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Λ AND K_s^0 PRODUCTION IN pC COLLISIONS AT 10 GeV/c

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The experimental data from the 2-m propane bubble chamber have been analyzed for $p\text{C} \to \Lambda(K_s^0)X$ reactions at 10 GeV/c. The estimation of experimental inclusive cross sections for Λ and K_s^0 production in the p^{12}C collision is equal to $\sigma_\Lambda = (13.3 \pm 1.7)$ mb and $\sigma_{K_s^0} = (4.6 \pm 0.6)$ mb, respectively.

The measured $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio from pC reaction is equal to $(5.3 \pm 0.8) \cdot 10^{-2}$, and it is approximately two times larger than the $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio simulated by the FRITIOF model and than that of experimental pp reactions at the same energy. The $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio has a significant enhancement for C + C collisions at $4{-}10A$ GeV/c.

Экспериментальные данные, полученные на двухметровой пропановой пузырьковой камере, были проанализированы для реакций $p\text{C} \to \Lambda(K_s^0)$ при 10 ГэВ/c. Оценка экспериментальных инклюзивных сечений образования Λ- и K_s^0-мезонов в p^{12}C-столкновении дает значения $\sigma_\Lambda = (13{,}3 \pm 1{,}7)$ мб и $\sigma_{K_s^0} = (4{,}6 \pm 0{,}6)$ мб соответственно.

Измеренное соотношение $\langle\Lambda\rangle/\langle\pi^+\rangle$ для pC-реакции равно $(5{,}3 \pm 0{,}8) \cdot 10^{-2}$, что приблизительно в два раза больше оценки, которую дает для него модель FRITIOF, то же относится и к величине отношения, полученной в pp-реакциях при той же энергии. Отношение $\langle\Lambda\rangle/\langle\pi^+\rangle$ сильно увеличилось для C + C-столкновений при $4{-}10A$ ГэВ/c.

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INTRODUCTION

Strange particles have been obtained extensively in hadron–nucleus and nucleus–nucleus collisions in 4–15 GeV regions [1–6]. The number of Λ's produced in $\overline{p}+\text{Ta}$ 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 $\langle K^+\rangle/\langle\pi^+\rangle(\langle\Lambda\rangle/\langle\pi^+\rangle)$ ratio is four to five times larger than the $\langle K^+\rangle/\langle\pi^+\rangle(\langle\Lambda\rangle/\langle\pi^+\rangle)$ 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 π^+ yield ($\langle K^+\rangle/\langle\pi^+\rangle$ ratio), from $p+p$ reactions at momenta 4–160A 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

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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 thermal equilibration model [11–14].

It has already been experimentally observed in the energy dependence of the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio, and is predicted to be even more pronounced in the $\langle\Lambda\rangle/\langle\pi^+\rangle$ 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 $\Lambda(K_s^0)$ production and $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio are presented for the reaction $p+{}^{12}$C at 10 GeV/c.

1. EXPERIMENTAL PROCEDURE

1.1. Method. Experimental data on ≈ 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: $|\operatorname{tg}\alpha| < 0.02$, $1.62 < \beta < 1.69$ rad. The fit GRIND-based program GEOFIT [16, 17] is used to measure the kinematic track parameters p, α, β. 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 $0.150 \leqslant P \leqslant 0.900$ GeV/c and $K^\pm$ of $0.05 \leqslant P \leqslant 0.6$ GeV/c.

1.2. Identification of Λ and K_s^0. The events with V^0 (Λ and K_s^0) were identified using the following criteria [19, 20]: 1) V^0 stars from the photographs were selected according to $\Lambda \to \pi^- + p$, $K_S^0 \to \pi^- + \pi^+$ and $\gamma \to e^+ + e^-$ hypotheses. The low momentum limits of K_s^0 and Λ 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 Λ; 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_Λ hypothesis and after the fit, $\chi^2_{V^0}$ should be selected over the range less than 12; 5) the analyzed experimental data have shown that the events with undivided ΛK_s^0 were assumed to be Λ 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) primary proton beams, b) secondary charged particles and c) secondary neutral particles.

