

Δ -Isobar contribution to the pion production in the reaction $pp \rightarrow \{pp\}_s \pi^0$

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Abstract. ANKE@COSY data on the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$, where $\{pp\}_s$ is the proton pair in the 1S_0 state at small excitation energy $E_{pp} = 0 - 3$ MeV, obtained at beam energies 0.5 - 2.0 GeV are analyzed within the one-pion exchange model. The model involves the subprocess $\pi^0 p \rightarrow \pi^0 p$ and accounts for the final state pp-interaction. A broad maximum observed in the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1.4 GeV in the forward direction is explained by this model as a dominant contribution of the isospin $\frac{3}{2}$ in the $\pi^0 p$ -scattering. The second bump in data at 2 GeV is underpredicted within this model by one order of magnitude. An explicit excitation of the $\Delta(1232)$ -isobar using the box-diagram is also considered in the region of the first maximum.

1 Introduction

Study of the reaction $pp \rightarrow \{pp\}_s \pi^0$, where $\{pp\}_s$ is the proton pair (diproton) in the 1S_0 state at small excitation energy $E_{pp} = 0 - 3$ MeV, is motivated by several reasons. First, this is the simplest inelastic process in the pp-collision, which can reveal underlying dynamics of NN interaction. Second, restriction by only one partial wave (s-wave) in the final pp-state considerably simplifies a comparison with theory making it basically similar to that for the other simplest reaction of this type, $pp \rightarrow d\pi^+$. However, while for the reaction $pp \rightarrow d\pi^+$ there are a lot of data including spin observables [1], which are used to test theoretical models in the GeV region [2, 3], data on the reaction $pp \rightarrow \{pp\}_s \pi^0$ above 0.4 GeV were absent until recent measurements at COSY [4–6]. Third, the kinematics of the quasi-binary reaction $pp \rightarrow \{pp\}_s \pi^0$ is very similar to that of the reaction $pp \rightarrow d\pi^+$, but its dynamics can be essentially different. In fact, quantum numbers of the diproton state ($J^\pi = 0^+$, $I = 1$, $S = 0$, $L = 0$) differ from those for the deuteron ($J^\pi = 0^+$, $I = 0$, $S = 1$, $L = 0, 2$). Therefore, transition matrix elements for these two reactions are also different. Using the generalized Pauli principle and angular momentum and P-parity conservation, one can easily find that only negative parity states are allowed in the reaction $pp \rightarrow \{pp\}_s \pi^0$. Thus, for the intermediate ΔN state the odd partial waves (p-, f-, ...) are allowed, whereas the even waves (s-, d-, ...) are forbidden. Therefore, at the nominal $\Delta(1232)$ -threshold of the reaction $NN \rightarrow \Delta N$, $T_p = 0.63$ GeV, the lowest allowed partial wave is the p-wave, which, however, has to be suppressed by the centrifugal barrier. In contrast, in the $pp \rightarrow d\pi^+$

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reaction both negative and positive parity $\Delta - N$ states are allowed. As a consequence, the contribution of the Δ -mechanism to the reaction $pp \rightarrow \{pp\}_s \pi^0$ is expected to be suppressed as compared to the reaction $pp \rightarrow d\pi^+$. This argument was applied in [7] to explain a very small ratio (less of few percents) of the spin-singlet to spin-triplet pn-pairs observed in the LAMPF data [8] in the final state interaction region of the reaction $pp \rightarrow pn\pi^+$ at proton beam energy 0.8 GeV. Obviously, this argument is valid for any intermediate N^*N - states with other nucleon isobars N^* of positive parity. Furthermore, since Δ -type mechanisms are of long-range type, reduction of their contribution would mean that other mechanisms, like N^* -exchanges [9] which are more sensitive to short-range NN-dynamics, could be more important in the reaction $pp \rightarrow \{pp\}_s \pi^0$ as compared to the $pp \rightarrow d\pi^+$ reaction [10].

The cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ was measured recently at energy 0.8 GeV in [4, 6] and at beam energies 0.5 - 2.0 GeV in [5]. (For measurements at energies below 0.425 GeV see [11–13].) At the zero angle, the data [5] show a broad maximum in the energy dependence of the cross section at 0.5 - 1.4 GeV. This maximum is similar in shape and position to the well known Δ - maximum in the reaction $pp \rightarrow d\pi^+$. However, a comparison with the calculation [14] performed within a microscopical model, which includes $\Delta(1232)$ -isobar excitation and s-wave πN -scattering, shows very strong disagreement between the model and the data obtained at energies 0.5 - 0.9 GeV [5] both in the absolute value and shape of energy dependence of the cross section.

