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Observation of resonance-like behavior of the $pp \rightarrow \{pp\}_s\pi^0$ reaction around $\sqrt{s} = 2.65$ GeV

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Abstract. The $pp \rightarrow \{pp\}_s\pi^0$ reaction, where $\{pp\}_s$ denotes a diproton, i.e. an unbound interacting proton pair in the $^1S_0$ state, has been studied in order to obtain the forward differential cross section $d\sigma/d\Omega$ at 11 energy values in the region of 0.8–2.8 GeV. A resonance-like peak with the energy $E_0 = 2.647 \pm 0.005$ GeV and the width $\Gamma = 0.26 \pm 0.03$ GeV has been observed in the energy dependence of the differential cross section $d\sigma/d\Omega$ at zero angle. The slope of the angular dependence for the energies in the peak region is different compared with the energies around it. Possible implications on this phenomenon are discussed.

1 Introduction

Single pion production in nucleon-nucleon collisions, $NN \rightarrow NN\pi$, is one of the basic methods to study strong interactions at intermediate energies. While chiral perturbation theory can be employed to describe these processes near the pion production threshold [1], at the energies of $\Delta(1232)$-isobar excitation and above various phenomenological models are used (see e.g. [2] and refs. therein).

The $pp \rightarrow d\pi^+$ reaction is a classical example of an $NN \rightarrow NN\pi$ channel that has long been the subject of extensive experimental studies. A way to get more information about the $NN \rightarrow NN\pi$ dynamics is to study together channels with the production of a deuteron and its spin-isospin partner, a diproton. A diproton, $\{pp\}_s$, is an unbound interacting proton pair in the $^1S_0$ final state. The quantum numbers of the $\{pp\}_s$ system are $I = 1$, $S = 0$, $L = 0$ instead of $I = 0$, $S = 1$, $L = 0, 2$ for the deuteron. This difference in quantum numbers of the deuteron and diproton was the main point why the paper [3] suggested to change the deuteron by the $\{pp\}_s$ in the backward elastic scattering $pd \rightarrow dp$ in the GeV region. A subsequent experimental study of the suggested reaction $pd \rightarrow \{pp\}_s n$ [4] and its theoretical interpretation [5] allowed one to get more insight into short-range behavior of the NN-interaction potential. After that a set of measurements of the $pp \rightarrow \{pp\}_s\pi^0$ reaction has been carried out at ANKE [6–9], mostly for the energies in the region of $\Delta(1232)$-isobar excitation.

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It has long been known that the energy dependence of the forward differential cross section for the $pp \to d\pi^+$ reaction exhibits two peaks: the first one around the proton beam energy $T_p \approx 0.55$ GeV, and the second one – around $T_p \approx 3$ GeV [10]. The first peak is caused by three dominant transitions exhibiting a resonance behavior in the intermediate two-baryon system: ${}^1D_2p$, ${}^3F_3d$ and ${}^3P_2d$ [11]. Here the standard notation ${}^{2S+1}L_J$ is used for the state of the initial proton pair with the orbital angular momentum L, spin S, and the total angular momentum J, while the small letters denote the angular momentum of the final pion. The $pp \to \{pp\}_s\pi^0$ reaction exhibits a similar peak with the maximum slightly shifted towards higher energies, $T_p \approx 0.65$ GeV. The analysis of this peak indicates that it is caused by two interfering resonance transitions: ${}^3P_2d$ and ${}^3P_0s$ [9]. The transitions responsible for the second peak in the $pp \to d\pi^+$ spectrum remain much less clear. Thus, new data for the spin-isospin partner of this reaction, $pp \to \{pp\}_s\pi^0$, might be useful for its understanding.

An earlier ANKE study [7] has revealed that for the $pp \to \{pp\}_s\pi^0$ reaction the forward differential cross section, after reaching a minimum at $T_p \approx 1.4$ GeV, rises again at $T_p \approx 2.0$ GeV, possibly indicating the presence of the second peak similar to that of $pp \to d\pi^+$. To investigate this phenomenon, measurements of the $pp \to \{pp\}_s\pi^0$ differential cross section have been performed at 11 energies in the energy range $T_p = 0.8$–2.8 GeV.

2 Measurements and results

The measurements were carried out using the ANKE spectrometer [12] at the COSY-Jülich storage ring. The experimental setup is shown in Fig. 1. Charged particles produced in the interaction of the stored proton beam with a hydrogen cluster-jet target [13] pass through the analyzing magnet, 3 blocks of track gas chambers and 2 planes of scintillation hodoscopes. The measurements used for earlier studies [6, 7, 9] have been supplemented with more data at various energies in the energy range 1.0–2.8 GeV. The analysis of the data at 0.8 GeV was repeated because more accurate geometry alignment and kinematic fitting procedures had been developed.

