Study of multipion production in np-interaction at intermediate energies

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Abstract. The reactions of the multipion production in np-interactions were studied at the momenta of incident neutrons from 1.73 to 5.20 GeV/c. The pions multiplicity of the studied reactions was from 2 to 6. It was shown that the characteristics of the reactions were satisfactorily described within the framework of OPER-model (One Pion Reggeized Exchange). Additionally the diagrams of one baryon exchange (OBE) were used for a better description of the data at the momenta of incident neutrons below 3 GeV/c.

1 Introduction

Multi pion production in NN collisions is one way to obtain information about the NN, πN and $\pi\pi$ states, including:

- dibaryons (including $I=2$ in $pp\pi$),
- dipions (narrow σ -meson, $\pi\pi$ states with $I=2$),
- pentaquarks ($I=5/2$, $S=+1$),
- missing resonances etc.

An important task is to test the models of pion production in NN-interactions such as Valencia model [4], Xu Cao model [5], (OPER+OBE) model [6–8].

Various modifications of the one pion exchange models (OPE) are used to describe the experimental data of the inelastic NN-, $N\bar{N}$ - and πN -interactions. Parameters of these models are different for various processes and even for concrete reactions at various energies.

The most developed and detailed model of Reggeized π -meson exchange is the model elaborated at ITEP [6]. The advantages of this model are:

- small number of free parameters (3 in our case),
- wide region of the described energies (2÷200 GeV),
- calculated values are automatically normalized to the reaction cross-section.

2 Experiment

The neutron-proton interactions were studied by using the neutron beam and liquid hydrogen bubble (target) at the JINR Synchrophasotron [1]. Unique complete and precise data were obtained. It allowed one to carry out a detailed study of inelastic np interactions in a wide

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range of energies using the quasimonochromatic neutrons with $P_0 < 2.5\%$ under condition of 4π geometry.

The accuracy of the momentum and scattering angle reconstruction for the secondary charged particles was $\sigma_p/p \sim 2\%$ and $\sigma_\Theta \sim 10$ mrad, respectively. The separation of the reaction channels was carried out by the standard χ^2 procedure using the corresponding constraint equations [3].

A detailed description of the data processing and reaction channels separation was presented in [2].

3 2π production

The reactions $np \rightarrow np\pi^+\pi^-$, $np \rightarrow pp\pi^-\pi^0$ and $np \rightarrow d\pi^+\pi^-$ were studied at the momenta of incident neutrons $P_0 = 1.73, 2.23, 3.83$ and 5.20 GeV/c. The cross sections of the considered reactions were presented in [2].

3.1 Reaction $np \rightarrow np\pi^+\pi^-$

This reaction is characterized by the plentiful production of Δ_{1232} -resonance and a number of N^* and Δ^* resonances in $N\pi\pi$ system.

The main diagrams describing the reaction are the following:

Figure 1. Main OPER diagrams for the reaction $np \rightarrow np\pi^+\pi^-$

At the momentum of incident neutrons $P_0 < 3.0$ GeV/c it is also necessary to take into account the diagrams of one-baryon exchange (OBE):

Figure 2. Main OBE diagrams for the reaction $np \rightarrow np\pi^+\pi^-$

The contributions of these diagrams into the reaction are presented in Fig. 3.

Figure 3. The contribution of the diagrams in Figs. 1 and 2 into the reaction $np \rightarrow np\pi^+\pi^-$. Open crosses present our data

The results of the study of the reaction $np \rightarrow np\pi^+\pi^-$ at $P_0=5.20$ GeV/c are presented in Fig. 4. One can see a good agreement between the experimental data and theoretical calculations. The signal of ρ -meson production is not observed in $\pi\pi$ -combinations..