The V^0's are classified into three 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 ΛK_s^0. For correct identification of the undivided V^0's, the α (Armenteros parameter) and the $\cos\theta^*_{\pi^-}$ distributions (Fig. 1) are used:

$$\alpha = (P_\parallel^+ - P_\parallel^-)/(P_\parallel^+ + P_\parallel^+), \tag{1}$$

where $P_\parallel^+$ and $P_\parallel^-$ are the momentum components of positive and negative charged tracks relative to the direction of the V^0 momentum. The $\theta^*_{\pi^-}$ is the angle between π^- (from

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**

Channel	The amount of V^0 events	
	All	With restriction
$\rightarrow \Lambda(\text{only})x$	5276	5075
$\rightarrow K_s^0(\text{only})x$	4122	3887
$\rightarrow (\Lambda \text{ and } K_s^0)x$	3381	1887

V^0 decay) and V^0 in the V^0 rest frame. The α (Fig. 1, *a*) and the $\cos\theta^*_{\pi^-}$ distributions from $K_s^0(\Lambda)$ decay were isotropic in the K_s^0 rest frame after removing the undivided $K_s^0(\Lambda)$. Then, these $K_s^0(\Lambda)$ events were assumed as Λ hyperons. After this, as shown in Fig. 1, *c*

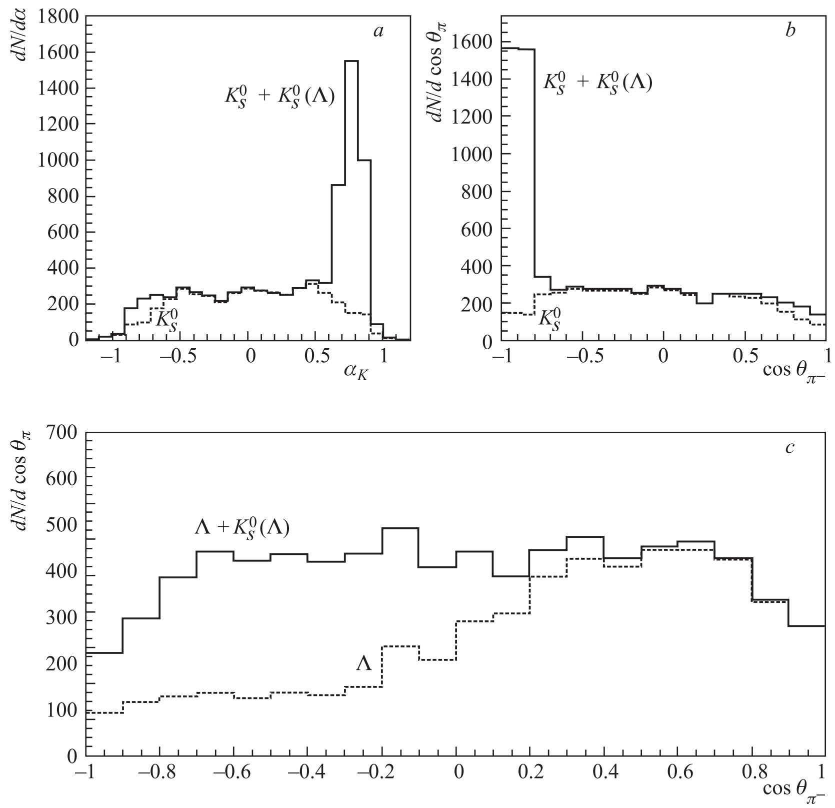

Fig. 1. Distributions of α (Armenteros parameter) and cos θ^* are used for correctly identification of the undivided $K_s^0(\Lambda)$. $\alpha = (P_{\parallel}^+ - P_{\parallel}^-)/((P_{\parallel}^+ + P_{\parallel}^-)$, where $P_{\parallel}^+$ and $P_{\parallel}^-$ are the parallel components of momenta of positive and negative charged tracks from the V^0 relative direction of the V^0 momentum. cos θ^* is the angular distribution of π^- from $K_s^0(\Lambda)$ decay in the rest frame of $K_s^0(\Lambda)$. Distributions of α and cos θ must be isotropic in the rest frame of K_s^0. Therefore, undivided ΛK_s^0 must be passed as Λ hyperons

