Inclusive production of \( \Lambda, K_s^0 \) and exotic narrow resonances for systems \( K_s^0 p, K_s^0 \Lambda, \Lambda p \) from \( p+\text{propane} \) interactions at 10 GeV/c

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Abstract. Experimental data from the 2m propane bubble chamber for production of \( \Lambda, K_s^0 \) have been used to search of exotic baryon states, in the \( K_s^0 p, K_s^0 \Lambda \) and \( \Lambda p \) decay mode for the reaction \( p+\text{propane} \) at 10 GeV/c. The estimation of experimental inclusive cross sections for \( \Lambda \) and \( K_s^0 \) production in the \( p^{12}C \) collision is equal to \( \sigma_{\Lambda} = 13.3 \pm 1.7 \text{ mb} \) and \( \sigma_{K_s^0} = 3.8 \pm 0.6 \text{ mb} \), respectively. The measured \( \Lambda/\pi^+ \) ratio from pC reaction is equal to \( (5.3 \pm 0.8) \times 10^{-2} \). The experimental \( \Lambda/\pi^+ \) ratio in the pC reaction is approximately two times larger than the \( \Lambda/\pi^+ \) ratio simulated by FRITIOF model in the pC reaction. The invariant mass spectrum \( \Lambda K_s^0 \) registered narrow peaks in regions of 1750 and 1795 MeV/\( c^2 \). The statistical significance of these peaks has been estimated as 5.6 and 3.3 S.D., respectively. These would be candidates for the \( N^0 \) or the \( \Xi^0 \) pentaquark states. The \( pK_s^0 \) invariant mass spectrum shows resonant structures with \( M_{K_s^0 p}=1540, 1613, 1821 \text{ MeV/}c^2 \). The statistical significance of these peaks have been estimated as 5.5, 4.8 and 5.0 S.D., respectively. The invariant mass spectrum \( S=-1 \Lambda p \) observed a narrow peaks at 2100, 2175, 2285 and 2353 MeV/\( c^2 \). Their excess above background by the second method is 6.9, 4.9, 3.8 and 2.9 S.D., respectively.

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1. Introduction

Strange particle production [1] has been analyzed regarding such reaction mechanisms as the multinucleon effect, or the fireball effect, or possible signature for the quark-gluon plasma (QGP), or as the deconfinement signal, within the context of thermal equilibration models. In particular, the $\Lambda/\pi^+$ ratio of particle production have been observed extensively on hadron - nucleus and nucleus-nucleus collisions 4-15 GeV regions.

Multi-quark states, glueballs and hybrids have been searched for experimentally for a very long time, but none is established. Several models ([2]-[5]) predict the multiplet structure and characteristics of multi quark hadrons and pentaquarks.

Results from a wide range of recent experiments [2] are consistent with the existence of an exotic S=+1 resonance, the $\Theta^+(1540)$ with a narrow width and a mass near 1540 MeV.

Preliminary results on a search for the $N^0$ or the $\Xi^0$ pentaquark states in the decay mode $\Lambda K_0^*$ with the mass $1734 \pm 0.5 \pm 5 \text{ MeV}/c^2$ is presented in the article S. Kabana, hep-ph/0501121, 2005.

Metastable strange dibaryons were searched a long time ago at LHE JINR, too. This group succeeded in finding resonance-like peaks [3, 4] only in five of them $\Lambda p$, $\Lambda p\pi$, $\Lambda\Lambda$, $\Lambda\Lambda p$, $\Lambda\pi^+\pi^+$.

2. Experimental procedure

2.1. **Identification of $\Lambda$ and $K_0^*$**

The experimental events with $V^0$'s were searched on $\approx 700000$ stereo photographs from the 2m propane bubble chamber of JINR, LHE exposed proton beams at 10 GeV/c [1]. The events with $V^0$ ($\Lambda$ and $K_0^*$) were identified using the following criteria: 1) $V^0$ stars from the photographs were selected according to $\Lambda \rightarrow \pi^- + p$, neutral $K_0^* \rightarrow \pi^- + \pi^+$ or $\gamma \rightarrow e^+ + e^-$ hypothesis. A momentum limit of $K_0^*$ and $\Lambda$ is greater than 0.1 and 0.2 GeV/c, respectively ; 2) $V^0$ stars should have the effective mass of $K_0^*$ and of $\Lambda$; 3) these $V^0$ stars are directed to some vertices(complanarity); 4) they should have one vertex, a three constraint fit for the $M_K$ or $M_\Lambda$ hypothesis and after the fit, $\chi^2_{V^0}$ should be selected over range less than 12; 5)The analysis has shown that the events with undivided $\Delta K_0^*$ were assumed to be events as $\Lambda$(Fig.1a,1b). As a result of above procedure have lost of $K_0^*$ 8.5% and admixture of $K_0^*$ in $\Lambda$s events 4.6%.

