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Neutral strange particle production in $K^+$ and $\pi^+$ collisions with Al and Au nuclei at 250 GeV/c

EHS-NA22 Collaboration

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Abstract. Data are presented on inclusive $\bar{K}_S^0$ and $\Lambda$ production in $K^+$ and $\pi^+$ collisions with Al and Au nuclei at 250 GeV/c. Results are given on total inclusive cross sections and their $A$ dependence, as well as on distributions in Feynman-$x_F$, rapidity $y$ and transverse momentum. Ratios of $\bar{K}_S^0$ and of $\Lambda$ to $\pi^-$ production are presented. The data are compared with predictions of the quark-parton model FRITIOF.

1 Introduction

In this paper we report on a study of inclusive production of $\bar{K}_S^0$, $\Lambda$ and $\bar{\Lambda}$ in interactions of $K^+$ and $\pi^+$ mesons with Al and Au nuclei at 250 GeV/c, corresponding to the reactions

$$K^+ + Al \to K_S^0 + X,$$

$$K^+ + Au \to K_S^0 + X,$$

$$\pi^+ + Al \to K_S^0 + X,$$

$$\pi^+ + Au \to K_S^0 + X,$$

and

$$K^+ \to \Lambda + X,$$

$$K^+ \to \Lambda + X,$$

$$\pi^+ \to \Lambda + X,$$

$$\pi^+ \to \Lambda + X,$$

$$K^+ \to \bar{\Lambda} + X,$$

$$K^+ \to \bar{\Lambda} + X,$$

$$\pi^+ \to \bar{\Lambda} + X,$$

$$\pi^+ \to \bar{\Lambda} + X.$$
2 Experimental procedure

The experimental set-up of EHS and the trigger conditions are described in detail in [4]. The characteristics of the nuclear targets are described in [5]. Here, we mention only the details specific for the reactions studied. The neutral strange particles are detected as $K^0$s in a cylindrical bubble chamber which has a diameter of 80 cm and depth 40 cm, wherein the nuclear targets are placed at 15.5 cm from the entrance window of the beam.

A total of about 2900 $K^+$ and 7500 $\pi^+$ events, candidate interactions in the foils, is measured. The sample of events, selected for this analysis, satisfies the following criteria:

- the beam track is well measured and matches with the hits in the upstream wire chambers;
- the reconstructed vertex position is within one of the foils;
- the event is not a candidate for a quasi-elastic or coherent interaction;
- A quasi-elastic event is defined by the following criteria:
  1. the charge multiplicity equals two,
  2. the missing transverse momentum is less than 0.2 GeV/c,
  3. the missing longitudinal momentum is less than 9 GeV/c.
  
- A coherent interaction is defined by the requirements that
  1. the charge multiplicity is odd and $\leq 5$,
  2. all charged particles have rapidities larger than one, if measured in the $K^+$-nucleon c.m. system.

The number of accepted events amounts to 1211, 991, 3410 and 2834 for $K^+$ Al, $K^+$ Au, $\pi^+$ Al and $\pi^+$ Au interactions, respectively. The admixture of interactions in the hydrogen of the bubble chamber is estimated to be less than 4% in the Al and less than 2% in the Au sample. Microbarn equivalents are obtained by normalization of the number of events to the corresponding inelastic cross sections at 250 GeV/c [6].
The inclusive cross sections for reactions (1-8) in the interval $-1 < x < 0.1$ are collected in Table 3. The first error is statistical, the second systematical. In the remainder of the paper, all errors quoted are statistical.

