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# EXOTIC NARROW RESONANCE SEARCHES IN THE SYSTEM $\Lambda K_s^0$ IN $p$+PROPANE COLLISIONS AT 10 GeV/$c$

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Поиск узких барионных резонансов со странностью $S = 0$ в системе $\Lambda K_s^0$ в реакции $p$+$C_3H_8$ при импульсе пучка 10 ГэВ/$c$

В спектре эффективных масс системы $\Lambda K_s^0$ обнаружен ряд особенностей при значениях 1650–1680, 1740–1750, 1785–1805, 1835–1860 и 1925–1950 МэВ/$c^2$. Из всех вышеуказанных областей только при массе (1750±18) и (1795±20) МэВ/$c^2$ с шириной $\Gamma = (14 \pm 6)$ МэВ/$c^2$ получается высокая статистическая значимость 5,6 и 3,3 соответственно. Экспериментальные отклонения в спектре по эффективной массе в указанных областях являются возможными отражениями от $N^0$ и $\Xi^0$ пентакварковых состояний, состоящих из $udsds$- и $udssd$-кварков соответственно.

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Exotic Narrow Resonance Searches in the System $\Lambda K_s^0$ in $p$+Propane Collisions at 10 GeV/$c$

A number of peculiarities were found in the effective mass spectrum of system $\Lambda K_s^0$ in the ranges 1650–1680, 1740–1750, 1785–1805 and 1925–1950 MeV/$c^2$ in collisions of protons of a 10 GeV/$c$ momentum with propane. A detailed research of structure of mass spectrum has shown that the maximum statistical significance, equal to 5.6 and 3.3 SD, has been obtained in effective mass ranges (1750±18) and (1795±20) MeV/$c^2$. These peaks are possible candidates for two pentaquark states: the $N^0$ with quark content $udsds$ decaying into $\Lambda K_s^0$ and the $\Xi^0$ with quark content $udssd$ decaying into $\Lambda\overline{K_s^0}$.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energies, JINR.

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## 1. INTRODUCTION

Several models predict the multiplet structure and characteristics of pentaquarks, for example, the chiral soliton model, the uncorrelated quark model, correlated quark models, QCD sum rules, thermal models, lattice QCD, etc. [1–18]. Multiquark states, glueballs and hybrids have been searched for experimentally for a very long time but none is established.

Results from a wide range of recent experiments [19] are consistent with the existence of an exotic $S = +1$ resonance, the $\Theta^+(1540)$ with a narrow width and a mass near 1540 MeV [1]. Results from this experiment are $M_{\Theta^+}$ = (1540$\pm$8) MeV/$c^2$, $\Gamma_{\Theta^+}$ = (9.2$\pm$1.8) MeV/$c^2$ ($\Gamma_{\Theta^+}$ =(9.2$\pm$0.3) MeV/$c^2$, PDG-2004).

However, recent significant advances in theoretical and experimental work led to a number of new candidates in the last 2 years of searches. Candidates for other pentaquarks have been presented recently, in particular for the $\Xi^{--}(1862)$, $\Xi^{-}(1850)$, $\Xi^{0}(1864)$ [20] and $\Theta_c^0(3099)$ [21]. Preliminary results on the STAR (Solenoidal Tracker at RHIC) of a search for $N^0$ or the $\Xi^0$ pentaquark states in the decay mode $\Lambda K_s^0$ with the mass $(1734 \pm 0.5 \pm 5)$ MeV/$c^2$ is presented in the article [22]. A significant signal for $\approx \Xi^0(1750) \to \Xi^-\pi^+$ was observed [23].

## 2. EXPERIMENT

The JINR 2-m bubble chamber is the most suitable instrument for this purpose [24]. The experimental information of more than 700 000 stereo photographs is used to select the events with $V^0$ strange particles.

The events with $V^0$ ($\Lambda$ and $K_s^0$) were identified by using the following criteria [24, 30]: 1) $V^0$ stars from the photographs were selected according to $\Lambda \to \pi^- + p$, neutral $K_s \to \pi^- + \pi^+$ or $\gamma \to e^+ + e^-$ hypothesis. A momentum limit of $K_s^0$ and $\Lambda$ is greater than 0.1 and 0.2 GeV/$c$, respectively ; 2) $V^0$ stars should have the effective mass of $K_s^0$ and of $\Lambda$; 3) these $V^0$ stars are directed to some vertices (coplanarity); 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 in the range less than 12; 5) the analysis has shown that the events with undivided $\Lambda, K_s^0$ were assumed to be $\Lambda$.