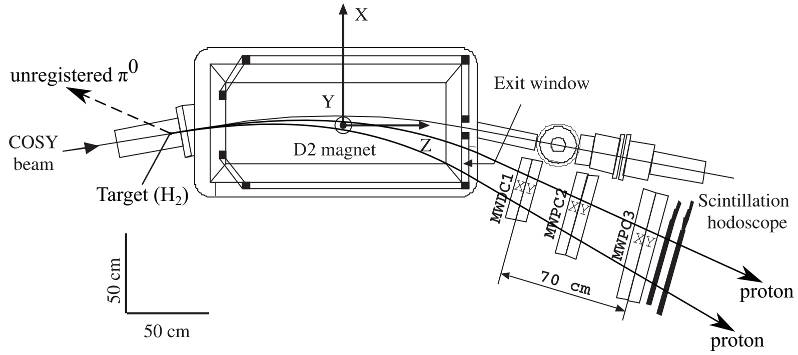

Figure 1. The ANKE spectrometer setup (top view), showing the positions of the hydrogen cluster-jet target and the forward detector (FD)

Reconstruction of the three-momenta and trajectories of the particles, identification of the $pp \to \{pp\}_s\pi^0$ candidates, and their further analysis repeated the procedure described in [6, 7, 9]. The only significant new feature of the analysis was that we used the kinematic fitting technique [14] based on a widely used FUMILI code [15]. If the event satisfied 3% confidence level after kinematic fitting, it was used for further processing.

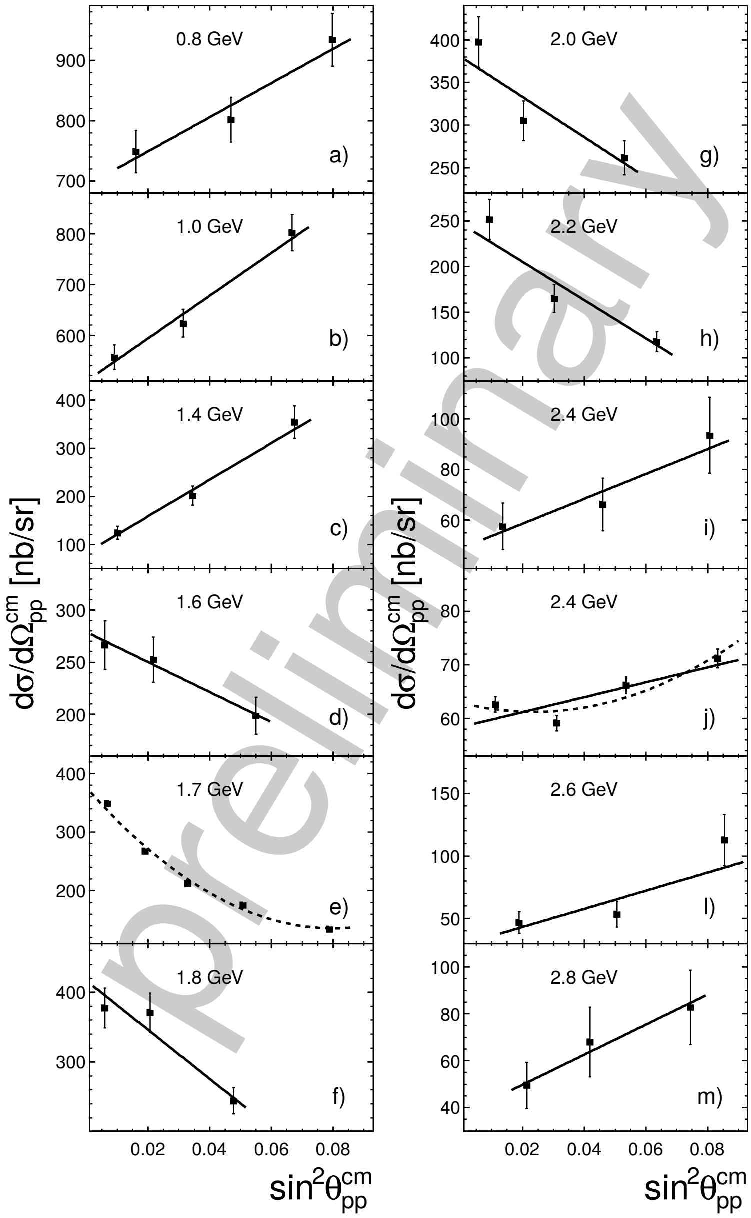

Figure 2. Differential cross sections of the $pp \to \{pp\}_s\pi^0$ reaction at all analyzed energies. The results for 2.4 GeV in the panels i) and j) correspond for the data from two different beam times. The solid lines correspond to the linear fit (1), the dashed ones to the quadratic one (2)