The ratios $\sigma_{\pi^+ A} / \sigma_{K^+ A}$ for $K_0^+$ and $A$ production, given in Table 3, are compatible within errors with the ratios of the inelastic $\pi^+$ and $K^+$ cross sections on Al and Au nuclei at 250 GeV/c [6]

$$\frac{\sigma_{\pi^+ A}}{\sigma_{K^+ A}} = 1.14 \pm 0.05,$$

$$\frac{\sigma_{\pi^+ A}}{\sigma_{K^+ A}} = 1.05 \pm 0.05.$$  

The ratios $\sigma_{\pi^+ A} / \sigma_{K^+ A}$ for $K_0^+$ and $A$ production, given in Table 3, are compatible within errors with the ratios of the inelastic $\pi^+$ and $K^+$ cross sections on Al and Au nuclei at 250 GeV/c [6]

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$$\frac{\sigma_{\pi^+ A}}{\sigma_{K^+ A}} = 1.05 \pm 0.05.$$  

In Table 4 we compare the average multiplicities of $K_0^+$ and $A$ in $K^+$ and $\pi^+$ interactions on nuclei to those in "elementary" $K^+p$ and $\pi^+p$ interactions [7,8]. Both $\langle K_0^+ \rangle$ and $\langle A \rangle$ are the same within errors for $K^+$ and $\pi^+$ induced interactions on both nuclei. From Table 4 we observe that the average numbers of produced $A$’s on both targets and for both projectiles, are compatible within one standard deviation with the relation

$$\langle n_A (MA) \rangle = \langle n_A (MP) \rangle \cdot \langle \nu_A \rangle,$$  

where $M$ is either $K^+$ or $\pi^+$ and $\langle \nu_A \rangle$ is the average number of projectile collisions in the nucleus $A$, equal to 1.67 for Al and 2.61 for Au. In other words, the probability to produce a $A$ in a meson-nucleus collision is proportional to the number of projectile collisions. For $K_0^+$ production in $\pi^+$ interactions, the analogous relation

$$\langle n_{K_0^+} (MA) \rangle = \langle n_{K_0^+} (MP) \rangle \cdot \langle \nu_A \rangle$$  

is not observed: the experimental average number of produced $K_0^+$’s is systematically lower than the one expected from the average number of projectile collisions. These observations are in agreement with the ideas put forward in [13] about $A$ retention and reinteractions of kaons (see also Sect. 5).

The cross sections for the reactions (1-8) as a function of atomic weight $A$ are shown in Fig. 3a, b. The $K^+p$ and $\pi^+p$ data are taken from [7,8] but restricted to the same kinematic interval of $-1.0 < x < 0.1$. The cross sections are well fitted by the expression

$$\sigma = \sigma_0 A^\alpha.$$  

The fitted values for $\sigma_0$ and $\alpha$ are listed in Table 5. The slope parameter $\alpha$ is of the order of 0.9. A similar dependence is observed in $\pi^-A$ ($A = C$, Cu, Pb) interactions at 40 GeV/c [3].

The inclusive cross sections for reactions (1-8) are compared with the predictions of the quark-parton model FRITIOF [10] (version 3) and with a modified version FRITIOF' [7] of this model (see Table 3 and Fig. 3). The differences between the two versions of this model are:

- the value of the strangeness suppression parameter $\lambda_s$ in the Lund fragmentation scheme JETSET 6.3 was taken to be 0.2 in FRITIOF and 0.3 in FRITIOF' (default values were taken for all other parameters);
- in FRITIOF', the momentum sharing function of the $J$-quark was modified to the form

$$f(x_J) = x_J(1-x_J)^\alpha.$$  

in Figs. 2a-c. The $K_0^+$, $A$ and $\bar{A}$ effective mass distributions in the combined $K^+$ and $\pi^+$ samples