The effective mass distribution of 8657 events with $\Lambda$ and 4122 events with $K_s^0$ particles is consistent with their PDG values (Fig. 1). The effective mass resolution of $\Lambda K_s^0$ system was estimated to be on the average 1%.

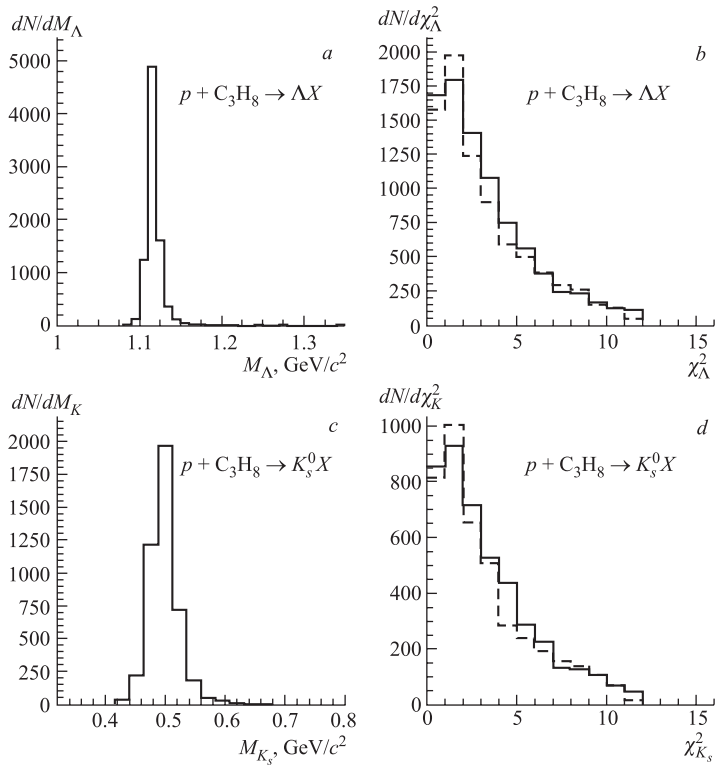


Fig. 1. The distribution of experimental $V^0$ events produced from interactions of beam protons with propane: *a*) for the effective mass of $M_\Lambda$; *b*) for $\chi^2_\Lambda(1V-3C)$ of the fits via the decay mode $\Lambda \to \pi^- + p$; *c*) for the effective mass of $M_{K_s^0}$; *d*) for $\chi^2_{K_s^0}(1V-3C)$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

Each $V^0$ event was weighted by a factor $w_{\rm geom} = 1/e_\tau$, where $e_\tau$ is the probability for potentially observed $V^0$; this can be expressed as

$$e_\tau = \exp\left(-L_{\rm min}/L\right) - \exp\left(-L_{\rm max}/L\right),$$

where L = $cp\tau/M$ is the flight length of $V^0$, $L_{\rm max}$ is the path length from the reaction point to the boundary of fiducial volume, and $L_{\rm min}$ (0.5 cm) is an observable minimum distance between the reaction point and the $V^0$ vertex.

$M$, $\tau$, and $p$ are the mass, lifetime, and momentum of $V^0$. The average geometrical weights are 1.34±0.02 for $\Lambda$ and 1.22±0.04 for $K^0$.

FRITIOF Model [26] is used as a background method. Figure 2 compares the momentum, cos $\theta$ in the c.m. nucleon–nucleon system, transverse momentum ($p_t$) and longitudinal rapidity distributions of $\Lambda$ and $K^0_s$ for experimental events (solid line) and those simulated by the FRITIOF model [26, 27] (broken line) in $p$+propane interactions. From Fig. 2 one can see that the experiment is satisfactorily described by the FRITIOF model.

