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EXOTIC STRANGE MULTIBARYON STATE SEARCHES WITH Λ-HYPERON AND K_s^0-MESON SYSTEMS IN p+A COLLISIONS AT MOMENTUM 10 GeV/c

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Exotic strange multibaryon states have been observed in the effective mass spectra of $\Lambda\pi^+$, $\Lambda\pi^-$, Λp and Λpp, and of ΛK_S^0, $K_S^0\pi^\pm$ and $K_S^0 p$ subsystems. The invariant mass of $\Lambda\pi^+$ and $K_S^0\pi^\pm$ spectra has shown the well known $\Sigma^{*+}(1385)$ and $K^{*\pm}(892)$ resonances. The width of $\Sigma^{*-}(1385)$ from the p+A reaction is two times larger than that presented in PDG. The cross section of $\Xi^- \to \Lambda\pi^-$ is more than 4 times larger than expected on the basis of the geometrical cross section in $p+$propane interaction. A few events detected in the photographs of the propane bubble chamber were interpreted as $S = -2$ light and heavy $H^{0,+}$ dibaryons.

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1. *Introduction*

There are a few actual problems of nuclear and particle physics which are concerning for this report. These are following goals: in-medium modification of hadrons, the origin of hadron masses, the restoration of chiral symmetry, the confinement of quarks in hadrons, the properties of cold dense baryonic matter and non-perturbative QCD, strange baryons in medium, Λ yields, the structure of neutron stars. Back in 1977, Jaffe [1] suggested the existence of multi-quark states, glueballs and hybrids, using the bag model in which confined colored quarks and gluons interact as in perturbative QCD, but until now none has been established. Recently, the existence of discrete nuclear bound states of $\overline{K}^0$p has been predicted with phenomenological kaonic nuclear cluster (KNC) model which is based on the experimental information on the $\overline{K}^0$N scattering lengths, kaonic hydrogen atom and the $\Lambda^*(1405)$ resonance [2, 3]. Experimental efforts to find S=+1 Θ^+ pentaquark have been motivated by the report in Ref. [4], where antidecuplet baryons were studied by using the chiral soliton (Skyrme) models.

Searches for exotic strange multibaryon states with Λ - hyperon and K^0_S-meson systems were published in reports [5] – [7].

2. *Experiment*

The full experimental information of more than 700000 stereo photographs of 10^6 p+propane inelastic interactions were used to select the events with V^0 strange particles [8]. The masses of the observed 8657 events with Λ hyperon and 4122 events with K^0_s meson are consistent with their PDG values [8]. The experimental total cross sections are equal to 13.3 and 4.6 mb for Λ and K^0_s production, respectively, in the p+C collisions at 10 GeV/c. As has already been published, the experimental data are satisfactorily described by the FRITIOF model. The experimental Λ/π^+ ratio in the pC reaction is approximately two times larger than ratio from the pp reactions or from simulated pC reactions by FRITIOF model [9] at the same energy [8].

For the fit of the resonance signals, the mass spectra were taken to have the form [10, 11] $\mathrm{d}\sigma(M)/\mathrm{d}m = BG(M) + BW(M) * PS(M)$, where BG, BW and PS represent background, Breit-Wigner (BW) function and phase space, respectively. The background has been obtained by three methods. The first is a polynomial (or Legendre polynom) method. The second method of the randomly mixing angle between decayed particles from different experimental events, as described in Refs. [12, 10]. The third type of background has been obtained by the FRITIOF model [9].

The statistical significance (in standard deviations, SD) of resonance peaks was calculated as $NP/\sqrt{NB}$, where NB is the number of counts in the background under the peak and NP is the number of counts in the peak above the background.

