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SEARCH FOR NARROW BARYONIA

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The problem of the existence of multiquark states is of great significance for the development of a strong interaction theory. However, an experimental search for such states has not yet led to convincing results.

A narrow exotic state, a baryonium with negative strangeness decaying into Λ, $\bar{p}$ and pions, has been observed in the WA-62 experiment carried out in a hyperon beam at the CERN SPS [1-4]. Unlike the experiment in the hyperon beam, the BIS-2 experiment performed in a neutron beam allowed one to search for baryonia with negative and positive strangeness alike. The existence of the narrow baryonium with negative strangeness was confirmed, a new baryonium with positive strangeness and doubly charged states of these baryonia were indicated [4-10]. In the BIS-2 experiment it was searched for a baryonium with hidden strangeness as well [8-13].

New results on a search for the narrow baryonia produced in neutron-nucleus and neutron-proton interactions are presented in this paper. The results are based on larger statistics in comparison with [7,13]. The experiment was carried out in a neutron beam of the Serpukhov accelerator. The mean momentum of the beam consisting mainly of neutrons was 40 GeV/c. A layout of the main elements of the BIS-2 spectrometer [14-16] is presented in fig.1. The magnetic field in the analyzing magnet M directed along the OY axis caused a 0.64 GeV/c change of the transversal momentum of charged particles crossing the field region. The system consisting of multicell threshold gas Cerenkov counters C1 and C2 was used to identify charged hadrons [17,18]. The counter C1 was filled with air and C2 - with freon-12 under atmospheric pressure. The identification system allowed one to identify with some probability charged hadrons in multiparticle events. The

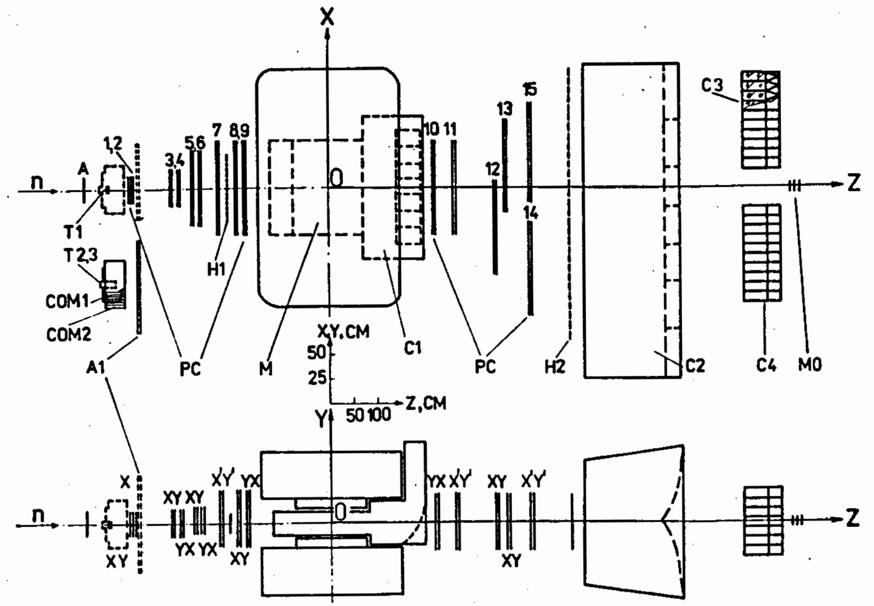

Fig.1. Layout of the BIS-2 spectrometer. T1/T2,3 - targets, COM1/2 - target surrounding counters, PC 1-15 - two-coordinate proportional chambers. C1/2 - multicell threshold gas Cherenkov counters. C3/4 - glass Cherenkov counters, MO - neutron monitor, M - analyzing magnet.

trigger conditions required the passage of more than four charged particles.

The thicknesses of the liquid-hydrogen target and the nuclear ones were 2.1 g/cm^2 and $3.4\cdot A^{1/3}$ g/cm^2 respectively, where A is the atomic weight of target nuclei. The nuclear targets were interchanged each $(40\div50)\cdot10^3$ recorded events. The results presented here are based on the analysis of $1.9\cdot10^7$ neutron-proton and $3.1\cdot10^7$ neutron-nucleus interactions.