Figure 4. The distributions from the reaction $np \rightarrow np\pi^+\pi^-$ at $P_0=5.20$ GeV/c. Solid line – calculations using OPER-model

The diagrams in Fig. 1, however, were insufficient to get a full description of the reaction $np \rightarrow np\pi^+\pi^-$ at lower energies. The study of effective mass spectra of np-combinations at $P_0=2.23$ and 1.73 GeV/c (Fig. 5) has shown a clear peak near the threshold. Therefore the model of Redge poles with baryon exchange (OBE, see Fig 2.) was used to describe these features.

Figure 5. The effective mass spectra from the reaction $np \rightarrow np\pi^+\pi^-$ at a) $P_0=2.23$ and b) 1.73 GeV/c. Dashed line – calculations using OPER-model, dash-dot line – calculations using OBE-model

The combined (OPER+OBE)-model allows one to get a good description of the characteristics of the reaction $np \rightarrow np\pi^+\pi^-$ at the momenta of incident neutrons in a region from $P_0=1.73$ to $P_0=5.2$ GeV/c.

More detailed results of the study of this reaction were presented in [9, 10].

3.2 Reaction $np \rightarrow pp\pi^-\pi^0$

We have also got a good description of the characteristics of the reaction $np \rightarrow pp\pi^-\pi^0$ using the diagrams similar to the diagrams for the reaction $np \rightarrow np\pi^+\pi^-$. The details of this study were presented in [9].

3.3 Reaction $np \rightarrow d\pi^+\pi^-$

The reaction $np \rightarrow d\pi^+\pi^-$ is characterized by a fusion of neutron and proton into the deuteron. Thus it seems to be reasonable to take into account OBE diagrams shown in Fig. 6 to describe the experimental data of this reaction:

Figure 6. Diagrams corresponding to the reaction $np \rightarrow d\pi^+\pi^-$ in the framework of the one baryon exchange (OBE) model

In Fig. 7 one can see clear peaks in the masses of $\pi^+\pi^-$ -combinations close to ~ 350 and ~ 400 MeV/c² (so called ABC and DEF anomaly). These effects, momenta and mass distributions are good reproduced within framework of OBE model. But the theoretical curve for angular distributions of deuteron and pions are too sharp. It is necessary to develop further the OBE model to improve the description of the experimental data.

Figure 7. The distributions for the reaction $np \rightarrow d\pi^+\pi^-$ at $P_0=1.73$ GeV/c. Solid line – calculations using OBE-model. One can see ABC and DEF bumps in 2π mass spectrum

As far as dipion masses concerned from the reaction $np \rightarrow d\pi^+\pi^-$ at $P_0=2.23$ GeV/c, it is difficult to say that ABC and DEF bumps are confidently observed. Obviously it is due to insufficient statistics.

The details of the study of this reaction were presented in [9].

4 3π and 4π production

The reactions $np \rightarrow pp\pi^+\pi^-\pi^-$, $np \rightarrow pp\pi^+\pi^-\pi^0$ and $np \rightarrow np\pi^+\pi^+\pi^-\pi^-$ were studied at the momenta of incident neutrons $P_0=3.83, 4.42$ and 5.20 GeV/c. The cross sections of the considered reactions were presented in [2].

The following diagrams were taken into account to calculate the characteristics of the reactions $np \rightarrow NN3\pi$ and $np \rightarrow NN4\pi$:

Figure 8. Diagrams of OPER model for the reactions of 3π and 4π meson production in np interactions

4.1 Reaction $np \rightarrow pp\pi^+\pi^-\pi^-$

The results of the calculations using OPER model for the reaction $np \rightarrow pp\pi^+\pi^-\pi^-$ are shown in Fig. 9 for the data at $P_0 = 5.2$ GeV/c.

Figure 9. The distributions for the reaction $np \rightarrow pp\pi^+\pi^-\pi^-$ at $P_0=5.20$ GeV/c. Solid line – calculations using OPER model

One can see a good agreement between the experimental data and theoretical calculations. Also a good description was obtained for this reaction at the incident momenta $P_0=3.83$ and 4.42 GeV/c. The details of the study of this reaction were presented in [9].