Table 2. The average $K_0^+$, $A$ and $\bar{A}$ weights in the reactions (1-12)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$K^+ A$</th>
<th>$K^+ Au$</th>
<th>$\pi^+ A$</th>
<th>$\pi^+ Au$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle W_{K_0^+} \rangle$</td>
<td>5.40</td>
<td>4.77</td>
<td>4.36</td>
<td>4.18</td>
</tr>
<tr>
<td>$\langle W_A \rangle$</td>
<td>4.79</td>
<td>4.73</td>
<td>5.48</td>
<td>4.80</td>
</tr>
<tr>
<td>$\langle W_{\bar{A}} \rangle$</td>
<td>10.33</td>
<td>8.24</td>
<td>8.00</td>
<td>6.42</td>
</tr>
</tbody>
</table>
Table 3. The $K^0_S$ and $A$ inclusive cross sections in reactions (1–8) in the interval $-1.0 < x_F < 0.1$, together with their ratio in $K^+$ and $\pi^+$ collisions on nuclei Al and Au. Predictions are given of two versions of the FRITIOF model (see text) for the cross sections in the same kinematic interval

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Experiment $\sigma_{exp}$ (mb)</th>
<th>Model (mb)</th>
<th>$\sigma^{exp}/\sigma^{model}$ (from exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\text{Al} \rightarrow K^0_S + X$</td>
<td>74.9 ± 8.6 ± 7.5</td>
<td>77</td>
<td>90</td>
</tr>
<tr>
<td>$\pi^+\text{Al} \rightarrow K^0_S + X$</td>
<td>75.7 ± 5.7 ± 7.6</td>
<td>70</td>
<td>95</td>
</tr>
<tr>
<td>$K^+\text{Au} \rightarrow K^0_S + X$</td>
<td>412 ± 53 ± 41</td>
<td>529</td>
<td>596</td>
</tr>
<tr>
<td>$\pi^+\text{Au} \rightarrow K^0_S + X$</td>
<td>457 ± 30 ± 46</td>
<td>447</td>
<td>576</td>
</tr>
<tr>
<td>$K^+\text{Al} \rightarrow A + X$</td>
<td>46.3 ± 7.5 ± 4.6</td>
<td>27</td>
<td>40</td>
</tr>
<tr>
<td>$\pi^+\text{Al} \rightarrow A + X$</td>
<td>44.0 ± 4.8 ± 4.4</td>
<td>34</td>
<td>48</td>
</tr>
<tr>
<td>$K^+\text{Au} \rightarrow A + X$</td>
<td>348 ± 50 ± 35</td>
<td>205</td>
<td>282</td>
</tr>
<tr>
<td>$\pi^+\text{Au} \rightarrow A + X$</td>
<td>336 ± 32 ± 34</td>
<td>227</td>
<td>320</td>
</tr>
</tbody>
</table>

This was found necessary to describe the inclusive spectra of baryons in $\pi^+p$ and $K^+p$ interactions [7].

The predicted cross sections, based on 20,000 generated events per channel, are given in Table 3 and the dependence of the $K^0_S$ and $A$ cross sections on atomic weight $A$ is shown in Fig. 3a, b. Both versions of the model correctly predict the $A$-dependence of the $A$ production cross section in reactions (5) to (8) but the cross section values are considerably better reproduced by the modified version of the model. The cross sections for $K^0_S$ in interactions on Al are reasonably well predicted by both versions of the model. However, a too high cross section is predicted by FRITIOF' for $K^0_S$ production in $K^+\text{Au}$ interactions.

Table 4. The average $K^0_S$ and $A$ multiplicity per inelastic collision in the interval $-1.0 < x_F < 0.1$ for reactions (1–8), compared to that in $K^+p$ and $\pi^+p$ collisions. In the fourth and sixth columns, the average $K^0_S$ and $A$ multiplicities computed according to (14) are given

