarrow \Lambda^0 \gamma$ and $\eta^0 \rightarrow \gamma\gamma$. The Σ^0 cross section is approximately 40% that of the inclusive Λ^0 cross section (sect. 4) and is of the order of 1 mb. If it is assumed that the ratio, R , of η^0 to π^0 production is the same at 110 GeV/c as it is at 14.3 GeV/c [8], i.e. $R = 0.18 \pm 0.07$, then:

$$\sigma(\pi^0) = (\sigma_\gamma - \sigma_{\Sigma^0})/(2 + 0.87R) = 63 \pm 6 \text{ mb}$$

where 0.87 is the average number of γ s coming directly from the decay of one η^0 meson without an intermediate π^0 .

Fig. 2 shows the $\gamma\gamma$ effective mass distribution for all events with at least two seen γ s. A clear π^0 signal is seen, but there is no significant evidence for $\eta^0 \rightarrow \gamma\gamma$, hence the assumption of the η^0 to π^0 ratio used above. An estimate of the π^0 cross section from this distribution yields a value that is consistent with the value obtained above, but with very large errors.

Table 2 gives the γ multiplicity as a function of charged topology, where the multiplicity for particles i is defined in the usual way:

$$\langle i \rangle = \sigma_i / \sigma_{\text{inelastic}} \quad (8)$$

The inelastic topological cross sections used here are those previously published by this Collaboration [9]. The γ multiplicity rises linearly with charged topology up to 12 charged prongs, and then becomes independent of the charged topology, within the errors. A similar effect has been observed in K^-p interactions at 70 GeV/c [10].

Fig. 3 shows the total cross sections for $K^-p \rightarrow \gamma + X$, $K^-p \rightarrow \pi^0 + X$ and $K^-p \rightarrow \pi^\pm + X$ from 3 GeV/c to 110 GeV/c [8,10-13]. The charged pion cross sections at 110 GeV/c were evaluated using the method of ref. [10]. The γ and π^0 cross sections are rising faster than the π^+ and π^- cross sections; at 110 GeV/c the π^0 cross section is significantly higher than the π^+ and π^- cross sections, at 32 GeV/c they are comparable. The rise in the π^0 cross section could either be real, or there is an increasingly important non- π^0 source of γ s, thus invalidating the assumption used to calculate it. As already seen in fig. 2, there is no evidence for an enhanced η^0 signal being such a source.

It is interesting to note that the strong rise in the γ and π^0 cross sections claimed at 70 GeV/c [10] is not confirmed by the 110 GeV/c results.

4. INCLUSIVE K^n , Λ^0 AND $\bar{\Lambda}^0$ PRODUCTION

As in the case of γ s several weights and corrections must be applied to the data sample in order to obtain physical cross sections. The first is the potential weight to compensate for V^0 s decaying outside the fiducial volume and too close to the primary vertex. The minimum projected length cut applied to V^0 s is 4 cm; this is shorter than that for γ s as close V^0 s tend to be slow, have finite opening angles, and are more easily seen than γ s close to the primary vertex. This weight includes a correction for V^0 s lost by V^0 -p interactions, increasing the average weights by $\sim 5\%$. Table 3 gives the average potential weights obtained for K^n , Λ^0 and $\bar{\Lambda}^0$.

The data have also to be corrected for the rejection of those V^0 's that give K^n/Λ^0 and $K^n/\bar{\Lambda}^0$ ambiguous fits. The procedure adopted here uses the parameters of the Armenteros-Podolansky plot [14] to compute a weight from the probability that a given V^0 would yield an ambiguous fit. The procedure is described in detail in ref. [6]. The average values of the weights so obtained are given in table 3. The effect of this weight is a statistical division of the number of ambiguous V^0 's, which have been rejected, among the remaining unique K^n 's, Λ^0 's and $\bar{\Lambda}^0$'s in the approximate ratio of 9 : 9 : 2.

Table 4 gives the inclusive production cross sections for K^n , Λ^0 and $\bar{\Lambda}^0$, and for $K^n K^n$ and $\Lambda^0 K^n$, after applying the above corrections together with the scanning efficiency, passing rate, the correction for the 1% probability cut, the correction for the neutral decay modes [4], and normalising with the microbarn equivalent. The $K^n K^n$ and $\Lambda^0 K^n$ cross sections are computed assuming that the individual decays are uncorrelated. Also shown are the corresponding multiplicities $\langle i \rangle$, as defined by eq. (8).