the $\cos\theta^*_{\pi^-}$ 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 Λ events is 4.6%. The third group comprised V^0's which could be the invisible V^0's at a large azimuth angle ϕ [19]. The average ϕ 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 Λ.

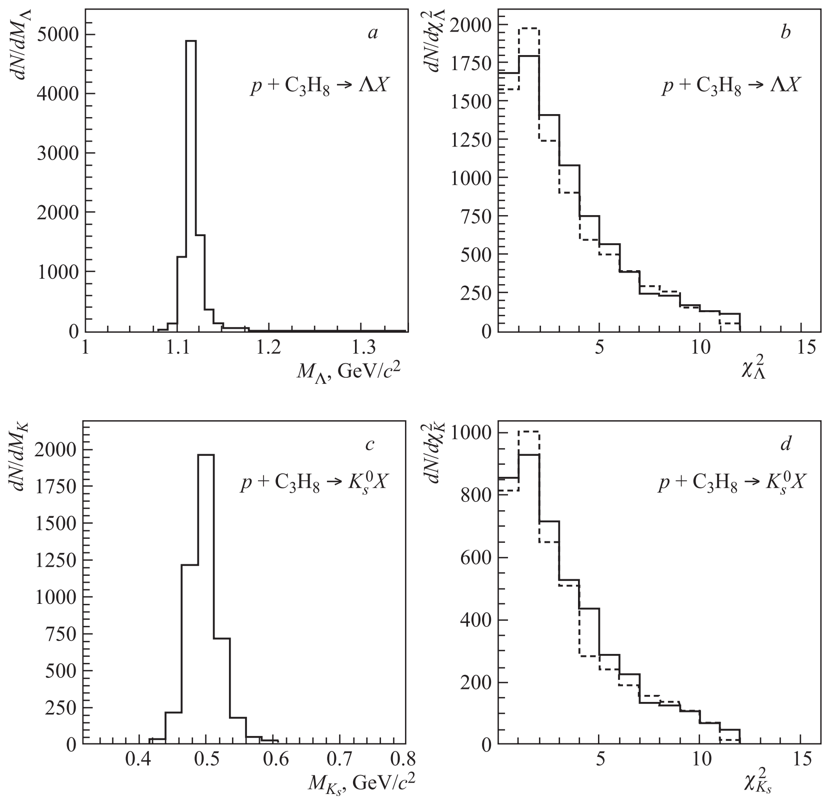

Fig. 2. The distribution of experimental V^0 events produced from interactions of beam protons with propane: *a*) for the effective mass of M_Λ; *b*) for $\chi^2_\Lambda(1V - 3C)$ of the fits via the decay mode $\Lambda \to \pi^- + p$; *c*) for the effective mass of $M_{K_s^0}$; *d*) for $\chi^2_{K_s^0}(1V - 3C)$ of the fits via the decay mode $K_s^0 \to \pi^- + \pi^+$. The expected functional form for χ^2 is depicted by the dashed histogram

The panels *a*, *c* and *b*, *d* of Fig. 2 show the effective mass distributions of Λ (8657-events), K^0 (4122-events) particles and their χ^2 from kinematic fits, respectively. Each V^0 event is weighted by a factor $w_{\rm geom}$, where the average geometrical weights are 1.34 ± 0.03 for Λ and 1.22 ± 0.04 for K^0.