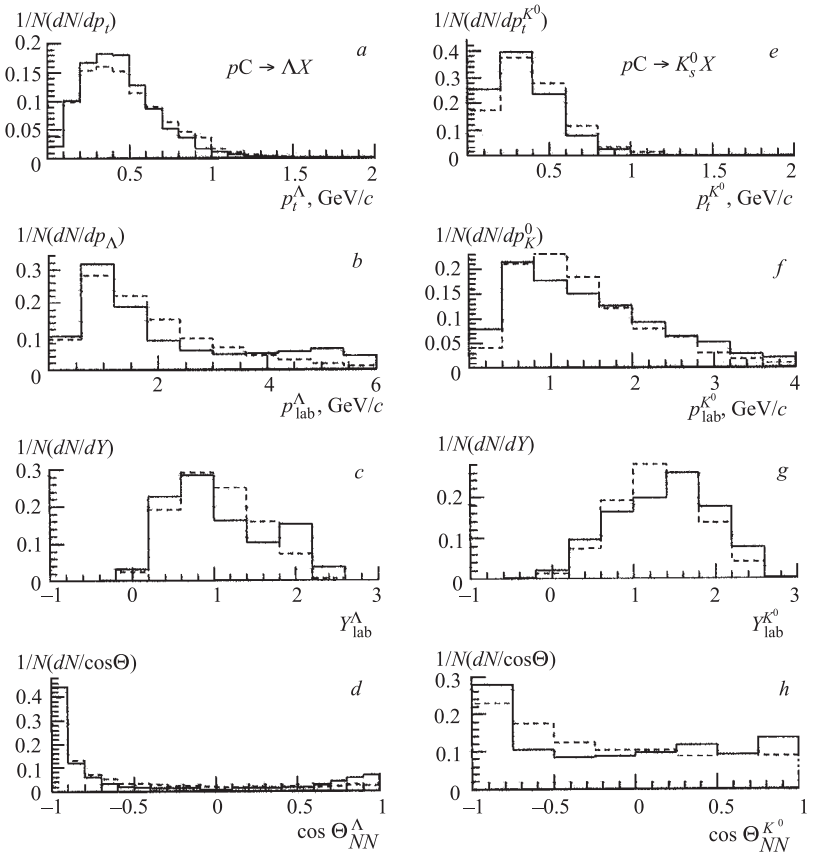


Fig. 2. Experimental (solid) and simulation by FRITIOF model (dashed) distributions of $\Lambda$ hyperons and $K^0_s$ mesons in $p$+C interaction at 10 GeV/$c$: *a*) and *e*) at the transverse momentum $p_t$; *b*) and *f*) at the momentum $p_{\rm lab}$; *c*) and *g*) at the longitudinal rapidity $Y_{\rm lab}$; *d*) and *h*) at the azimuthal angle cos $\Theta$ (in the SM of $p + p$ collisions)

The experimental estimation of inclusive cross sections for $\Lambda$ and $K^0_s$ production in the $p^{12}$C collision is equal to $\sigma_\Lambda$ = (13.3±1.7) mb and $\sigma_{K^0_s}$ = (3.8±0.6) mb, respectively [24].

## 3. $\Lambda K_s^0$-SPECTRUM ANALYSIS

The total experimental background has been obtained by three methods (Fig. 3–6). In the first method, the experimental effective mass distribution was

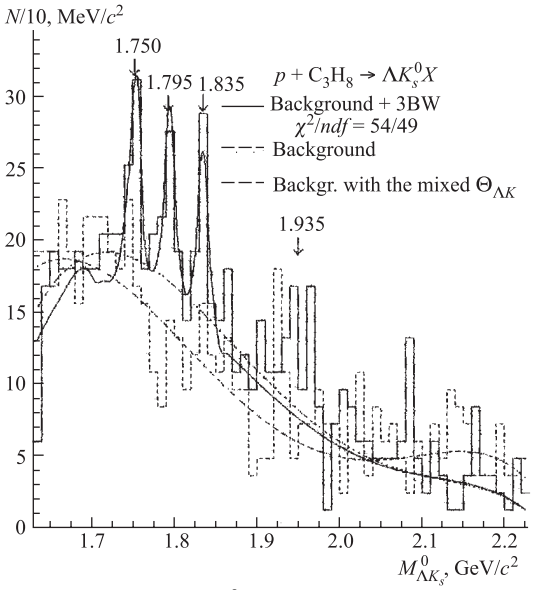


Fig. 3. Invariant mass distribution ($\Lambda K_s^0$) with the bin size 10 MeV/$c^2$ in the inclusive reaction $p$+$C_3H_8$. The solid curve is the sum of the experimental background by the first method (dot-dashed curve) and three Breit–Wigner resonance curves. The dashed histogram is the experimental background [25]