The K^0 and $\bar{K}^0$ cross sections have been estimated using the method described in ref. [13]. If it is assumed that:

- (a) All K^0 's come from the final states $N\bar{K}K\bar{K} + X$, $YK\bar{K} + X$, and $\Xi K + X$, where N is a nucleon, Y is a Λ^0 or Σ , and X is any number of pions.
- (b) The distribution of charge among the particles in these final states obeys a statistical isospin model [15].

it can be shown that the following relationship holds:

$$\begin{aligned} \sigma(K^0) = & 0.34(\sigma(\Lambda^0 K^n) + \sigma(\Sigma^\pm K^n)) \\ & + 0.63 \sigma(K^n K^n) + \sigma(\Xi^-). \end{aligned} \quad (9)$$

The naive assumption that all final states of a given type are equiprobable leads to essentially the same result, the two numerical factors in (9) being replaced by 1/3 and 2/3. At present no measurement of $\sigma(\Sigma^\pm)$

and $\sigma(\Xi^-)$ is available; their cross sections are estimated by extrapolation from 14.3 GeV/c [16]. If it is assumed that the ratio $\sigma(\Sigma^+ K^N)/\sigma(\Lambda^0 K^N)$, and the cross section $\sigma(\Xi^-)$ have the same values at 110 GeV/c as at 14.3 GeV/c, then

$$\sigma(\Sigma^+ K^N) = 1.05 \pm 0.4 \text{ mb}, \quad \sigma(\Xi^-) = 0.13 \pm 0.02 \text{ mb}.$$

Using these values, and the measured values of $\sigma(K^N K^N)$ and $\sigma(\Lambda^0 K^N)$ results in the following values:

$$\sigma(K^0) = 3.7 \pm 0.8 \text{ mb}$$

$$\sigma(\bar{K}^0) = \sigma(K^N) - \sigma(K^0) = 9.2 \pm 0.8 \text{ mb}.$$

The errors have been doubled to allow for the approximate nature of the assumptions involved.

Using the method of ref. [13] it is also possible to estimate the cross sections for the semi-inclusive processes $K^- p \rightarrow N \bar{K} K \bar{K} + \text{pions}$ and $K^- p \rightarrow Y K \bar{K} + \text{pions}$. It can be shown that

$$\alpha_{N \bar{K} K \bar{K}} = 1.27 \sigma(K^N K^N) - 0.33(\sigma(\Lambda K^N) + \sigma(\Sigma^+ K^N)) \quad (10)$$

and

$$\alpha_{Y K \bar{K}} = \sigma(\Lambda K^N) + \sigma(\Sigma^+ K^N) \quad (11)$$

Again, the assumption that all final states of a given type are equiprobable yields essentially the same result, the numerical constants in (10) being replaced by 4/3 and 1/3. Substituting in the values of $\sigma(K^N K^N)$ and $\sigma(\Lambda K^N)$, and assuming the above value of $\sigma(\Sigma^+ K^N)$ results in the values

$$\sigma(K^- p \rightarrow N \bar{K} K \bar{K} + \text{pions}) = 4.0 \pm 0.8 \text{ mb}$$

$$\sigma(K^- p \rightarrow Y K \bar{K} + \text{pions}) = 3.2 \pm 0.6 \text{ mb}$$

This result indicates that an extra $K \bar{K}$ pair is produced in approximately 40% of all inelastic reactions, compared with $\sim 18\%$ at 32 GeV/c [13], and $\sim 9\%$ at 14.3 GeV/c [16].

The average multiplicities for K^n and Λ^0 are shown as a function of charged topology in table 2. Both the K^n and Λ^0 multiplicities are roughly constant between a charged multiplicity of 2 and 8, and then decrease. The K^n multiplicity is ~ 5 times the Λ^0 multiplicity over the whole range of charged topologies.

