DYNAMICS OF $^1S_0$ DIPROTON FORMATION IN THE REACTIONS $pp \rightarrow \{pp\}_s\pi^0$ AND $pp \rightarrow \{pp\}_s\gamma$ IN THE GEV REGION

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Abstract

COSY-ANKE data on the cross section of the reactions $pp \rightarrow \{pp\}_s\pi^0$ and $pp \rightarrow \{pp\}_s\gamma$, where $\{pp\}_s$ is the proton pair in the $^1S_0$ state at small excitation energy $E_{pp} < 3$ MeV, are analyzed at beam energies $0.5 - 2.0$ GeV within the one-pion exchange model. The model includes the subprocesses $\pi^0 p \rightarrow \pi^0 p$ and $\pi^0 p \rightarrow \gamma p$ for the pion- and photo-production, respectively, and accounts for the final state pp-interaction. A broad maximum in the energy dependence of the $\pi^0$ production at $\sim 0.5 - 0.6$ GeV and fast increase of the $\gamma$-production cross section at $0.3 - 0.55$ GeV observed in the data are explained by the $\Delta$-isobar contribution. An analogy with the dynamics of the deuteron breakup reaction $pd \rightarrow \{pp\}_s n$ in the $\Delta$-region is outlined.

1 Introduction

Quasi-binary reactions $AB \rightarrow \{pp\}_sC$ with formation of a proton pair at small excitation energy $E_{pp} = 0 - 3$ MeV, i.e. the $^1S_0$ diproton $\{pp\}_s$, are of great interest at high transferred momenta since transition amplitudes of these reactions require high momentum components of the pp-wave function. In comparison to very similar (in kinematics) reactions $AB \rightarrow dC$ with the final deuteron $d$, the reactions with the diproton are expected to give more definite information on short-range NN-dynamics. The reason is that the contribution of non-short range mechanisms related to excitation of the $\Delta$-isobars in intermediate states is expected to be strongly suppressed for the $AB \rightarrow \{pp\}_sC$ reactions as compared to the $AB \rightarrow dC$ due to isospin symmetry and conservation of angular momentum and parity. So, in the reaction $pd \rightarrow \{pp\}_s n$ this suppression is given by the factor $\frac{1}{5}$ [1]. Furthermore, in the reaction $pp \rightarrow \{pp\}_s\pi^0$ the intermediate S-wave $\Delta N$ state is completely forbidden [2]. Similarly, in the $pp \rightarrow \{pp\}_s\gamma$ reaction direct excitation of the $\Delta$-isobar, dominating the $\gamma d \rightarrow pn$ reaction via $M1$ transition is also forbidden.

Contrary to those expectations, the cross section of the reactions $pp \rightarrow \{pp\}_s\pi^0$ [3] and $pp \rightarrow \{pp\}_s\gamma$ [4] recently measured in forward direction for beam energies $0.5 - 2.0$ GeV and $0.35 - 0.55$ GeV, respectively, demonstrate prominent peaks in the $\Delta(1232)$-isobar region. In the deuteron breakup reaction $pd \rightarrow \{pp\}_s n$ measured in Ref.[5] the $\Delta(1232)$ peak is non-visible in the energy dependence of the cross section for the backward scattered neutron, however, theoretical analyses [6, 7] suggest, that the $\Delta$ contribution dominates in this reaction at $0.5 - 1.3$ GeV.

Observation of the $\Delta$ peaks in the data on the reactions $pp \rightarrow \{pp\}_s\pi^0$ [3] and $pp \rightarrow \{pp\}_s\gamma$ [4] would mean that the high momentum component of the NN-wave function, which might be hidden by the $\Delta$-contribution in the corresponding reactions with the deuteron, is actually rather week. In other words, new data [3, 4], most likely, confirm the result of the previous analysis of the reaction $pd \rightarrow \{pp\}_s n$ [6], which suggests softness of the
NN-interaction potential at short distances. To study this conjecture theoretical analysis is required.

Here we present the results of calculations of the differential cross sections of the reactions $pp \to \{pp\}_s\pi^0$ and $pp \to \{pp\}_s\gamma$ at $\theta_{cm} = 0^\circ$ within the one-pion exchange model, which includes the subprocesses $\pi^0p \to \pi^0p$ and $\pi^0p \to \gamma p$, respectively. A similar model with the subprocess $\pi^0d \to np$ was applied earlier to the reaction $pd \to \{pp\}_s n$ \[7\].

