INVESTIGATION OF THE $pp \rightarrow p\pi^0$ REACTION
AT TWO ENERGIES NEAR 1 GeV

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1. Introduction

The pion production in the $NN$ interactions is the main inelastic process at the energies below 1 GeV. Despite the fact that a lot of experiments have been performed, many questions on this process are not yet answered. One of them is a question of the contribution of the isoscalar ($I = 0$) channel to the inelastic neutron-proton collisions. Since the neutron-proton scattering amplitude contains both isoscalar and isovector ($I = 1$) parts, a detailed investigation of the neutral pion production in the $pp$ collisions (isovector contribution only) might give the most accurate information on the isovector channel that, in a combination with the neutron-proton data, would allow one to extract more correctly the contribution of the isoscalar channel.

Various theoretical models, more or less successful, arose while the data on the pion production in $NN$ collisions were accumulated. Most of them work for pion production near the production threshold and are not applied at higher energies.

For the energy range 1–3 GeV an earlier peripheral or one-pion exchange (OPE) model suggested by E. Ferrary and F. Selleri assumed the dominance of the one-pion exchange term in the inelastic amplitude. Pole diagram matrix elements were calculated using the uncertain betweenhand form factor, the interference between diagrams being neglected. The form factor function was obtained then by fitting to experimental data, so in fact this was a semiphenomenological model. Its predictions were in a good agreement with rather rough measurements of the differential cross sections in the energy range 800–1300 MeV.

The later modifications of the one-pion exchange model have described rather well (with the accuracy 5–10%) the differential spectra for the $pp \rightarrow p\pi^+$ reaction which provided the largest piece of experimental information that time. The total cross sections were predicted to be a little lower than the observed ones. For other reactions, e.g. for $pp \rightarrow p\pi^0$, the discrepancies between the theory and experiment were even larger.

It should be noted that the experimental data on the $pp \rightarrow p\pi^0$ reaction near the energy of 1 GeV are much more scarce than those for $pp \rightarrow p\pi^+$ channel. The KEK data contain the information on total cross sections only. The only data on the spectra of secondaries at the energy 970 MeV were provided by D.V. Bugg et al., the statistics being rather poor. For this reason it would be important to perform more accurate measurement of the cross sections in this energy region and to compare carefully the differential distributions of the final particles in the $pp \rightarrow p\pi^0$ reaction with the predictions of the modern OPE model. Such a comparison would allow one to see the strong and weak aspects of this simplest theoretical model, as well as to judge about the necessity of some additional nonperipheral mechanisms of the pion production in $NN$ collisions. The results on the study of neutral pion production in the energy range below 900 MeV were published earlier in our work [1]. Here we present the results [2] of the investigation of differential spectra at two higher momenta (1581 and 1683 MeV/c) and their comparison with the OPE-model advanced by V.K. Suslenko et al.

2. Experiment

The experiment was performed at the PNPI 1 GeV synchrocyclotron with the help of the 35 cm hydrogen bubble chamber disposed in the 1.48 T magnetic field. The proton beam (after corresponding degrader for the momenta 1581 MeV/c) was formed by three bending magnets and by eight quadrupole lenses. The incident proton momentum value was defined independently by the kinematics of the elastic scattering events. The accuracy of the incident momentum value was about 0.5 MeV/c, the momentum spread being 25 and 7 MeV/c (FWHM) at 1581 and 1683 MeV/c, respectively. A total
of $10^5$ stereo frames were obtained at both proton momenta.

According to kinematics of the pion production in $NN$ collisions, the laboratory angles of secondary protons are in the forward hemisphere, maximum angle being not larger than $60^\circ$ at our energies. For this reason we selected two-prong events with track angles in the plane of the film not larger than $60^\circ$.

The events selected so can belong not only to the neutral pion production but also to the elastic $pp$ scattering or to the $\pi^+$ production reactions. The events in the fiducial volume of the chamber were measured and geometrically reconstructed. The identification of the events was performed on the strength of the $\chi^2$ criterion, the confidence level being equal to 1%. If the event had a good $\chi^2$ for the elastic version (4C-fit), it was considered as elastic one. If several inelastic versions revealed a good $\chi^2$, we used visual estimate of the ionization density to distinguish between the proton and pion.

The standard bubble chamber procedure was used to obtain absolute cross sections. Absolute values were measured with an accuracy about 4%.

3. One-pion exchange model

According to the OPE model, the main role in the reaction $NN \to NN\pi$ is played by the pole diagrams (Fig. 1). The matrix element of any diagram in Fig. 1 can be presented as a product of three factors: the propagator, the amplitude of the $\pi N$ scattering and the $\pi NN$ vertex function

$$M_i \sim \frac{1}{k_i^2 + \mu^2} \Im(z_i, q_i^2; k_i^2)G(k_i^2),$$

where $z_i$ is the total energy of the $\pi N$ system, $q_i^2$ is the four-momentum transfer square in the $\pi N$ scattering vertex, $k_i^2$ is the four-momentum square of the virtual pion and $\mu^2$ is the pion mass squared.

