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RESONANCES IN THE SYSTEM OF $\pi^+\pi^-$ MESONS FROM $np \to np\pi^+\pi^-$ REACTION AT $P_n = 5.20$ GeV/c: SEARCH, RESULTS OF DIRECT OBSERVATIONS, INTERPRETATION

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Ten resonances were found in the mass spectrum of the $\pi^+\pi^-$ system based on 66075 events from the reaction $np \to np\pi^+\pi^-$ in np interactions at $P_n = (5.20 \pm 0.16)$ GeV/c in the 1-m HBC of JINR's LHE by using the criterion $\cos \Theta^* p > 0$. These masses are the following: (347 ± 12), (418 ± 6), (511 ± 12), (610 ± 5), (678 ± 17), (757 ± 5), (880 ± 12), (987 ± 12), (1133 ± 15), and (1285 ± 22) MeV/c^2; their excess above background is 2.9, 5.2, 3.5, 1.4, 2.0, 8.5, 4.8, 3.8, 5.2, and 6.0 S. D., respectively. The experimental widths of the resonances vary within the region from 16 to 94 MeV/c^2. Such effects were not found in $\pi^-\pi^0$ combinations from the reaction $np \to pp\pi^-\pi^0$. Therefore, it is necessary to attribute the value of isotopic spin $I = 0$ to the resonances found in the mass spectrum of the $\pi^+\pi^-$ system. The spin was estimated for the most statistically provided resonances at masses of 418, 511 and 757 MeV/c^2. We determine with a high degree of confidence that $J = 0$ for the resonances at $M_R = 757$ MeV/c^2 and $M_R = 418$ MeV/c^2 and the most probable value of $J = 0$ for the resonance at $M_R = 511$ MeV/c^2. Therefore, it can be affirmed that at least three states with quantum numbers of σ_0 meson $0^+(0^{++})$ have been found at masses of 418, 511 and 757 MeV/c^2. The fact that low-mass σ_0 mesons are glueballs is one of the possible interpretations. The comparison with the data of other papers has also been made.

На статистике 66075 событий реакции $np \to np\pi^+\pi^-$ np-взаимодействий при $P_n = (5{,}20 \pm 0{,}16)$ ГэВ/с в 1-метровой водородной пузырьковой камере ЛВЭ ОИЯИ обнаружено 10 резонансов в спектре эффективных масс $\pi^+\pi^-$-мезонов. При этом использован критерий $\cos \Theta^* p > 0$. Значения эффективных масс равны (347 ± 12), (418 ± 6), (511 ± 12), (610 ± 5), (678 ± 17), (757 ± 5), (880 ± 12), (987 ± 12), (1133 ± 15) и (1285 ± 22) МэВ/с^2 с превышением над фоном 2,9, 5,2, 3,5, 1,4, 2,0, 8,5, 4,8, 3,8, 5,2 и 6,0 стандартных отклонений соответственно. Экспериментальные ширины находятся в диапазоне от 16 до 94 МэВ/с^2. Таких эффектов не обнаружено в $\pi^-\pi^0$-комбинациях в реакции $np \to pp\pi^-\pi^0$, что указывает на значение изотопического спина $I = 0$ для найденных в $\pi^+\pi^-$-системе резонансов. Значения спина определены для наиболее статистически обеспеченных резонансов при массах 418, 511 и 757 МэВ/с^2. С высокой степенью вероятности $J = 0$ для резонансов с массами $M_R = 757$ МэВ/с^2 и $M_R = 418$ МэВ/с^2. Наиболее вероятное значение $J = 0$ также и для резонанса с массой $M_R = 511$ МэВ/с^2. Таким образом, обнаружено по крайней мере три состояния при массах 418, 511 и 757 МэВ/с^2, имеющие квантовые числа σ_0-мезона $0^+(0^{++})$. Возможна интерпретация низколежащих σ_0-мезонов как глюболов. Проведено сравнение с данными других исследований.

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INTRODUCTION

This work is devoted to a search for and study low-mass ($M < 1.3$ GeV/c^2) resonances in the $\pi^+\pi^-$ system. Their existence can clarify the properties of low-lying scalar mesons (the so-called σ_0 mesons), whose investigation is important both for the mechanism of realization of chiral symmetry for corresponding Lagrangians and for an adequate description of an attractive part of the nucleon–nucleon interaction potential [1].