The two-dimensional registration efficiency for the pp pairs depending on their excitation energy E_{pp} and the polar angle of the pair in the reaction center-of-mass system (CMS) $\theta_{pp}^{\rm cm}$ was determined by Monte-Carlo simulations with the uncertainty of about 3%. Systematic errors were estimated to be $\approx$ 8%. In order to get differential cross section of the reaction

$d\sigma/d\Omega$ we used the luminosity estimated using the $pp \to pp$ process which ranged from few tens nb^{-1} to few pb^{-1}.

The angular range was divided into the bins containing approximately the same number of events. After taking into account all the corrections for every exposition, the differential cross sections $d\sigma/d\Omega$ were obtained, which are presented in Fig. 2. For all the energies we restricted ourselves by the range of the CMS polar angle $0^\circ \leq \theta_{pp}^{\rm cm} \lesssim 18^\circ$ in order to obtain the evolution of process over the whole energy range, though at the low energies the apparatus acceptance was larger [9].

The cross sections were fitted by either a linear of a quadratic function over $\sin^2\theta_{pp}^{\rm cm}$:

$$d\sigma/d\Omega = d\sigma/d\Omega(0)\left(1 + k\sin^2\theta_{pp}^{\rm cm}\right), \quad (1)$$

$$d\sigma/d\Omega = d\sigma/d\Omega(0)\left(1 + k\sin^2\theta_{pp}^{\rm cm} + k'\sin^4\theta_{pp}^{\rm cm}\right), \quad (2)$$

depending on the available statistical precision and the resulting $\chi^2/{\rm ndf}$ value.

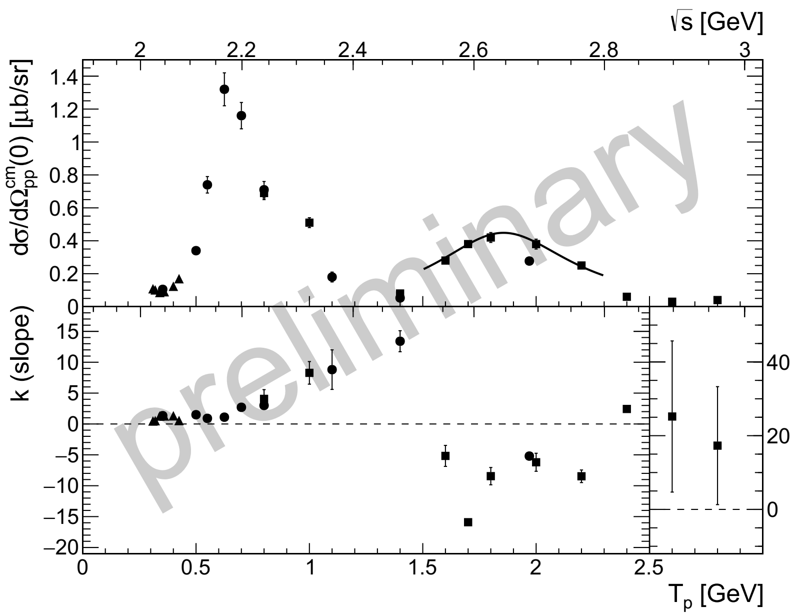

Figure 3. Differential cross sections at zero angle $d\sigma/d\Omega(0)$ for the $pp \to \{pp\}_s\pi^0$ reaction are shown in the upper panel, and values for the slope parameter k in the lower panel. Triangles are WASA experimental values from [16], circles are the previously published ANKE ones from [7, 9], squares stand for current results. The curve is the result of fit of the simple Breit-Wigner distribution (3) to the values from the current measurement. The fit gives the position of the resonance peak $E_0 = 2.647 \pm 0.005$ GeV and the width $\Gamma = 0.26 \pm 0.03$ GeV

It is worth noting that the slope of the angular dependence for the energy range 1.6–2.2 GeV is different compared with all the other energies outside this range measured so far [6, 7, 9, 16] (Figs. 2, 3). The differential cross section at zero angle $d\sigma/d\Omega(0)$ in this 1.6–2.2 GeV range exhibits a pronounced peak surrounded by the minima at ≈ 1.4 GeV and ≈ 2.6 GeV, see Fig. 3.