Fig. 1c and 1d shows the effective mass distribution of $\Lambda$(8657-events) and $K_0^*(4122$-events) particles, respectively. The masses of the observed $\Lambda$, $K_0^*$ are consistent with their PDG values.
3. The measured cross sections $\Lambda$ and $K^0$

The cross section is defined by the formula:

$$\sigma = \frac{\sigma_0 \cdot N_r^{V^0}}{e} \prod_i w_i = \frac{\sigma_r \cdot N_r^{V^0} \cdot w_{hyp} \cdot w_{geom} \cdot w_{\phi} \cdot w_{kin} \cdot w_{int}}{N_r \cdot e_1 \cdot e_2 \cdot e_3},$$  (3.1)

where $e_1$ is the efficiency of search for $V^0$ on the photographs, $e_2$ the efficiency of measurements. The $V^0$s of 75% (preliminary) could be successfully reconstructed and accepted in the analysis. $e_3$ the probability of decay via the channel of charged particles ($\Lambda \rightarrow p\pi^-$, $K^0 \rightarrow \pi^+\pi^-$), $\sigma_0 = \sigma_r/N_r$ the total cross section, where $\sigma_r$ and $N_r$ is the total cross section and number of registered events. The propane bubble chamber method have been permitted the registration of the part of all elastic interactions with the propane [1], therefore the total cross section of registered events is equal to: $\sigma_r(p + C_3H_8) = 3\sigma_{pp}(inelastic) + 8\sigma_{pp}(inelastic) + 8\sigma_{pp}(elastic)0.70 = (1049 \pm 60)$mb. $w_i$ are weights for the lost events with $V^0$ for: $w_{geom}$ - the $V^0$ decay outside the chamber; $w_{\phi}$ - the required isotropy for $V^0$ in the azimuthal (XZ) plane; $w_{hyp}$ - the undivided $\Lambda K^0_s$ events; $w_{kin}$ - the kinematic conditions (with FRITIOF); $w_{int}$ - the $V^0$+ propane interactions. The criteria for selection of interaction with carbon has shown [1].

Table 1 show that the experimental cross sections are calculated by formula 3.1 for inclusive productions $\Lambda$ hyperons and $K^0_s$ mesons for the interactions of $pp$ and $pC$ at beam momentum 10 GeV/c. The experimental data of multiplicities $p\pi^+$ mesons taken from experiments. The experimental $\Lambda/\pi^+$ ratio from the pC reaction is approximately two times larger than the experimental $\Lambda/\pi^+$ ratio for $pp$ and the simulated FRITIOF model from pC reactions. The $\Lambda/\pi^+$ ratio for C+C reaction at momentum 10 GeV/c have been obtained by using the Glauber approach on the experimental cross section for $p+C \rightarrow \Lambda X$ reaction(Fig.2). As can be seen from experimental data and thermal statistical model (Fig.2) there is a very clearly pronounced enhancement specially in the $\Lambda/\pi^+$ ratio for hadron-nucleus and nucleus collisions at 10-15 A GeV/c.

4. $pK^0_s, \Lambda K^0_s$ and $Ap$ spectrum analysis

4.1. The experimental background

The total experimental background has been obtained by three methods [2],[5]. In the first method, the experimental effective mass distribution was approximated by the polynomial function after cutting out the resonance ranges because this procedure has to provide the fit with $\Sigma^2=1$ and polynomial coefficient with errors less than 30 %. The second of the randomly mixing method of the angle between of decaying particles from the resonance for experimental events is described in V.L.Lyuboshits et al.(see [2]). The third background method has been obtained by
using FRITIOF model with experimental conditions. The analysis done by three methods has shown that while fitting these distributions had the same coefficients and order of the polynomial function. The values for the mean position of the peak and the width obtained by using Breit Wigner fits.

4.2. $pK^0_s$ - spectrum for protons with a momentum of $0.350 \leq p_p \leq 0.900 \text{ GeV}/c$

The $pK^0_s$ effective mass distribution 2300 combination (Fig.3a) is shown resonant structures with $M_{K^0_s}=1540, 1613, 1821 \text{ MeV}/c^2$ and $\Gamma_{K^0_s}= 9.2, 16.1, 28.0 \text{ MeV}/c^2$ ([2]). The statistical significance of these peaks have been estimated as 5.5,4.8 and 5.0 s.d., respectively. There are also small peaks in 1690( 3.6 s.d.), 1750 (2.3 s.d.) and 1980(3.0 s.d.) $\text{MeV}/c^2$ mass regions.

4.3. $\Lambda K^0_s$ - spectrum analysis

Figure 3b shows the invariant mass of 1012 ($\Lambda K^0_s$)combinations with bin sizes 18 $\text{MeV}/c^2$([5]). There are significant enhancements in mass regions of 1750 and 1795 $\text{MeV}/c^2$(Fig.3b). Their excess above background by the first method is 5.0 and 3.0 S.D,respectively. There are small enhancement in mass regions of 1670,1850 and 1935 $\text{MeV}/c^2$.