Fig. 3 shows the cross sections for inclusive K^n , Λ^0 , $\bar{\Lambda}^0$ and K^0 production in K^-p interactions from 3 GeV/c to 110 GeV/c; Fig. 4 shows the cross sections for $K^n K^n$ and $\Lambda^0 K^n$ production in the same energy range [10,12,13,17-22].

The inclusive K^n cross section rises smoothly with increasing energy between 3 GeV/c and 110 GeV/c. The rate of increase is slightly slower than that for inclusive $\pi^\pm$ production. The K^0 cross section is rising rapidly between 14.3 GeV/c and 110 GeV/c, the main contributions coming from the rising $K^n K^n$ and $\Lambda^0 K^n$ cross sections, as seen in fig. 4. The rise of the K^n cross section is also mainly attributable to these contributions.

The inclusive Λ^0 cross section falls from ~ 5 mb at 3 GeV/c to 2.4 mb at 14.3 GeV/c, and then stays essentially constant up to 110 GeV/c. It is known that inclusive Λ^0 production at K^- momenta below 14.3 GeV/c comes primarily from the final state $\Lambda^0 + \text{pions}$, and that this channel decreases in cross section between 3 GeV/c and 14.3 GeV/c. It has been shown at 32 GeV/c [23] that a significant part of the Λ^0 cross section at that energy comes from the channel $\Lambda^0 + K\bar{K} + \text{pions}$, and that this channel increases in cross section between 14.3 GeV/c and 32 GeV/c. The stability of the Λ^0 cross section above 14.3 GeV/c could be due to the continuing decrease of the $\Lambda^0 + \text{pions}$ channel, together with a strong increase of the $\Lambda K\bar{K} + \text{pions}$ channel and some increase of the $\Lambda B\bar{B} + \text{pions}$ channel, where B is a baryon. Indeed, eq. (11) implies that the $\Lambda^0 K^n$ cross section is numerically equal to the $\Lambda^0 K\bar{K}$ cross section [18], the proportion of Λ^0 's coming from the latter channel has risen from 41% at 32 GeV/c to nearly 80% at 110 GeV/c. This rise is well shown in fig. 4, where the $\Lambda^0 K^n$ cross section is seen to rise steeply between 3.93 GeV/c and 110 GeV/c. It is interesting to note that the $K^n K^n$ cross section,

which is lower than the $\Lambda^0 K^n$ cross section at 14.3 GeV/c, has risen much faster with energy and at 110 GeV/c is double the $\Lambda^0 K^n$ cross section.

The present statistics do not permit an accurate measurement of the Σ^0 cross section; from inspection of the $\Lambda^0 \gamma$ effective mass distribution in those events with both a seen Λ^0 and seen γ s an estimate of $\sigma(\Sigma^0)/\sigma(\Lambda^0) \sim 40\%$ is all that can be obtained, corresponding to $\sigma(\Sigma^0) \sim 1$ mb.

The inclusive $\bar{\Lambda}^0$ cross section shows a dramatic rise between 14.3 GeV/c and 110 GeV/c, by a factor of more than 20. This increase is probably to a large extent due to the increasing production of $B\bar{B}$ pairs with increasing energy. This is another feature that would help explain the stability of the inclusive Λ^0 cross section and should cause it to start rising again at higher energies.

5. INVARIANT DIFFERENTIAL CROSS SECTIONS

Fig. 5 shows the invariant differential cross section for inclusive K^n production at 110 GeV/c:

$$F(x) = \frac{1}{\pi P_{\max}^{\text{cm}}} \int_{E^{\text{cm}}} \frac{d^2\sigma}{dx dP_T^2} dP_T^2 \quad (12)$$

where $P_{\max}^{\text{cm}}$ is the maximum allowed centre of mass momentum of a K^n ($\sim \sqrt{s}/2$), E^{cm} is the centre of mass energy of the K^n , x is the Feynman x variable, defined as $x = P_{\parallel}^{\text{cm}}/P_{\max}^{\text{cm}}$, and P_T^2 is the squared transverse momentum of the K^n , relative to the beam axis. Comparison with the corresponding distributions at 14.3 GeV/c [24] and 32 GeV/c [25] (also shown in fig. 5) shows that these distributions are consistent with scaling behaviour over the full x -range.