The narrow baryonium with negative strangeness was searched for by its decays into Λ, $\bar{p}$ and pions:

$$\Lambda\,\bar{p}\,\pi^+ \quad , \qquad (1a)$$

$$\Lambda\,\bar{p}\,\pi^+\pi^- \quad , \qquad (1b)$$

$$\Lambda\,\bar{p}\,\pi^+\pi^+ \qquad (1c)$$

and $\Lambda\,\bar{p}\,\pi^-$, (1d)

and the charge conjugated baryonium with positive strangeness, - by its decays into:

$$\bar{\Lambda}\,p\,\pi^- \quad , \qquad (2a)$$

$$\bar{\Lambda}\,p\,\pi^+\pi^- \quad , \qquad (2b)$$

$$\bar{\Lambda}\,p\,\pi^-\pi^- \qquad (2c)$$

and $\bar{\Lambda}\,p\,\pi^+$. (2d)

The baryonium with hidden strangeness was searched for according to its decays into:

$$\Lambda\,\bar{p}\,K^+, \qquad (3a)$$

$$\bar{\Lambda}\,p\,K^-, \qquad (3b)$$

$$\Lambda\,\bar{p}\,K^+\pi^+, \qquad (4a)$$

$$\bar{\Lambda}\,p\,K^-\pi^+, \qquad (4b)$$

$$K^o_s\,p\,\bar{p}\,K^+, \qquad (4c)$$

$$\Lambda\,\bar{p}\,K^+\pi^-, \qquad (4d)$$

$$\bar{\Lambda}\,p\,K^-\pi^- \qquad (4e)$$

and $K^o_s\,p\,\bar{p}\,K^-$. (4f)

The considered states involve all three and four particle decays of the searched baryonia which could be detected in the experiment. Five particle final states, involving doubly charged ones, were not observed practically due to a small acceptance in comparison with the states quoted above.

The neutral strange particles Λ, $\bar{\Lambda}$ and K^o_s were identified by their decays:

$$\Lambda \longrightarrow p\,\pi^-, \qquad (5a)$$

$$\bar{\Lambda} \longrightarrow \bar{p}\,\pi^+, \qquad (5b)$$

$$K^o_s \longrightarrow \pi^+\pi^- . \qquad (5c)$$

A pair of oppositely charged particles with the distance between their tracks being not more than the fourfold value of the resolution, was accepted as V^0. It was also required that the vertices of the V^0's were downstream the liquid hydrogen target and 10 cm beyond the solid targets along the beam. The Λ, $\bar{\Lambda}$ and K^0_s were identified according to effective masses of the systems $(p\pi^-)$, $(\bar{p}\pi^+)$ and $(\pi^+\pi^-)$ respectively. $6\cdot10^5$ events with V^0's – Λ candidates, $9.1\cdot10^4$ events with $\bar{\Lambda}$ candidates and $4.7\cdot10^5$ events with K^0_s candidates were selected, for which the effective mass of the $(p\pi^-)/(\bar{p}\pi^+)/(\pi^+\pi^-)$ systems were differed from the $\Lambda/\bar{\Lambda}/K^0_s$ table mass no more than 4-fold of the experimental resolution.

To search for the baryonia in the final states (1a-4f), the events containing Λ, $\bar{\Lambda}$ or K^0_s and two or more charged hadrons h^+ and h^- emerging from a common interaction vertex were selected. This vertex was required to be located inside the target and the mean quadratic distances between the trajectories of $\Lambda/\bar{\Lambda}/K^0_s$, $h^\pm$ and the common vertex did not exceed the fourfold resolution. This resolution was different (from 0.2 to 0.5 cm) in the runs with the different targets. Using the above quoted conditions 80102 / 11610 / 72812 events containing Λ / $\bar{\Lambda}$ / K^0_s -candidates and two or more charged particles, respectively, were selected.

Effective mass spectra of the final states were obtained under assumption that larger momenta correspond to heavier particles. This allowed one to lower a combinatorial background.

The information obtained from C1/2 was used to reduce the background due to the misidentification of charged particles. Relative probabilities W(i) of the each charged particle identification with i-type particles ($i=\pi^\pm$, $K^\pm$ or $p/\bar{p}$) were calculated by comparison of the signals in different C1 and C2 channels with a calculated distribution of the Cherenkov light and the corresponding number of photoelectrons from the detected charged particles over these channels. The relative probabilities W(i) were normalized in such a way that their sum for each of the detected charged particles would be $W(p/\bar{p})+W(K^\pm)+W(\pi^\pm)=3$. Thus, the value W(i)=3 means a 100% reliability of the particle identification as a type i. A condition $W(p/\bar{p})=W(K^\pm)=W(\pi^\pm)=1$ means a completely unidentified particle and so on. Some ambiguities of the charged particle identification were caused by the Cherenkov light from one particle to fall in several channels. The calculated identification efficiency shows that this depends not only on the momentum of the charged particle, but on the total number of these particles in an event as well.