3. *(Λ, π^+) and (Λ, π^-) spectra*

The $\Lambda\pi^+$ effective mass distribution for all 12088 combinations, with bin size of 13 MeV/c^2, is shown in Fig. 1a [13], without undivided (Λ,K^0_s) events. The resonance $\Sigma^{*+}(1382) \to \Lambda\pi^+$, with similar decay properties, was registered as a test of this method (Fig. 1a). The decay width is equal to $\Gamma \approx 45$ MeV/c^2. $\Delta M/M = 0.7$ is in the range of $\Sigma^{*+}(1382)$ invariant mass. The cross section of $\Sigma^{*+}(1382)$ production (540 simulated events) was estimated by FRITIOF model and is approximately equal to 1 mb for p+C interaction.

The $\Lambda\pi^-$ effective mass distribution for all 4940 combinations, with bin sizes of 18 and 12 MeV/c^2, is shown in Figs. 1b and c, respectively, The solid curve (Fig. 1b) is the sum of the background (the polynomial method) and a Breit-Wigner resonance ($\chi^2/N.D.F. = 39/54$). There is a significant enhancement in the mass range of 1372 MeV/c^2 with 11.3 SD, Γ =93 MeV/c^2. The cross section of

Σ^{*-} production ($\approx$ 680 events) is equal to $\approx$ 1.3 mb at 10 GeV/c for the p+C interaction. The observed broadening width of Σ^{*-} is $\approx$ 2 times larger than the PDG value. One possible explanation are the nuclear medium effects on invariant mass spectra of hadrons decaying in nuclei [14].

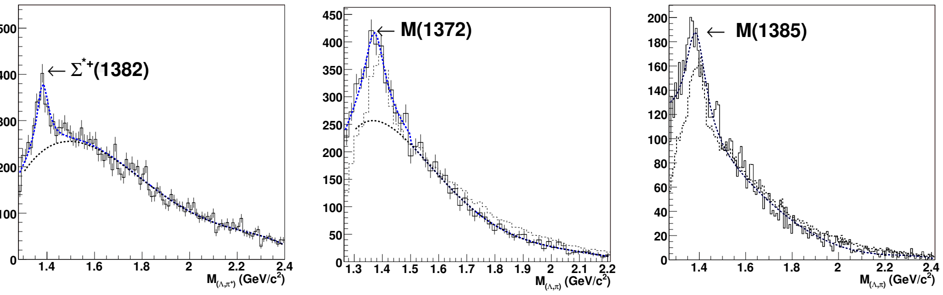

Fig. 1. a) The $\Lambda\pi^+$ spectrum with bin size of 13 MeV/c^2*; b) All $\Lambda\pi^-$ comb. with bin size of* 18 MeV/c^2*. c) $\Lambda\pi^-$ spectrum with bin size of* 12 MeV/c^2*. The simulated events by FRITIOF are shown by the dashed histogram. The dashed curve shows the background.*

Figure 1c shows the effective mass distribution with bin size of 12 MeV/c^2, where there are also significant enhancements in the mass regions of 1345 (3.0 SD) and 1480 (3.2 SD). The solid curve (Fig. 1c) is the sum of the background and a Breit-Wigner resonance ($\chi^2/N.D.F. = 109/88$). The background (dashed) curve is the sum of the sixth-order polynomial and a Breit-Wigner function with parameters for identified resonance $\Sigma^{*-}(1385)$ (Fig. 1c). There are negligible enhancements in the mass regions of 1410, 1520 and 1600 MeV/c^2. The cross section of Ξ^- production ($\approx$ 60 events), stopped in nuclear medium, is equal to 15 μb at 10 GeV/c for p+propane interaction. The expected number events due to Ξ^- is equal 16 events ($w = 1/e_\Lambda = 5.3$, where w is the full geometrical weight registered for Λs). We observed that the experimental production of Ξ^- is more than 4 times larger than the number of Ξ^- events which were simulated by the FRITIOF model. The figures show that the $\Sigma^{*-}(1480)$ correlation has been observed, in agreement with the SVD2 report [15].