The analysis of experimental data was done with the use of the FRITIOF model [21, 22] for collision $p + \text{propane} \to \Lambda(K_s^0)X$. A possibility of Λ and K_s^0 of imitating neutron stars was made by the FRITIOF model. The hypotheses reactions $p + \text{propane} \to n + X$, $n + \text{propane} \to \pi^- p$ (or $\pi^-\pi^+$)X^0 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 Λ and 0.001 for K_s^0 events.

1.3. The Selection of Interactions in Carbon Nucleus. The $p + \text{C} \to \Lambda(K_s^0)X$ reactions were selected from C_3H_8 by using the following criteria [18, 25]:

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

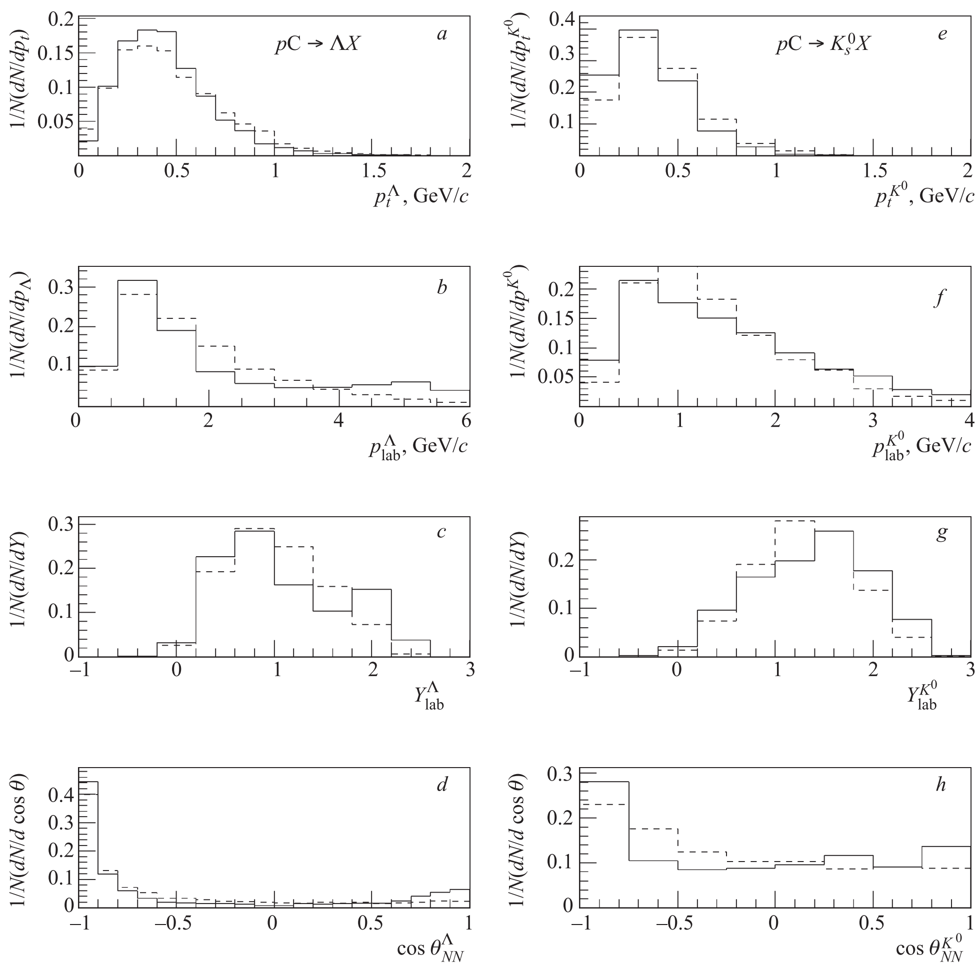

Fig. 3. Experimental (solid) and FRITIOF model-simulated (dashed) distributions of Λ hyperons and K_s^0 mesons in $p + \text{C}$ interaction at 10 GeV/c: *a*, *e*) by the transverse momentum (p_t); *b*, *f*) by the momentum (p_{lab}); *c*, *g*) by the longitudinal rapidity (Y_{lab}); *d*, *h*) by the azimuthal angle cos θ (in the SM of $p + p$ collisions)