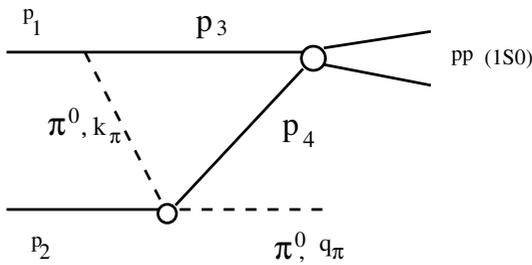


Figure 1. The OPE mechanism of the reaction $pp \rightarrow \{pp\}_s \pi^0$

In view of qualitative arguments given above, this disagreement would mean that the observed maximum of the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1.4 GeV is of non- Δ -isobar origin. Here we analyze these data employing a simpler model, which includes the subprocess $\pi^0 p \rightarrow \pi^0 p$ and the final state $pp(^1S_0)$ -interaction (Fig. 1). We show in Section 2 that the observed shape of the peak and, to some extent, its magnitude are in agreement with assumption of dominance of the isospin $T = 3/2$ contribution to the subprocess $\pi^0 p \rightarrow \pi^0 p$. However, an explicit inclusion of the $\Delta(1232)$ -isobar via the box diagram given in Section 3 shows [15] that the agreement between this mechanism and the data both in a shape and absolute value of the cross section is only qualitative.

2 The OPE model

We consider the reaction $pp \rightarrow \{pp\}_s \pi^0$ within the mechanism which corresponds to the triangle diagram in Fig. 1. A very similar mechanism was successfully applied for analysis of the $pp \rightarrow d\pi^+$ reaction in the region of the $\Delta(1232)$ -isobar [16, 17] and at higher energies too [16].

The amplitude of the reaction $pp \rightarrow \{pp\}_s \pi^0$ consists of two terms, $A = A^{dir} - A^{exch}$, where A^{dir} is the direct term and A^{exch} is the exchange one. These terms are related to one another by permutation of two initial protons. The one-loop integral for the direct term A^{dir} is evaluated very similarly to the OPE-II model of the reaction $pd \rightarrow \{pp\}_s n$ considered in [18].

Thus, A^{dir} takes the following form:

$$A^{dir}(p_1, \sigma_1, p_2, \sigma_2) = \frac{f_{\pi NN}}{m_\pi} N_{pp} 2m_p F_{\pi NN}(k_\pi^2) \times \quad (1)$$

$$\times \sum_{\sigma_3 \sigma_4 \mu} \left(\frac{1}{2} \sigma_3 \frac{1}{2} \sigma_4 |00\rangle \right) \left(1 \mu \frac{1}{2} \sigma_3 \left| \frac{1}{2} \sigma_1 \right. \right) J^\mu(\vec{p}, \gamma) A_{\sigma_2}^{\sigma_4}(\pi^0 p \rightarrow \pi^0 p),$$

here $f_{\pi NN}$ is the πNN coupling constant with $f_{\pi NN}^2/4\pi = 0.0796$, $F_{\pi NN}(k_\pi^2) = (\Lambda^2 - m_\pi^2)/(\Lambda^2 - k_\pi^2)$ is the πNN form factor, k_π is the four-momentum of the virtual π -meson, m_p (m_π) is the nucleon (pion) mass, σ_i ($i = 1, \dots, 4$) is the z-projection of the spin of i th proton; $A(\pi^0 p \rightarrow \pi^0 p)$ is the amplitude of the $\pi^0 p$ elastic scattering which is taken on-mass-shell; the vector J_μ is defined by the transition form factors as

$$J^\mu(\vec{p}, \gamma) = \sqrt{\frac{E_1 + m_p}{2m_p} \frac{m_p}{E_1}} \left\{ R^\mu F_0(\vec{p}, \gamma) - i \hat{p}^\mu \Phi_{10}(\vec{p}, \gamma) \right\}, \quad (2)$$

where

$$F_0(\vec{p}, \gamma) = \int_0^\infty dr r j_0(\vec{p}r) \psi_k^{(-)*}(r) \exp(-\gamma r), \quad (3)$$