4.4. $\Lambda p$ - spectrum analysis for protons with a momentum of $0.250 \leq p_p \leq 0.900 \text{ GeV}/c$

Figure 3c shows the invariant mass of 2434 ($\Lambda p$)combinations with bin sizes 15 $\text{MeV}/c^2$([4]). The values for the mean position of the peak and the width obtained by using Breit Wigner fits. There are significant enhancements in mass regions of 2100, 2175, 2285 and 2353 $\text{MeV}/c^2$(Fig.1c).Their excess above background by the second method is 6.9, 4.9, 3.8 and 2.9 S.D., respectively. There is also a small peak in 2225( 2.2 s.d.) $\text{MeV}/c^2$ mass region.

5. Conclusion

The experimental data from the 2 m propane bubble chamber have been analyzed from pC$\rightarrow \Lambda(K^0_s)X$ reactions at 10 $\text{GeV}/c$. The estimation of experimental inclusive cross sections of $\Lambda$ and $K^0_s$ production for pC collisions is equal to $\sigma_\Lambda= 13.3\pm1.7 \text{ mb}$ and $\sigma_{K^0_s}= 3.8\pm0.6 \text{ mb}$, respectively. The measured $\Lambda/\pi^+$ ratio for pC is equal to $(5.3\pm0.8)*10^{-2}$. The $\Lambda/\pi^+$ ratio for C+C collisions at 10 $\text{A GeV}/c$ obtained that is $\approx 3-4$ times larger than the $\Lambda/\pi^+$ ratio from C+C reactions at the same energy simulated by FRITIOF model.

A number of peculiarities were found in the effective mass spectrum of $K^0_sp$, $\Lambda K^0_s$ and $\Lambda p$(section 4). The $N^0$ can be from the antidecuplet, from an octet (D. Diakonov, V. Petrov , V.Guzey and M.Polyakov or an 27-plet(J. Ellis et al.). On
the other hand, Jaffe and Wilczek predicted a mass around 1750 MeV and a width 50% larger for these states than that of the $\Theta^+$. These peaks in the effective mass spectrum $\Lambda K^0_s$ are possible candidates for two pentaquark states: the $N^0$ with quark content udsds decaying into $\Lambda K^0$ and the $\Xi^0$ quark content udssd decaying into $\Lambda K^0$. The calculated rotational $\Theta^+$ and $N^0$ spectra from theoretical reports of D.Akers, Y Nambu, M.H. Mac Gregor and A.A. Arkhipov agreed with experimental reports of Yu. A. Troyan and P.Zh Aslanyan [2].

The experimental result for $S=-1$ $\Lambda p$ dibaryon spectrum shows that the predicted peaks with the bag model has been confirmed [3].

![Fig. 1](image)

**Fig. 1.** (a) and (b) distributions of $\alpha$ (Armenteros parameter) and $\cos \Theta^*$ are used for correctly identification of the undivided $V^0$s. $\alpha = (P^+_\parallel - P^-\parallel)/((P^+_\parallel + P^-\parallel)$. Where $P^+_\parallel$ and $P^-\parallel$ are the parallel components of momenta positive and negative charged tracks. $\cos \Theta^*$ is the angular distribution of $\pi^-$ from $K^0_s$ decay. Distributions of $\alpha$ and $\cos \theta^*$ were isotropic in the rest frame of $K^0_s$ when undivided $\Lambda K^0_s$ were assumed to be events as $\Lambda$. c) and (d) distributions of experimental $V^0$ events produced from interactions of beam protons with propane: c) for the effective mass of $M_\Lambda$; d) for the effective mass of $M_{K^0_s}$.

### References

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Fig. 2. Prediction of the statistical-thermal model (note the factor 5) for $\Lambda/\pi^+$ (solid line), and $\Xi^-/\pi^+$ (dashed line) and $\Omega^-/\pi^+$ ratios a function of $\sqrt{s}$. For compilation of AGS data see (above point) [1]. The $\Lambda/\pi^+$ ratio is presented by using data from this experiment for C+C interaction.

Fig. 3. The effective mass distribution for systems: (a) $pK^0$, (b) $\Lambda K^0$ and (c) $\Lambda p$.

4. P.Z. Aslanyan et al., hep-ex/0406034, 2004.
5. P.Z. Aslanyan et al., hep-ex/0403044, 2005; JINR Commun., E1-2005-149.

| Type of reaction | $N_{V0}^{exp}$ | $W_{sum}$ | $N_{V0}^{T}$ | $n_{V0} = N_{V0}^{T}/N_{in}$ | $\sigma$ |
|------------------|----------------|------------|---------------|-----------------------------|---------|
| pC→ΛX            | 6126           | 4.37±0.37  | 26770         | 0.053±0.005                 | 13.3±1.6|
| pp→ΛX            | 836            | 5.15±0.44  | 4303          | 0.026±0.003                 | 0.80±0.08|
| pC→$K^0$X        | 3188           | 2.93±0.25  | 9341          | 0.018±0.002                 | 3.8±0.5 |
| pp→$K^0$X        | 699            | 3.31±0.28  | 2313          | 0.015±0.001                 | 0.43±0.04|

Table 1. Cross sections $\Lambda$ hyperons and $K^0_s$ mesons for pp and pC interactions at beam momentum 10 GeV/c.