Different theoretical models give various predictions for masses and widths of σ_0 mesons. Early quark-bag models gave $M_{\sigma_0} > 1.5$ GeV/c^2 and $\Gamma_{\sigma_0} \geq 0.5$ GeV/c^2 [2]. Later works predicted $M_{\sigma_0} = 500 \div 1000$ MeV/c^2 and $\Gamma_{\sigma_0} = 200 \div 500$ MeV/c^2 for low-lying $(q\bar{q})$ states [3]. Some models of a spontaneous break of chiral symmetry predict $M_{\sigma_0} \approx 700$ MeV/c^2 and $\Gamma_{\sigma_0} \geq 500$ MeV/c^2 [4]. Using QCD sum rules and assuming that the σ_0 meson is a low-lying glueball, the calculations give the following predictions: $M_{\sigma_0} = 280 \div 700$ MeV/c^2 and $\Gamma_{\sigma_0} = 2 \div 60$ MeV/c^2 [5] (see also [6]).

1. SELECTION OF KINEMATICS CRITERIA AND RESULTS OF INVESTIGATIONS

This paper continues a series of works devoted to the study of the $\pi^+\pi^-$ systems with different kinematics criteria [7, 8].

66075 events of the reaction $np \rightarrow np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c have been treated. The data were obtained in an exposure of the 1-m H_2 bubble chamber of LHE (JINR) to a monochromatic neutron beam ($\Delta P_n/P_n \approx 2.5\,\%$, $\Delta\Omega_{\rm channel} = 10^{-7}$ sr) [9].

The events of various reaction channels were separated by the standard χ^2 procedure [10–12].

Figure 1 shows the effective mass distribution of $\pi^+\pi^-$ combinations from the total statistics of the reaction $np \rightarrow np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c. The distribution is approximated by a polynomial background curve and by three resonance curves taken in the Breit–Wigner form. Three resonance peaks are found at masses of 418, 511 and 757 MeV/c^2. The excess is more than 3 S. D. above background.

Figure 2 shows the effective mass distribution of $\pi^+\pi^-$ combinations for the events with a secondary neutron flying in the forward hemisphere in the c. m. s. of the reaction, i. e., $\cos\,\Theta^*_n > 0$. No noticeable deviations above background have been observed in this distribution.

Earlier, we have already studied the reaction $np \rightarrow np\pi^+\pi^-$ [13], and the OPE exchange with a dominated exchange of the charged π meson has been shown to be the main mechanism of this reaction. It leads to a plentiful production (up to 70 % of the total reaction cross-section) of Δ^{++} and Δ^- resonances in the lower and upper vertices of the corresponding diagrams. The OPE mechanism contributes the major part to the events with a neutron flying into the forward hemisphere.

Therefore, it seems reasonable to study the resonances in the $\pi^+\pi^-$ system of the reaction $np \rightarrow np\pi^+\pi^-$, selecting the events on condition that $\cos\,\Theta^*_p > 0$. The total contribution

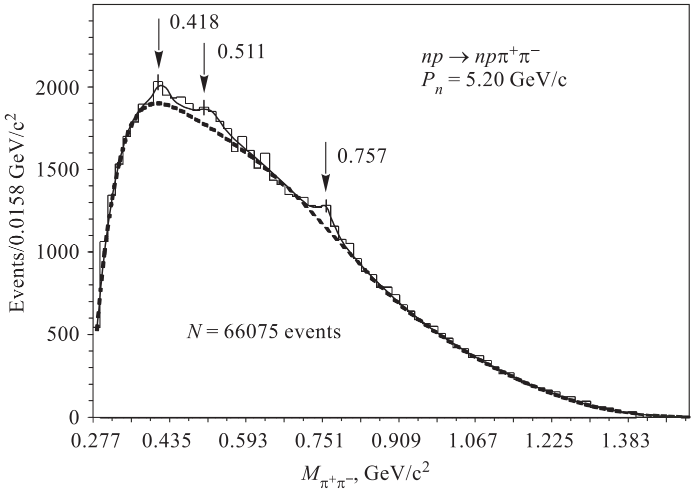

Fig. 1. The effective mass distribution of $\pi^+\pi^-$ combinations from the total statistics of the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c. The dotted curve is the background taken in the form of a superposition of Legendre polynomials up to the 10th degree, inclusive. The solid curve is the sum of the background and three Breit–Wigner resonance curves