The identification of $\bar{p}$ leads to a more significant reduction of the background among the final states. Unfortunately about 80% of all negative particles, candidates in $\bar{p}$, have momenta below the threshold of the Cherenkov radiation for kaons. As a rule, for these particles $W(\bar{p})=W(K^-)\leq1.5$. So, to select $\bar{p}$ it was required:

$$W(\bar{p})\geq1.1. \qquad (6)$$

For the identification of p, K^+ and K^- there were used following criteria:

$$W(p)\geq0.9, \qquad (7)$$

$$W(K^+)\geq1.1 \qquad (8)$$

and $$W(K^-)\geq0.9. \qquad (9)$$

Two charged particles were identified to select the most of the considered final states. But three charged particles should be identified for the selection of the states (4c and 4f). So, less stringent criteria than (7) and (8) were used for the $K^\pm$ and p identification in these states to avoid an essential reduction of the detection efficiency.

The identification criteria for the charged particles raised 9 times the relative ratio of events containing $\bar{p}$ whereas their losses were ≈ 20%, raised ≈ 2÷3 times the relative ratio of events containing K^+, 2.5÷7 times – containing K^- and more than 2 times – containing p.

The effective mass spectra obtained for the selected combinations of the neutral, charged and doubly charged final states with negative strangeness (1a–d) are presented in figs. 2(a), 2(b) and 2(c), respectively. The effective mass spectra of the final states with positive strangeness (2a–d) are presented in figs. 2(d), 2(e) and 2(f). The numbers of combinations entered

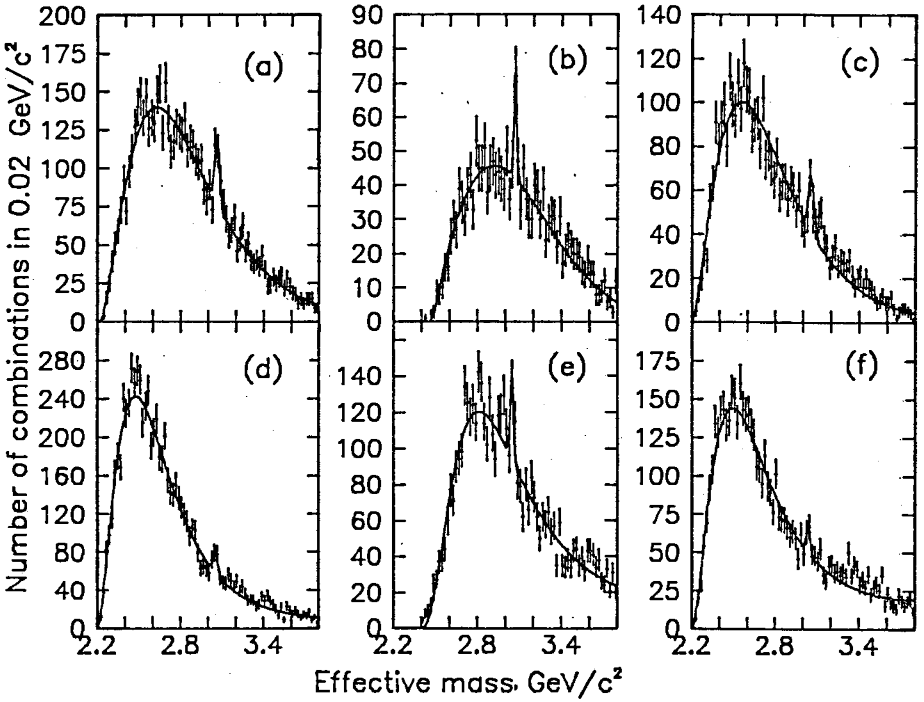

Fig.2. Spectra of effective masses $\Lambda\bar{p}\pi^+$ (a), $\Lambda\bar{p}\pi^+\pi^\pm$ (b), $\Lambda\bar{p}\pi^-$ (c), $\bar{\Lambda}p\pi^-$ (d), $\bar{\Lambda}p\pi^-\pi^\mp$ (e) and $\bar{\Lambda}p\pi^+$ (f).

into these spectra are presented in table 1. In all spectra the bin width of 20 MeV/c^2 was chosen to be close to a two-fold value of the experimental mass resolution. The spectra were approximated by smooth functions. Enhancements of different statistical significances were seen in all the spectra. They were fitted by a normal distribution. The obtained parameters of the enhancements are shown in table 1. A combinatorial background

in the presented spectra is insignificant – the ratio of the number of combinations to that of events does not exceed 1.1.

