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THE EVIDENCE OF $\sigma[0^+(0^{++})]$ MESON AT A MASS OF $M_{\pi^+\pi^-} = (759 \pm 5)$ MeV/c^2 OBSERVED IN $\pi^+\pi^-$ COMBINATIONS FROM THE REACTION $np \to np\pi^+\pi^-$ AT AN INCIDENT MOMENTUM OF $P_n = (5.20 \pm 0.16)$ GeV/c

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The enhancement, exceeding a background by 6.12 S.D., is observed in the effective mass spectrum of $\pi^+\pi^-$ combinations at a mass of $M_{\pi^+\pi^-} = (759 \pm 5)$ MeV/c^2 for the sampling of events from the reaction $np \to np\pi^+\pi^-$ at $P_n = (5.20 \pm 0.16)$ GeV/c selected under the condition of $\cos\theta^*_p > 0$. The full experimental width of the enhancement $\Gamma = (35 \pm 12)$ MeV/c^2, the isospin $I = 0$ and the most probable value of spin $J = 0$. The cross section of the observed effect $\sigma = (38 \pm 9)$ μb. This enhancement can be interpreted as σ meson with quantum numbers $0^+(0^{++})$. The obtained results are in good agreement with the data from other papers.

The investigation has been performed at the Laboratory of High Energies and at the Laboratory of Computing Techniques and Automation, JINR.

Данные о $\sigma[0^+(0^{++})]$-мезоне с массой $M_{\pi^+\pi^-} = (759 \pm 5)$ МэВ/c^2, наблюдаемом в $\pi^+\pi^-$-комбинациях из реакции $np \to np\pi^+\pi^-$ при импульсе налетающего нейтрона $P_n = (5{,}20 \pm 0{,}16)$ ГэВ/с

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В событиях из реакции $np \to np\pi^+\pi^-$ при $P_n = (5{,}20 \pm 0{,}16)$ ГэВ/с, выбранных с условием $\cos\theta^*_p > 0$, наблюдается особенность в спектре эффективных масс $\pi^+\pi^-$-комбинаций при $M_{\pi^+\pi^-} = (759 \pm 5)$ МэВ/c^2, превышающая фон на 6,12 стандартных отклонений. Сечение наблюдаемого эффекта $\sigma = (38 \pm 9)$ мкб. Полная экспериментальная ширина особенности $\Gamma = (35 \pm 12)$ МэВ/c^2, изотопический спин $I = 0$, наиболее вероятное значение спина $J = 0$. Эта особенность может быть интерпретирована как σ-мезон с квантовыми числами $0^+(0^{++})$. Полученные результаты находятся в хорошем согласии с данными других работ.

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The existence and properties of low-lying scalar meson (the so-called σ meson) are closely related to the question on the structure of the ground state of scalar mesons nonet and the nature of scalar mesons. From the theoretical point of view, σ meson is necessary to describe the attractive part of the nucleon-nucleon interaction potential [1].

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

The scalar meson (or σ meson) can decay into two pions. Therefore, it can be observed in the effective mass spectrum of $\pi^+\pi^-$ combinations from the reactions of nucleon-nucleon interactions accompanied by $\pi^+\pi^-$-pair production.

We have large statistics of *np* interactions obtained in an exposure of the 1 m H_2 bubble chamber of LHE (JINR) to monochromatic neutron beams ($\Delta P_n/P_n \simeq 2.5\%$, $\Delta\Omega_n \sim 10^{-7}$ sterad.) at 8 values of P_n from 1.25 to 5.20 GeV/c [7]. In this number, there are more than 70000 and ~ 12000 measured events of 3-prong stars of *np* interactions at $P_n = 5.20$ and 3.83 GeV/c, respectively.