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\langle \pi^- \rangle$</th>
<th>$\langle K^0_S \rangle$</th>
<th>$\langle K^0_S \rangle$ from (14)</th>
<th>$\langle A \rangle$</th>
<th>$\langle A \rangle$ from (14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+p$</td>
<td>2.78 ± 0.02</td>
<td>0.181 ± 0.019</td>
<td>input</td>
<td>0.082 ± 0.010</td>
<td>input</td>
</tr>
<tr>
<td>$\pi^+p$</td>
<td>2.75 ± 0.02</td>
<td>0.184 ± 0.011</td>
<td>input</td>
<td>0.086 ± 0.012</td>
<td>input</td>
</tr>
<tr>
<td>$K^+\text{Al}$</td>
<td>4.26 ± 0.16</td>
<td>0.260 ± 0.057</td>
<td>0.302 ± 0.032</td>
<td>0.161 ± 0.042</td>
<td>0.137 ± 0.017</td>
</tr>
<tr>
<td>$\pi^+\text{Al}$</td>
<td>4.72 ± 0.13</td>
<td>0.233 ± 0.045</td>
<td>0.307 ± 0.032</td>
<td>0.134 ± 0.028</td>
<td>0.144 ± 0.020</td>
</tr>
<tr>
<td>$K^+\text{Au}$</td>
<td>6.17 ± 0.24</td>
<td>0.299 ± 0.069</td>
<td>0.472 ± 0.050</td>
<td>0.252 ± 0.062</td>
<td>0.214 ± 0.026</td>
</tr>
<tr>
<td>$\pi^+\text{Au}$</td>
<td>5.93 ± 0.22</td>
<td>0.316 ± 0.054</td>
<td>0.480 ± 0.050</td>
<td>0.232 ± 0.046</td>
<td>0.224 ± 0.031</td>
</tr>
</tbody>
</table>

This table shows the results of a fit with the expression $\sigma = \sigma_{exp} A^4$ for the inclusive $K^0_S$ and $A$ cross sections in $K^+/\pi^+$ interactions on $p/\text{Al/Au}$ at 250 GeV/c in $-1 < x_F < 0.1$.

Table 5. Results of a fit with the expression $\sigma = \sigma_{exp} A^4$ for the inclusive $K^0$ and $A$ cross sections in $K^+/\pi^+$ interactions on $p/\text{Al/Au}$ at 250 GeV/c in $-1 < x_F < 0.1$, together with their ratio in $K^+$ and $\pi^+$ collisions on nuclei Al and Au. Predictions are given of two versions of the FRITIOF model (see text) for the cross sections in the same kinematic interval

<table>
<thead>
<tr>
<th>Beam</th>
<th>Particles</th>
<th>$A_{exp}$ (mb)</th>
<th>$A_{model}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>$K^0_S$</td>
<td>0.882 ± 0.043</td>
<td>3.981 ± 0.435</td>
</tr>
<tr>
<td></td>
<td>$A$</td>
<td>1.041 ± 0.049</td>
<td>1.445 ± 0.197</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$K^0_S$</td>
<td>0.979 ± 0.034</td>
<td>2.709 ± 0.266</td>
</tr>
<tr>
<td></td>
<td>$A$</td>
<td>0.986 ± 0.044</td>
<td>1.786 ± 0.244</td>
</tr>
</tbody>
</table>

Table 6. Inclusive cross sections for events with two $V^0$-particles in the final state in $K^+\text{Al/Au}$ and $\pi^+\text{Al/Au}$ interactions at 250 GeV/c; the number of events is given in brackets

<table>
<thead>
<tr>
<th>Final particles</th>
<th>Cross sections (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+\text{Al}$</td>
<td>17 ± 7 (6)</td>
</tr>
<tr>
<td>$K^+\text{Au}$</td>
<td>202 ± 91 (7)</td>
</tr>
<tr>
<td>$\pi^+\text{Al}$</td>
<td>15 ± 4 (14)</td>
</tr>
<tr>
<td>$\pi^+\text{Au}$</td>
<td>107 ± 29 (17)</td>
</tr>
<tr>
<td>$A$</td>
<td>30 ± 19 (3)</td>
</tr>
<tr>
<td>$\pi^+\text{Al}$</td>
<td>81 ± 63 (2)</td>
</tr>
<tr>
<td>$\pi^+\text{Au}$</td>
<td>1.7 ± 1.2 (2)</td>
</tr>
<tr>
<td>$\pi^+\text{Al}$</td>
<td>28 ± 16 (3)</td>
</tr>
<tr>
<td>$\pi^+\text{Au}$</td>
<td>282 ± 77 (27)</td>
</tr>
</tbody>
</table>
Table 6 gives the inclusive cross sections of $K^+$ and $\pi^+$ interactions on Al and Au nuclei for channels with two neutral strange particles in full phase space (the number of events is given in brackets). For events with two $K_S^0$ mesons, the parametrization (15) yields values of the slope parameter $\alpha = 0.92 \pm 0.14$ and $0.90 \pm 0.06$ for $K^+$ and $\pi^+$ beams, respectively. They are equal within errors to those for inclusive $K_S^0$ production.