4. (Λ, p) and (Λ, p, p) spectra

Figure 2a shows the invariant mass for all 13103 Λp combinations with the bin size of 11 MeV/c^2, without undivided Λ,K_s^0) events [5]. There are enhancements in the mass regions of 2100, 2150, 2225 and 2353 MeV/c^2 (Fig. 2a). Figure 2b shows the invariant mass of 2434 Λp combinations with the bin size of 15 MeV/c^2 [5, 13] for identified protons with momentum in the range of $0.350 < P_p < 0.900$ GeV/c. There are significant enhancements in the mass regions of 2100, 2175, 2285 and 2353 MeV/c^2 (Fig. 2b). Their excess above the background (the second method) is 6.9, 4.9, 3.8 and 2.9 SD, respectively. There is also a small peak at 2225 MeV/c^2 (2.2 SD).

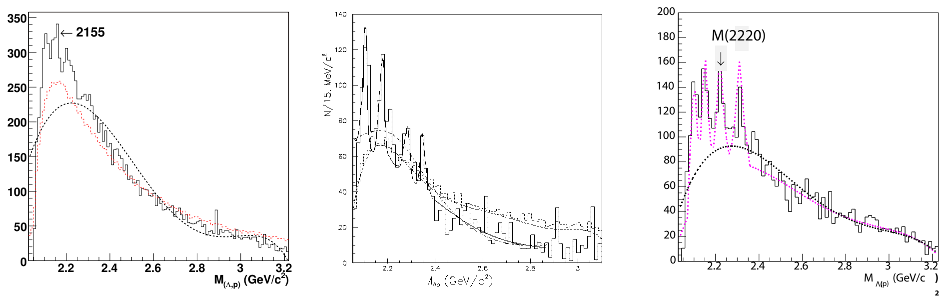

Fig. 2. a) All comb. for the Λp *spectrum with bin size of 11* MeV/c^2*; b)* Λ p *spectrum with with bin size of 15* MeV/c^2 *for identified protons in the momentum range of* $0.35 < P_p < 0.90$ GeV/c*; c)* Λp *spectrum with bin size of 15* MeV/c^2 *for stopped protons in momentum range of* $0.14 < P_p < 0.30$ GeV/c*. The dashed histogram shows simulated events by FRITIOF.*

Figure 2c shows the invariant mass of 4011 Λp combinations with the bin size 15 MeV/c^2, for stopped protons in the momentum range of $0.14 < P_p < 0.30$ GeV/c. The dashed curve is the sum of the 8th-order polynomial and of four Breit-Wigner curves with $\chi^2 = 30/25$ obtained from the fits (see Table 1). A significant peak at the invariant mass 2220 MeV/c^2 (6.1 SD), $B_K \sim 120$ MeV, was specially highlighted by Professor T. Yamazaki on μCF2007, Dubna, June-19-2007 as a confirmation of the KNC model prediction of channel $K^- pp \to \Lambda p$.

TABLE 1. The effective mass, width (Γ*) and the statistical significance (SD) for* Λp *resonances with protons stopped in the momentum range of* $0.14 < P_p < 0.30$ GeV/c *in* $p+$*propane collisions.*

Resonance decay mode	$M_{K\pi}$ (MeV/c^2)	Experimental width Γ_e (MeV/c^2)	Γ $\approx$	Statistical significance
Λp	2100	36	24	5.7
	2150	32	19	5.7
	2220	36	23	6.1
	2310	44	30	3.7
	2380	46	32	3.5

The effective Λp mass distribution for 4253 combinations with relativistic protons in the momentum of $P > 1.65$ GeV/c without undivided (Λ,K_s^0) events, is shown in Fig. 3a. The solid curve is the 6th-order polynomial function (χ^2/n.d.f=271/126). The background for the analysis of the experimental data was based on the FRITIOF and the polynomial method. There are significant enhancements in the mass regions 2150 (4.4 SD), 2210 (3.8 SD), 2270 (3.4 SD), 2670 (3.1 SD) and 2900 MeV/c^2 (3.1 SD). The observed peaks for combinations with relativistic protons $P > 1.5$ GeV/c agree with peaks for combinations with identified protons and with stopped protons.