2 The deuteron breakup reaction $pd \to \{pp\}_s n$

The deuteron breakup reaction $pd \to \{pp\}_s n$ was studied at COSY \[5\]. A theoretical analysis \[6\] was performed within the sum of the following mechanisms: one-nucleon-exchange (ONE) with initial and final state interaction included, $\Delta$-isobar excitation ($\Delta$) and single-scattering (SS). The analysis shows (see Fig. 1) that at 0.8 GeV the ONE mechanism has a minimum due to repulsive core in the NN-interaction at $r_{NN} \sim 0.5\text{fm}$, but the $\Delta$ contribution has a maximum at 0.6 GeV and completely dominates this reaction. This $\Delta$-maximum is not visible as a bump in the cross section due to a large ONE contribution below the ONE-node. However, only rather soft NN-interaction potential like the CD Bonn one \[8\] provides agreement with the data. When replacing a hard NN-interaction potential (RSC \[9\], Paris \[10\]) by the soft one (CD Bonn) the ONE contribution decreases, whereas the $\Delta$ contribution increases providing agreement with the COSY data. On the other hand, more

![Figure 1: The pd → {pp}_s n data \[5\] (●) at θ^cm = 180° versus the beam energy in comparison with the ONE (1, 2) and Δ mechanisms (3,4) calculations from Ref. \[6\]. Replacement of the Paris NN potential (1,3) by the CD Bonn one (2,4), decreases the ONE contribution, but increases the Δ-contribution.](image)
hard NN-models like Paris and especially RSC provide too large magnitude of the high momentum components of the NN-wave function and, therefore, lead to strong contradiction with the data especially above 1 GeV (see Ref. [6]). Further analysis [7] within the OPE model with the subprocess $\pi^0d \rightarrow pn$ provided an independent confirmation of the dominant contribution of the $\Delta(1232)$-isobar in this reaction at $0.5 - 1$ GeV and suggested sizable admixture of the ONE mechanism compatible with the CD Bonn model.

3 The reaction $pp \rightarrow \{pp\}_s\pi^0$

The reaction $pp \rightarrow \{pp\}_s\pi^0$ is the simplest inelastic process in the pp-collision, which can reveal underlying dynamics of NN interaction. Restriction to only one pp-partial wave (s-wave) in the final state considerably simplifies a comparison with theory. The reaction $pp \rightarrow \{pp\}_s\pi^0$ is very similar kinematically to the reaction $pp \rightarrow d\pi^+$, but its dynamics can be essentially different. In fact, quantum numbers of the diproton state ($J^P = 0^+, I = 1, S = 0, L = 0$) differ from these for the deuteron ($J^P = 0^+, I = 0, S = 1, L = 0, 2$). Therefore, transition matrix elements for these two reactions are also different. Due to the generalized Pauli principle and angular momentum and P-parity conservation only negative parity states are allowed in the reaction $pp \rightarrow \{pp\}_s\pi^0$. Thus, for the intermediate $\Delta N$ state only odd partial waves are allowed. In contrast, in the $pp \rightarrow d\pi^+$ reaction both negative and positive parity states are allowed and formation of the intermediate S-wave $\Delta N$ state with $J^P = 2^+$ leads to a perfect resonance looping in the $^1D_2$ pp-partial wave in the respective Argand diagram [11]. Therefore, the relative contribution of the $\Delta$-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 Ref. [12] to explain a very small ratio (less of few percents) of the spin-singlet to spin-triplet $pn$-pairs observed in the LAMPF data [13] in the final state interaction region of the reaction $pp \rightarrow pn\pi^+$ at proton beam energy 0.8 GeV. Furthermore, since $\Delta-$type mechanisms are of long-range type, reduction of their contribution would mean that other mechanisms, like $N^*$-exchanges [14] which are more sensitive to short-range NN-dynamics, could be more pronounced in the reaction $pp \rightarrow \{pp\}_s\pi^0$ as compared to the $pp \rightarrow d\pi^+$ reaction [15].

![Diagram](image)

Figure 2: The OPE mechanism of the reaction $pp \rightarrow \{pp\}_s\pi^0$.

The cross section of the reaction $pp \rightarrow \{pp\}_s\pi^0$ was measured recently at energy 0.8 GeV in Ref. [16] and at beam energies 0.5 – 2.0 GeV in Ref. [3]. At zero angle, the data [3] 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 $\Delta-$ maximum in the
reaction \( pp \rightarrow d\pi^+ \). However, a comparison with the microscopical model calculation [2], which includes \( \Delta(1232) \)-isobar excitation and s-wave \( \pi N \)-rescattering, reveals very strong disagreement between the model and the data [3] at energies 0.5 – 0.9 GeV both in the absolute value and shape of energy dependence of the cross section.

