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THE SEARCH AND STUDY OF THE RESONANCES IN THE SYSTEM OF $\pi^+\pi^-$-MESONS FROM THE REACTION $np \to np\pi^+\pi^-$ AT $P_n = 5.20$ GeV/c

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There were carried out the search and study of the resonances in $\pi^+\pi^-$-system based on 45388 events from the reaction $np \to np\pi^+\pi^-$ in np-interactions at $P_n = (5.20 \pm 0.16)$ GeV/c in 1 m HBC of LHE JINR. Using the criterions $\cos\Theta^*_p > 0$ and $\left|X^*_{\pi^+\pi^-}\right| \leq 0.5$, nine peculiarities were found at the masses of (350 ± 11), (405 ± 10), (505 ± 8), (609 ± 5), (665 ± 11), (754 ± 4), (878 ± 10), (1155 ± 11), and (1235 ± 23) MeV/c^2. The excess above the background for them were 2.3, 4.8, 4.1, 2.5, 2.9, 7.8, 2.2, 4.9, and 4.7 S.D., respectively. The experimental widths of the resonances vary within the region from 16 to 43 MeV/c^2, that is comparable with the experimental mass resolution. The comparison with effective mass spectrum of $\pi^-\pi^0$-combinations from the reaction $np \to pp\pi^-\pi^0$ shows that the corresponding peculiarities mentioned above were absent in this spectrum. Therefore it is necessary to attribute the value of isotopic spin $I = 0$ for the peculiarities found in the mass spectrum of $\pi^+\pi^-$-systems. The estimation of spin was carried out for most statistically provided resonances at the masses of 405, 505, and 754 MeV/c^2. It is determined with high degree of confidence that $J = 0$ for $M_R = 754$ MeV/c^2; and the most probable value $J = 0$ for 405 MeV/c^2 and $M_R = 505$ MeV/c^2.

Therefore it can be affirmed that there were found at least 3 states with quantum numbers of σ_0-meson $0^+(0^{++})$ at the masses of 405, 505, and 754 MeV/c^2.

The comparison with the data of other papers was carried out.

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

Поиск и исследование резонансов в системе $\pi^+\pi^-$-мезонов в реакции $np \to np\pi^+\pi^-$ при $P_n = 5{,}20$ ГэВ/с

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На 45388 событиях реакции $np \to np\pi^+\pi^-$, выделенной в np-взаимодействиях при $P_n = (5{,}20 \pm 0{,}16)$ ГэВ/с в однометровой водородной пузырьковой камере ЛВЭ ОИЯИ, произведены поиск и исследования резонансов в системе $\pi^+\pi^-$. При использовании критериев $\cos\Theta^*_p > 0$ и $\left|X^*_{\pi^+\pi^-}\right| \leq 0,5$ выделено девять особенностей

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при массах (350 ± 11), (405 ± 10), (505 ± 8), (609 ± 5), (665 ± 11), (754 ± 4), (878 ± 10), (1155 ± 11) и (1235 ± 23) МэВ/с^2. Превышение над фоном составляет 2,3, 4,8, 4,1, 2,5, 2,9, 7,8, 2,2, 4,9 и 4,7 стандартных отклонений соответственно. Экспериментальные ширины резонансов меняются в пределах от 16 до 43 МэВ/с^2, что сравнимо с экспериментальным разрешением по массам. Сравнение со спектром эффективных масс $\pi^-\pi^0$-комбинаций из реакции $np \to pp\pi^-\pi^0$ показывает, что соответствующие особенности в этом спектре отсутствуют. Поэтому найденным особенностям в спектре масс $\pi^+\pi^-$ надо приписать значение изотопического спина $I = 0$. Оценка спина произведена для наиболее статистически обеспеченных резонансов при массах 405, 505 и 754 МэВ/с^2. Для $M_R = 754$ МэВ/с^2 с высокой степенью достоверности $J = 0$; для $M_R = 405$ МэВ/с^2 и $M_R = 505$ МэВ/с^2 наиболее вероятное значение $J = 0$.