Table 1

Final states	Number of comb.	Parameters of the enhancements		
		Mean mass, MeV/c^2	Width, MeV/c^2	Number of combinations
$\Lambda\bar{p}\pi^+$	5754	3067±7±20	45±15	105
$\bar{\Lambda}p\pi^-$	6532	3060±7±20	35±15	54
$\Lambda\bar{p}\pi^+\pi^\pm$	1987	3065±6±20	32±10	48
$\bar{\Lambda}p\pi^-\pi^\mp$	4688	3050±7±20	33±12	66
$\Lambda\bar{p}\pi^-$	3745	3060±8±20	55±17	71
$\bar{\Lambda}p\pi^+$	5131	3045±8±20	25±15	51

A total spectrum of all the final states with negative strangeness (1a–d) is presented in fig.3. It was obtained by summarizing the distributions presented in figs.2(a), 2(b) and 2(c). A clear peak is seen in this spectrum near a mass of 3060 MeV/c^2. In the window of fig. 3 the spectrum in the peak region is presented, which is fitted by a normal distribution for the peak and a line function for the background. It was obtained that the peak is caused by 180 combinations above the background of 460 ones. A sum of the final states with positive strangeness (2a–d) is shown in fig.4. This spectrum contains a peak in the same mass region, as in fig.3. In the window of fig. 4 this peak is fitted by a normal distribution. It was obtained that the peak is caused by 162 combinations over the background of 585 ones. Statistical significances of the observed peaks in figs. 3 and 4 are 8.4 and 7 standard deviations above the background, respectively. This enables one to consider them as physical signals.

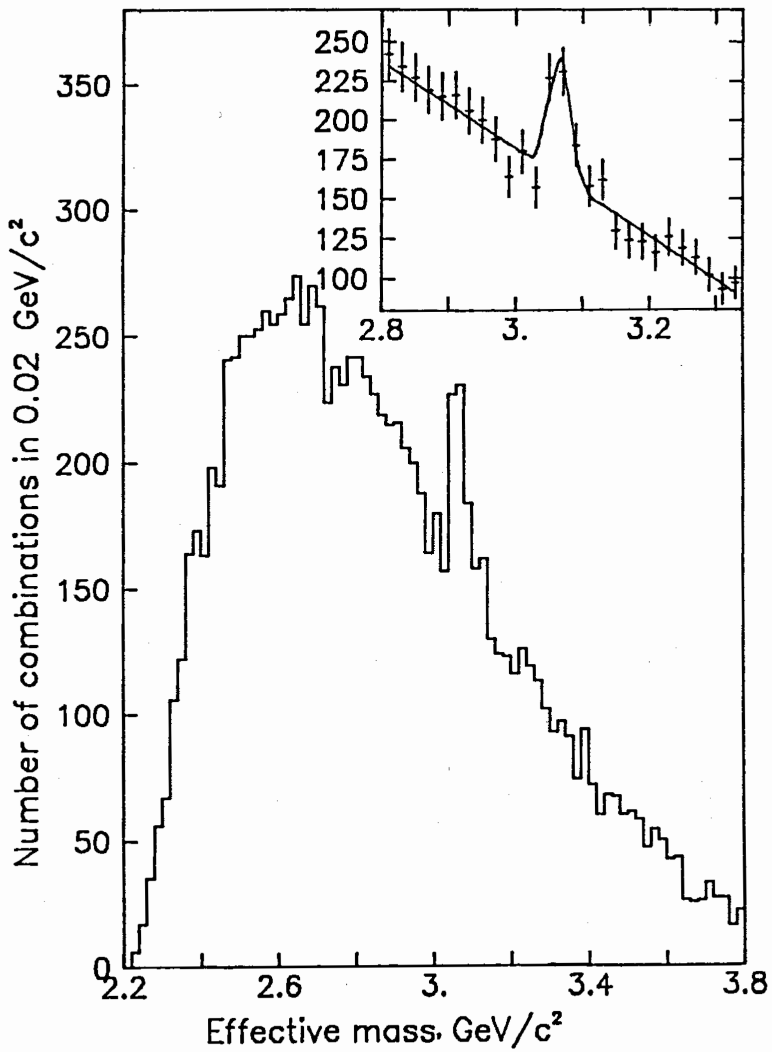

Fig.3.The sum of the spectra of effective masses $\Lambda\bar{p}\pi^+$ (a), $\Lambda\bar{p}\pi^+\pi^\pm$ (b) and $\Lambda\bar{p}\pi^-$ (c).

Fig.5 (a and b) shows the effective mass spectra of the neutral final states (3a and 3b). Fig. 6 (a,b and c) presents combined effective mass spectra of the charged final states containing Λ – (4a-4d), K^0_s– (4c-4f) and $\bar{\Lambda}$ – (4b-4e), respectively. These spectra were fitted by smooth functions.