4.2 Reaction $np \rightarrow pp\pi^+\pi^-\pi^0$

The results of the calculations using OPER model for the reaction $np \rightarrow pp\pi^+\pi^-\pi^0$ are shown in Fig. 10 for the data at $P_0 = 5.20$ GeV/c.

Figure 10. The distributions for the reaction $np \rightarrow pp\pi^+\pi^-\pi^0$ at $P_0=5.20$ GeV/c. Solid line – calculations using OPER model

One can see a good agreement between the experimental data and theoretical calculations. A clear signals of η^0 and ω^0 mesons production are observed at the masses of $\pi^+\pi^-\pi^0$ combinations. To describe these peaks, the following diagrams were taken into account:

Figure 11. Diagrams of OPER model for the reactions $np \rightarrow pp\pi^-\eta^0$ and $np \rightarrow pp\pi^-\omega^0$

The diagrams a) and b) describe η^0 -meson production through the production of N_{1535}^* resonance in πN interaction with the consequent decay $N_{1535}^* \rightarrow N\eta^0$. The "hanged" diagrams c) and d) describe ω^0 meson production due to $\pi\rho$ interaction.

The cross-sections of η and ω meson production were determined as equal to $\sigma_\eta=(13 \pm 2)\mu\text{b}$ and $\sigma_\omega=(18 \pm 3)\mu\text{b}$ at $P_0=5.20$ GeV/c.

The results at $P_0=4.42$ GeV/c and $P_0=3.83$ GeV/c are not presented due to a poor statistics. But OPER model also described satisfactorily the experimental distributions and the signals of η^0 and ω^0 meson production at these energies.

4.3 Reaction $np \rightarrow np\pi^+\pi^+\pi^-\pi^-$

We have also got a good description of the characteristics of the reaction $np \rightarrow np\pi^+\pi^+\pi^-\pi^-$. The details of this study were presented in [9].

5 5π and 6π production

The reactions $np \rightarrow pp\pi^+\pi^+\pi^-\pi^-\pi^-$, $np \rightarrow pp\pi^+\pi^+\pi^-\pi^-\pi^0$ and $np \rightarrow np\pi^+\pi^+\pi^-\pi^-\pi^-$ were studied at the momenta of incident neutrons $P_0=5.20$ GeV/c. The cross sections of these reactions were presented in Tab. 1.

Table 1. Cross-sections of 5π and 6π meson production

reaction	cross-section (μb)
$np \rightarrow pp\pi^+\pi^+\pi^-\pi^-\pi^-$	18.7 ± 4.1
$np \rightarrow pp\pi^+\pi^+\pi^-\pi^-\pi^0$	3.6 ± 1.0
$np \rightarrow np\pi^+\pi^+\pi^-\pi^-\pi^-$	3.7 ± 1.0

The only reaction $np \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ was studied in details. Other reactions (6π production) have had too poor statistics.

The following diagrams were taken into account to calculate the characteristics of the reaction of 5π -meson production:

Figure 12. Diagrams of OPER model for the reaction $np \rightarrow pp\pi^+\pi^+\pi^-\pi^-\pi^-$

Fig. 13 shows a good agreement between the experimental data and theoretical calculations by means of OPER-model.

6 Conclusion

Multi π -meson production in np-interactions is provided by the excitation and decay of Δ^* - and N^* -resonances (taken from PWA and GIM).

The large peripherality of the secondary hadrons leads to the idea of using some exchange models (π , P , etc.)

It has been shown that there is no noticeable signal of ρ -meson production in the considered reactions.

Figure 13. The distributions for the reaction $np \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ at $P_0=5.20$ GeV/c. Solid line – calculations using OPER model

OPER-model allows one to get a good description of the characteristics from 2 up to 6 pion production in np interactions. At lower energies ($P_0 < 3$ GeV/c) it is necessary to take into account another mechanism of the reactions (such as OBE-model).

(OPER+OBE)-model can be used as an efficient tool to simulate various reactions of hadron interactions: NICA project, HADES set-up, intranuclear interactions (hA and AA).

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