Fig. 5 also shows the invariant differential cross section at 110 GeV/c for K^n s produced together with another K^n . Most of these K^n s are centrally produced and are mainly the result of $K^0 \bar{K}^0$ pair production, either in the channel $N\bar{K}K\bar{K} + \text{pions}$ or $YK\bar{K} + \text{pions}$. The increase in the

production of K^0 , already seen to be mainly a consequence of the increase in $\sigma(K^n K^n)$ with energy, is seen here to be the result of central $K\bar{K}$ pair production, a process expected to increase with energy.

Fig. 6 shows the invariant distribution of eq. (12) for inclusive Λ^0 production, with data from 3.93 GeV/c [18], 7.3 GeV/c [19], 14.3 GeV/c [18] and 32 GeV/C [23] shown for comparison. There is a considerable reduction in the invariant cross section over the whole x-range with increasing energy, and in addition the shape changes from one with a central maximum at low energies to one with a flat central region at medium energies, and finally to one with very pronounced forward and backward peaks and a deep central dip at our energy. This behaviour can be explained by considering that Λ^0 production consists of three main components: $K^- p \rightarrow \Lambda^0 + \text{pions}$ ("hypercharge annihilation"), $K^- p \rightarrow \Lambda^0 + KK + \text{pions}$, and $K^- p \rightarrow \Lambda^0 + B\bar{B} + \text{pions}$, where N is a nucleon. Fig. 7 shows the invariant Feynman x distribution of Λ^0 s produced together with a K^n . This distribution can be interpreted using the model of ref. [13] as the distribution of Λ^0 s from the channel $\Lambda K\bar{K} + \text{pions}$. From this interpretation we observe that the Λ^0 s from this channel are produced predominantly backwards and furthermore by comparison with the total inclusive Λ^0 distribution (also shown in fig. 7) we conclude that the channel $\Lambda^0 K\bar{K} + \text{pions}$ accounts for all the backward Λ^0 production^(*). From results at 32 GeV/c [23] it is known that the Λ^0 s from the process $\Lambda^0 + \text{pions}$ have an essentially uniform distribution in invariant x, and that those from the channel $\Lambda^0 B\bar{B} + \text{pions}$ are produced mainly forwards. An explanation of the change of the shape of the invariant x distribution with energy is then as follows. At low energies the $\Lambda^0 + \text{pions}$ contribution dominates and produces a centrally peaked distribution. This contribution decreases in size relative to the two fragmentation processes until at 110 GeV/c the distribution is dominated by the two fragmentation components.

(*) The effect seen in two bins of the Λ^0 with associated K^n distribution (the non-inclusive data are higher than the inclusive data) is simply due to the application of large weights to a small subsample of the data.

Fig. 8 shows the invariant differential cross section of eq. (12) for inclusive $\bar{\Lambda}^0$ production at 110 GeV/c, with data from 14.3 GeV/c [21] and 32 GeV/c [26] for comparison. Within the limited statistics the general trend of the distribution, to peak at slightly positive x , seems to be the same as at the lower energies. This is not surprising as it is possible to produce $\bar{\Lambda}^0$'s via the fragmentation of the incident K^- ; such $\bar{\Lambda}^0$'s will tend to be at positive x . This process requires the creation of only two $q\bar{q}$ pairs, and thus should occur with a higher probability than central production.

Fig. 9 shows the invariant differential cross section

$$F(y) = \frac{1}{\pi} \int \frac{d^2\sigma}{dy dP_T^2} dP_T^2 \quad (13)$$

for inclusive K^n production at 110 GeV/c, where y is the centre of mass rapidity variable, defined as $y = 1/2 \ln[(E^{cm} + P_L^{cm})/(E^{cm} - P_L^{cm})]$. Also shown are the data from 14.3 GeV/c [18], 32 GeV/c [25] and 70 GeV/c [10] for comparison. Despite the broadening of the distribution with increasing energy, it retains a distinct peak, which moves to increasingly large y as the energy increases.