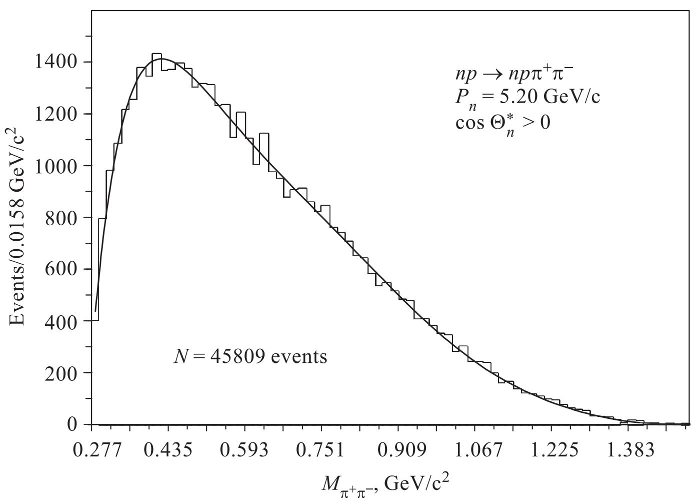

Fig. 2. The effective mass distribution of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c, selected under condition of $\cos\Theta_n^* > 0$. The solid curve is the background taken in the form of a superposition of Legendre polynomials up to the 8th degree, inclusive

of the Δ^{++} and Δ^- resonances is no more than 17 % for these events, and the background from resonance decays decreases greatly. The number of events with $\cos\Theta_p^* > 0$ is equal to 20266, which is approximately 1/3 of all the events from the reaction $np \to np\pi^+\pi^-$.

Figure 3 shows the effective mass distribution of $\pi^+\pi^-$ combinations for the events with a secondary proton flying into the forward hemisphere in the c. m. s. of the reaction.

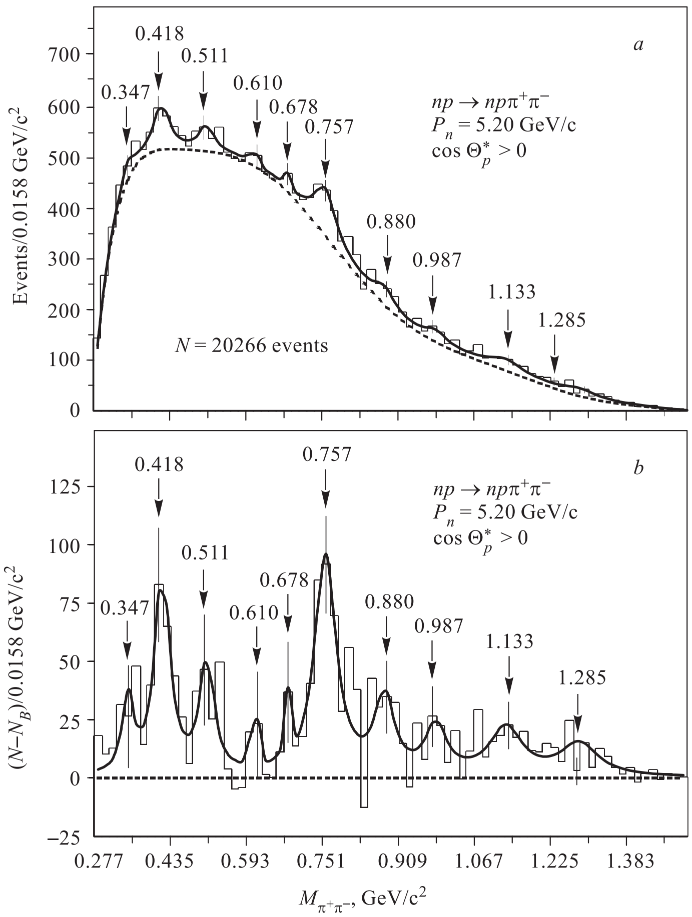

Fig. 3. *a*) The effective mass distribution of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c, selected under condition of $\cos\,\Theta_p^* > 0$. The dotted curve is the background taken in the form of a superposition of Legendre polynomials up to the 9th degree, inclusive. The solid curve is the sum of the background and 10 Breit–Wigner resonance curves. *b*) The same as Fig. 3, *a*, minus background

