PHYSICS OF ELEMENTARY PARTICLES  
AND ATOMIC NUCLEUS. EXPERIMENT

Λ and $K^0_s$ Production in $pC$ Collisions at 10 GeV/c

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Abstract—The experimental data from the 2-m propane bubble chamber have been analyzed for $pC \rightarrow \Lambda(K^0_s)X$ reactions at 10 GeV/c. The estimation of experimental inclusive cross sections for $\Lambda$ and $K^0_s$ production in the $p^{12}C$ collision is equal to $\sigma_\Lambda = (13.3 \pm 1.7) \text{ mb}$ and $\sigma_{K^0_s} = (4.6 \pm 0.6) \text{ mb}$, respectively. The measured $\langle \Lambda/\pi^+ \rangle$ ratio from $pC$ reaction is equal to $(5.3 \pm 0.8) \times 10^{-2}$, and it is approximately two times larger than the $\langle \Lambda/\pi^+ \rangle$ ratio simulated by the FRITIOF model and than that of experimental $pp$ reactions at the same energy.


INTRODUCTION

Strange particles have been obtained extensively in hadron–nucleus and nucleus–nucleus collisions in 4–15 GeV regions [1–6]. The number of $\Lambda$'s produced in $\bar{p} + \text{Ta}$ reaction at 4 GeV/c was 11.3 times larger than that expected from the geometrical cross section [1]. In AGS experiments with Au(Si) + Au collisions at 10.7 [4], 11.6 [5], and 14.6A GeV/c [6], the $\langle K^+/(\pi^+)\rangle (\langle \Lambda/\pi^+ \rangle)$ ratio is four to five times larger than the $\langle K^+/(\pi^+)\rangle (\langle \Lambda/\pi^+ \rangle)$ ratio from $p + p$ reaction at the same energy. In heavy ion Pb + Pb central interactions (NA49 collaboration), the $K^+$ yield from $p + p$ reactions increases faster with the beam energy compared with the $\pi^+$ yield $\langle K^+/(\pi^+) \rangle$, from $p + p$ reactions at momenta 4–160 GeV/c [12–14].

Therefore, the analysis of strange hyperon and $K^+$ total yields [12–14] are of great interest as an indicator of strange quark production. If the hadronic rescattering mechanism dominates strangeness enhancement at 10A GeV, how rapidly does it reduce as the beam energy is increased [13]? This behavior is of particular interest as it could be a signal of the appearance of new dynamics for strangeness production. Strangeness enhancement has been analyzed regarding such reaction mechanisms as a possible signature for the quark–gluon plasma (QGP) [7, 8], as the multinucleon effect [9], or the fireball effect [10], or as the deconfinement signal, within the context of the thermal equilibration model [11–14].

It has already been experimentally observed in the energy dependence of the $\langle K^+/(\pi^+) \rangle$ ratio and is predicted to be even more pronounced in the $\langle \Lambda/\pi^+ \rangle$ ratio [11–14]. However, there have not been sufficient experimental data concerning strange-hyperon production in hadron–nucleus and nucleus–nucleus collisions over 4–15 GeV/c momentum range. In this paper, the new results on the inclusive cross sections for $\Lambda(K^0_s)$ production and $\langle \Lambda/\pi^+ \rangle$ ratio are presented for the reaction $p + ^{12}C$ at 10 GeV/c.

1. EXPERIMENTAL PROCEDURE

1.1. Method

Experimental data on $\sim 700000$ stereo photographs by the JINR, LHE 2-m propane bubble chamber exposed proton beams at 10 GeV/c [15–20] were analyzed. The primary proton beams must satisfy the conditions: $|\tan \alpha| < 0.02$, $1.62 < \beta < 1.69$. The fit GRIND-based program GEOFIT [16, 17] is used to measure the kinematic track parameters $\rho$, $\alpha$, $\beta$. Measurements were repeated three times for events which failed in reconstruction by GEOFIT.

The estimation of ionization for charged tracks and length for stopped particles permitted one to identify them over the following momentum ranges: protons of 0.150 GeV/c $\leq P \leq 0.900$ GeV/c and $K^\pm$ of 0.05 GeV/c $\leq P \leq 0.6$ GeV/c.

1.2. Identification of $\Lambda$ and $K^0_s$

The events with $V^0$ ($\Lambda$ and $K^0_s$) were identified using the following criteria [19, 20]: (1) $V^0$ stars from the photographs were selected according to $\Lambda \rightarrow \pi + p$,
\( K_s^0 \rightarrow \pi^+ + \pi^-, \) and \( \gamma \rightarrow e^+ + e^- \) hypotheses. The low momentum limits of \( K_s^0 \) and \( \Lambda \) are greater than 0.1 and 0.2 GeV/c, respectively; (2) \( V^0 \) stars should have the effective mass of \( K_s^0 \) and of \( \Lambda \); (3) the \( V^0 \) momentum and momenta of particles from the \( V^0 \) decay are located in the same plane (complanarity); (4) they should have one vertex—three constraints fit for the \( M_K \) or \( M_\Lambda \) hypothesis and after the fit, \( \chi^2 \) should be selected over the range less than 12; (5) the analyzed experimental data have shown that the events with undivided \( \Lambda K_s^0 \) were assumed to be \( \Lambda \) hyperons [19].