The form factor function of the $\pi NN$ vertex taking into account the nonpole diagram contributions was not determined in the frame of the OPE model. The following expression was suggested for the form factor

$$G(k_i^2) = \alpha \mu^2 / [k_i^2 + (\alpha + 1)\mu^2].$$

The choice of $\alpha$ in the range $8-9$ gave a good description of the experimental data on the $pp \to pn\pi^+$ reaction in the energy range 600-1000 MeV.

The $\pi N$ scattering amplitude $\Im(z_i, q_i^2; k_i^2)$ and its off-shell behavior were taken according to the paper of E. Ferrary et al., where the off-shell corrections were introduced into partial waves. We confined ourselves to the $P_{33}$ wave only in the partial wave expansion, assuming the leading role of the $\Delta_{33}$ resonance in the $\pi N$ scattering.

\begin{figure}[h]
\centering
\begin{tabular}{cccc}
\hline
 & A & B & C & D \\
$\rho_1$ & $q_1$ & $q_2$ & $p_1$ & $q_1$ \\
$\rho_2$ & $q_2$ & $q_1$ & $p_2$ & $q_2$ \\
\hline
\end{tabular}
\caption{Feynman diagrams of the OPE model for the $NN \to NN\pi$ reaction}
\end{figure}

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The reaction matrix element is the sum of matrix elements of diagrams of Fig. 1

\[ M = M_A - M_B - M_C + M_D, \]

where the choice of signs is determined by the Pauli principle. All possible interference terms were taken into account.

We used a FOWL simulation program in order to obtain all necessary distributions at once.

4. Experimental results and discussion

The main evidence for the pole diagram contribution would definitely be the observation of a peak in the momentum transfer distribution from the target particle to the secondary proton (e.g., for the diagram A) in the distribution on \( \Delta^2 = -(p_2 - q_2)^2 \) at low momenta. But since there is no difference between the final protons in the \( pp \rightarrow ppm^0 \) reaction, it is difficult to separate the contribution of a certain diagram experimentally. The whole \( \Delta^2 \) distribution is rather complex, because other diagrams have singularities on their own variables which spread the studied one. So the contribution of the diagram A really contains the low momentum peak, while the B diagram contribution has a maximum at high \( \Delta^2 \). It is quite natural because the diagram B has a singularity in \( \Delta^2 = -(p_1 - q_2)^2 \) distribution, so for this diagram the beam proton is a spectator and \( \Delta^2 \) is not small \( (p_2 \text{ is the nucleon mass in the laboratory system and } q_2 \text{ is almost equal to } p_1) \). The contributions of diagrams C and D are similar to those of B and A, respectively, but more spread out.

![Figure 2](image_url)

**Fig. 2.** The four-momentum transfer \( \Delta^2 \) distributions. The solid and dotted curves are the calculations of the OPE model and the phase space normalized to the total experimental number of events.

Figure 2 shows the \( \Delta^2 \) distributions for our energies together with the OPE model predictions (solid lines) and phase space calculations (dotted lines) normalized to the total experimental number of events, because the absolute values of the OPE model calculations do not agree with the experiment. We shall return to this question later when we will discuss the energy dependence of the cross sections.

Forgetting for a while the underestimated absolute cross section values, we can see that the OPE model describes qualitatively well the data on \( \Delta^2 \) at both energies studied. It is remarkable because one should bear in mind that only the \( P_{33} \) wave was taken into account in the \( \pi N \) scattering.

Perhaps, the \( \Delta^2 \) distribution is mainly sensitive to the pole diagram propagator, and the dependence on the \( \pi N \) amplitude manifests itself in other distributions.

Figure 3 shows the laboratory momentum spectra of final protons of the \( pp \rightarrow ppm^0 \) reaction. In the proton spectra one can see two peaks, one in the region 300-400 MeV/c (independently of the...
Fig. 3. The laboratory momentum spectra of final protons. The curves have the same meaning as in Fig. 2

incident energy) and the second moving to the left with the decrease of beam energy. The low-energy peak corresponds to the target spectator proton, while the high-energy one corresponds to the incident proton being a spectator. The OPE calculations describe the experiment satisfactorily, contrary to the phase space ones. The pion spectra calculated are close to the phase space and experimental distributions.

Figure 4 shows the $M_{\pi p\bar{p}}$ effective mass distributions. It looks like that the distributions on $M_{\pi p\bar{p}}$ consist of two parts: one is the phase space distribution, while the other has the form of a peak with the width $\sim 100$ MeV/$c^2$. The peak location corresponds to the $\Delta_{33}$ mass. The origin of these two contributions is quite clear in the frame of the OPE model, if one keeps in mind that the $\pi N$ scattering comes from the $P_{33}$ wave only. When the $M_{\pi p\bar{p}}$ is calculated for the spectator proton, (e.g., $q_2$ in the diagram A, Fig. 1) one has the phase space distribution. When the proton comes from the $\pi N$ scattering block the resulting $M_{\pi p\bar{p}}$ distribution corresponds to the $\Delta_{33}$ isobar peak. As can be seen in Fig. 4, OPE calculations are in qualitative agreement with the experiment at both energies studied.