The n_+ and n_- are the numbers of positive and negative particles in the star; n_p and n_Λ are the numbers of protons and Λ hyperons with momentum $P < 0.75$ GeV/c in the star. n_p^b, n_Λ^p are the numbers of protons and Λ 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 Λs) in the lab. system. m_t 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 $p +$ propane $\to \Lambda(K_s^0)$ 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 the simulated $p +$ propane$\to \Lambda(K_s^0)$ reactions. This simulation has shown that the lost events were equal to 18 and 20% from interactions $p\text{C} \to \Lambda X$ and $p\text{C} \to K_s^0 X$, respectively. These results are obtained without correcting by condition, when all undivided $K_s^0(\Lambda)$ were assumed as Λ hyperons. Contributions from reactions of $pp \to \Lambda X$ and $pp \to K_s^0 X$ to reactions of $p\text{C} \to \Lambda X$ and $p\text{C} \to K_s^0 X$ were estimated by the FRITIOF model similarly and they were equal to 1.0 and 0.3%, respectively. Figure 3 compares the momentum, $\cos\theta$ in the c.m. nucleon–nucleon system, transverse momentum (p_t) and longitudinal rapidity distributions of Λ and K_s^0 for experimental events (solid line) and those simulated by the FRITIOF model (dashed line) in $p +$C interactions, which are selected from $p +$ propane$\to \Lambda(K_s^0)X$. From Fig. 3 one can see that the experiment is described by the FRITIOF model satisfactorily.

2. THE MEASURED CROSS SECTIONS Λ AND K^0

The cross section is defined by the formula

$$\sigma = \frac{\sigma_0 N_r^{V^0}}{e} \prod_i w_i = \frac{\sigma_r N_r^{V^0} w_{\text{hyp}} w_{\text{geom}} w\phi w_{\text{kin}} w_{\text{int}}}{N_r e_1 e_2 e_3}, \qquad (2)$$

where $1/e_1 = 1.14 \pm 0.04$ is the efficiency of search for V^0 on the photographs, $1/e_2 = 1.25 \pm 0.02$ is the efficiency of measurements and gathering V^0 events after all measurements. e_3 is the probability of decay via the channel of charged particles ($\Lambda \to p\pi^-, K^0 \to \pi^+\pi^-$), $\sigma_0 = \sigma_r/N_r$ — the total cross section, where σ_r is the total cross section for registered events. $N_r^{V^0}$ (Table 1) and $N_r = 504249 \pm 29650$ are the experimental numbers of: registered V^0's and proton + carbon interactions over the effective range of the chamber, respectively. $\sigma_t(p + \text{C}_3\text{H}_8) = 3\sigma_{p\text{C}} + 8\sigma_{pp} = (1456 \pm 88)$ mb [26], where $\sigma_t, \sigma_{p\text{C}}$ and σ_{pp} are the total cross sections in interactions $p + \text{C}_3\text{H}_8$, $p + \text{C}$ and $p + p$, respectively. The propane bubble chamber method has permitted the registration of the part of all elastic interactions with the propane, therefore the total cross section of registered events is equal to: $\sigma_r(p + \text{C}_3\text{H}_8) = 3\sigma_{p\text{C}}(\text{inelastic}) + 8\sigma_{pp}(\text{inelastic}) + 8\sigma_{pp}(\text{elastic})\,0.70 = (1049 \pm 60)$ mb [23, 24].

Registration efficiencies are obtained for experimental conditions and they are defined as: $e_i = n_i/N$ and $\Delta e_i = \sqrt{e_i(1 + e_i)/N}$, where n is the number of selected events with some experimental conditions and N is the full number of events. $w_i = 1/e_i$ are the average weights for the lost events with V^0 (Table 2) for: w_{geom} is the V^0 decay outside the chamber; w_ϕ is the required isotropy for V^0 in the azimuthal (XZ) plane; w_{kin} is equal to 1.18 ± 0.02 and 1.04 ± 0.01 in pC reaction for Λ and K_s^0 production, respectively, which is obtained from simulation of V^0 by using FRITIOF with experimental conditions for limits of momenta; w_{int}

is equal to 1.11 ± 0.05 and 1.04 ± 0.02 for the $\Lambda +$ propane and $K_s^0 +$ propane interactions, respectively.