The distribution is approximated by a polynomial background curve and by 10 resonance curves taken in the Breit–Wigner form (Fig. 3, *a*). The description of the intervals between the resonances by the background gives $\chi^2 = 0.98 \pm 0.19$ and $\sqrt{D} = 1.47 \pm 0.14$. This is close to theoretical values of 1 and 1.41 for the distribution of random values at one constraint equation (normalization to the number of events). The description of the full distribution by the same background, normalized to 100 % experimental events, gives $\chi^2 = 1.28 \pm 0.11$ and $\sqrt{D} = 1.60 \pm 0.14$. The background curve, χ^2 and $\sqrt{D}$ values were given by the histogram with a step equal to half the step presented in Fig. 3. The description of the full distribution by background and 10 resonance curves gives $\chi^2 = 0.81 \pm 0.11$ and $\sqrt{D} = 1.33 \pm 0.08$. The same distribution minus background is shown in Fig. 3, *b*.

The results of approximation are given in the table below.

No.	$M_{\rm exp} \pm \Delta M_{\rm exp}$, MeV/c^2	$\Gamma_{\rm exp} \pm \Delta\Gamma_{\rm exp}$, MeV/c^2	σ, μb	S. D.
1	347 ± 12	36 ± 35	10 ± 5	2.9
2	418 ± 6	39 ± 13	26 ± 7	5.2
3	511 ± 12	40 ± 23	15 ± 6	3.5
4	610 ± 5	24 + 13	5 ± 5	1.4
5	678 ± 17	16 + 14	6 ± 4	2.0
6	757 ± 5	51 ± 15	38 ± 7	8.5
7	880 ± 12	45 ± 24	14 ± 5	4.8
8	987 ± 12	49 ± 36	11 ± 4	3.8
9	1133 ± 15	80 ± 30	10 ± 3	5.2
10	1285 ± 22	94 ± 30	10 ± 2	6.0

The first column of the table contains the experimental values of the resonance masses (including errors) obtained in the process of approximation. The second column includes the experimental values of the resonance widths. The third column contains the production cross-sections for the corresponding resonances. For the values in the cross-section errors, we have taken into account the cross-section error for the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c ($\sigma_{np\to np\pi^+\pi^-} = (6.22 \pm 0.28)$ mb) [11]. The fourth column contains the number of standard deviations of the effects above background: $\mathrm{S.\,D.} = N_{\rm res}/\sqrt{N_{\rm back}}$.

The observed resonance at a mass of $M_R = 757$ MeV/c^2 has already been inserted in RPP-2000, RPP-2002 (S. D.= 6.0) [16]. It should be noted that the increase of standard deviations in comparison with the previously obtained results corresponds exactly to the increase of the event statistics.

2. SPIN AND ISOTOPIC SPIN OF THE RESONANCES

To determine the spin of the resonances, the angular distributions of π mesons were studied in the helicity coordinate system [14].

For strong decays, such distributions should be described by the sum of Legendre polynomials of even degree with a maximum power of $2J$, where J is the resonance spin.

The distributions of this angle are shown in Fig. 4 for the resonances at $M_R = 418$, 511 and 757 MeV/c^2.

The solid lines correspond to the isotropic distribution $(J = 0)$. Therefore, the most probable spin values for the resonances at masses of 418, 511 and 757 MeV/c^2 are equal to 0. The spins of other resonances have not been determined due to low statistics.

