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P. Zh. Aslanyan[1,2], V. N. Emelyanenko[1], G. G. Rikhvitskaya[1]

OBSERVATION OF $S = +1$ NARROW RESONANCES IN THE SYSTEM pK_s^0 FROM $p + \mathrm{C_3H_8}$ COLLISION AT 10 GeV/c

[1]Joint Institute for Nuclear Research
[2]Yerevan State University; E-mail: paslanian@jinr.ru

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Обнаружение $S = +1$ узких резонансов в системе
pK_s^0 в $p + C_3H_8$-столкновениях
при импульсе 10 ГэВ/c

Исследование по поиску Θ^+-бариона по каналу распада pK_s^0 проводилось на экспериментальном материале, полученном с помощью 2-м пропановой камеры для реакции $p + C_3H_8$ при импульсе пучка 10 ГэВ/c. В спектре инвариантных масс для pK_s^0-системы обнаружены значимые резонансные пики в районах $M_{pK_s^0} = 1540 \pm 8,\ 1613 \pm 10,\ 1821 \pm 11$ МэВ/c^2. Ширина и статистическая значимость этих пиков равны соответственно $\Gamma_{pK_s^0} = 9{,}2 \pm 1{,}8,\ 16{,}1 \pm 4{,}1,\ 28{,}0 \pm 9{,}4$ МэВ/c^2 и 5,5, 4,8, 5,0 стандартных отклонения (s. d.). Также с меньшей статистической значимостью наблюдалась резонансная структура в районах масс 1487 (3,0 s. d.), 1690 (3,6 s. d.) и 1980 (3,0 s. d.) МэВ/c^2.

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Observation of $S = +1$ Narrow Resonances
in the System pK_s^0 from
$p + C_3H_8$ Collision at 10 GeV/c

Experimental data from a 2 m propane bubble chamber have been analyzed to search for an exotic baryon state, the Θ^+ baryon, in the pK_s^0 decay mode for the reaction $p + C_3H_8$ at 10 GeV/c. The pK_s^0 invariant mass spectrum shows resonant structures with $M_{pK_s^0} = 1540 \pm 8$, 1613 ± 10, 1821 ± 11 MeV/c^2 and $\Gamma_{pK_s^0} = 9.2 \pm 1.8$, 16.1 ± 4.1, 28.0 ± 9.4 MeV/c^2. The statistical significance of these peaks has been estimated as 5.5, 4.8 and 5.0 s. d., respectively. There are also small peaks in mass regions of 1487 (3.0 s. d.), 1690 (3.6 s. d.) and 1980 (3.0 s. d.) MeV/c^2.

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

Communication of the Joint Institute for Nuclear Research. Dubna, 2004

INTRODUCTION

Recent experimental efforts have been strongly motivated by Diakonov, Petrov and Polyakov [1], who studied antidecuplet baryons using the chiral soliton (Skyrme) models. The lightest member of the pentaquark antidecuplet, Θ^+ baryon predicted in [1], has positive strangeness, the mass $M = 1530$ MeV/c^2, 1/2 spin and even parity. Jaffe and Wilczek have suggested an underlying quark model structure of this state [2]. There are other theoretical speculations which have predicted this state [3–6]. The rotational states of the $S = +1\,\Theta^+$ baryon are shown in the paper by Akers [5]. Experimental evidence of $\Theta^+(1530)$ baryon with positive strangeness has come recently from several experimental groups (LEPS [7]], DIANA-ITEP [8], CLAS [9], SAPHIR [10], HERMES [11], SVD-2 experiment, IHEP [12]). By using the bubble chamber method, a resonant structure in the pK_s^0 and nK^+ invariant mass spectra has been observed [8, 13–16].