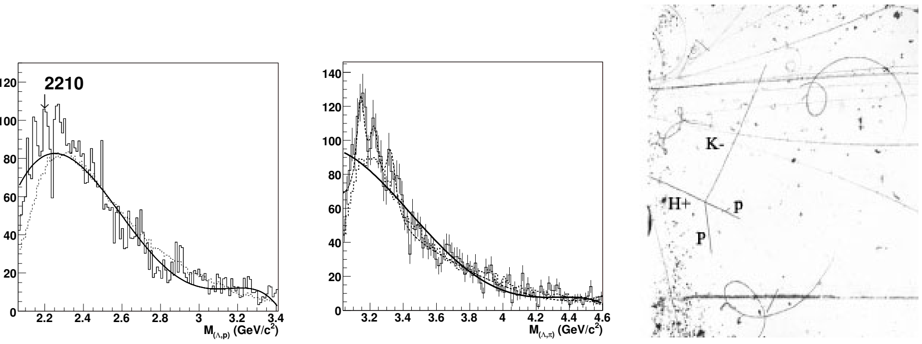

Fig. 3. a) Λp spectrum for relativistic positive tracks in the range of $P_p > 1.5$ GeV/c with bin size of 15 MeV/c^2; b) Λpp spectrum for identified protons with bin size of 16 MeV/c^2; c) The weak decay for $H^+ \to K^- pp$. The dashed histogram shows simulated events by FRITIOF. The experimental background is shown by the solid curve.

The Λpp effective mass distribution for 3401 combinations of identified protons with a momentum of $P_p < 0.9$ GeV/c is shown in Fig. 3b [13, 7]. The solid curve is the 6th-order polynomial function (χ^2/n.d.f=245/58, Fig. 3b). The backgrounds for the analysis of the experimental data are based on the FRITIOF and the polynomial method. There is a significant enhancements in the mass region of 3138 MeV/c^2 (6.1 SD), with a width of 44 MeV/c^2. There are also small enhancements in the mass regions of 3199 (3.3 SD), 3320 (5.1 SD), 3440 (3.9 SD) and 3652 MeV/c^2 (2.6 SD). These peaks from Λp and Λpp spectra were partly confirmed by experimental results from FOPI(GSI), FINUDA(INFN), OBELIX(CERN) and E471(KEK).

4.1. Heavy $S = -2$, $H^+ \to K^- pp$ dibaryon

The searches for stable $S = -2$ dibaryon states are going on in several laboratories [24, 7, 13, 16]. A new candidate for $S = -2$ H^+ dibaryon is shown in Fig. 3c. The first part of the track is 15.8 cm long, with a momentum of $p_{H^+} = 1.2 \pm 0.12$ GeV/c and the average relative ionization greater than 2. The second part is due to two stopped protons. The momentum of negative K^- is equal to 0.56 ± 0.03 GeV/c ($I/I_0 \approx 1.5$). The kinematic threshold does not permit ($\sqrt{s} = 1.96$ GeV/c) imitating the reaction with a deuteron including the Fermi motion. The $H^+ \to K^- pp$ hypothesis fits the event with χ^2(1V-3C)=2.6, C.L.= 28%, and $M_{H^+} = 2482 \pm 48$ MeV/c^2. There is also a possibility for the fit by the hypothesis of decay channel $H^+ \to \Sigma^+ \pi^- p$ which has a much smaller probability than the above hypothesis.

5. $K_s^0 p$ - *spectrum analysis*

5.1. $K_s^0 p$ - *spectrum at momentum of* $0.350 \leq p_p \leq 0.900$ GeV/c

Recently, new reports on Θ^+ observation were published, with statistical significance for $\Theta^+ \to K_s^0 p$ increased to 7.3 SD from DIANA [17] and 8.0 SD from SVD2 [15] collaborations. The results obtained from this experiment [18] are: $M_{\Theta^+} = (1540 \pm 8)$ MeV/c^2, $\Gamma = (9.2 \pm 1.8)$ MeV/c^2 ($\Gamma = (9.2 \pm 0.3)$ MeV/c^2 from PDG-04).