Таким образом, можно утверждать, что обнаружено по крайней мере 3 состояния с квантовыми числами σ_0-мезона $0^+(0^{++})$ при массах 405, 505 и 754 МэВ/с^2.

Проведено сравнение с данными других работ.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

This work is devoted to the search and study of low-masses ($M < 1.3$ 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 the chiral symmetry for corresponding Lagrangians and for adequate description of the 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]. Further 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 spontaneous break of chiral symmetry predict $M_{\sigma_0} \approx 700$ MeV/c^2 and $\Gamma_{\sigma_0} \geq 500$ MeV/c^2 [4]. The calculations, using QCD sum rules and assuming that σ_0-meson is a low-lying glueball, 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]).

45388 events of the reaction $np \to np\pi^+\pi^-$ were used in this work. The data were obtained in an exposure of the 1m H_2 bubble chamber of LHE (JINR) to quasi-monochromatic neutron beam ($P_n = 5.20$ GeV/c; $\Delta P_n/P_n \approx 2.5\,\%$; $\Delta\Omega_{\text{channel}} = 10^{-7}$ sr.) [7].

The reaction channels were separated by the χ^2 method for 4-c fit and 1-c fit [8–10]. In this case, the events of 4-c fit ($np \to pp\pi^-$) were preferred to those with 1-c fit ($np \to pp\pi^-\pi^0$ and $np \to np\pi^+\pi^-$). For events with overlapped hypotheses of 1-c fit, preference was given to the hypothesis of a lesser value of χ^2_{1c}. Moreover, some additional kinematics conditions were used to satisfy the isotopic symmetry for the reaction $np \to np\pi^+\pi^-$. Due to this processing, the admixture of the background in the reaction channels of 3-prong stars of np-interactions does not exceed 5 %.

Figure 1 shows the effective mass distribution of $\pi^+\pi^-$-combinations from total statistics of the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c. The distribution is approximated by an incoherent sum of the background curve (taken in the form of a superposition of Legendre polynomials up to 11th power, inclusive) and by 3 resonance curves taken in the Breit–Wigner form. Three resonance peaks are found at the masses of 406 ± 4, 504 ± 6, and 752 ± 8 MeV/c^2. The exceeding above the background curve is 3, 3, and 4 S.D., respectively.

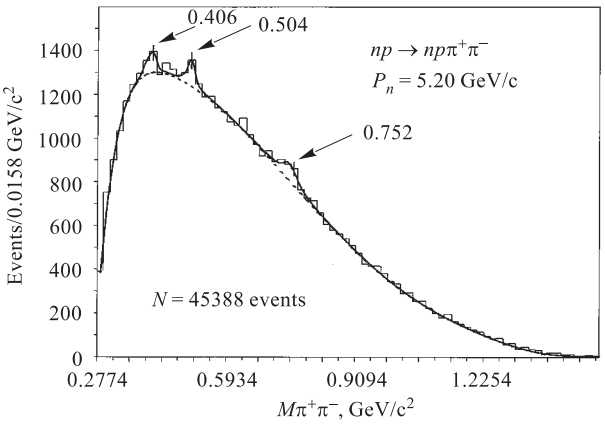

Fig. 1. The effective mass distribution of $\pi^+\pi^-$-combinations from the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c (total statistics). The dotted line — the background taken in the form of a superposition of Legendre polynomials up to 11th power, inclusive. The solid curve — sum of the background and 3 Breit–Wigner resonance curves

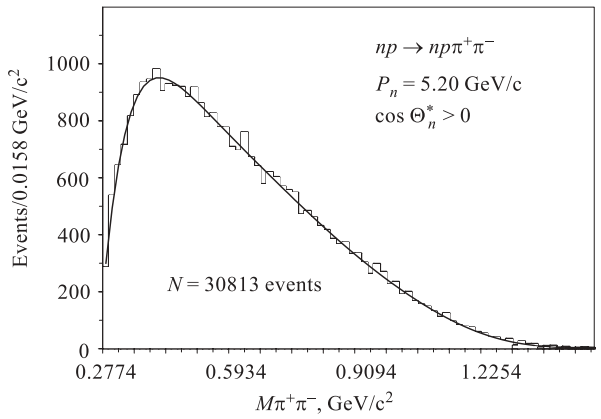

Fig. 2. The effective mass distribution of $\pi^+\pi^-$-combinations from the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c, selected under condition of $\cos\theta_n > 0$. The solid curve — the background taken in the form of a superposition of Legendre polynomials up to 9th power, inclusive