$$\Phi_{10}(\vec{p}, \gamma) = i \int_0^\infty dr j_1(\vec{p}r) \psi_k^{(-)*}(r) (1 + \gamma r) \exp(-\gamma r), \quad (4)$$

here $j_l(x)$ ($l = 0, 1$) is the spherical Bessel function, $\psi_k^{(-)}(\mathbf{r})$ is the pp-scattering wave function that is the solution of the Schrödinger equation at the cms momentum $|\mathbf{k}|$ with the interaction potential $V(^1S_0)$ for the following boundary condition at $r \rightarrow \infty$:

$$\psi_k^{(-)}(\mathbf{r}) \rightarrow \frac{\sin(kr + \delta)}{kr}. \quad (5)$$

Here δ is the 1S_0 phase shift (for simplicity we omit here the Coulomb interaction, which is taken into account in real numerical calculations). In Eq. (1) the combinatorial factor $N_{pp} = 2$ takes into account identity of two protons. Kinematic variables in Eqs. (2) - (4) are defined as

$$\gamma^2 = \frac{T_1^2}{(E_1/m_p)^2} + \frac{m_\pi^2}{E_1/m_p}, \quad \mathbf{R} = -\mathbf{p}_1 \frac{m_p T_1}{(E_1 + m_p)E_1}, \quad \vec{\mathbf{p}} = \frac{\mathbf{p}_1}{E_1/m_p}, \quad (6)$$

where E_1 , \mathbf{p}_1 and $T_1 = E_1 - m_p$ are the total energy, 3-momentum and kinetic energy of the initial proton p_1 , respectively, in the rest frame of the final diproton. The exchange amplitude A^{exch} can be obtained from Eqs.(1)-(6) by interchanging $1 \leftrightarrow 2$.

The OPE cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ in the cm system is

$$\frac{d\sigma}{d\Omega} = \frac{1}{(4\pi)^5} \frac{p_f}{s_{pp} p_i} \int_0^{k^{max}} dk^2 \frac{k}{\sqrt{m_p^2 + k^2}} \frac{1}{2} \int d\Omega_{\mathbf{k}} |\overline{A_{fi}}|^2, \quad (7)$$

where k^{max} is the maximal relative momentum in the final pp-system, related to the maximal relative energy E^{max} as $k^{max} = \sqrt{E^{max} m_p}$, p_i (p_f) is the cms momentum in the initial (final) state of the $pp \rightarrow \{pp\}_s \pi^0$ reaction, s_{pp} is the squared invariant mass of the initial pp-system. The factor $\frac{1}{2}$ in front of the integral over directions of \mathbf{k} takes into account identity of two

final protons. Keeping only the direct term of Eq. (1), one can finally find from Eq. (7)

$$\frac{d\sigma}{d\Omega_\theta} (pp \rightarrow \{pp\}_s \pi^0) = \frac{1}{24\pi^2} \frac{p_f}{p_i} \frac{s_{\pi p}}{s_{pp}} \left[\frac{f_{\pi NN}}{m_\pi} N_{pp} m_p F_{\pi NN}(k_\pi^2) \right]^2 \times \int_0^{k^{\max}} dk \frac{2k^2}{\sqrt{m_p^2 + k^2}} \left\{ 2|J^{\mu=0}(\vec{p}, \delta)|^2 + |J^{\mu=1}(\vec{p}, \delta)|^2 \right\} \frac{d\sigma}{d\Omega_\phi} (\pi^0 p \rightarrow \pi^0 p). \quad (8)$$

The differential cross section of the reaction $\pi^0 p \rightarrow \pi^0 p$ is taken in Eq. (8) at the squared invariant mass of the πp system, $s_{\pi p}$, defined as

$$s_{\pi p} = (m_\pi + m_p)^2 + 2T_\pi m_p. \quad (9)$$

Here T_π is the kinetic energy of the final meson π^0 in the rest frame of the final diproton. If θ is the angle between the cms momenta of the diproton and the proton p_1 , which emits the virtual pion in the direct OPE diagram in Fig. 1, and ϕ is the cms scattering angle of the π^0 -meson in the process $\pi^0(k_\pi) + p_2 \rightarrow p_4 + \pi^0(q_\pi)$, then one can find the following relation:

$$p_{20}q_0 + |\mathbf{p}_2||\mathbf{q}_\pi| \cos \phi = \sqrt{m_p^2 + p_i^2} \sqrt{m_\pi^2 + p_f^2} - p_i p_f \cos \theta, \quad (10)$$

where the four-momenta of the initial proton $p_2 = (p_{20}, \mathbf{p}_2)$ and the final π^0 -meson $q_\pi = (q_0, \mathbf{q}_\pi)$ in the cms of the πp system can be written as

$$p_{20} = \frac{1}{2\sqrt{s_{\pi p}}} (s_{\pi p} + m_p^2 - k_\pi^2), \quad q_0 = \frac{1}{2\sqrt{s_{\pi p}}} (s_{\pi p} + m_\pi^2 - m_p^2), \\ |\mathbf{q}_\pi| = \sqrt{q_0^2 - m_\pi^2}, \quad |\mathbf{p}_2| = \sqrt{p_{20}^2 - m_p^2}. \quad (11)$$

The squared four-momentum of the intermediate π -meson is

$$k_\pi^2 = 2m_p^2 + p_i p_f \cos \theta - \sqrt{m_p^2 + p_i^2} \sqrt{M_{pp}^2 + p_f^2}, \quad (12)$$

where M_{pp} is the mass of the final diproton. One can find from Eqs. (10), (11) and (12) that backward $\pi^0 p$ scattering ($\phi = 180^\circ$) dominates diproton formation in the forward direction ($\theta = 0^\circ$).

Analysis of the reaction $pp \rightarrow d\pi^+$ in the Δ region, performed in [17] shows that the contribution of the pole diagram with the neutron exchange is small but non-negligible and being added to the OPE diagram with πN rescattering improves the agreement with the data. For the reaction $pp \rightarrow \{pp\}_s \pi^0$ a similar pole diagram seems to be less important and is not taken into account here. The point is that at $T_p = 0.5 - 2.0$ GeV and $\theta = 0^\circ$ the $pp \rightarrow \{pp\}_s$ vertex in the pole diagram of the reaction $pp \rightarrow \{pp\}_s \pi^0$ involves the high momentum component of the wave function $\psi_{\mathbf{k}}^{(-)}(\mathbf{q})$ at the relative momentum between protons $q = 0.4 - 0.6$ GeV/c, but in contrast to the $pn \rightarrow d$ vertex, does not contain the D-wave which is important for the pole diagram at large q . Furthermore, the S-wave component of the wave function $\psi_{\mathbf{k}}^{(-)}(\mathbf{q})$ has a node at $q \approx 0.4$ GeV/c (see, for example, [18]).

2.1 Numerical results and discussion

In numerical calculation we used the data on the elementary πN reactions from SAID [1]. The scattering wave function $\psi_{\mathbf{k}}^{(-)}(\mathbf{r})$ of the pp system at low energy < 3 MeV is largely independent of the NN model and is calculated here using the Reid soft core potential plus Coulomb interaction [19]. The calculated forward cross section multiplied by the factor 0.45