The reaction channels were separated by the χ^2 method for 4-c fit and 1-c fit [8,9]. In this case, the events of 4-c fit were preferred to those with 1-c fit. 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 kinematic conditions were used to satisfy the isotopic symmetry for the reaction $np \to np\pi^+\pi^-$. Due to this processing, the admixture of background in the reaction channels of 3-prong stars of *np* interactions does not exceed 5%. Finally, more than 30000 and ~ 6000 events of the reaction $np \to np\pi^+\pi^-$ were obtained at $P_n = 5.20$ and 3.83 GeV/c, respectively.

The reached accuracy of measurement allows one to get the mass resolution with full width $\Gamma_{\text{resol.}}$ near $4 \div 30$ MeV/c^2 for $\pi^+\pi^-$ combinations. The resolution function [9,10] is approximately of the Gauss type, and its parameter $\Gamma_{\text{resol.}}$ depends linearly on the mass of $\pi^+\pi^-$ combinations:

$$\Gamma_{\text{resol.}}(M) = 0.042\ (M - 2m_\pi) + 2.8\ \text{MeV}/c^2.$$

For example $\Gamma_{\text{resol.}}(M = 750\ \text{MeV}/c^2) \simeq 23\ \text{MeV}/c^2$.

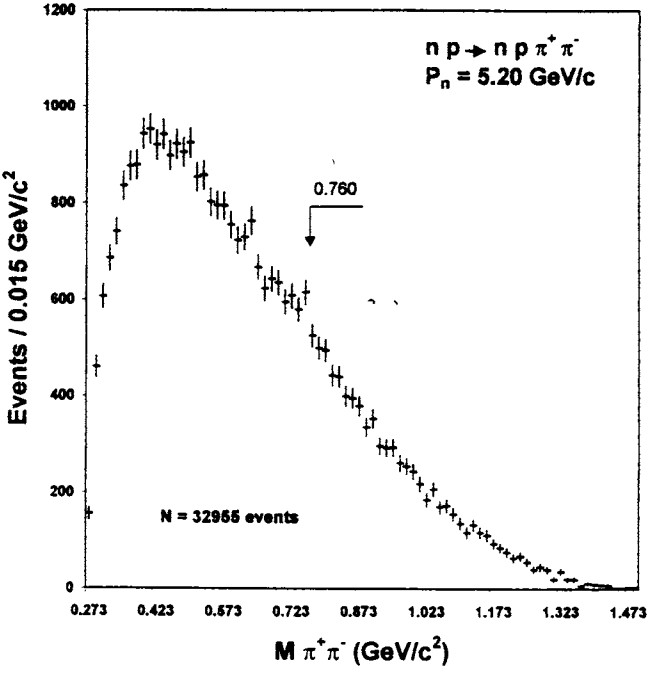

Fig.1. The effective mass distribution of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at P_n = 5.20 GeV/c

Figure 1 shows the effective mass distribution of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at P_n = 5.20 GeV/c. In all, there are 32955 events in the distribution. One can see an enhancement near a mass of ~ 760 MeV/c^2.

For a further investigation of the effective mass spectrum of $\pi^+\pi^-$ combinations, the additional condition was used for the events from the reaction $np \to np\pi^+\pi^-$. Figure 2 shows the effective mass spectrum of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at P_n = 5.20 GeV/c for the events with protons emitted in the forward hemisphere in the general c.m.s. One can observe a strong increase of the peak near a mass of 760 MeV/c^2 and there appear three additional peaks.

The distribution is approximated [10] by an incoherent sum of the background curve (taken in the form of superposition of Legendre polynomials up to the 9th power, inclusive) and by four Breit–Wigner curves corresponding to possible resonances in the $\pi^+\pi^-$ system. The most statistically significant peak, exceeding the background by 6.12 S.D., is observed at a mass of $M = (759 \pm 5)$ MeV/c^2 with the full experimental width $\Gamma =$ $= (35 \pm 12)$ MeV/c^2. The real width of the resonance is calculated by the formula