Figure 2 shows the effective mass distribution of $\pi^+\pi^-$-combinations for the events with the secondary neutron flying in the forward hemisphere in c.m.s. of the reaction, i.e., $\cos\Theta_n^* > 0$. The considerable deviations above the background are not observed in this distribution.

We have studied the reaction $np \to np\pi^+\pi^-$ earlier [11]. It was shown that the main mechanism of this reaction is OPE-exchange with the dominant exchange of charged π-meson. It leads to a plentiful production (up to 70 % of total cross section of the reaction) of Δ^{++} and Δ^--resonances in lower and upper vertexes of the corresponding diagrams. In this case, the neutron from Δ^--decay is moving in the direction of projective neutron and the proton

from Δ^{++}-decay is moving in the direction of target proton. $\pi^{\pm}$-mesons from Δ-decays produce the background in the effective mass distribution of $\pi^+\pi^-$-combinations. This is especially powerful for the events with $\cos\Theta^*_n > 0$. This mechanism describes the structure of the spectra shown in Figs. 1 and 2.

Therefore it seems to be reasonable that resonances in $\pi^+\pi^-$-system are necessary to study selected events of the reaction $np \to np\pi^+\pi^-$ under condition of $\cos\Theta^*_p > 0$. The total contribution of Δ^{++} and Δ^--resonances is not more that 17% for these events and the background from their decays is strongly decreased. The number of events with $\cos\Theta^*_p > 0$ is equal to 13954.

An additional intensification of some effects arises due to the use of some more criterion, the essence of that is clearly seen in Fig. 3.

Figure 3 shows 2-dimensional plot for the events selected under condition of $\cos\Theta^*_p{>}0$. Here: abscissa is effective mass of $\pi^+\pi^-$-combination and ordinates are the quantity $X^*_{\pi^+\pi^-} = \left(P^{*\mathrm{II}}_{\pi^+} + P^{*\mathrm{II}}_{\pi^-}\right)/P^{*\max}_{\pi}$ — the sum of longitudinal momenta of π^+- and π^--mesons divided by the maximum momentum of π-meson that is possible in the reaction $np \to np\pi^+\pi^-$ at the momentum of incident neutron for the concrete event. It is seen a concentration of events at some masses of $\pi^+\pi^-$-systems along the band with the centre near $X^*_{\pi^+\pi^-} = 0$. The events inside the band $\left|X^*_{\pi^+\pi^-}\right| \le 0.5$ were used for the further investigation. Under this condition, neither the values of resonance masses nor their widths did change as compared with the selection by more weak criterion $\cos\Theta^*_p > 0$, but the statistical confidences of some resonances have increased. The distribution of effective masses of $\pi^+\pi^-$-combinations from the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c is given in Fig. 4 for the events selected under conditions of $\cos\Theta^*_p > 0$ and $\left|X^*_{\pi^+\pi^-}\right| \le 0.5$ (totally 11299 events).