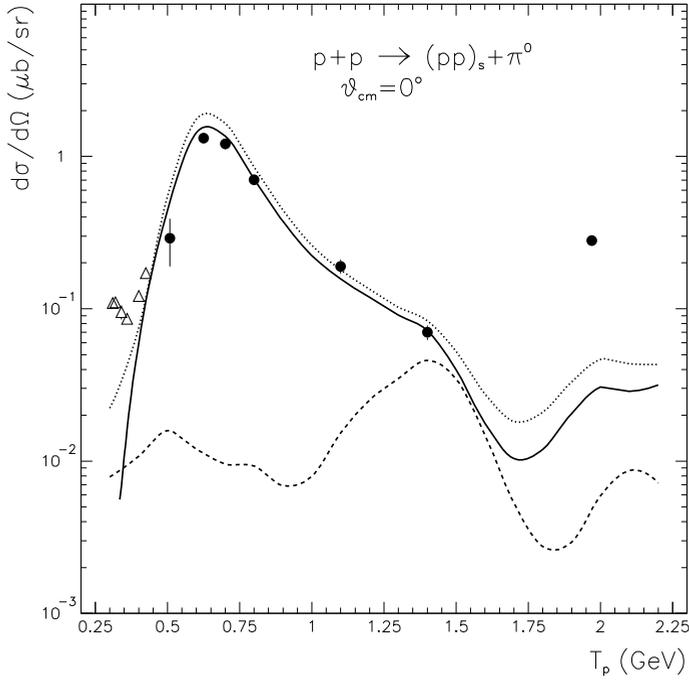


Figure 2. The cms cross sections of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at $\theta = 0^\circ$ versus beam energy. Data are taken from [13] (Δ) and [5] (\bullet). The dotted curve presents the calculated cross section for the incoherent sum of the direct and exchange terms of the OPE model amplitude. Other curves are obtained with the direct term A^{dir} only for the isospin term a_3 excluded from (dashed line) and included (full line) in the $\pi^0 p \rightarrow \pi^0 p$ amplitude, as explained in the text. All curves are scaled by the factor 0.45

is shown in Fig. 2. When comparing the dotted and full lines in Fig. 2, one can see that the contribution of the exchange term $|A^{exch}|^2$ is much less important than the direct term $|A^{dir}|^2$ at $\theta = 0^\circ$. Thus, we neglect below the term A^{exch} . As seen from Fig. 1, the OPE model is in good agreement with the observed shape of the cross section at 0.5 - 1.4 GeV. Note that the form factors $F_0(\vec{p}, \gamma)$ and $\Phi_{10}(\vec{p}, \gamma)$ in Eq. (2) are smooth functions of the beam energy T_p . Therefore, the calculated shape of the $pp \rightarrow \{pp\}_s \pi^0$ cross section follows mainly the T_p -dependence of the $\pi^0 p \rightarrow \pi^0 p$ cross section at the cms angle $\phi = 180^\circ$. The disagreement in absolute value by factor 0.45 corresponds to a typical factor of absorptive distortions in the initial pp state [20]. The distortions are not taken into account in the present work in view of their dependence on unknown details of the production mechanism, in particular, on off-shell behaviour of the $\pi^0 p$ -scattering amplitude. Furthermore, one should note that when calculating the diagram in Fig. 1, we factor the amplitude of the elastic $\pi^0 p$ scattering outside the integral sign. Within this approximation, the contribution of intermediate $\Delta - N$ states of positive parity is not excluded from this reaction as it should be according to the discussion in the Introduction. Therefore, one should not expect that this simple model provide a precise description of the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$. For this reason, in the next section we consider another mechanism with explicit inclusion of the Δ -isobar that allows

one to take into account the Pauli principle correctly providing exclusion of the intermediate states with the positive parity.

Another reason for disagreement in the absolute value of the cross section can be caused in part to the neglected off-shell effects in the $\pi^0 p \rightarrow \pi^0 p$ amplitude and contribution of the mesons η , η' and ω in the intermediate state.

In order to exhibit sensitivity of the calculated cross section to the Δ -isobar contribution, one can completely exclude the contribution of the isospin $\frac{3}{2}$ from the $\pi^0 p$ scattering. The isospin decomposition of the $A(\pi^0 p \rightarrow \pi^0 p)$ amplitude is the following:

$$A(\pi^0 p \rightarrow \pi^0 p) = \frac{1}{3}(a_{\frac{1}{2}} + 2a_{\frac{3}{2}}), \quad (13)$$

here $a_{\frac{1}{2}}$ ($a_{\frac{3}{2}}$) is the amplitude with the total isospin $\frac{1}{2}$ ($\frac{3}{2}$). The cross section of the $\pi^0 p$ elastic scattering can be written as

$$d\sigma(\pi^0 p \rightarrow \pi^0 p) = \frac{1}{2}\{d\sigma(\pi^+ p) + d\sigma(\pi^- p) - d\sigma(\pi^0 n \rightarrow \pi^- p)\}, \quad (14)$$

where $d\sigma(\pi^+ p)$, $d\sigma(\pi^- p)$ and $d\sigma(\pi^0 n \rightarrow \pi^- p)$ are the differential cross section of the $\pi^+ p$ and $\pi^- p$ elastic scattering and charge exchange reaction $\pi^0 n \rightarrow \pi^- p$, respectively. After the amplitude $a_{\frac{3}{2}}$ is excluded from Eq. (13), the cross section of the $\pi^0 p$ scattering takes the form

$$d\bar{\sigma}(\pi^0 p \rightarrow \pi^0 p) = \frac{1}{18}\{3d\sigma(\pi^- p) - d\sigma(\pi^+ p) + 3d\sigma(\pi^0 n \rightarrow \pi^- p)\}. \quad (15)$$