$$\Gamma_R = \sqrt{\Gamma^2 - \Gamma^2_{\text{resol.}}},$$

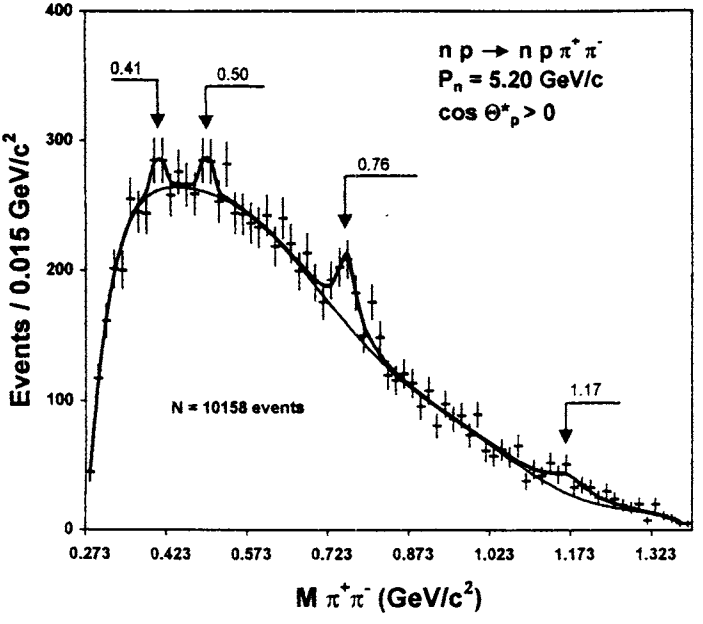

Fig.2. The effective mass spectrum of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at P_n = 5.20 GeV/c for the events with protons emitted in the forward hemisphere in the general c.m.s.

where Γ is the experimental resonance width and $\Gamma_{\text{resol.}}$ is the resolution for a corresponding mass of the $\pi^+\pi^-$ system, and turned out to be equal to $\Gamma = (27 \pm 16)$ MeV/c^2. The total probability of a random deviation is $P \simeq 10^{-9}$ for the resonance at a mass of $M = 759$ MeV/c^2.

Figure 3 shows the effective mass spectrum of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at P_n = 5.20 GeV/c for the events with neutrons emitted in the forward hemisphere in the general c.m.s. No significant enhancement near a mass of 760 MeV/c^2 is observed.

Such a behaviour of this resonance peak under different kinematic conditions can be explained, in particular, by the fact that the main part (~ 70%) of the cross section of the reaction $np \to np\pi^+\pi^-$ is due to exchange diagrams [11] accompanied by the emission of neutrons in the forward hemisphere and protons in the backward one. Therefore, the condition $\cos\theta_p^* > 0$ suppresses the contribution of these diagrams to the $M_{\pi^+\pi^-}$ spectrum, and the condition $\cos\theta_n^* > 0$ intensifies it. Moreover, one can show using isotopic relations that the contribution of this resonance to the reaction $np \to np\pi^+\pi^-$ must be at least four times larger under the condition $\cos\theta_p^* > 0$ than under the condition $\cos\theta_n^* > 0$.

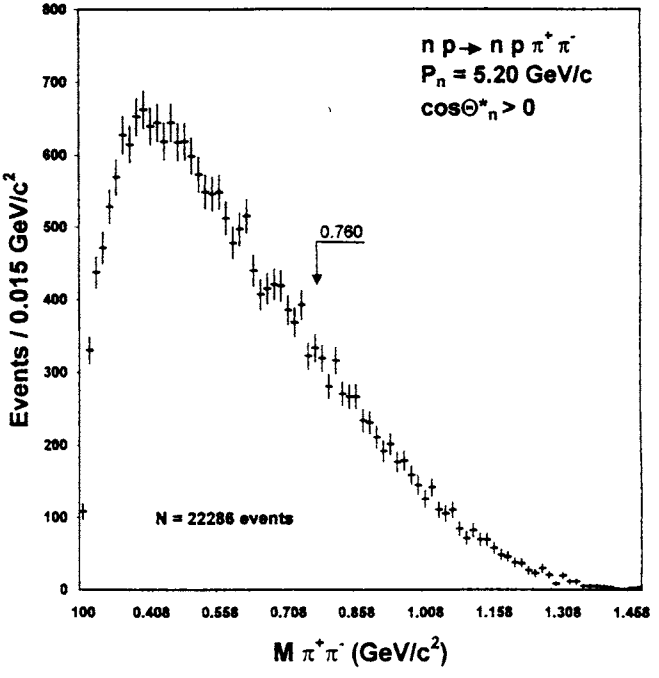

Fig.3. The effective mass spectrum of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$ at P_n = 5.20 GeV/c for the events with neutrons emitted in the forward hemisphere in the general c.m.s.