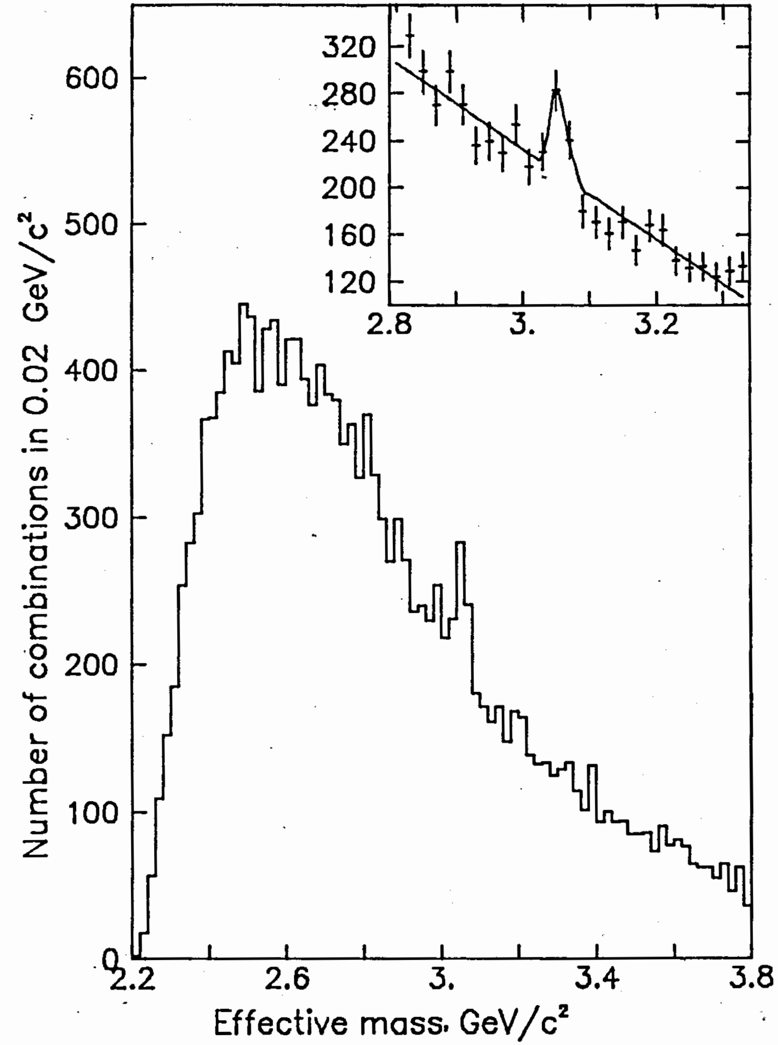

Fig.4.The sum of the spectra of effective masses $\bar{\Lambda}p\pi^-$ (d), $\bar{\Lambda}p\pi^-\pi^\pm$ (e) and $\bar{\Lambda}p\pi^+$ (f).

Narrow peaks are seen in all the spectra at almost the same mass. These peaks were fitted by normal distribution. The obtained characteristics are presented in table 2.

Table 2

Final state	Number of comb.	Characteristics of the peaks		
		Mean mass, MeV/c^2	Width, MeV/c^2	Number of combinations
$\Lambda \bar{p} K^+$	6758	3250±8±20	45±15	80
$\bar{\Lambda} p K^-$	4069	3260±7±20	30±10	37
$\Lambda \bar{p} K^+ \pi^\pm$	1309	3250±7±20	24±10	28
$\bar{\Lambda} p K^- \pi^\pm$	1692	3245±9±20	46±20	40
$K^0_s p \bar{p} K^\pm$	2480	3270±6±20	53±12	58

Fig.7 shows the sum of the effective mass spectra of all the considered states with zero strangeness (3a-4f). A statistically significant peak is seen near the mass of 3260 MeV/c^2. This peak was fitted by a normal distribution (the window of fig.7). The peak contains 240 combinations above the background of 800. The statistical significance of the signal is 8 standard deviations from the background.

The narrowness of the observed enhancements and their presence in the effective mass spectra of different systems excludes a possibility of their interpretation as a kinematic reflection of any resonances. However, the hypothesis of the kinematic reflection was checked directly. The masses of $\pi^\pm$ and $K^\pm$ were ascribed to the p/$\bar{p}$ candidates in all the considered final states. No narrow enhancements were observed in the effective mass spectra obtained in such a way. So, the hypothesis of enhancements as the kinematic reflections of resonances in other systems is excluded.

Thus, the data obtained indicate the existence of narrow meson resonances with positive, zero and negative strangeness decaying into the final states containing baryon and antibaryon.