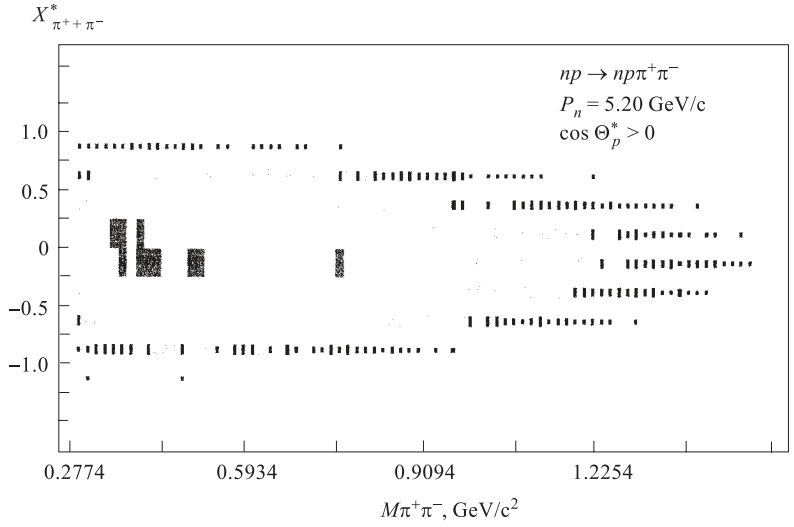

Fig. 3. Plot of $M_{\pi^+\pi^-}$ vs $X^*_{\pi^+\pi^-}$ for the events selected under condition of $\cos\theta_p > 0$ from the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c

The distribution is approximated by an incoherent sum of the background curve (taken in the form of a superposition of Legendre polynomials up to 10th power, inclusive) and

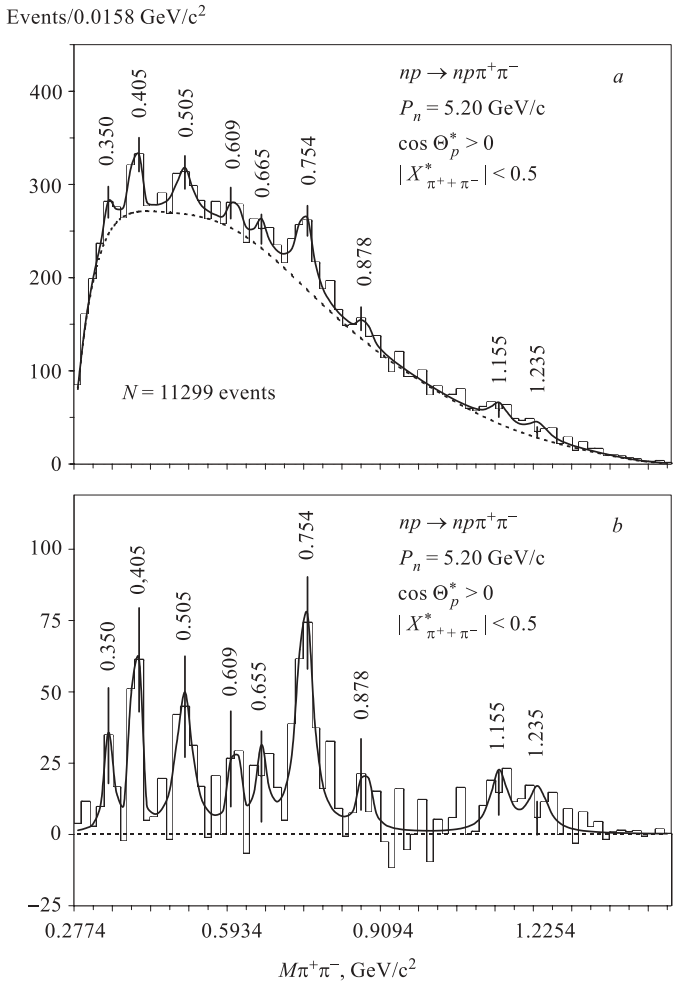

Fig. 4. *a*) The effective mass distribution of $\pi^+\pi^-$-combinations from the reaction $np \to np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c, selected under condition of $\cos\theta_n > 0$ and $|X^*_{\pi^+\pi^-}| < 0.5$. The dotted line — the background taken in the form of a superposition of Legendre polynomials up to 10th power, inclusive. The solid curve — sum of the background and 3 Breit–Wigner form resonance curves. *b*) The same as in Fig. 4,*a* for subtracted backgroung

by 9 resonance curves taken in the Breit–Wigner form (Fig. 4,*a*). In Fig. 4,*b* the same distribution is shown for the subtracted background. The description of the intervals between the resonances by the background gives $\chi^2 = 0.86 \pm 0.21$ and $\sqrt{D} = 1.25 \pm 0.15$ that is near the theoretical values 1 and 1.41 for the distribution of random values at 1 constraint equation (normalization to the number of events). The description of the full distribution by the background and 9 resonance curves gives $\chi^2 = 0.68 \pm 0.17$ and $\sqrt{D} = 0.68 \pm 0.12$.