In order to exclude the term $a_{\frac{3}{2}}$ from the $\pi^0 p$ elastic scattering in calculation of the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ one should substitute Eq. (15) instead of Eq. (14) into Eq. (8). When we do so, the absolute value of the calculated cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.4 - 1.1 GeV diminishes by two orders of magnitude and comes in strong contradiction with the data (see dashed line in Fig. 2). Since the amplitude $a_{\frac{3}{2}}$ of the πN elastic scattering is dominated by the $\Delta(1232)$ -isobar at $\sqrt{s_{\pi N}} \sim 1.15 - 1.35$ GeV, this analysis shows that the excitation of the $\Delta(1232)$ -isobar dominates in the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1.0 GeV too. On the other hand, since the s -wave intermediate $\Delta - N$ state is forbidden, but was not excluded from the reaction amplitude within this model, the agreement obtained between the calculated and measured shape of the cross section suggests that the absence of this s -state in an exact OPE amplitude would be not so crucial for the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.4-1.1 GeV, as might follow from the qualitative arguments given in the Introduction. In other words, it would mean that the p -wave and higher odd waves in the intermediate $\Delta - N$ system are not suppressed drastically and make a valuable contribution to this reaction. To some extent this assumption is confirmed within the box-diagram mechanism with explicit Δ -isobar contribution discussed in the next section.

Let us make some further comments. Firstly, the second maximum of the forward $pp \rightarrow \{pp\}_s \pi^0$ cross section is, most likely, observed at 1.97 GeV in ANKE data [5]. New data were obtained recently by ANKE@COSY [21] in this region. The forward $pp \rightarrow d\pi^+$ cross section also exhibits a maximum at ≈ 3 GeV. [1]. This peculiarity of the $pp \rightarrow d\pi^+$ cross section was interpreted in [16] within the OPE model as a manifestation of heavy nucleon resonances in the elastic πN scattering. One can see from Fig. 2 that the OPE model considerably underestimates the magnitude of the observed second maximum in the $pp \rightarrow \{pp\}_s \pi^0$ cross section. One may suppose that excitation of heavy Δ 's or N^* is not sufficient to explain the data on the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 2 GeV. Therefore, other mechanisms of this reaction like N^* exchange or Reggeon exchange recently discussed in [18] or

more exotic ones, like dibaryons excitation make a contribution in this region. To choose between the heavy Δ -isobars excitation and the N^* (or Reggeon) exchange mechanism one should measure the ratio of the cross sections $pp \rightarrow \{pp\}_s \pi^0$ and $pn \rightarrow \{pp\}_s \pi^-$ [18].

Secondly, concerning the angular dependence of the differential cross section, we can show, that the present model predicts a smooth increase (5-15%) of the differential cross section with increasing scattering angle θ in forward direction at $\theta = 0^\circ - 15^\circ$, that is in qualitative agreement with the data [5] at 2 GeV, but is in disagreement at lower energies. A more detailed model, with distortions and explicit Δ -isobars included, has to be developed to understand the angular dependence of the cross section.

3 The box-diagram with the Δ excitation

Differential cross section and vector analyzing power A_y of the one-pion production reaction $pp \rightarrow \{pp\}_s \pi^0$ in forwards hemisphere were measured by ANKE@COSY [6] at proton beam energies 0.3-0.8 GeV. A resonance behavior of the differential cross section was observed at 0.6-0.8 GeV. This data on the differential cross section and A_y were described using fit by two isovector Breit-Wigner resonances in the 3P_0 and 3P_2 states. Contribution of the Δ -isobar mechanism to this reaction depicted in Fig. 3 was studied in [15]. The coupling constants and