![Figure 3: The differential cross section of the reaction \( pp \rightarrow \{pp\}_s\pi^0 \) versus the beam energy at \( \theta_{cm} = 0^\circ \). The OPE model (full line) is compared with the data: • – [3], triangles – [18]. The dashed curve shows the OPE result obtained without the isospin 3/2 contribution to the amplitude \( \pi^0p \rightarrow \pi^0p \). The calculated cross sections are scaled by the factor 1/6 (see text).](image)

Here [17] we analyse these data employing a simpler model, which includes the subprocess \( \pi^0p \rightarrow \pi^0p \) and the final state \( pp(1S_0) \)-interaction (Fig.2). The formalism is very similar to that developed for the \( pd \rightarrow \{pp\}_s n \) reaction [7]. We use the impulse approximation, i.e. the amplitude of the reaction \( \pi^0p \rightarrow \pi^0p \) is taken off the loop integral sing. Therefore, the cross section of the reaction \( pp \rightarrow \{pp\}_s\pi^0 \) in forward direction is proportional to the forward cross section of the reaction \( \pi^0p \rightarrow \pi^0p \) taken from the data [11]. The structure formfactor is calculated using the CD Bonn model for pp-interaction [8]. The cutoff parameter for the monopole formfactor in the \( \pi NN \) vertex is taken as \( \Lambda = 0.65 \) GeV/c. The results presented in Fig.3 by full line show that the observed shape of the peak is in agreement with the dominance of the \( \Delta(1232) \)-isobar contribution. Indeed, exclusion of the the isospin 3/2 contribution from the amplitude of reaction \( \pi^0p \rightarrow \pi^0p \) (dashed curve) leads to strong disagreement with the data. In absolute value the OPE cross section overestimates the data by factor of 6. The main part of this factor can be explained by the employed impulse approximation. Indeed, within the impulse approximation one cannot exclude intermediate \( \Delta N \)-states of positive parity, which are forbidden in this reaction. In order to exclude these states one needs to consider the \( \Delta \)-isobar excitation explicitly.
4 The reaction \( pp \rightarrow \{pp\}_s\gamma \)

Another simplest process which allows to probe fundamental properties of NN system is photoabsorption on two nucleon systems. The deuteron photodisintegration reaction \( \gamma d \rightarrow pn \) is widely used as a testing ground for different theoretical models of the NN-interaction, however, much less is known on the photodisintegration of the diproton, \( \gamma\{pp\}_s \rightarrow pp \), or the inverse process of the photoproduction \( pp \rightarrow \{pp\}_s\gamma \). Whereas in the photodisintegration of the deuteron the M1 magnetic dipole transition dominates at several hundred MeV through the excitation of the \( \Delta(1232) \) isobar, in the reaction with the \( ^1S_0 \) diproton M-odd multipoles are forbidden due to angular momentum and parity conservation. Therefore, there is no direct contribution of the intermediate S-wave \( \Delta N \) states in the reaction \( pp \rightarrow \gamma\{pp\}_s \).

Non-direct excitation of the \( ^5S_2 \) \( \Delta N \) state is possible via the E2 transition \[^9\]
[19], but this contribution is expected to be less important than the M1-transition. The OPE model of the reaction \( pp \rightarrow \{pp\}_s\gamma \) allows to account for the \( \Delta \) contributions via the subprocess \( \pi^0p \rightarrow p\gamma \). The corresponding OPE diagram is similar to those in Fig. 2 but with the subprocess \( \pi^0p \rightarrow p\gamma \) in the down vertex. The result of the OPE calculations are shown in Fig.4. One can see that this model explains the observed in Ref. [4] rise of the cross section almost quantitatively. The second bump at 1.6 GeV is caused by the energy dependence of the \( \pi^0p \rightarrow p\gamma \) cross section \[^11\] and related to excitation of more heavy nucleon isobars.

![Figure 4: The forward differential cross section \( pp \rightarrow \{pp\}_s\gamma \) in comparison with the OPE model (curve scaled by the factor 0.8). Data (•) are taken from Ref. [4].](image)

5 Conclusion

Parity and angular momentum conservation exclude the S-wave \( \Delta N \)-intermediate state from the reaction \( pp \rightarrow \{pp\}_s\pi^0 \). In similar way, the M1 transition, dominating in the
The $\gamma d \to pn$ reaction at several hundred MeV via excitation of the $\Delta$-isobar, is forbidden in the reaction $pp \to \{pp\}_s\gamma$. This suppression is similar to that in the reaction $pd \to \{pp\}_s\pi^+$ as compared to the $pd \to dp$ process. Therefore, one could expect that some features of the short-range dynamics, which, perhaps, are not visible in the reactions with deuteron, $pp \to d\pi^+$ and $\gamma d \to pn$, may reveal themselves in the corresponding reactions with the diproton. The OPE calculations, in agreement with the data show, however, that the $\Delta$-contribution is still significant in the reactions $pp \to \{pp\}_s\pi^0$ and $pp \to \{pp\}_s\gamma$. It would mean that short-range effect is rather minor itself in these reactions in the considered region.

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