The statistical significance of the peaks in each of the spectra considered (figs 2,5,6) does not allow one to establish the presence of signals in all the final states. But the number

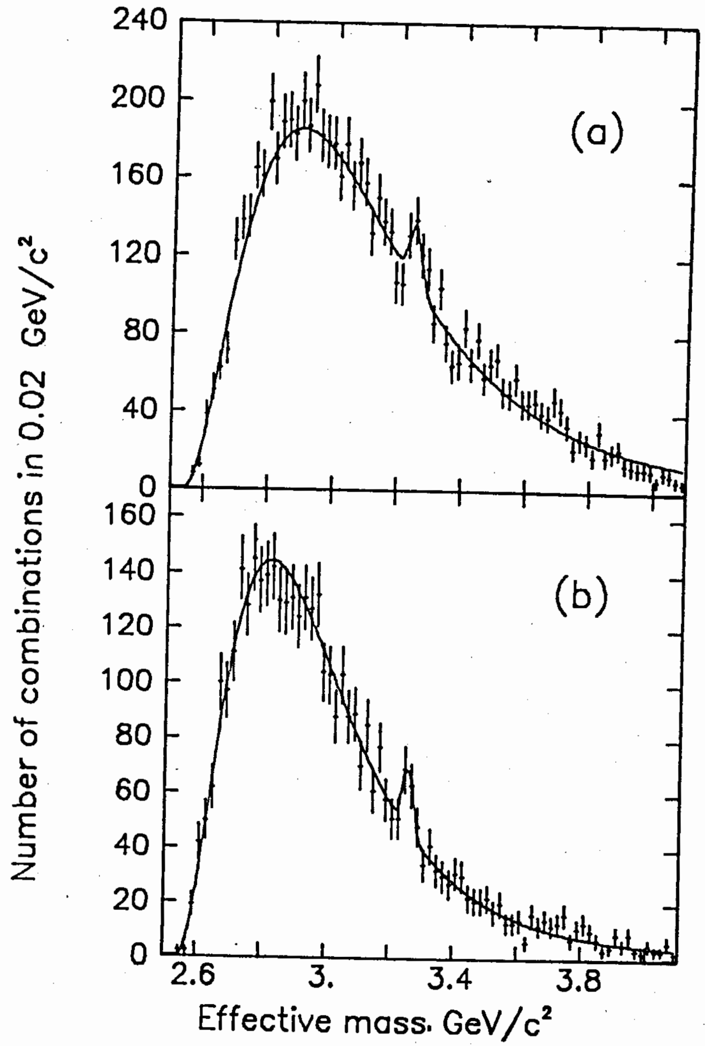

Fig.5 Spectra of effective masses $\Lambda \bar{p} K^+$ (a) and $\bar{\Lambda} p K^-$ (b).

of combinations in the peaks presented in the combined spectra of figs.3, 4 and 7 coincide within the error with the sums of the numbers of combinations in the peaks seen in all the spectra of the final states.

The mean mass of the resonances with the open and zero strangeness are 3060±5(st.)±20(syst.) and 3260±5(st.)±20(syst.) MeV/c^2, respectively. Their widths do not exceed (35±5) MeV/c^2.