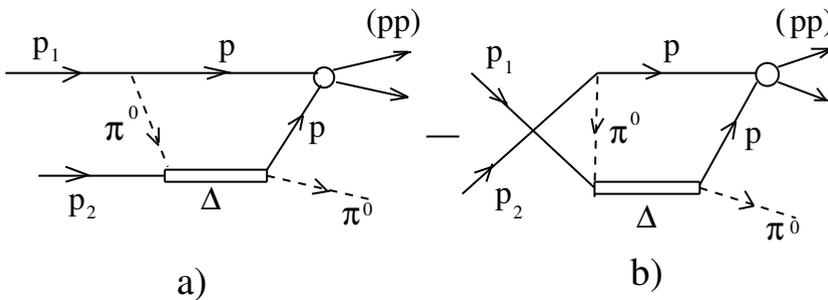


Figure 3. The Δ -isobar mechanism of the reaction $pp \rightarrow \{pp\}_s \pi^0$ with the direct (a) and exchange (b) terms

parameters of the vertex form factors which were used previously to explain the COSY data on the reaction $dp \rightarrow \{pp\}_s \pi N$ [22, 24], are applied in [15] to the reaction $pp \rightarrow \{pp\}_s \pi^0$. The form factors in vertices πNN and $\pi N\Delta$ $F_{\pi NN}(t) = F_{\pi N\Delta}(t) \equiv F_\pi(t)$ are chosen in monopole form, $F_\pi(t) = (\Lambda^2 - m_\pi^2)/(\Lambda^2 - t)$. The energy-dependent Δ -isobar width is

$$\Gamma = \Gamma_0 \left(\frac{q_R}{q_{on}} \right)^3 Z(s_\Delta, m_p^2, m_\pi^2), \quad (16)$$

where $Z(s_\Delta, p_p^2, t) = (q_R^2 + \kappa^2)/(q^2(s_\Delta, p_p^2, t) + \kappa^2)$; here q is the off-mass-shell relative momentum between the proton and the pion at the vertex $\pi N\Delta$, determined as $q^2(s_\Delta, p^2, t) = \lambda(s_\Delta, p^2, t)/4s_\Delta$, and $\lambda(a, b, c)$ is the function of triangle; s_Δ , p^2 and t are the 4-momenta squared for the Δ -isobar, proton and pion, respectively. For the proton, pion and Δ -isobar being on mass-shell the momentum q is $q_R = q(m_\Delta^2, m_p^2, m_\pi^2)$, where m_i is the mass of the i th particle ($i = \Delta, p, \pi$). For the mass-shell proton and pion and off-mass-shell Δ -isobar we have $q_{on} = p(s_\Delta^2, m^2, m_\pi^2)$. Factor $\sqrt{Z(s_\Delta, p^2, t)}$ enters the $\pi N\Delta$ vertex. We use $\Gamma_0 = 0.115 \text{ GeV}/c^2$, $\kappa = 0.180 \text{ GeV}/c$. Cutoff parameter $\Lambda = 0.55 \text{ GeV}/c$ was taken from [22]. The differential

cross section of the reaction $dp \rightarrow \{pp\}_s \pi N$ for the deuteron beam energy 1.6 - 2.27 GeV measured in [24] are well described using the Δ -isobar mechanism with these parameters.

The calculated energy dependence of the differential cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at zero angle of the pion is dominated by three partial waves of the pp -channel ${}^3P_0, {}^3P_2$ and 3F_2 being in qualitative agreement in a shape with the data at energy 350-800 MeV (Fig. 4). One should note that the fit made in [6] uses only two partial waves, 3P_0 and 3P_2 . The model explains the position of the peak observed at ≈ 0.7 GeV and zero diproton scattering angle, but underestimates its absolute value if the off-shell 4-momenta of the pion and proton are taken into account in the $\pi N \Delta$ -vertices, i.e. the momentum $q(s_\Delta, p^2, t)$ is taken instead of the momentum $q_{on} = p(s_\Delta^2, m^2, m_\pi^2)$ in the Z -factor [15]. Furthermore, the Δ -mechanism, as the OPE mechanism, discussed in the previous section, is in contradiction with the sign of the slope of the angular dependence of $d\sigma/d\Omega$ and does not explain the large analyzing power A_y observed in [6]. Therefore, other mechanisms and first of all more complicated diagrams with the Δ -isobar accounting for $\Delta - N$ interaction in intermediate state should be considered in the region of the observed peak.