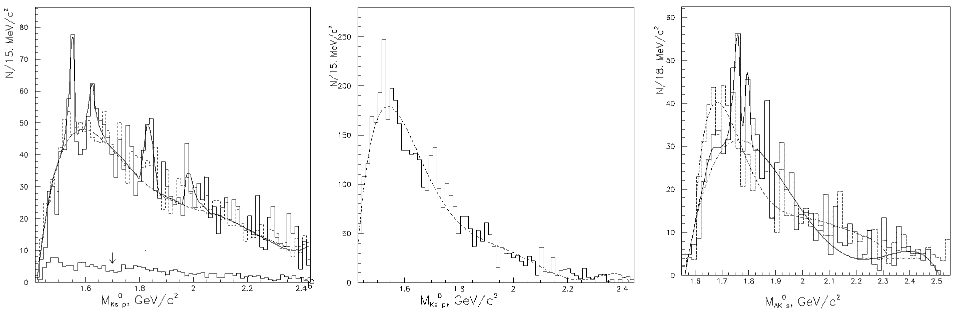

Fig. 4. a) $K_s^0 p$ spectrum for identified protons in the range of $0.35 < P_p < 0.90$ GeV/c ($\overline{K^0}p$ comb. by FRITIOF - lower histogram); b) (K_s^0, pos. relativistic tracks) spectrum in the momentum range of $0.9 < P_p < 1.7$ GeV/c; c) $K_s^0 \Lambda$ spectrum. The dashed histogram shows simulated events by FRITIOF.

The $K_s^0 p$ effective mass distribution for 2300 combinations is shown in Fig. 4a [18]. The solid curve is the sum of the background and four Breit-Wigner resonance curves. The $K_s^0 p$ invariant mass spectrum shows resonant structures with $M_{K_s^0 p}$=1540±8, 1613±10, 1821±11 MeV/c^2 and $\Gamma_{K_s^0 p}$= 9.2±1.8, 16.1±4.1, 28.0±9.4 MeV/c^2, respectively. The statistical significance of these peaks has been estimated at 5.5, 4.8 and 5.0 SD, respectively. Small peaks are also observed in the mass regions of 1690 (3.6 SD) and 1980 (3.0 SD) MeV/c^2. The primary total cross section for $\Theta^+(1540)$ production in $p + C_3H_8$ interactions is estimated to be $\approx$ 90 μb. The experimental spectrum of Θ^+ agrees with the calculated rotational spectra from the theoretical reports of Akers [19], MacGregoret al. [20] and Arkhipov [21].

Significant enhancements have been also observed for the (K_s^0, pos.tracks) invariant mass distribution with the momentum range $p_p \geq 1.7$ GeV/c (3500 combinations) in mass regions of 1487, 1544, 1612 and 1805 MeV/c^2 [18]. Their excess above background is 3.0, 3.9, 3.7 and 4.0 SD, respectively. There is also a small peak in the mass region of 1685 MeV/c^2 .

5.2. (K_s^0, *pos.tracks*) - *spectra for* $0.9 \leq p_p \leq 1.7$ GeV/c

The (K_s^0, *pos.track*) invariant mass spectrum shows resonant structures with M =1515 (5.3 SD) and 1690 MeV/c^2 (3.8 SD) in Fig. 4b [18]. No obvious structure in the mass regions of 1540, 1610 and 1821 MeV/c^2 is seen in Fig. 4b. The observed peaks are reflections from resonances Λ(1520) and Λ(1700) in (p$\overline{K^0}$) invariant mass spectrum from ($\overline{K^0}$n) in reactions p+p → $K^+(\overline{K^0}pnX)$.

6. ΛK_s^0 - *spectrum analysis*

Figure 4c shows the invariant mass of 1012 (ΛK_s^0) combinations with bin sizes 18 MeV/c^2 [10]. The solid curve is the sum of the background obtained by the first method and two Breit-Wigner curves (Fig. 4c). A number of peculiarities were found in the effective mass spectrum of the system ΛK_s^0 in the ranges (1650 – 1680), (1740 – 1750), (1785 – 1805), (1835 – 1860) and (1925 – 1950) MeV/c^2 in collisions of protons of momentum 10 GeV/c in propane. A detailed study of the structure of mass spectrum has shown that significant enhancements have been obtained in two effective mass ranges, 1750 MeV/c^2 and 1795 MeV/c^2. These peaks could be interpreted as possible candidates of two pentaquark states: the N^0 with the quark content *udsds* decaying into ΛK_s^0 and the Ξ^0 with the quark content *udssd*, decaying into $\Lambda\overline{K_s^0}$. The preliminary total cross section for $N^0(1750)$ production in p+propane interactions is estimated to be ≈ 30μb.