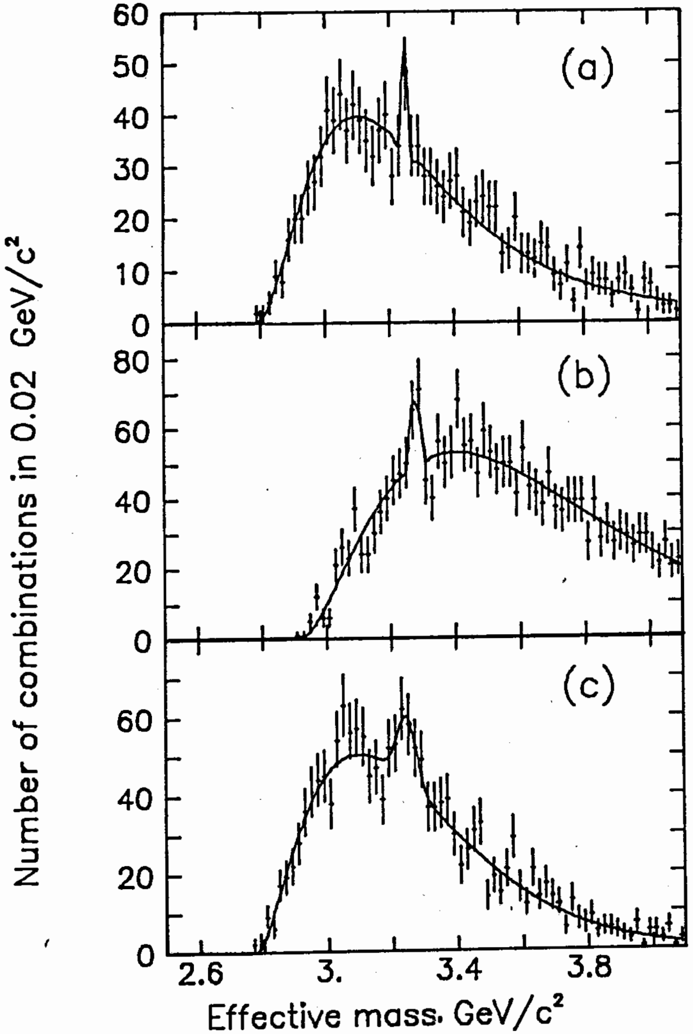

Fig.6 Spectra of the sums of effective masses $\Lambda\bar{p}K^{+}\pi^{\pm}$ (a), $K^{0}_{s}p\bar{p}K^{\pm}$ (b) and $\bar{\Lambda}pK^{-}\pi^{\pm}$ (c).

The detection efficiencies of the resonance events were calculated to evaluate the cross sections of their production. The production cross sections of the events responsible for the considered resonances in the available kinematic region

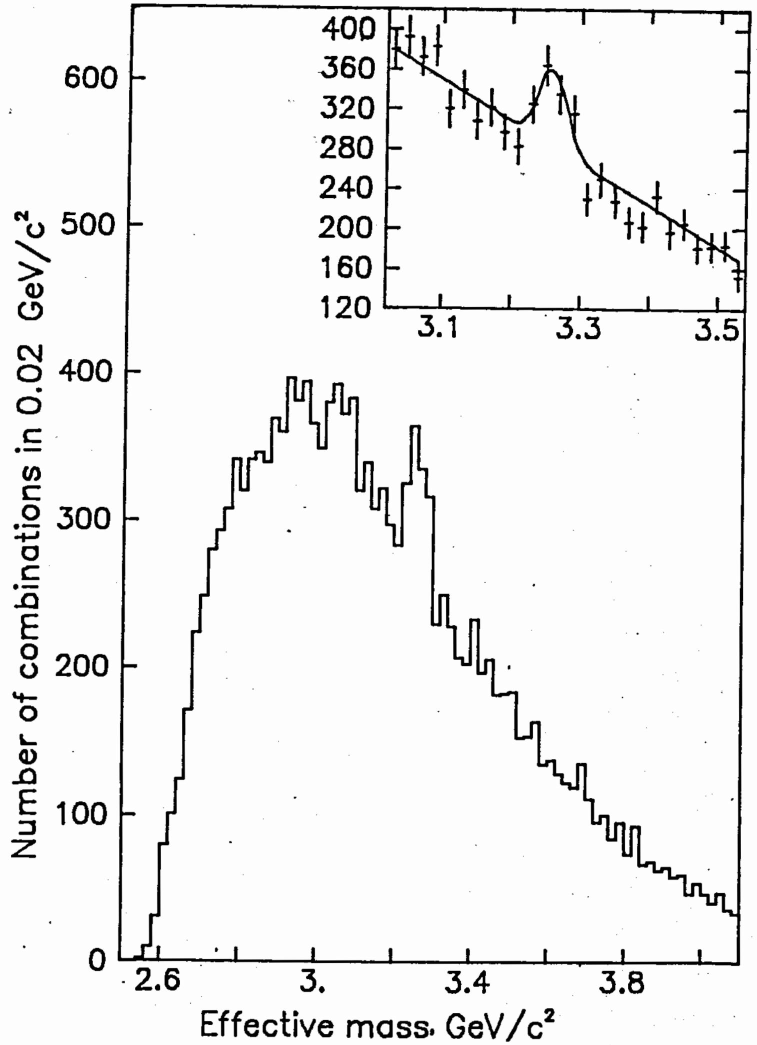

Fig.7 The sum of the spectra of effective masses $\Lambda\bar{p}K^{+}$, $\bar{\Lambda}pK^{-}$, $\Lambda\bar{p}K^{+}\pi^{\pm}$, $K^{0}_{s}p\bar{p}K^{\pm}$ and $\bar{\Lambda}pK^{-}\pi^{\pm}$.

$$X_F \geq 0.2 \qquad (10)$$
$$P_T \leq 1.0\ \text{GeV/c}$$

are from 0.3 to 1.0 µb per nucleon (90% C.L.). For these estimations it was assumed that the cross section depends on the atomic weight (A) of the target nuclei as $A^{2/3}$.