4 Inclusive spectra

4.1 Feynman-$x_F$ and rapidity distributions

Feynman $x_F$ and rapidity $y$ are calculated in the c.m.s. of the projectile and a nucleon of the nucleus. The Feynman-$x_F$ distributions for $K_S^0$ and $\Lambda$ production are shown in Figs. 4 and 5; the rapidity distributions are given in Table 7.

Figure 4 shows that the $K_S^0$ spectra up to $x_F = 0.1$ are very similar in $K^+$ and in $\pi^+$ induced reactions on Al, as well on the heavy Au nucleus. Both versions of the FRITIOF model describe $K_S^0$ production (Fig. 4) reasonably well. Exceptions are reactions on Al in the target fragmentation region, where the models predict a too low cross section, and $K^+$Au interactions in the central region, where the model is too high.

The $\Lambda$-hyperons in the reactions (5) to (8) are primarily produced from target fragmentation. As for collisions on hydrogen [7], the FRITIOF model predicts a double bump structure of the $d\sigma/dx$ spectra of the $\Lambda$-hyperons which is not observed experimentally (see Fig. 4a-d. Feynman-$x_F$, distributions for $K_S^0$ production in a $K^+$Al, b $K^+$Au, c $\pi^+$Al and d $\pi^+$Au interactions. The curves are predictions of the quark-parton models FRITIOF (full line) and FRITIOF' (dotted line).

Table 7. Differential cross section $d\sigma/dy$ (in mb) for $K_S^0$ and $\Lambda$ production in $K^+$Al, $K^+$Au, $\pi^+$Al and $\pi^+$Au collisions

<table>
<thead>
<tr>
<th>Channel</th>
<th>$K^+$ Al</th>
<th>$K^+$ Au</th>
<th>$\pi^+$ Al</th>
<th>$\pi^+$ Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S^0$</td>
<td>$K^+$ Al</td>
<td>$K^+$ Au</td>
<td>$\pi^+$ Al</td>
<td>$\pi^+$ Au</td>
</tr>
<tr>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
</tr>
<tr>
<td>$K^+$ Al</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
</tr>
<tr>
<td>$K^+$ Au</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
</tr>
<tr>
<td>$\pi^+$ Al</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
</tr>
<tr>
<td>$\pi^+$ Au</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
<td>$d\sigma/dy$</td>
</tr>
</tbody>
</table>

The $\Lambda$ production cross section is given in Table 7.
Fig. 5a-d. As in Fig. 4, for Λ production

Fig. 6a-d. ρ^2 distributions for K^0 production in a K^+ Al, b K^+ Au, c π^+ Al and d π^+ Au interactions. The curves are predictions from the FRITIOF model

Fig. 7a-d. As in Fig. 6, for Λ production

4.2 Transverse momentum distributions

Figures 6 and 7 present the distributions in the transverse momentum squared, dσ/dp_T^2, for K^0 and Λ in the reactions (1-8). The values of 〈p_T〉 and 〈p_T^2〉 are given in Table 8. The results of a fit to a single exponential form a exp(−b p_T^2) are given in Table 9. As seen from Table 9, the values of the slope parameters are the same within errors for interactions on Al as on Au nuclei and for Λ production. The p_T^2-distributions as a function of the transverse mass m_T=(m_K^2+p_T^2)^1/2 are very well described by the form a exp(−b m_T) with the...
parameters given in Table 10. The slope parameters in this parametrization are the same, within the measurement accuracy, for interactions on Al and Au.