approximated by the polynomial function after cutting out the resonance ranges because this procedure has to provide the fit with $\chi^2$=1 and polynomial coefficient with errors less than 30%. The second of the randomly mixing method of the angle between $K_s^0$ and $\Lambda$ for experimental events is described in [25]. Then, these background events were analyzed by using the same experimental condition and the effective mass distribution $\Lambda K_s^0$ was fitted by the sixth-order polynomial. The third type of background for $\Lambda K_s^0$ combinations has been obtained by FRITIOF model [26, 27]. In all figures the background distribution has been normalized to the experimental distribution. The analysis of the background done by three methods has shown that there is no observable structure in the range of peaks. The background analysis of the experimental data is based on the polynomial method. The values for the mean position of the peak and the width are obtained by using Breit–Wigner fits.

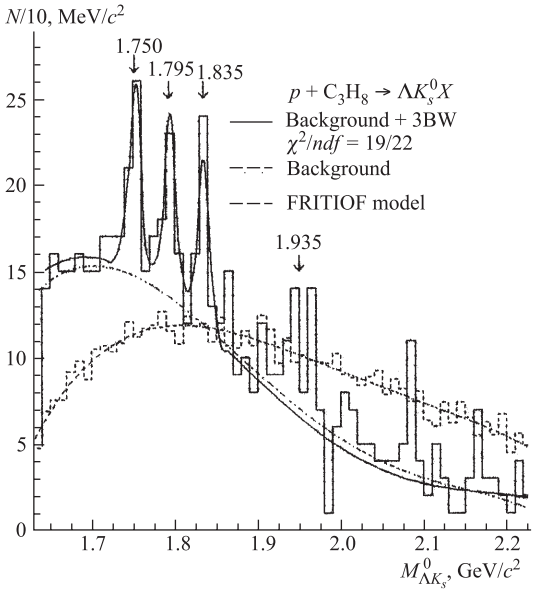


Fig. 4. Invariant mass distribution ($\Lambda K_s^0$) with the bin size 10 MeV/$c^2$ in the inclusive reaction $p$+$C_3H_8$. The solid curve is the sum of the experimental background by the first method (dot-dashed curve) and three Breit–Wigner resonance curves. The dashed histogram is the simulation by FRITIOF model [26, 27]

Figure 3 shows the invariant mass of 1012 $\Lambda K_s^0$ combinations with bin sizes 10 MeV/$c^2$. The solid curve is the sum of the background by the first method and 3 Breit–Wigner resonance curves. The background distribution was fitted by the sixth-order polynomial. There are significant enhancements in the mass regions of 1750, 1795, and 1835 MeV/$c^2$ (Fig. 3). Their excess above the background by the first method is 4.0, 2.7 and 3.0 SD. There is small enhancement in the mass region of 1935 MeV/$c^2$. The simulation with FRITIOF model for $\Lambda K_s^0$ combinations has shown in Fig. 4 that there is no significant reflection from well-known resonances in this distribution. Similar results have been obtained when using a Breit–Wigner distribution and different bin sizes.

Figure 5 shows the invariant mass of $\Lambda K_s^0$ with bin sizes 11 MeV/$c^2$. There are significant enhancements in the mass regions of 1670, 1750, 1795, and 1850 MeV/$c^2$ (Fig. 5). Their excess above background by the first method is 2.9, 4.7, 2.3, and 2.4 SD.

The effective mass distribution of $\Lambda K_s^0$ with bin size 18 MeV/$c^2$ is shown in Fig. 6. This bin size is consistent with the experimental resolution within the errors. There are significant enhancements in the mass regions of 1750 and 1795 MeV/$c^2$. Their excess above background by the first method is 5.6 and 3.3 SD