Table 1 has presented the part of identified experimental \( V^0 \) (70%) events which were identified from different types of interactions for (a) all ranges and (b) with a constrain on the effective ranges of the chamber.

The \( V^0 \)'s are classified into two groups. The first group comprised \( V^0 \)'s which could be uniquely identified with the above criteria (1–4) and with bubble densities from the positive track of \( V^0 \)s. The second grade comprised \( V^0 \)'s which could be the undivided \( \Lambda K_s^0 \). For correct identification of the undivided \( V^0 \)'s, the \( \alpha \) (Armenteros parameter) and the \( \cos \theta^* \) distributions (Fig. 1) are used:

\[
\alpha = \frac{(P_\|^+ - P_\|^+)}{(P_\|^- + P_\|^+)} ,
\]

where \( P_\|^+ \) and \( P_\|^+ \) are the momentum components of positive and negative charged tracks relative to the direction of the \( V^0 \) momentum. The \( \theta^* \) is the angle between \( \pi^- \) (from \( V^0 \) decay) and \( V^0 \) in the \( V^0 \) rest frame. The \( \alpha \) (Fig. 1a) and the \( \cos \theta^* \) distributions from \( K_s^0 \) (\( \Lambda \)) decay were isotropic in the \( K_s^0 \) (\( \Lambda \)) rest frame after removing the undivided \( K_s^0 \) (\( \Lambda \)) events. Then, these \( K_s^0 \) (\( \Lambda \)) events were assumed as \( \Lambda \) hyperons. After this, as shown in Fig. 1c the \( \cos \theta^* \) distributions for the \( \Lambda + K_s^0 \) (\( \Lambda \))'s are also isotropic in the \( V^0 \) rest frame. The results of the above procedure are the following: the loss of \( K_s^0 \) is 8.5% and the admixture of \( K_s^0 \) in \( \Lambda \) events is 4.6%.

The third group comprised \( V^0 \)'s which could be the invisible \( V^0 \)'s at a large azimuth angle \( \phi \) [19]. The average \( \phi \) weights were made: they are equal to \( \langle w_\phi \rangle = 1.06 \pm 0.02 \) for \( K_s^0 \) and \( \langle w_\phi \rangle = 1.14 \pm 0.02 \) for \( \Lambda \).

Table 1. The amount of \( V^0 \) events from interactions of beam protons with propane bubble chambers in all volume and with restriction on effective ranges

<table>
<thead>
<tr>
<th>Channel</th>
<th>The amount of ( V^0 ) events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>all</td>
</tr>
<tr>
<td>( \Lambda(\text{only})x )</td>
<td>5276</td>
</tr>
<tr>
<td>( K_s^0 ) (only) ( x )</td>
<td>4122</td>
</tr>
<tr>
<td>( \Lambda ) and ( K_s^0 ) ( x )</td>
<td>3381</td>
</tr>
</tbody>
</table>

The average geometrical weights are \( 1.34 \pm 0.03 \) for \( \Lambda \) and \( 1.22 \pm 0.04 \) for \( K_s^0 \).

The analysis of experimental data was done with the use of the FRITIOF model [21, 22] for collision \( p + \text{propane} \rightarrow \Lambda(K_s^0)X \). A possibility of \( \Lambda \) and \( K_s^0 \) of imitating neutron stars was made by the FRITIOF model. The hypotheses reactions \( p + \text{propane} \rightarrow n + X \), \( n + \text{propane} \rightarrow \pi p \) (or \( \pi^+ \pi^-X \)) with including of Fermi motion in carbon were simulated. Then, these events were analyzed by using the same experimental conditions as those used for the selection of \( V^0 \)'s. This analysis has shown that the backgrounds from neutron stars are equal to 0.1% for \( \Lambda \) and 0.001 for \( K_s^0 \) events.

### 1.3. The Selection of Interactions in Carbon Nucleus

The \( p + C \rightarrow \Lambda(K_s^0)X \) reactions were selected from \( C_3H_8 \) by using the following criteria [18, 25]:

1. \( Q = n_s - n_c > 2 \);
2. \( n_p + n_\Lambda > 1 \);
3. \( n_p^b + n_\Lambda^b > 0 \);
4. \( n_c > 2 \);
5. \( n_s = 2k + 1 (k = 0, 1, 2, \ldots) \);
6. \( m_x = (E_{p\Lambda} - P_{p\Lambda}) \cos \theta_{p\Lambda} > m_p \).

The \( n_s \) and \( n_c \) are the numbers of positive and negative particles in the star; \( n_p \) and \( n_\Lambda \) are the numbers of protons and \( \Lambda \) hyperons with momentum \( P < 0.75 \text{ GeV/c} \) in the star. \( n_p^b \) and \( n_\Lambda^b \) are the numbers of protons and \( \Lambda \) hyperons, emitted in backward hemisphere. \( E_{p\Lambda} \), \( P_{p\Lambda} \), and \( \theta_{p\Lambda} \) are an energy, a momentum, and an emitted angle of protons (or \( \Lambda \))s in the lab. system. \( m_x \) and \( m_p \) are the effective mass of target and the mass of proton, respectively. Only \( \approx 83\% \) of inelastic \( p + C \) interactions were separated by these criteria [25].

The \( p + \text{propane} \rightarrow \Lambda(K_s^0) \) reaction was simulated by using the FRITIOF model [21, 22] with experimental conditions. Then, the influence of the above criteria was analyzed when \( pC \) interactions were selected from