It is possible to use the K^n rapidity distribution to check the values of $\sigma(K^0)$ and $\sigma(K^0)$ obtained in sect. 4. If it is assumed that all K^0 's are produced centrally, via $K\bar{K}$ pair production, and that all backward $\bar{K}^0$'s are also produced by this mechanism, then:

$$\sigma(K^0)_{y < 0} \approx \sigma(K^0)_{y > 0}$$

$$\sigma(K^0)_{y < 0} \approx \sigma(\bar{K}^0)_{y < 0}$$

which leads to the following relationship:

$$\sigma(K^0) = \sigma(K^n)_{y < 0} = 3.4 \pm 0.5 \text{ mb}$$

$$\sigma(\bar{K}^0) = \sigma(K^n)_{y > 0} = 9.5 \pm 0.5 \text{ mb.}$$

These numbers are quite consistent with those obtained in sect. 4.

Fig. 10 shows the invariant rapidity distribution for inclusive Λ^0 production. The expansion of the central region afforded by the use of the rapidity variable emphasises the central dip. Fig. 11 shows the same distribution for inclusive $\bar{\Lambda}^0$ production.

Fig. 12 shows the invariant differential cross section

$$F(p_T^2) = \int \frac{d^2\sigma}{dp_T^2 dx} dx \quad (14)$$

for inclusive K^n production at 110 GeV/c. This distribution is well described by an exponential $e^{-bp_T^2}$ with $b = 4 \pm 0.2(\text{GeV/c})^{-2}$ below $p_T^2 = 1(\text{GeV/c})^2$. Fig. 13 shows the distribution of eq. (14) for inclusive Λ^0 production; the corresponding exponential slope is $3.8 \pm 0.3(\text{GeV/c})^{-2}$ below $p_T^2 = 1(\text{GeV/c})^2$. Table 5 gives the mean values of p_T and p_T^2 for inclusive K^n , Λ^0 , and $\bar{\Lambda}^0$ production. The values of p_T and p_T^2 for Λ^0 and $\bar{\Lambda}^0$ production are somewhat higher than for K^n production, although the exponential slopes are the same within the errors.

6. $(1 - x)^n$ FITS

Current theoretical ideas based on quark counting rules ref. [28] for example] predict the values of the exponent, n , if the fragmentation regions (large $|x|$) of the Feynman x distributions of produced particles are parametrised in the form $(1 - |x|)^n$. In order to test these ideas this form has been fitted to the forward part of the K^n invariant x distribution, and to both the forward and backward parts of the Λ^0 invariant x distribution. Table 6 shows the ranges of the fits, the resulting values of n , and the predictions of ref. [26], which assumes a gluon exchange mechanism. The values of n obtained for the K^n distribution, and for the forward Λ^0 distribution are consistent with the predictions, and the value for the backward Λ^0 s is less than 2 standard deviations from the prediction.

7. CONCLUSIONS

- (a) The inclusive γ production cross section in K^-p interactions is increasing faster with energy than inclusive π^+ and π^- production; either a rapid rise in π^0 production is responsible, or other sources of γ 's are becoming more important.
- (b) The inclusive K^n cross section is increasing slowly, at the same rate as the average charged multiplicity, most of the rise being due to the rapid increase in the central production of $K\bar{K}$ pairs.
- (c) Inclusive Λ^0 production stays constant at ~ 2.5 mb between 14.3 GeV/c and 110 GeV/c, after falling from 5 mb at 3 GeV/c. The continuing decrease in the hypercharge annihilation channel is compensated for by the increase in the fragmentation processes $\Lambda K\bar{K} + \text{pions}$ and $\Lambda N\bar{N} + \text{pions}$. At 110 GeV/c $\sim 80\%$ of the total Λ^0 cross section comes from the $\Lambda K\bar{K} + \text{pions}$ channel. This behaviour is strikingly observed in the invariant Feynman x distribution, where a deep central dip is observed at 110 GeV/c.
- (d) The inclusive $\bar{\Lambda}^0$ cross section is rising very fast with energy; it has increased by a factor of ~ 20 from 14.3 GeV/c.
- (e) It is found that an extra pair of strange particles is produced in about 40% of inelastic interactions at 110 GeV/c, compared to $\sim 18\%$ at 32 GeV/c and $\sim 9\%$ at 14.3 GeV/c.
- (f) Fits to the invariant P_T^2 distributions for inclusive K^n and Λ^0 production result in essentially the same exponential slope (4 ± 0.2 and $3.8 \pm 0.3(\text{GeV}/c)^{-2}$ respectively).
- (g) Fits of the form $(1 - |x|)^n$ in the fragmentation regions of the K^n and Λ^0 invariant Feynman x distributions yield values of n that are consistent with quark counting rule predictions.