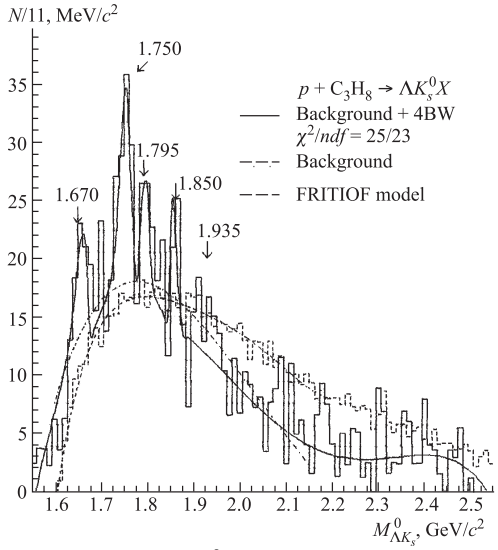


Fig. 5. Invariant mass distribution ($\Lambda K_s^0$) with the bin size 11 MeV/$c^2$ in the inclusive reaction $p$+$C_3H_8$. The solid curve is the sum of the experimental background by the first method (dot-dashed curve) and four Breit–Wigner resonance curves. The dashed histogram is the simulation by FRITIOF model [26, 27]

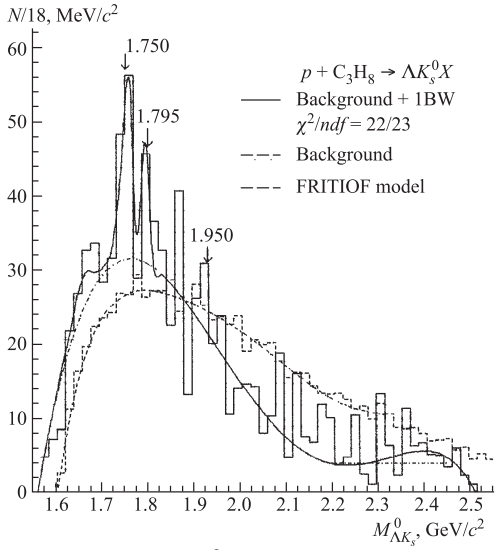


Fig. 6. Invariant mass distribution ($\Lambda K_s^0$) with the bin size 18 MeV/$c^2$ in the inclusive reaction $p$+$C_3H_8$. The solid curve is the sum of the experimental background by the first method (dot-dashed curve) and two Breit–Wigner resonance curves. The dashed histogram is the simulation by FRITIOF model [26, 27]

respectively. There are negligible enhancements in the mass regions of 1680, 1860 and 1950 MeV/$c^2$.

## 4. CONCLUSIONS

A number of peculiarities were found in the effective mass spectrum of system $\Lambda K_s^0$ in the ranges 1740–1750, 1785–1800 and 1835–1860 MeV/$c^2$ in collisions of protons of a 10-GeV/$c$ momentum with propane nuclei. The detailed research of structure of mass spectrum has shown that the maximum statistical significance has been obtained in effective mass ranges submitted in table.

**The statistical significance, the width ($\Gamma$) and the effective mass resonances in collisions of protons with propane at 10 GeV/$c$**

| Resonance decay mode | $M_{\Lambda K_s^0}$, MeV/$c^2$ | Experimental width ($\Gamma_e$), MeV/$c^2$ | $\Gamma$ | Maximum statistical significance ($N_{\mathrm{SD}}$) |
|---|---|---|---|---|
| $K_s^0\Lambda$ | 1750±18 | 32±6 | 14±6 | 5.6 |
| $K_s^0\Lambda$ | 1795±18 | 44±15 | 26±15 | 3.3 |

The preliminary total cross section for $N^0(1750)$ production in $p + \mathrm{C_3H_8}$ interactions is estimated to be $\approx 30\,\mu$b.

The $N^0$ can be from the antidecuplet, from an octet [1], [2] or a 27-plet [8]. On the other hand, Jaffe and Wilczek predicted a mass around 1750 MeV and a width 50% larger for these states than that for the $\Theta^+$ [5].

These peaks are possible candidates for two pentaquark states: the $N^0$ with quark content $udsds$ decaying into $\Lambda K_s^0$ and the $\Xi^0$ with quark content $udssd$ decaying into $\Lambda\overline{K_s^0}$, which agree with the calculated rotational spectra $N^0$ and $\Xi^0$ from the theoretical report of D. Akers and V. H. MacGregor [28], A. A. Arkhipov [29] and with $\Theta^+$ spectra from the experimental reports of Yu. A. Troyan and P. Aslanyan [19].

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