CONCLUSION

The narrow enhancements have been observed at almost the same masses in the effective mass spectra of the different final states with negative ($\bar{\Lambda}p\pi^{\pm}$, $\bar{\Lambda}p\pi^{+}\pi^{\pm}$) and positive ($\bar{\Lambda}p\pi^{\mp}$, $\bar{\Lambda}p\pi^{-}\pi^{\mp}$) strangeness. They are not the kinematic reflections of any resonances in other systems and can be considered as a strong indication of the existence of the baryonia with negative and positive strangeness. Their mean mass is 3060±5(st.)±20(syst.) MeV/c^2 and the width is smaller than 35±5 MeV/c^2.

The existence of the enhancements in the spectra of the doubly charged final states $\bar{\Lambda}p\pi^{-}$ and $\bar{\Lambda}p\pi^{+}$ indicates that an isotopic spin of the baryonia is ≥ 3/2.

The narrow enhancements are observed at almost the same mass in the eight effective mass spectra of the final states involving a baryon, antibaryon and particles with opposite strangeness.

Their mean mass is 3260±5(st.)±20(syst.) MeV/c^2, and the width is lower than 35±5 MeV/c^2. These peaks indicate to the existence of the baryonium with zero strangeness and an isotopic spin ≥ 1.

The difference between the masses of the baryonium with zero strangeness and the baryonia with positive and negative strangeness is ≈ 200 MeV/c^2 – a typical mass splitting in an SU(3) multiplets of baryons for the states differing by one unit of hypercharge [19]. This allows one to assume that all the observed resonances are the members of the same SU(3) multiplet of multiquark states. The baryonia with zero strangeness can be considered as a candidate for a multiquark baryonium with hidden strangeness. The considered baryonia could be identified as multiquark states described in a number of theoretical papers [20-30].

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Поиск узких барионией

На серпуховском ускорителе в пучке нейтронов со средним импульсом 40 ГэВ/с осуществлен поиск барионией, распадающихся соответственно на $\Lambda+\bar{p}$+пионы и $\bar{\Lambda}$+p+пионы. Получено указание на существование таких барионией в четырех зарядовых состояниях: отрицательных, нейтральных, положительных и дважды заряженных. Среднее значение их массы 3060±5(стат.)±±20(сист.) МэВ/с², а ширина не превышает 35±5 МэВ/с². Изотопический спин этих барионией ≥3/2. При анализе спектров эффективных масс конечных состояний $\Lambda+\bar{p}+K^{+}(+\pi^{\pm})$, $\bar{\Lambda}+p+K^{-}(+\pi^{\pm})$ и $K^0_s p\bar{p}K^{\pm}$ получены также данные, указывающие на существование узкого бариония со скрытой странностью. Среднее значение массы бариония 3260±5(стат.)±20(сист.) МэВ/с², а ширина не превышает 35±5 МэВ/с². Произведения сечений барионией в регистрируемой кинематической области, $X_F \geq 0{,}2$ и $P_T \leq 1$ ГэВ/с, на вероятности наблюдаемых каналов распада находятся в пределах (0,3÷1,0) мкб на нуклон с 90% уровнем достоверности.

Работа выполнена в Лабораториях высоких и сверхвысоких энергий ОИЯИ.

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Search for Narrow Baryonia

A search for baryonia with negative and positive strangeness decaying respectively into $\Lambda+\bar{p}$+pions and $\bar{\Lambda}$+p+pions has been carried out in a neutron beam with a mean momentum of ≈40 GeV/c in an experiment performed at the Serpukhov accelerator.There is a strong indication of the existence of these baryonia.The following four charge states are indicated for negative and positive strangeness: neutral,negative,positive and doubly charged.Their mean mass is 3060±5(st.)±20(syst.) MeV/c² and the width $\Gamma \leq (35\pm5)$ MeV/c². The data show that the isotopic spin of the baryonia is ≥ 3/2. In the effective mass spectra of the final states $\Lambda + \bar{p} + K^{+} +(\pi^{\pm})$, $\bar{\Lambda} + p + K^{-}+(\pi^{\pm})$ and $K^0_s + p + \bar{p} + K^{\pm}$ narrow peaks are observed at near the same masses. These peaks indicate the existence of a narrow baryonium with hidden strangeness. The mean value of its mass is 3260±5(st.)±20(syst.) MeV/c², and the width $\Gamma \leq (35\pm5)$ MeV/c². The production cross-sections of the events causing the observed peaks, in the kinematic region $X_F \geq 0.2$, $P_T \leq 1$ GeV/c, is (0.3 ÷ 1.0) μb/per nucleon (90% C.L.).

The investigation has been performed at the Laboratories of High and Superhigh Energies, JINR

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