1. METHOD

A reliable identification of the above-mentioned resonance [7–16] needs using 4π detectors and high-precision measurements of the sought objects. The bubble chamber is the most suitable instrument for this purpose [8, 13–18]. The experimental information of more than 700 000 stereo photographs are used to select the events with V^0 strange particles. The GEOFIT based on the Grind–CERN program [19] is used to measure the kinematic parameter of track momenta, $\mathrm{tg}\,\alpha$ (α — is a dip angle) and azimuthal angle (β) in the photographs. The relative error of measuring momentum P and the average track length L of charged particles are found to be $\langle \Delta P/P \rangle = 2.1\%$, $\langle L \rangle = 12$ cm for stopped particles and $\langle \Delta P/P \rangle = 9.8\%$, $\langle L \rangle = 36$ cm for nonstopped particles. The mean values of measurement errors for the dip and azimuthal angles are equal to $\langle \Delta\,\mathrm{tg}\,\alpha \rangle = (0.0099 \pm 0.0002)$ and $\langle \Delta\beta \rangle = (0.0052 \pm 0.0001)$ rad.

The estimation of ionization, the peculiarities of the end track points of the stopped particles (p, $K^{\pm}$) allowed one to identify them. Protons can be identified over the following momentum range: $0.150 \leqslant P \leqslant 0.900$ GeV/c. In the momentum range $P > 0.900$ GeV/c, protons couldn't be separated from other particles. Therefore, the experimental information has been analyzed similarly in two separate ranges.

1.1. Identification of Λ and K_s^0. The events with V^0 (Λ and K_s^0) were identified by using the following criteria [20–22]: 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 Λ is greater than 0.1 and 0.2 GeV/c, respectively; 2) V^0 stars should have the effective mass of K_s^0 or Λ; 3) these V^0 events are directed to some vertices (coplanarity); 4) they should have one vertex, a three-constraint 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 analysis has shown [21] that the events with undivided Λ, K_s^0 particles were assumed to be Λ.

Figures 1, *a, c* and 1, *b, d* show the effective mass distribution of 8657 events with Λ, 4122 events with K_s^0 particles and their χ^2 from kinematic fits, respectively. The measured masses of these events have the following Gaussian distribution parameters $\langle M(K_s^0)\rangle = 497.7 \pm 3.6$, s.d. $= 23.9$ MeV/c^2 and

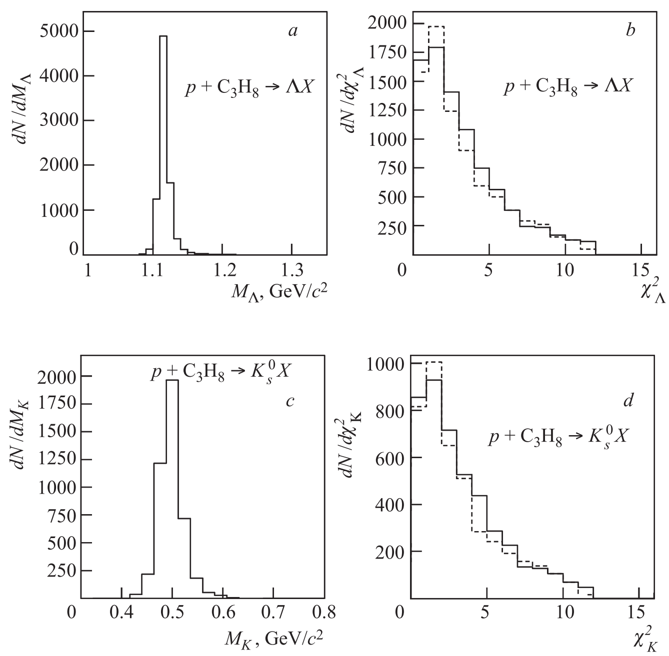

Fig. 1. The distribution of experimental V^0 events produced from interactions of beam protons with propane: for the effective mass of M_Λ (*a*); for $\chi^2_\Lambda(1V - 3C)$ of the fits via the decay mode $\Lambda \to \pi^- + p$ (*b*); for the effective mass of $M_{K_s^0}$ (*c*); for $\chi^2_{K_s^0}(1V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

$\langle M(\Lambda)\rangle = 1117.0 \pm 0.6$, s. d. $= 10.0$ MeV/c^2. The masses of the observed Λ, K_s^0 are consistent with their PDG values [23]. The effective mass of the $\Theta^+ \to pK_s^0$ system, like that of the $\Lambda \to \pi^- + p$ system, has been measured with a precision of $\langle \Delta M_{(pK_s^0)}/M_{(pK_s^0)}\rangle \approx 1.1\%$. Then the effective mass resolution of pK_s^0 system was estimated to be on the average 0.6% for identified protons with a momentum $0.150 \leqslant P \leqslant 0.900$ GeV/c.