To clarify the question on the isospin of the observed resonance at a mass of 759 MeV/c^2, a study of the reaction $np \to pp\pi^-\pi^0$ was carried out. If the isospin of this resonance were $I = 1$, then the resonance peak would be observed in the effective mass spectrum of $\pi^-\pi^0$ combinations from the reaction $np \to pp\pi^-\pi^0$ not less clearly than in the spectrum of $\pi^+\pi^-$ combinations from the reaction $np \to np\pi^+\pi^-$. This is the result of isotopic relations and the analysis of the exchange diagrams for the reactions $np \to np\pi^+\pi^-$ and $np \to pp\pi^-\pi^0$.

Figure 4 presents the effective mass distribution of $\pi^-\pi^0$ combinations from the reaction $np \to pp\pi^-\pi^0$ at an incident neutron momentum of P_n = 5.20 GeV/c. No statistically significant enhancement is observed near a mass of 759 MeV/c^2. Therefore, one can conclude that the isotopic spin of the resonance observed in the $\pi^+\pi^-$ system at a mass of 759 MeV/c^2 is $I = 0$.

To determine the spin of this resonance, the angle distribution between the direction of resonance motion (general c.m.s.) and the π-meson momentum from its decay in the c.m.s

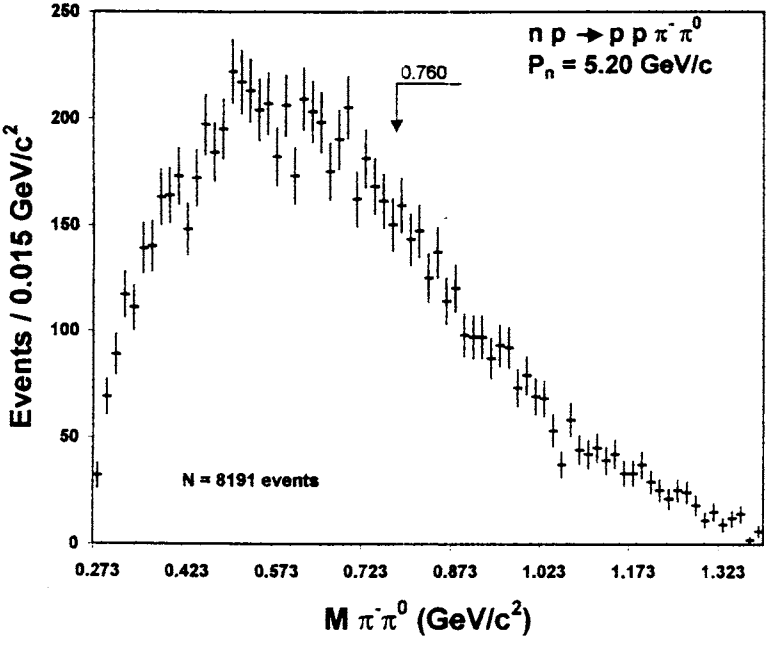

Fig.4. The effective mass distribution of $\pi^-\pi^0$ combinations from the reaction $np \to np\pi^-\pi^0$ at $P_n = 5.20$ GeV/c

of $\pi^+\pi^-$ combinations (helicity coordinate system) [10,12] was constructed and analysed. For strong decays, such a distribution must be described by the sum of Legendre polynomials of even powers with a maximum power of $2J$, where J is the resonance spin.