7. $K_s^0\pi^\pm$ *spectra analysis*

The scalar mesons have vacuum quantum numbers and are crucial for a full understanding of the symmetry breaking mechanisms in QCD, and presumably also for the confinement [22]. Suggestions that the $\sigma(600)$ and $\kappa(800)$ could be glueballs have been made.

Ref. [23] reports the study of vector mesons $K^{*\pm}(892)$ from pp interactions at 12 and 24 GeV/c by using data (280000 - events) from exposure of CERN 2m hydrogen bubble chamber to p beams. Total inclusive cross sections for $K^{*\pm} \to K_s^0\pi^\pm$X in pp interactions are equal to 0.27 ± 0.03 and 0.04 $\pm^{0.02}_{0.03}$ for K^{*+} and K^{*-}, respectively.

7.1. $K_s^0\pi^+$ - *spectrum*

Figure 5a shows the invariant mass distribution from all experimental 6400 ($K_s^0\pi^+$) combinations with the bin size of 16 MeV/c^2 [13, 7]. The average effective mass resolution of $K_s^0\pi$ system is equal to ≈2%. The dashed curve is the background taken in the form of a polynomial up to the 8th degree (Figure 5a) which agreed with background obtained by FRITIOF. There are enhancements in the mass regions 720, 780, 840, 890 and 1060 MeV/c^2. The peak $M(890)$ in the invariant mass spectrum is identified as the well known resonance from PDG The preliminary interpretation of the peak in mass range of 1060 MeV/c^2 is a reflection from the well known Φ resonance through the channel $\Phi \to K_s^0(\pi^+\pi^-)$.

The effective mass distributions of 3259 ($K_s^0\pi^+$) combinations in the momentum range of $0.05 < p_{\pi^+} < 0.900$ GeV/c with the bin size 18 MeV/c^2 is shown in Fi. 5b. Backgrounds by FRITIOF and polynomial methods have a similar form. There are enhancements in the mass regions 720, 778 and 890 MeV/c^2. The solid curve in

Fig. 5b is the sum of two BW functions and the background (black solid curve) taken in the form of a polynomial up to the 6th degree. The dashed curve (red) is the background by polynomial outside the range of $0.75 < M_{K_s^0\pi} < 0.98$ MeV/c^2 whith one BW function.

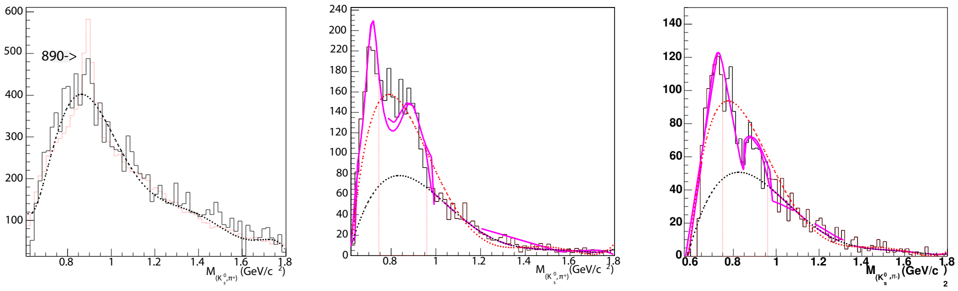

Fig. 5. a) The invariant mass distribution of $K_s^0\pi^+$ without cuts and with bin size of 18 MeV/c^2; b) $K_s^0\pi^+$ spectrum in the momentum range of $P_p < 0.9$ GeV/c with bin size of 18 MeV/c^2, without background from comb. with protons; c) the invariant mass distribution of $K_s^0\pi^-$ without cuts and with bin size of 15 MeV/c^2. The dashed histogram shows simulated events by FRITIOF.