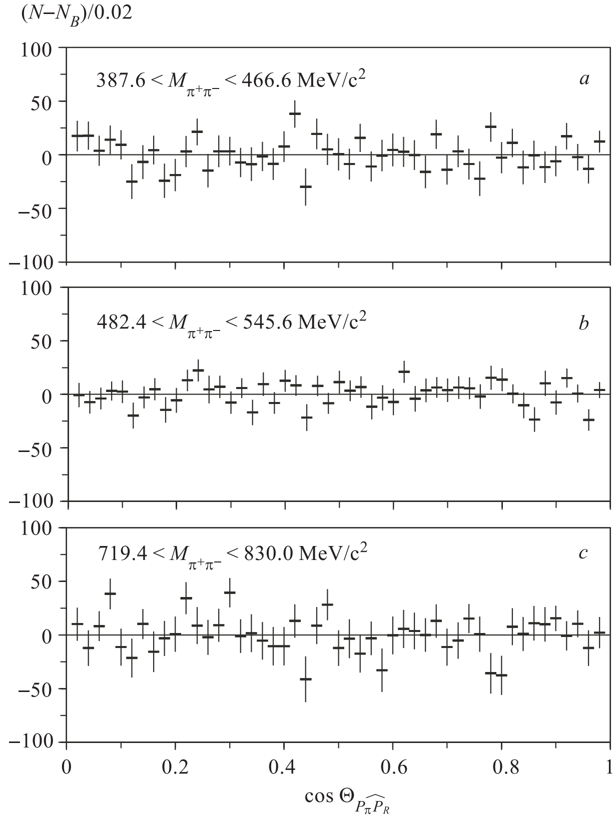

Fig. 4. The distribution of decay angle for $\pi^+\pi^-$ resonances: *a*) with $M_R = 418$ MeV/c^2; *b*) with $M_R = 511$ MeV/c^2; *c*) with $M_R = 757$ MeV/c^2. The solid lines correspond to the isotropic distribution

From the generalized Pauli principle for the 2π system, it follows that the isotopic spin at $J = 0$ must be only even. As it follows from isotopic relations for $I = 2$, the effects at the corresponding masses in the $\pi^-\pi^0$ system from the reaction $np \rightarrow pp\pi^-\pi^0$, which has also been studied by us, could be observed with a statistical significance 4.5 times as great as that in the reaction $np \rightarrow np\pi^+\pi^-$. But there are no such effects in the $\pi^-\pi^0$ system [7].

Therefore, it can be affirmed that at least three states have the quantum numbers $I^G(J^{PC}) = 0^+(0^{++})$ and may be identified as σ_0 mesons at masses of 418, 511 and 757 MeV/c^2.

3. INTERPRETATION OF LOW-MASS σ_0 MESONS AS GLUEBALLS

The fact that low-mass σ_0 mesons are glueballs is one of the possible interpretations.

The estimate of the width of the σ_0 glueball given in paper [6] is based on the low-energy theorems: $\Gamma_{(\sigma_0 \rightarrow \pi\pi)} = \left[(M/1\ \text{GeV})^5\right]^{\times 220}_{\times 550}$ MeV/c^2, where 220 and 550 are the values from a gluon condensate corresponding to two variants of the theory.

Let us consider the resonance at $M_R = 757$ MeV/c^2. In our experiment, the mass resolution for the $\pi^+\pi^-$ system depends on mass and equals $\Gamma_{\rm resol}(M) = 0.042(M - 2m_\pi)+$ 2.8 (all the values are in MeV/c^2) [15]. The width of the resolution function is $\Gamma_{\rm resol}(757) =$ 23 MeV/c^2 for $M_R = 757$ MeV/c^2. If the mass resolution function has a normal distribution form (realized for $M_R = 757$ MeV/c^2), the true width of the resonance can be estimated equal to $\Gamma_R = \sqrt{\Gamma^2_{\rm exp} - \Gamma^2_{\rm resol}} = \sqrt{(51 \pm 15)^2 - (23)^2} = 46^{+16}_{-18}$ MeV/c^2 and it is within the range from 36 to 66 MeV/c^2.

If the resonance at a mass of 757 MeV/c^2 is a glueball, then its width determined by the formula from the low-energy theorems is $\Gamma_{(\sigma\to\pi\pi)} = \left[(0.757)^5\right]^{\times 220}_{\times 550} = [0.249]^{\times 220}_{\times 550} =^{55}_{137}$ MeV/c^2

Therefore, the width of the σ_0 meson at a mass of 757 MeV/c^2 determined in our experiment does not contradict its interpretation as a glueball.

The widths of the resonances at masses of 418 and 511 MeV/c^2 do not contradict their interpretation as glueballs either.

4. COMPARISON WITH OTHER DATA

A large number of publications are dedicated to the search and study of σ_0 mesons (see [16]). All of them are based on the PWA of πN or $\tilde{p}p$ interactions. The obtained σ_0-meson masses ranging from 400 to 1200 MeV/c^2 coincide with the mass sequence observed in our experiment. We should emphasize that the results of our study are based on the observed direct signals from the resonances in the effective mass spectra of the corresponding particle combinations, unlike all the works devoted to the search for low-mass ($M < 1.3$ GeV/c^2) σ_0 mesons. However, the resonance widths extracted from PWA are considerably larger than those obtained in our experiment. It may be necessary to use other ideas and more complicated methods of analysis to gain a better understanding of these phenomena.

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