Fig. 4. $M_{\pi p\bar{p}}$ effective mass spectra. The curves have the same meaning as in Fig. 2

The c.m.s. angular distributions of protons are given in Fig. 5. OPE calculations are in rather good agreement with the experimental data, with the exception for the small proton scattering angles. A possible explanation of this discrepancy is the presence of the sole $P_{33}$ wave in the $\pi N$ scattering amplitude. It is clear that a small admixture of other waves interfering with the main one should manifest itself mainly in the angular distributions.

The angular distributions of pions together with the OPE predictions are given in Fig. 6. One
should say that the distributions are far from being isotropic. Since the c.m.s. angular distributions of pions should be symmetrical, we tried fitting to them by the formula

\[ \frac{d\sigma}{d\Omega_{\pi^0}} \sim \frac{k}{2\pi}(1/3 + b \cos^2 \theta_{\pi^0}). \]  

(4)

The results of such a fit are shown in Fig. 7 together with the values found by other authors. The problem is important, being connected with the attempts to estimate the contribution from the isoscalar channel to the inelastic np-interaction. If this contribution is zero, the angular distributions of charged pions in the \( np \rightarrow p\pi^- \) (\( nn\pi^+ \)) reactions should be similar to those of \( \pi^0 \) mesons in the \( pp \rightarrow pp\pi^0 \) reaction. The presence of terms linear in \( \cos \theta_{\pi^0} \) in the angular distribution of np-reactions might be considered as an indication to the isoscalar contribution. It is clear that to catch a small contribution of the isoscalar channel one needs to know well enough a form of the isovector contribution for which the \( pp \rightarrow pp\pi^0 \) reaction provides better opportunity.

As it is seen in Fig. 7, the anisotropy factor \( b \) is rather badly determined and a scatter of values is fairly large. Nevertheless one can see that \( b \) increases gradually together with the energy and starting with the momentum of \( \sim 1.2 \text{ GeV/c} \) it is in the range 0.2-0.4.

As one can see in the above-given Figures, there is a good qualitative agreement of the OPE model with experimental differential spectra while the predictions for the total cross sections underestimate the data. The existing experimental data on the total cross sections are shown in Fig. 8 together with the model predictions. It is seen that there is an obvious discrepancy between the OPE model
calculations (solid curve) and experimental cross sections. Why does the OPE model fail to describe the cross section values for the $pp \rightarrow pp\pi^0$ reaction? One can obtain better agreement with a proper choice of the form factor, but such a choice destroys the agreement with total cross sections of the $pp \rightarrow pn\pi^+$ reaction, as was shown in Ref. [1]. One might guess that the reason for such a situation is that the $\pi N$ amplitude is not good enough because only the $P_{33}$ wave was taken into account. The dashed curve in Fig. 8 corresponds to the predictions of the Deck model, where the $\pi N$ vertex includes all the waves obtained in the partial-wave analysis of Karlsruhe group. One can see that this does not change the situation significantly. One should keep in mind, however, that, with an exception for $P_{33}$ wave, there is no good prescription for the calculation of the off-shell correction being very important. So the question is still open.

The present measurements together with our previous data at lower energies [1] as well as measurements of cross sections of the $pn \rightarrow pp\pi^-$ reaction\(^1\) allow one to obtain the energy dependence of the isoscalar inelastic cross section

$$\sigma(I = 0) = 3[2\sigma(pn \rightarrow pp\pi^-) - \sigma(pp \rightarrow pp\pi^0)].$$

(5)

Figure 9 shows one third of the isoscalar inelastic $NN\pi$ cross section for the energies at which the reaction $pp \rightarrow pp\pi^0$ was investigated by us [1, 2] and also by G. Rappenecker et al. The values of $\sigma(np \rightarrow pp\pi^-)$ were obtained by the interpolation to the same final kinetic energy in the center-of-mass system.

One can see that the isoscalar cross section is close to zero up to the momentum 1.4 GeV/c, and furthermore it rises in agreement with the prediction of the Deck model (solid curve).

Fig. 9. Isoscalar inelastic cross section. The curve is the calculation of the Deck model

5. Conclusion

A detailed study of differential cross sections of the $pp \to ppp^0$ reaction has been performed at two incident energies near 1 GeV. The shape of the distributions is described by the OPE model quite well, in spite of the fact that the $P_{33}$ wave only is used in the $\pi N$ scattering amplitude. On the other hand, the OPE model fails to predict the correct total cross sections and it cannot be improved by the simple choice of the form factor.

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References