Table 2. **Weights of the lost experimental events with Λ hyperon and K_s^0 mesons for pC and pp interactions**

Type of reaction	$1/e_1$	$1/e_2$	w_{geom}	w_ϕ	w_{int}	w_{kin}	$1/e_3$	W_{sum}
$p\text{C} \to \Lambda X$	1.14	1.25	1.34	1.14	1.11	1.18	1.56	4.37
$pp \to \Lambda X$	1.14	1.25	1.36	1.14	1.11	1.37	1.56	5.15
$p\text{C} \to K_s^0 X$	1.14	1.25	1.22	1.06	1.04	1.04	1.47	2.93
$pp \to K_s^0 X$	1.14	1.25	1.36	1.06	1.05	1.06	1.47	3.31

Table 3. **Cross sections of Λ hyperons and K_s^0 mesons for pC interactions at beam momentum 10 GeV/c**

Type of reaction	$N_{V^0}^{\text{exp}}$	$\langle W_{\text{sum}} \rangle = \Pi_i w_i$	N_{V^0} Total	$\langle n_{V^0} \rangle = N_{V^0}^t / N_{\text{in}}$	σ, mb
$p\text{C} \to \Lambda X$	6126	4.37	26770	0.053	13.3 ± 1.7
$p\text{C} \to K_s^0 X$	3188	2.93	9341	0.018	4.6 ± 0.6

The experimental cross sections for interactions of $pp \to \Lambda X$ and $pp \to K_s^0 X$ at beam momentum 10 GeV/c are taken by using a compilation of cross sections and they are equal to 0.8 ± 0.08 for Λ hyperons and 0.43 ± 0.04 for K_s^0 mesons. The experimental number of events was estimated by using the cross section for $pp \to \Lambda(K_s^0)X$ which was used to determine the amount of lost events for reaction $p\text{C} \to \Lambda(K_s^0)X$ after using the criteria in Subsec. 1.3. These calculations had shown that the lost events were equal to 15.8% (14.8%) for $p\text{C} \to \Lambda(K_s^0)X$ from $p +$ propane $\to \Lambda(K_s^0)X$ reactions. The experimental cross sections shown in Table 3 were calculated from formula (2) for inclusive productions of Λ hyperons and K_s^0 mesons in the pC interactions at beam momentum 10 GeV/c.

Table 4. **Ratios of average multiplicities of Λ hyperons and K_s^0 mesons to multiplicities of π^+ mesons for $p + \text{C}$ interaction at beam momenta 4.2 and 10 GeV/c**

$(\langle n_{V^0} \rangle / \langle n_{\pi^+} \rangle) \cdot 10^2$	pC (this experiment) (10 GeV/c)	pC (FRITIOF) (10 GeV/c)	Cp (experiment [18, 22]) (4.2 GeV/c)	Cp (FRITIOF) (4.2 GeV/c)
$(\langle n_\Lambda \rangle / \langle n_{\pi^+} \rangle)$	5.3±0.8	2.6	0.7±0.3	0.9
$(\langle n_{K_s^0} \rangle / \langle n_{\pi^+} \rangle)$	1.8±0.3	1.8	0.3±0.2	0.3

Ratios of the average multiplicities of Λ hyperons and K_s^0 mesons to the multiplicities of π^+ mesons in $p + \text{C}$ interaction at beam momenta 4.2 and 10 GeV/c are shown in Table 4. Experimental data on multiplicities of π^+ mesons in the pC interactions at momenta 4.2 GeV/c ($\langle n_{\pi^+} \rangle = 0.71 \pm 0.01$) and 10 GeV/$c$ ($\langle n_{\pi^+} \rangle = 1.0 \pm 0.05$) are taken from publications [22] and [25], respectively. The experimental Λ/π^+ and $\langle n_{K_s^0} \rangle / \langle n_{\pi^+}$ ratios in Table 4 are agreed with simulated FRITIOF ratios at momentum 4.2 GeV/c, but the experimental $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio obtained is approximately two times larger than the ratio from the FRITIOF model at momentum 10 GeV/c in pC reaction.