The results of approximation are given in the Table.

$M_e \pm \Delta M_e$ (MeV/c^2)	$\Gamma_e \pm \Delta\Gamma_e$ (MeV/c^2)	$\sigma\mu b$	S.D.	P
350 ± 11	18^{+18}_{-8}	7 ± 3	2.3	$4.5 \cdot 10^{-1}$
405 ± 10	32^{+9}_{-9}	15 ± 5	4.8	$2.8 \cdot 10^{-5}$
505 ± 8	36^{+22}_{-15}	18 ± 7	4.1	$3.9 \cdot 10^{-4}$
609 ± 5	16^{+16}_{-14}	8 ± 5	2.5	$2.6 \cdot 10^{-1}$
665 ± 11	26^{+26}_{-23}	12 ± 6	2.9	$3.2 \cdot 10^{-2}$
754 ± 4	42^{+15}_{-15}	37 ± 7	7.8	$3.2 \cdot 10^{-14}$
878 ± 10	18^{+18}_{-15}	7 ± 5	2.2	$2.6 \cdot 10^{-1}$
1155 ± 11	43^{+43}_{-22}	11 ± 3	4.9	$9.1 \cdot 10^{-6}$
1235 ± 23	43^{+43}_{-22}	7 ± 2	4.7	$4.1 \cdot 10^{-5}$

The first column contains the fitted values of the resonances masses (including errors).

The second column contains the fitted values of the resonances widths. The errors for the widths of the resonances with a good statistics (at the masses of 405, 505, and 754 MeV/c^2) are taken from the approximation. The evaluation values of errors are presented for the other resonances.

The third column contains the production cross sections for the corresponding resonances. For these errors, it was taken into account the error of the cross section of 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) [9].

The fourth column contains the number of standard deviations of the effects above the background: $S.D. = N_{\rm res}/\sqrt{N_{\rm back}}$.

The fifth column contains the probability (multiplied by the number of bins) that observed peculiarity is due to a background fluctuations.

To determine the spin of the resonances, the distributions of the angle between the direction of motion of π-meson from the resonance decay and the direction of motion of resonance in reaction c.m.s. are constructed. For all that the values are taken in the resonance rest system (helicity coordinate system [12]).

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

The distributions of this angle from the events with $\cos\Theta^*_p > 0$ and $\left|X^*_{\pi^+\pi^-}\right| \leq 0.5$ are shown in Fig. 5 for the resonances at the masses of 405, 505, and 754 MeV/c^2. In the construction of these distributions, the background, taken from the left and from the right of the resonance region and normalized to the number of events in the resonance region, was subtracted.

The straight line corresponds to $J = 0$ (the isotropic distribution). The confidence levels are equal to 0.42, 0.64, and 0.56 for the corresponding resonance masses. Therefore, the most probable spin values for these three resonances are equal to 0. The determination of spins of other resonances was not carried out due to low statistics.

It follows from the generalized Pauli's principle for 2π-system 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 $\pi^-\pi^0$-systems from the reaction $np \to pp\pi^-\pi^0$ (that is also studied by us) will be observed with the statistical significance of 4.5 times more than in the reaction $np \to np\pi^+\pi^-$. But there are not such effects in $\pi^-\pi^0$-system.