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REFERENCES

- [1] I. Lehrs, CERN/EF/BEAM 76-3 (1976).
- [2] HYDRA System Manual, CERN.
- [3] F. Bruyant et al., HYDRA Applications Library Long Write-Up GEOMPAM, CERN.
- [4] Review of Particle Properties, Particle Data Group (1980).
- [5] M. Aderholz et al., HYDRA Applications Library Long Write-Up KINEMA, CERN.
- [6] P.R.S. Wright, Ph.D Thesis, University of London (1980).
- [7] A.S. Carroll et al., Phys. Lett. 61B (1976) 303.
- [8] A.C. Borg et al., Nucl. Phys. B106 (1976) 430.
- [9] G. Ransoné et al., Nucl. Phys. B167 (1980) 285.
- [10] J.M. Laffaile et al., Z. Phys. C2 (1979) 95.
- [11] D. Merrill et al., Nucl. Phys. B18 (1970) 403.
- [12] J.R. Fry et al., Nucl. Phys. B58 (1973) 408.
- [13] C. Cochet et al., Nucl. Phys. B124 (1977) 61.
- [14] J. Podolansky and R. Armenteros, Phil. Mag. Series 7, vol. 45 (1954) 13.
- [15] F. Cerulus, Nuovo Cimento 19 (1961) 528.
- [16] M. Bardadin-Otwinowska et al., Nucl. Phys. B90 (1975) 397.
- [17] R. Blokzijl et al., Nucl. Phys. B39 (1972) 141.
- [18] A.C. Borg et al., Nuovo Cimento 22A (1974) 559.
- [19] S.U. Chung et al., Phys. Rev. D11 (1975) 1010.
- [20] J. Bartsch et al., Nucl. Phys. B40 (1972) 103.
- [21] M. Bardadin-Otwinowska et al., Nuovo Cimento Lett. 13 (1975) 597.
- [22] H.G. Kirk et al., Nucl. Phys. B116 (1976) 99.
- [23] U. Gensch et al., Nucl. Phys. B173 (1980) 154.
- [24] A. Borg, Ph. D. Thesis, Saclay Note CEA-N-2029 (1978).
- [25] France-Soviet Union and CERN-Soviet Union Collaboration, paper submitted to Tokyo Conference 1978.

REFERENCES (Cont'd)

- [26] U. Gensch et al., Z. Phys. C2 (1979) 7.
- [27] Y.I. Arestov et al., France-USSR and CERN-USSR Collaborations, paper submitted to Tokyo Conference (1978).
- [28] J.F. Gunion, Phys. Lett. 88B 1 (1979) 150.

TABLE CAPTIONS

TABLE 1 Numbers of V^0 after kinematics.

TABLE 2 γ , K^n , and Λ^0 topological multiplicities.

TABLE 3 Mean weights of γ 's and V^0 's.

TABLE 4 Inclusive cross sections and average multiplicities.

TABLE 5 Mean values of p_T and p_T^2 for K^n , Λ^0 and $\bar{\Lambda}^0$.

TABLE 6 Results of $(1 - x)^n$ fits.

TABLE 1

Fits with p > 1%	
Category	No.
γ	4994
K^n	1157
Λ^0	354
$\bar{\Lambda}^0$	65
γ/K^n	71
γ/Λ^0	106
$\gamma/\bar{\Lambda}^0$	92
K^n/Λ^0	150
$K^n/\bar{\Lambda}^0$	86
$\gamma/K^n/\Lambda^0$	32
$\gamma/K^n/\bar{\Lambda}^0$	28
Other	9

TABLE 2

N_c	$\langle \gamma \rangle$	$\langle K^n \rangle$	$\langle \Lambda^0 \rangle$
2	5.83 ± 0.4 (a)	0.95 ± 0.12	0.15 ± 0.04
4	5.86 ± 0.25	0.73 ± 0.06	0.15 ± 0.04
6	7.23 ± 0.26	0.74 ± 0.05	0.15 ± 0.04
8	8.33 ± 0.29	0.72 ± 0.05	0.14 ± 0.04
10	9.71 ± 0.38	0.68 ± 0.06	0.13 ± 0.04
12	10.4 ± 0.6	0.52 ± 0.07	0.11 ± 0.04
14	8.49 ± 0.88	0.52 ± 0.1	0.12 ± 0.04
16	9.34 ± 1.43	0.25 ± 0.13	0.08 ± 0.05
18	8 ± 2.6	1 ± 0.6	-

(a) Errors statistical only.