The preliminary estimate of the experimental total cross sections is equal to $\sigma = (3.8 \pm 0.6)$ mb for K_s^0 production in the $p + {}^{12}$C collisions at 10 GeV/c.

2. pK_s^0-SPECTRUM ANALYSIS

2.1. pK_s^0 Spectrum for Identified Protons with a Momentum $0.350 \leqslant P_p \leqslant 0.900$ **GeV/c.** The pK_s^0 effective mass distribution for 2300 combinations is shown in Fig. 2. The solid curve is the sum of the background and four Breit–Wigner resonance curves.

The total experimental background has been obtained by two methods. 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 $\chi^2 = 1$ and polynomial coefficient with errors less than 10%. This distribution was fitted by the eighth-order polynomial. The second of the randomly mixing method of the angle between K_s^0 and p for experimental events is described in [24]. Then, these background events were analyzed by using the same experimental condition, and the effective mass distribution pK_s^0 was fitted by the eighth-order polynomial. The analysis done by two methods has shown that while fitting these distributions had the same coefficients and order of polynomial.

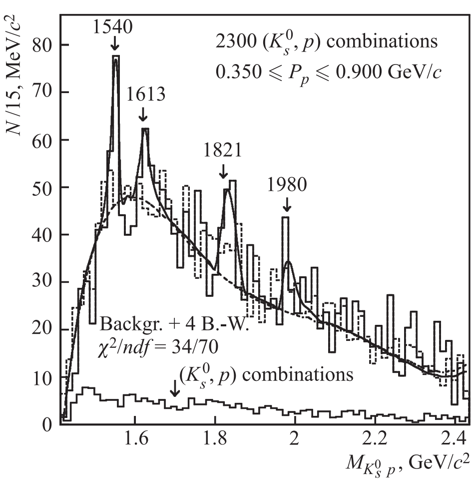

Fig. 2. The pK_s^0 invariant mass spectrum with a momentum $0.350 \leqslant P_p \leqslant 0.900$GeV/$c$ for identified protons in the reaction $p + C_3H_8 \to pK_s^0 + X$. The solid curve is the sum of the experimental background (by the first method) and four Breit–Wigner resonance curves ($\chi^2/ndf = 34/70$). The dashed histogram is the experimental background [24] taken in the form of the eighth-order polynomial (the dashed curve). The bottom histogram shows the simulated background for the spectrum of $p\overline{K^0}$ combinations

The background for $p\overline{K^0}$ combinations is estimated with FRITIOF model [25, 26] and no more than 10% has been obtained. No obvious structure in $p\overline{K^0}$ spectrum is seen in Fig. 2.

The statistical significance for the fit in Fig. 2 has been calculated as $NP/\sqrt{NB}$, where NP is the number of events corresponding to the signal on the fitted background top and NB is the number of events corresponding to the background in the chosen area. There are significant enhancements in mass regions of 1540, 1612 and 1821 MeV/c^2. There are small peaks in mass regions of 1480 and 1980 MeV/c^2 .

2.2. pK_s^0 Spectrum for Positively Charged Tracks with a Momentum $0.9 \leqslant P_p \leqslant 1.7$ GeV/*c*. The pK_s^0 invariant mass spectrum shows resonant structures with $M = 1515$ (5.3 s. d.) and 1690 (3.6 s. d.) MeV/c^2 in Fig. 3. No obvious structure in mass regions of 1540, 1610 and 1821 MeV/c^2 is seen in Fig. 3.