7.2. $K_s^0\pi^-$ - spectrum

Figure 5c shows the invariant mass distribution of 2670 ($K_s^0\pi^-$) combinations with bin size of 15 MeV/c^2 [13, 7]. The solid curve in Figure 5c is the sum of two BW functions and background (below black solid curve) taken in the form of a polynomial up to the 6th degree. The dashed curve (red) is the background by polynomial within the range of $0.75 < M_{K_s^0\pi} < 0.96$ MeV/c^2 whith one BW function. There are significant enhancements in the mass regions of 720, 780 and 890 MeV/c^2 (Table 2). The peak 890 MeV/c^2 in the invariant mass spectrum is identified as known resonances from PDG. The preliminary total cross section for the $M(720)$ production in p + propane interactions is larger than 30 μb.

TABLE 2. The effective mass, the width(Γ) and the statistical significance ($SD_{\max} - SD_{\min}$) for $K_s^0\pi^\pm$ resonances in p + propane collisions.

Resonance decay mode	$M_{K\pi}$ (MeV/c^2)	Experimental width Γ_e (MeV/c^2)	Γ	Statistical significance
$K_s^0\pi^\pm$	890	75	50	6.0-8.2
$K_s^0\pi^\pm$	780-800	33	10	2.5-4.2
$K_s^0\pi^\pm$	720-730	50-145	30-125	4.1-15.2

8. Conclusion

• Significant enhancements in the invariant mass ranges of 1382 MeV/c^2 for $\Sigma^{*+} \to \Lambda\pi^+$ and 890 MeV/c^2 ($K^{*\pm}(892) \to K_s^0\pi^\pm$) have been observed, which agree with PDG and are tests for the applied methods of analysis.

• A number of important peculiarities were observed in the effective mass spectra of pA→ $\Lambda(K_s^0)$X reactions by decay modes: $\Lambda\pi^\pm$, Λp (Table 1), Λpp, $K_s^0\Lambda$, $K_s^0\pi^\pm$ (Table 2) and $K_s^0 p$.

• The experimental Λ/π^+ ratio for average multiplicities in the pC reaction is approximately two times larger than this ratio from pp reaction.

• The width of the exited $\Sigma^{*-}(1385)$ is two times larger than the PDG (preliminary result).

• The production of stopped-in-medium $\Xi^- \to \Lambda\pi^-$ is more than 4 times larger than expected from the geometrical cross section for p+propane interaction (preliminary result).

• A few events were registered that seem to be the hypothetical $S = -2$ light and heavy $H^{0,+}$ dibaryons decaying through weak channels [24, 13].

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TRAŽENJE STRANIH EGZOTIČNIH VIŠEBARIONSKIH STANJA S Λ-HIPERONIMA I K_s^0-MESONIMA U SUDARIMA p+A PRI 10 GeV/c

Proučavamo strana egzotična višebarionska stanja putem efektivnih masenih spektara podsustava $\Lambda\pi^+$, $\Lambda\pi^-$, Λp i Λpp, te ΛK_S^0, $K_S^0\pi^\pm$ i $K_S^0 p$. Invariantna masa u $\Lambda\pi^+$ i $K_S^0\pi^\pm$ spektrima pokazuje poznate rezonancije $\Sigma^{*+}(1385)$ i $K^{*\pm}(892)$. Širina rezonancije $\Sigma^{*-}(1385)$ iz p+A reakcije je dvostruko veća od objavljene u PDG. Udarni presjek za $\Xi^- \to \Lambda\pi^-$ je $7-8$ puta veći od vrijednosti očekivane na osnovi geometrijskog udarnog presjeka za reakcije u p+propan. Nekoliko snimljenih događaja u propanskoj komori na mjehuriće tumačimo kao lake i teške $S=-2$ $H^{0,+}$ dibarione.