Table 5. **Ratios of average multiplicities of Λ hyperons to multiplicities of π^+ mesons for C + C interactions at beam momenta 4.2 and 10 GeV/c**

$(\langle n_{V^0}\rangle/\langle n_{\pi^+}\rangle)\cdot 10^2$	4.2 GeV/c [18, 22] (experiment)	10 GeV/c (experiment)
$(\langle n_\Lambda\rangle/\langle n_{\pi^+}\rangle)$	2.0±0.6	10.9±1.7

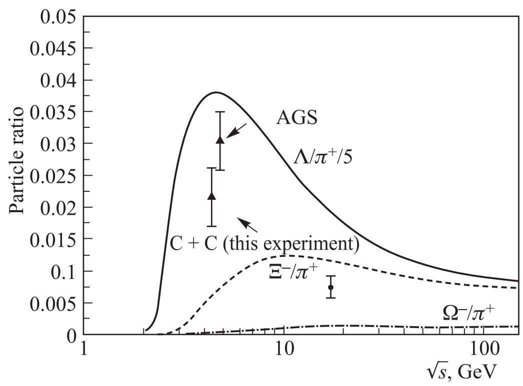

Fig. 4. Prediction of the statistical-thermal model [12] for $\langle\Lambda\rangle/\langle\pi^+\rangle$ (solid line) (note that this ratio is devided by factor of 5), and $\langle\Xi^-\rangle/\langle\pi^+\rangle$ (dashed line) and $\langle\Omega^-\rangle/\langle\pi^+\rangle$ (dash-dotted line) ratios as a function of $\sqrt{s}$. For compilation of AGS data, see [14]. The $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio in interaction C + C is obtained by using the data from this experiment

The $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio for C + C reaction is shown in Table 5 and in Fig. 4. This $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio for C + C reaction at momentum 10 GeV/c has been obtained by using the Glauber approach on the experimental cross section for $p + \mathrm{C} \to \Lambda X$ reaction and the simulation by the FRITIOF model. As can be seen from the experimental data in Table 5 and from the thermal statistical model (Fig. 4), there is a very clearly pronounced enhancement specially for the $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio in C + C collisions at 4–10A GeV/c.

CONCLUSION

The experimental data from the 2-m propane bubble chamber have been analyzed for $p\mathrm{C} \to \Lambda(K_s^0)X$ reactions at 10 GeV/c. The estimation of experimental inclusive cross sections for Λ and K_s^0 production in pC collisions is equal to $\sigma_\Lambda = (13.3 \pm 1.7)$ mb and $\sigma_{K_s^0} = (4.6 \pm 0.6)$ mb, respectively. The measured Λ/π^+ ratio in pC and pp reactions is equal to $(5.3{-}0.8)\cdot 10^{-2}$ and $(2.6{-}0.4)\cdot 10^{-2}$, respectively. The experimental $\langle\Lambda\rangle/\langle\pi^+\rangle$

ratio in the pC reaction is approximately two times larger than the $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio from pp reactions or from pC reactions simulated by the FRITIOF model for the same energy. There is a very clearly pronounced enhancement in the experimental $\langle\Lambda\rangle/\langle\pi^+\rangle$ ratio for $\mathrm{C}+\mathrm{C}$ and $\mathrm{Au}+\mathrm{Au}$ collisions at 4–15A GeV/c, as the thermal statistical hadron model predicted (Fig. 4).

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