TABLE 3

	γ	K^n	Λ^0	$\bar{\Lambda}^0$
<Potential weight>	8.523	1.484	1.55	1.5
<QED weight>	1.03	-	-	-
<Ambiguity weight>	-	1.093	1.303	1.363

TABLE 4

	$\sigma(\text{mb})$	$\langle i \rangle$
γ	137 ± 10	7.61 ± 0.22
π^0	63 ± 6	3.5 ± 0.17
K^n	12.9 ± 0.5	0.72 ± 0.03
Λ^0	2.5 ± 0.2	0.14 ± 0.01
$\bar{\Lambda}^0$	0.54 ± 0.1	0.03 ± 0.006
$K^n K^n$	3.97 ± 0.85	0.22 ± 0.05
$\Lambda^0 K^n$	2.05 ± 0.36	0.11 ± 0.02
K^0	3.7 ± 0.8	0.21 ± 0.04
$\bar{K}^0$	9.2 ± 0.8	0.51 ± 0.04

TABLE 5

	K^n	Λ^0	$\bar{\Lambda}^0$
$\langle p_T \rangle$ (GeV/c)	0.461	0.495	0.486
$\langle p_T^2 \rangle$ ((GeV/c) ²)	0.289	0.327	0.330

TABLE 6

	Range	n	Prediction [26]
K^n	$0.3 < x < 1.0$	0.98 ± 0.25	$1^{(*)}$
Λ^0	$0.4 < x < 1.0$	1.7 ± 0.9	2
	$-1.0 < x < -0.5$	0.5 ± 0.3	1

(*) Prediction for $\bar{K}^0$ production.

FIGURE CAPTIONS

- Fig. 1 Distribution of γ lab momentum, p_{lab} . The errors are statistical only.
- Fig. 2 $\gamma\gamma$ effective mass distribution.
- Fig. 3 Inclusive single particle cross sections as a function of incident K^- momentum, p_{lab} .
- Fig. 4 Inclusive two particle cross sections as a function of K^- momentum.
- Fig. 5 Invariant Feynman x distribution for inclusive K^n production with data from 14.3 GeV/c [24] and 32 GeV/c [25], and the distribution of K^n with another seen K^n . For clarity error bars are not drawn on the lower energy points; the errors on the 110 GeV/c data are statistical only.
- Fig. 6 Invariant Feynman x distribution for inclusive Λ^0 production with data from 3.93 GeV/c [18], 7.3 GeV/c [19], 14.3 GeV/c [18] and 32 GeV/c [23]. The errors are statistical only.
- Fig. 7 Invariant Feynman x distribution for inclusive Λ^0 production at 110 GeV/c, together with the distribution of Λ^0 where a K^n was also seen.
- Fig. 8 Invariant Feynman x distribution for inclusive $\bar{\Lambda}^0$ production with data from 14.3 GeV/c [21] and 32 GeV/c [24]. The errors are statistical only.
- Fig. 9 Invariant c.m.s. rapidity distribution for inclusive K^n production, with data from 14.3 GeV/c [18], 22 GeV/c [25], and 70 GeV/c [10].
- Fig. 10 Invariant c.m.s. rapidity distribution for inclusive Λ^0 production.

FIGURE CAPTIONS (Cont'd)

Fig. 11 Invariant c.m.s. rapidity distribution for inclusive $\bar{\Lambda}^0$ production.

Fig. 12 Invariant p_T^2 distribution for inclusive K^n production showing result of fit to form $ae^{-bp_T^2}$.

Fig. 13 Invariant p_T^2 distribution for inclusive Λ^0 production showing result of fit to form $ae^{-bp_T^2}$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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Fig. 13