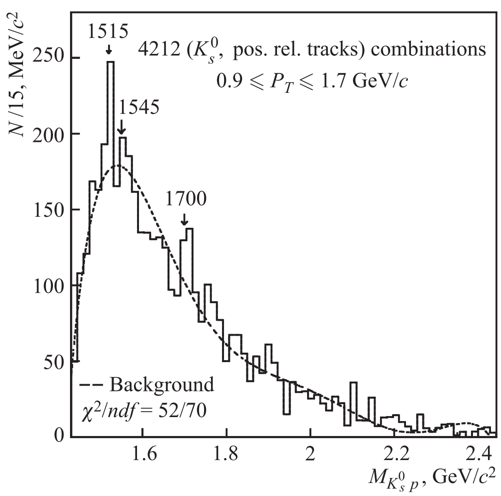

Fig. 3. The pK_s^0 invariant mass spectrum in the reaction $p + C_3H_8 \to pK_s^0 + X$, where protons were selected as positively charged tracks with the cuts of a momentum $0.9 \leqslant P \leqslant 1.7$ GeV/*c*. The dashed curve is the background distribution taken by the sixth-order polynomial

The FRITIOF [25, 26] model shows that the average multiplicity in this range for all positive tracks, protons and π^+ is equal to 1.2, 0.4 and 0.8, respectively. The background for $K_s^0\pi^+$ and $K_s^0K^+$ combinations is equal to 46.6% and 4.4%, respectively. These observed peaks can be a reflection of resonances $\Lambda(1520)$ and $\Lambda(1700)$, because in the $n\overline{K^0}$ invariant mass spectrum, where π^+ meson was detected in reactions $p + C_3H_8 \to \pi^+ n\overline{K^0}X$, π^+-meson mass was substituted by the mass of neutron.

2.3. pK_s^0 Spectrum with a Momentum $P_p \geqslant 1.7$ GeV/*c*. The pK_s^0 invariant mass distribution with a momentum $P_p \geqslant$ 1.7 GeV/*c* (3500 combinations) is shown in Fig. 4. The histogram is approximated by a polynomial background curve and by five resonance curves taken in the Breit–Wigner form. The dashed curve is the background taken in the form of a superposition of Legendre polynomials up to the 6th power inclusive. The analysis done by two methods has shown that while fitting these distributions had the same coefficient and order of polynomial. The average multiplicity (FRITIOF) in this range for all positive tracks, protons and π^+ is

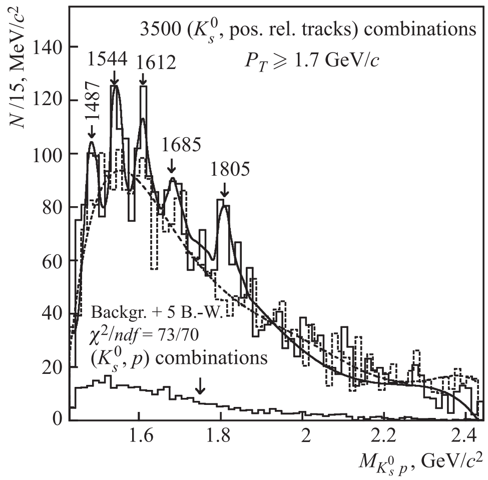

Fig. 4. The pK_s^0 invariant mass spectrum in the reaction $p + C_3H_8 \to pK_s^0 + X$, where protons were selected as positively charged tracks with the cuts of a momentum $P > 1.7$ GeV/c. The solid curve is the sum of the experimental background (by the first method) and five Breit–Wigner form resonance curves. The dashed histogram is the experimental background [24] taken in the form of the sixth-order polynomial (dashed curve). The bottom histogram shows the simulated background for the spectrum of $p\overline{K^0}$ combinations

equal to 1.3, 0.8 and 0.5, respectively. Therefore, the background for $K_s^0\pi^+$ and $K_s^0K^+$ combinations is equal to 20% and 5%, respectively. The estimate of contribution for $p\overline{K^0}$ combinations with FRITIOF model is equal to 8%. No obvious structure in $p\overline{K^0}$ spectrum is seen in Fig. 4.