The differential cross section values allow one to calculate also the integrated cross sections for the analyzed angular range $0^\circ \leq \theta_{pp}^{\rm cm} < 18^\circ$. It has a peak in the region 1.8–2.0 GeV as well.

3 Analysis and discussion

The one-pion-exchange mechanism (Fig. 4a) is one of the basic approaches that was used to describe both the $pp \to d\pi^+$ [17–19] and $pp \to \{pp\}_s\pi^0$ [20] reactions. In the work [20] the cross section of the $\pi^0 p \to \pi^0 p$ scattering, taken from the SAID partial wave analysis program [21], was used for the corresponding vertex of the diagram. This approach qualitatively succeeded to describe the first peak in energy dependence of the differential cross section at zero angle, but failed to reproduce the angular dependence. The triangular diagram in Fig. 4a can be expanded to a box diagram, Fig. 4b, though this approach also did not succeed to describe the experiment well. The reason could be the neglection of interaction between the proton and the excited baryon in the intermediate state. Gal and Garcilazo have shown in series of their works that such an interaction plays an important role in the nucleon-nucleon interactions at intermediate energies (see [22, 23] and refs. therein). The chiral constituent-quark models [24] are also being used to describe two-baryon interactions in the considered energy range. Thus, the one-pion-exchange mechanism could be considered only as an initial approximation for the underlying dynamics of the $pp \to \{pp\}_s\pi^0$ reaction.

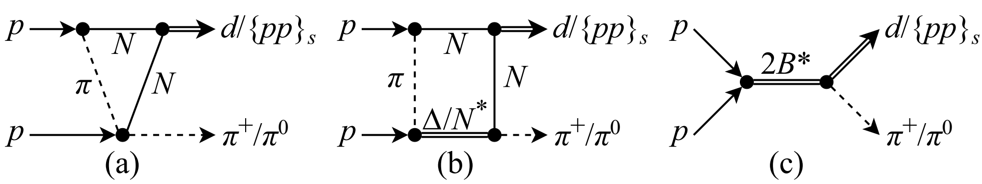

Figure 4. Various approaches to describe the $pp \to d\pi^+$ / $pp \to \{pp\}_s\pi^0$ reactions: (a) a triangular diagram for the one-pion-exchange mechanism; (b) a box diagram with non-interacting nucleon and resonance in the intermediate state; (c) a diagram with a two-baryon resonance state $2B^*$ in the intermediate state, without considering its inner structure

In this work we'd take only first steps towards the analysis of the second $pp \to \{pp\}_s\pi^0$ peak. We would treat the intermediate state as a "black box" without considering its inner structure. Thus, the process is interpreted as an s-channel excitation of a two-baryon resonance state (see Fig. 4). Due to the position of the peak being far from the threshold, the quantum numbers of the intermediate two-baryon system have little impact on the peak shape. Thus, we would describe the data with the simplest Breit-Wigner form with the fixed width:

$$d\sigma/d\Omega(0) = \frac{N}{(\sqrt{s} - E_0)^2 + \Gamma^2/4}, \tag{3}$$

where N is the normalization, E_0 is the position of the resonance peak, and Γ is its width. Since such Breit-Wigner description is only valid in the region of the peak maximum, we limit the fit to five data points comprising the central part of the peak. The fit gives the following parameters: $E_0 = 2.647 \pm 0.005$ GeV and $\Gamma = 0.26 \pm 0.03$ GeV (see Fig. 3). It is worth noting that the position of the second $pp \to d\pi^+$ peak is $E_0 \approx 3.0$ GeV [10], thus, the $pp \to \{pp\}\pi^0$ one is lower by ≈ 350 MeV.

4 Summary

- Differential cross sections have been measured for the $pp \to \{pp\}_s\pi^0$ reaction at forward angles for 11 energies in the region $T_p = 0.8$–2.8 GeV;

- In addition to the peak around $T_p \approx 0.65$ GeV that corresponds to the $\Delta(1232)$ excitation, the energy dependence of the cross section at zero angle exhibits a peak around $T_p \approx 1.85$ GeV, similar to the one known for the $pp \to d\pi^+$ reaction;
- The slope of the angular dependence for the energy range 1.6–2.2 GeV is different compared with the energies around this range;
- The process has been interpreted as s-channel excitation of the two-baryon resonance state, the fit of the simplest Breit-Wigner form to the data provides the following parameters of the peak: the position $E_0 = 2.647 \pm 0.005$ GeV and the width $\Gamma = 0.26 \pm 0.03$ GeV;
- The position of the peak is about 350 MeV lower than that of the $pp \to d\pi^+$ one.

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