Both versions of the FRITIOF model* describe fairly well the $p_T^2$-distributions of $K_S^0$'s but fail to reproduce the $A$-spectrum at large $p_T^2$.

The transverse spin polarization $P_A$ of the $A_0$ in the $K^+$-induced reactions (5) plus (6) and in the $\pi^+$-induced reactions (7) plus (8) was determined, using the same method as in [7] for interactions on protons. In $K^+$ collisions the polarization is found to be $P_A = -0.78 \pm 0.39$ ($-0.54 \pm 0.45$) for $P_T(A)$ smaller (larger) than 0.5 GeV/c. In $\pi^+$ collisions, the numbers are $P_A = 0.18 \pm 0.24$ and $P_A = -0.41 \pm 0.28$, respectively.

5 Ratios of strange particle to $\pi^-$ production

A dramatic increase in the ratio of strange to non-strange particles produced, is considered to be a possible signal of the formation of a quark-gluon plasma (QGP) in high energy heavy ion collisions. Data from a variety of interactions at 250 GeV/c to the form

\[ \frac{d\sigma}{dx} \propto \exp (-bP_T^2) \]

is presented in Fig. 8. The results for $K^+p$ and $\pi^+p$ reactions [8] are shown by full lines. In all cases the rate is smaller in meson-nucleus than in elementary interactions. The rates are the same in $K^+$ interactions on both nuclei in the central and target fragmentation regions. The latter observation also holds for $\pi^+$ collisions.

The relative production rate is about $5\%$ in all channels; thus no increase in the relative production rate of $K^0$'s is observed off nuclei w.r.t. elementary collisions.

The Feynman-$x_F$ dependence of the ratio

\[ R(x_F) = \frac{d\sigma(K_S^0)}{d\sigma(\pi^-)} \]

is given by Eq. (16). The results for $K^+p$ and $\pi^+p$ reactions [8] are shown by full lines. In all cases the rate is smaller in meson-nucleus than in elementary interactions. The rates are the same in $K^+$ interactions on both nuclei in the central and target fragmentation regions. The latter observation also holds for $\pi^+$ collisions.

The relative production rate

\[ R(p_T^2) = \frac{d\sigma(K_S^0)}{dp_T^2} \frac{d\sigma(\pi^-)}{dp_T^2} \]

is presented in Fig. 8. The results for $K^+p$ and $\pi^+p$ reactions [8] are shown by full lines. In all cases the rate is smaller in meson-nucleus than in elementary interactions. The rates are the same in $K^+$ interactions on both nuclei in the central and target fragmentation regions. The latter observation also holds for $\pi^+$ collisions.

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\[ R(p_T^2) = \frac{d\sigma(K_S^0)}{dp_T^2} \frac{d\sigma(\pi^-)}{dp_T^2} \]

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The ratio $R(x_r)$ of $K^0$ to $n^-$ production as a function of $x_r$ is shown in Fig. 8. Full lines in Fig. 9a and b are the data for $K^+ p$ and $\pi^- p$ interactions, respectively. The $p_T^2$-dependence in meson-nucleus collisions follows the same trend as in elementary collisions; the $K^0/n^-$ ratio increases with increasing $p_T^2$.