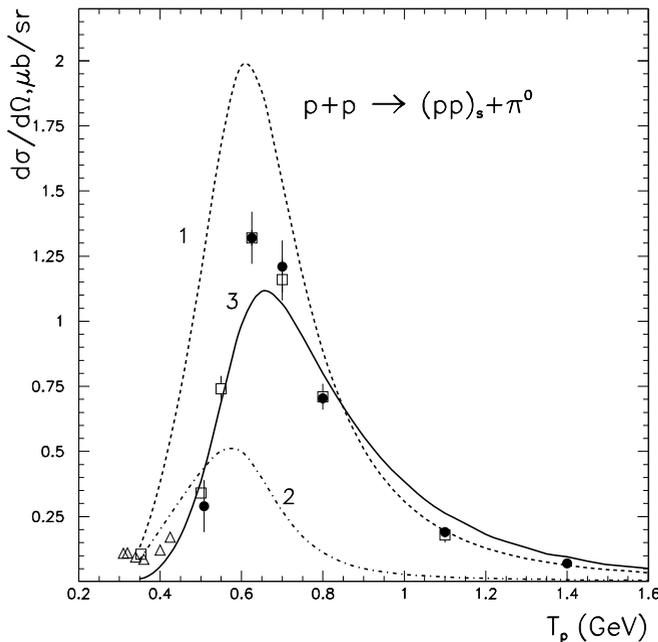


Figure 4. The differential cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at zero angle of the diproton. The lines show results of calculations [15] based on the Δ -mechanism (Fig. 3) for the direct (1), exchange (2) term and their coherent sum(3); experimental data are taken from [5] (●), [6] (□) and [13] (Δ)

4 Conclusion

Suggestion to change the deuteron in the final state by the 1S_0 diproton for the first time was done in [25] concerning the study of the proton-deuteron backward elastic scattering, $pd \rightarrow dp$, in the GeV region. This was a rather constructive idea. Subsequent experimental study of the suggested reaction $pd \rightarrow \{pp\}_s n$ [26] and its theoretical interpretation [27] showed that the process with the diproton is very sensitive to behaviour of the NN-interaction potential at short distances and more clean from theoretical point of view as compared to the process $pd \rightarrow dp$. This is caused by absence of the D-wave in the diproton state and suppression of the Δ -isobar contribution in the reaction $pd \rightarrow \{pp\}_s n$ by the isospin conservation [25, 28].

One may also expect to get more insight into the NN-dynamics with single pion production when consider the reaction $pp \rightarrow \{pp\}_s \pi^0$ at almost the same kinematics as the reaction $pp \rightarrow d\pi^+$. Indeed, arguments, based on parity and angular momentum conservation, show that the S-wave of the Δ N-intermediate state is forbidden in the reaction $pp \rightarrow \{pp\}_s \pi^0$, when the final pp-pair is produced in the 1S_0 -state. The microscopical model [14], which takes into account this specific feature of the reaction $pp \rightarrow \{pp\}_s \pi^0$ and very reasonably describes the reaction $pp \rightarrow d\pi^+$, is in strong disagreement with the data on the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1 GeV. On the other hand, a rather simple OPE model considered in the present work, which includes the subprocess $\pi^0 p \rightarrow \pi^0 p$ and the final state $pp(^1S_0)$ -interaction, reproduces the observed shape of energy dependence of the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1.4 GeV and to some extent agrees with its absolute value. Thus, the OPE model points out to dominance of the $\Delta(1232)$ -isobar in this region. However, the angular dependence of the $pp \rightarrow \{pp\}_s \pi^0$ cross section is not described within this model. Furthermore, the box diagram with explicit Δ -isobar excitation provides only qualitative agreement with the data on the energy dependence of the cross section at $\theta = 0$ in the “ Δ -isobar region”, 0.5-0.8 GeV, and fails to explain its anomalous angular dependence and large observed A_y . It is worth to note, that the box-diagram with the $\Delta(1232)$ -isobar (together with one-nucleon-exchange) allows to explain qualitatively the corresponding data on the $pp \rightarrow d\pi^+$ reaction [23]¹.

One may assume from this difference between the reactions $pp \rightarrow \{pp\}_s \pi^0$ and $pp \rightarrow d\pi^+$ that the origin of the maximum of the cross section at 0.6-0.7 GeV in these two reactions is different. More insight into the dynamics of the single pion production in pN collision can be gained by further measurement of the reaction $pn \rightarrow \{pp\}_s \pi^-$ at the same kinematic conditions. It would be also interesting to get data on the reaction $pp \rightarrow \{pp\}_s \pi^0$ at higher excitation energy of the final pp-pair, $E_{pp} = 3 - 10$ MeV, where small components of the pp-wave function start to contribute and allow the S-wave intermediate ΔN - state.

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