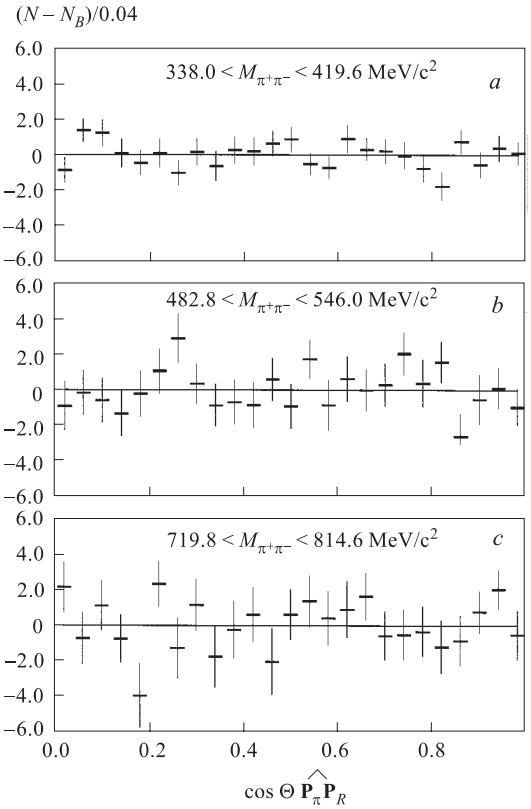

Fig. 5. The distribution of decay angle for $\pi^+\pi^-$-resonances: *a*) for the resonance with $M_R = 405$ MeV/c^2, *b*) for the resonance with $M_R = 505$ MeV/c^2, *c*) for the resonance with $M_R = 745$ MeV/c^2. The straight lines correspond to the isotropic distribution

Thus one can conclude that there are observed in our experiment at least 3 peculiarities at the masses of 405, 505, and 754 MeV/c^2 that have the quantum numbers $I^G\left(J^{PC}\right) = 0^+\,(0^{++})$ and may be identified as σ_0-meson.

A large number of works are connected with a search and study of σ_0-mesons (see [13]). All of them are based on the PWA-analysis of πN- or $\tilde{p}p$- interactions. The obtained values of σ_0-mesons masses are in the range from 400 to 1200 MeV/c^2 and coincide with the sequence of the masses observed in our experiment. Note that unlike all works devoted to the search for low-masses ($M < 1.3$ GeV/c^2) σ_0-mesons, in our work there were observed the direct signals from the resonances in the effective mass spectra of corresponding particles combinations. However, the resonance widths extracted from such analysis are considerably larger than obtained in our experiment. Maybe it is necessary to use another ideas and more complicated methods of analysis.

One of the possibilities is an interpretation of low-masses σ_0-mesons as glueballs.

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

Let us consider the resonance at the mass of $M_R = 754$ MeV/c^2. In our experiment, the mass resolution for $\pi^+\pi^-$-system depends on the mass and is equal to $\Gamma_{\rm res}(M) = 0.042\,(M - 2m_\pi) + 2.8$ (all values are in MeV/c^2) [14]. The width of the resolution function is $\Gamma_{\rm res}(754) = 23$ MeV/c^2 for $M_R = 754$ MeV/c^2. If the mass resolution function has the normal distribution form (that is realized for $M_R = 754$ MeV/c^2), the true width of the resonance will be estimated as $\Gamma_R = \sqrt{\Gamma^2_{\rm exp} - \Gamma^2_{\rm res}} = \sqrt{(42 \pm 5)^2 - (23)^2} = 35^{+17}_{-21}$ MeV/c^2 and the true width of the resonance is within interval from 14 to 52 MeV/c^2.

If the resonance at the mass of 754 MeV/c^2 is a glueball, then its width determined by the formula from low-energy theorems is: $\Gamma_{(\sigma\to\pi\pi)} = \left[(0.754)^5\right]^{\times 220}_{\times 550} = [0.244]^{\times 220}_{\times 550} = ^{54}_{134}$ MeV/c^2.

Therefore, the width of σ_0-meson at the mass of 754 MeV/c^2 determined in our experiment does not contradict its interpretation as a glueball.

Of course, the set of the resonances and their properties allows the other interpretations of their nature, too. But all of them have to result in narrow widths of resonances decaying into 2π-mesons. We could not generally observe in our experiment the effects at the widths given in [13] (if, of course, do not take into account various interference phenomena).

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