In Sect. 3 we observed that the average number of produced $A$'s is proportional to the average number of projectile collisions and thus follows (14a), whereas this does not hold for produced $K^0$'s. The same observation was made in [12], based on $p$ Ar, $p$ Xe and $\beta$ Xe interactions at 200 GeV/c. Preliminary results of the latter experiment led Nikolaev [13] to the concept of "$A$ retention property" of nuclear interactions, which can be stated simply as follows: a $A$ produced via fragmentation of a nucleon in the nucleus is not absorbed, but the $K^0/\bar{K}^0$ can reinteract and thereby disappear or even produce a $A$. Based on these considerations, Nikolaev predicts a number of properties of events containing a $A^0$ as compared to minimum bias (MB) events, i.e. they are expected to have

- a high central plateau, thus larger charge multiplicity $\langle n_c \rangle$;
- larger average number of protons $\langle n_p \rangle$ and of grey protons $\langle n_g \rangle$ i.e. protons with $0.2 < \beta < 0.7$;
- a relatively narrower multiplicity distribution: $D_c/\langle n_c \rangle$ smaller;
- increasing $\langle n_A \rangle$ with increasing $n_p$ or $n^-$.  

We have checked these expectations by calculating the quantities $\langle n_p \rangle$, $\langle n_g \rangle$ and $D_c/\langle n_c \rangle$ in the four available
Table 12. Comparison of events with a $K_0^-$ or a $\Lambda$ and minimum bias events

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Events</th>
<th>$\langle n_p \rangle$</th>
<th>$\langle n'_n \rangle$</th>
<th>$D_p$</th>
<th>$D_{p}/\langle n_p \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-\text{Al}$</td>
<td>all</td>
<td>1.11 ± 0.03</td>
<td>12.84 ± 0.21</td>
<td>7.13 ± 0.66</td>
<td>0.56 ± 0.05</td>
</tr>
<tr>
<td>$K_0^-$</td>
<td></td>
<td>1.60 ± 0.23</td>
<td>15.34 ± 0.79</td>
<td>7.03 ± 2.53</td>
<td>0.46 ± 0.17</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td></td>
<td>1.25 ± 0.22</td>
<td>15.83 ± 1.43</td>
<td>9.44 ± 4.52</td>
<td>0.60 ± 0.29</td>
</tr>
<tr>
<td>$K^+\text{Au}$</td>
<td>all</td>
<td>3.17 ± 0.16</td>
<td>19.49 ± 0.46</td>
<td>13.30 ± 1.18</td>
<td>0.68 ± 0.06</td>
</tr>
<tr>
<td>$K_0^+$</td>
<td></td>
<td>4.89 ± 0.70</td>
<td>28.44 ± 1.70</td>
<td>14.04 ± 5.20</td>
<td>0.49 ± 0.19</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td></td>
<td>4.72 ± 0.70</td>
<td>25.34 ± 1.65</td>
<td>10.87 ± 5.80</td>
<td>0.43 ± 0.23</td>
</tr>
<tr>
<td>$\pi^+\text{Al}$</td>
<td>all</td>
<td>1.16 ± 0.02</td>
<td>12.90 ± 0.13</td>
<td>7.02 ± 0.39</td>
<td>0.54 ± 0.03</td>
</tr>
<tr>
<td>$K_0^+$</td>
<td></td>
<td>1.44 ± 0.08</td>
<td>15.74 ± 0.56</td>
<td>7.97 ± 1.80</td>
<td>0.51 ± 0.12</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td></td>
<td>1.43 ± 0.14</td>
<td>16.78 ± 0.88</td>
<td>8.85 ± 2.75</td>
<td>0.53 ± 0.17</td>
</tr>
<tr>
<td>$\pi^+\text{Au}$</td>
<td>all</td>
<td>3.04 ± 0.05</td>
<td>19.74 ± 0.27</td>
<td>13.20 ± 0.70</td>
<td>0.67 ± 0.04</td>
</tr>
<tr>
<td>$K_0^+$</td>
<td></td>
<td>4.04 ± 0.16</td>
<td>25.60 ± 0.90</td>
<td>13.62 ± 2.66</td>
<td>0.53 ± 0.11</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td></td>
<td>5.32 ± 0.26</td>
<td>31.33 ± 1.28</td>
<td>14.29 ± 4.25</td>
<td>0.46 ± 0.14</td>
</tr>
</tbody>
</table>

channels for minimum bias events ("all"), for events with a $K_0^-$ and for events with a $\Lambda$. The results, given in Table 12, lead to the following conclusions:

1. $\langle n_p \rangle$ is indeed larger in $\Lambda$ events than in MB events, but it is also larger in $K_0^-$ events.
2. $\langle n_n \rangle$ is indeed larger in $\Lambda$ events than in MB events, but also in $K_0^-$ events.
3. $D_p/\langle n_p \rangle$ is indeed smaller (for the heavy Au nucleus) in $\Lambda$ events than in MB events, but so it is also in $K_0^-$ events.

From this we may conclude that strangeness production in general (and not particularly $\Lambda$ production) is accompanied by more protons and more charged particles; in other words strangeness is on average produced in more central collisions.*

The last question which we address here is whether relatively more strangeness is produced in central collisions.

* This can naively be expected if one considers that production of "rarer" particles requires more energy to be dumped in the interaction volume.

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![Figure 10a-d](image1.png)

**Fig. 10a-d**. The relative production rate $\langle n_p \rangle/\langle n_n \rangle$ as a function of $n_p$, the number of protons, with $s = K_0^-(s = \Lambda)$ in a, b $M^+\text{Al}$ and c, d in $M^+\text{Au}$ collisions. $M^+$ stands for the combined sample of $K^+$ and $\pi^+$ interactions.

![Figure 11a-d](image2.png)

**Fig. 11a-d**. As in Fig. 10 but $\langle n_p \rangle/\langle n_n \rangle$ is plotted versus $n_n$. 
sions, compared to ordinary matter as given e.g. by the number of negative hadrons \( n_h \). The number \( n_p \) of ejected protons or the number \( n_{-h} \) of negative hadrons can serve as a measure of the centrality of the collision.

Figure 10 shows the ratio \( \langle n_h \rangle / \langle n_{-h} \rangle \) (with \( s = K^0 \) in Fig. 10a, c and \( s = \Lambda \) in Fig. 10b, d) as a function of \( n_p \) for events which contain a neutral strange particle. Figure 11 shows the ratio \( \langle n_h \rangle / n_h \) versus \( n_h \). Both figures demonstrate that the relative production rate of strange particles does not increase with increasing centrality of the collisions.

6 Summary

We present results on the inclusive production of \( K^0 \) and \( \Lambda \) in \( K^+ \) and \( \pi^+ \) interactions with Al and Au nuclei at 250 GeV/c. The main results can be summarized as follows.

- The inclusive \( K^0 \) and \( \Lambda \) production cross sections follow a dependence \( \sigma \propto A^\alpha \), with \( \alpha \approx 0.9 \).
- The \( \Lambda \)-hyperons are mainly produced in the target fragmentation and central regions.
- The \( p_T^2 \) and \( m_T \) distributions of the \( K^0 \) and \( \Lambda \) in the reactions (1–8) are well described by a single exponential form.
- The relative production rate of \( K^0 \) to \( \pi^- \) shows a strong dependence on \( x_F \) and \( p_T^2 \), very similar to elementary collisions.
- The quark-parton FRITIOF model and in particular its modified version FRITIOF', is in reasonable agreement with the data.
- The average number of \( \Lambda \)'s is proportional to the number of projectile collisions, the average number of \( K^0 \)'s does not follow this trend.

- Strangeness production happens preferentially in central collisions but the relative production rate of strange to non-strange matter does not increase with increasing centrality.

Acknowledgements. We are indebted to the CERN SPS, beam and EHS crews for their support during the preparation and runs of our experiment. It is a pleasure to thank the scanning and measuring staffs of our laboratories for their tedious effort in scanning and measuring these events. The contribution of the groups which participated in the earlier phase of this experiment is gratefully acknowledged.

References