This $\cos\theta_{\mathbf{P}_{\pi^-}\mathbf{P}_R}$ distribution is shown in Fig.5 for masses of $723 < M_{\pi^+\pi^-} < 783$ MeV/c^2 of the events with protons emitted in the forward hemisphere. In the construction of this distribution, the background, taken from the left and the right of the resonance mass region and normalized to the total number of events in the resonance region, was subtracted. The only statistically significant description of this distribution is obtained by its approximation by the polynomial to power 0. The parameters of this approximation are: $\chi^2/N = 0.96 \pm 0.29$, R.M.S. $= 1.04 \pm 0.20$, CL $= 0.52$. Therefore, one can conclude that the spin of the observed resonance $J = 0$.

Proceeding from the foregoing and from some general properties of $\pi\pi$ systems, one can conclude that the quantum numbers of the resonance observed at a mass of 759 MeV/c^2 are most probably $I^G(J^{PC}) = 0^+(0^{++})$.

Our results are in good agreement with the data of the PWA analysis carried out by Svec [13] ($M = 753 \pm 19$ MeV/c^2, $\Gamma = 108 \pm 53$ MeV/c^2) and by the group of ITEP [14]

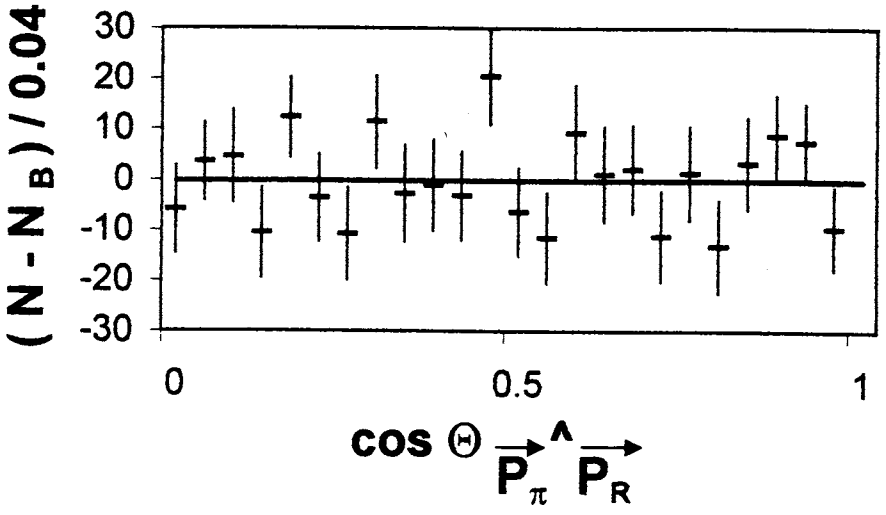

Fig.5. The distribution of $\cos\theta_{\hat{P_\pi P_R}}$ for the masses $723 < M_{\pi^+\pi^-} < 783$ MeV/c^2 of the events with protons emitted in the forward hemisphere. The background is subtracted

($M = 744 \pm 19$ MeV/c^2, $\Gamma = 77 \pm 22$ MeV/c^2). They have also observed a narrow resonance with quantum numbers $0^+(0^{++})$ in $\pi^+\pi^-$ system from the reactions $\pi^- p \to \pi^-\pi^+ n$ (at $P_0 = 17.2$ GeV/c [13] and $P_0 = 1.78$ GeV/c [14]) and $\pi^+ n \to \pi^+\pi^- p$ (at $P_0 = 5.98$ and 11.85 GeV/c [13]) on polarized targets. It should be noted that in our experiment the possible σ meson is observed directly for the first time (as far as we know).

As for other resonance peaks that are also observed in $\pi^+\pi^-$ combinations near masses of 0.41, 0.50 and 1.17 GeV/c^2, their location is in agreement with the data presented in Review of Particle Physics [15]. However, further investigations are required to determine their parameters.

In future, we intend to increase statistics of the reaction $np \to np\pi^+\pi^-$ up to $\sim 10^5$ events by processing the available data. It will allow the observed effects to be studied in more detail.

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