There are significant enhancements in mass regions of 1487, 1544, 1612, and 1805 MeV/c^2 (Fig. 4). Their excess over background is 3.0, 3.9, 3.7, and 4.0 s. d. There is a small peak in the mass region of 1685 MeV/c^2.

2.4. The Sum of pK_s^0 Spectrum. The total pK_s^0 invariant mass distribution for identified protons and positively charged tracks $P_p \geqslant 1.7$ GeV/c is shown in Fig. 5. The solid curve is the sum of the background and four Breit–Wigner

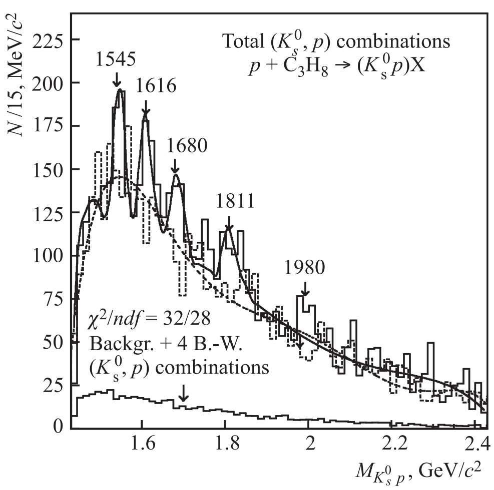

Fig. 5. The sum of the effective mass distribution of pK_s^0 combinations for protons with momenta $0.350 \leqslant P \leqslant 0.9$ GeV/c and $P > 1.7$ GeV/c. The solid curve is the sum of the experimental background (by the first method) and four Breit–Wigner resonance curves. The dashed histogram is the experimental background [24] taken in the form of the sixth-order polynomial (the dashed curve). The bottom histogram shows the simulated background for the spectrum of $p\overline{K^0}$ combinations

resonance curves. The background was fitted by the sixth-order polynomial. The total experimental background (dashed histogram) with the same experimental condition has been also obtained by the second method [24]. The dashed curve is the background taken in the form of a superposition of Legendre polynomials up to the 6th power inclusive. In Fig. 5, the bottom histogram shows the simulated background for the spectrum of $p\overline{K^0}$ combinations.

There are significant enhancements in mass regions of $(1545{\pm}12)$, $(1616{\pm}10)$ and (1811 ± 11) MeV/c^2. Their excess over background by the second method is (5.5 ± 0.5), (4.8 ± 0.5), and (5.0 ± 0.6) s. d., respectively. There are small peaks in mass regions of 1487 (3.0 s. d.), 1690 (3.6 s. d.), and 1980 (3.0 s. d.) MeV/c^2.

CONCLUSION

The effective mass spectra pK_s^0 in collisions of protons of a 10.0 GeV/c momentum with C_3H_8 nuclei, have resulted in the discovery of the peaks presented in table. Table shows the width (Γ) and the effective mass resonances which are based on the data from Fig. 2. The statistical significance in table is based on the data from Fig. 5. There are small peaks in mass regions of 1487, 1690 and 1980 MeV/c^2 (Fig. 5), their excess over background is 3.6 and 3.0 s. d., respectively. The primary total cross section for $\Theta^+(1540)$ production in $p + C_3H_8$ interactions is estimated to be ≈ 90 μb.

The statistical significance, the width (Γ) and the effective mass resonances in collisions of protons with C_3H_8 nuclei

Resonance system	M, MeV/c^2	$\Gamma_{\rm exp}$, MeV/c^2	Γ, MeV/c^2	The statistical significance, $N_{\rm s.d.}$
pK_s^0	1540 ± 8	18.2 ± 2.1	9.2 ± 1.8	5.5 ± 0.5
pK_s^0	1613 ± 10	23.6 ± 6.0	16.1 ± 4.1	4.8 ± 0.5
pK_s^0	1821 ± 11	35.9 ± 12.0	28.0 ± 9.4	5.0 ± 0.6

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141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@pds.jinr.ru
www.jinr.ru/publish/