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DETERMINATION OF DIFFERENTIAL CROSS SECTION OF THE $pp \to \{pp\}_s\pi^0$ REACTION IN THE ENERGY REGION OF 1.5–2.5 GeV*

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The $pp \to \{pp\}_s\pi^0$, where $\{pp\}_s$ reaction is an unbound interacting proton pair in the $^1S_0$ final state, was investigated at small angles in the beam energy range of $T_{\mathrm{beam}} = 1.5$–2.5 GeV. For the $pp \to \{pp\}_s\pi^0$ reaction, we obtained the angular dependences of the differential cross section $\mathrm{d}\sigma/\mathrm{d}\Omega$ at forward angles for several energies, the energy dependences of the cross section at zero angle $\mathrm{d}\sigma/\mathrm{d}\Omega(0)$ and angular slope k of the forward cross section. The obtained results confirm the existence of a second peak in the $\mathrm{d}\sigma/\mathrm{d}\Omega(0)$ energy dependence for the $pp \to \{pp\}_s\pi^0$ reaction and allow to estimate its maximum, mass, and width. The change in the sign of the slope k in comparison with the region of the first peak indicates a change in the reaction dynamics at the energies of $\sqrt{s} \approx 2.3$–2.6 GeV.

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1. Introduction

The main motivation to study proton scattering on few-body systems with large momentum transfers ($Q = 1$–2 GeV/c) is associated with the importance of obtaining additional information about NN interactions at a very small relative distance ($R_{NN} < 0.5$ fm). This information plays a fundamental role in explaining the nature of nuclear forces. According to modern approaches, the dynamics of NN interactions in this configuration space is determined by the properties of dibaryons [1, 2]. A classic example

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of such interactions is the reaction

$$p + p \to d + \pi^+ \,, \tag{1}$$

which has been widely studied, and for which rich statistics have also been collected [3, 4]. Moreover, in [5], the possibility of obtaining new information using $N + d \to N + \{NN\}_s$ reactions was shown for the first time. Later, this theoretical work served as the basis for a series of experiments at the COSY-Jülich storage ring. The following reactions:

$$p + d \;\to\; \{pp\}_s + n \,, \tag{2}$$
$$p + p \;\to\; \{pp\}_s + \pi^0 \,, \tag{3}$$
$$p + p \;\to\; \{pp\}_s + \gamma \tag{4}$$

were studied in [6–8]. Here, $\{pp\}_s$ denotes a diproton, *i.e.* an unbound interacting proton pair in the $^1S_0$ final state. The relative energy of the movement of the proton pair is $E_{pp} < 3$ MeV. The nucleons of the last pair $\{pp\}_s$ fly in the forward direction and have similar momenta, while the third particle, such as π-meson or photon, flies backwards. The fact that the quantum numbers of the diproton state ($I = 1$, $S = 0$, $L = 0$) differ from the corresponding quantum numbers of the deuteron ($I = 0$, $S = 1$, $L = 0, 2$) leads us to the usefulness of joint studying of reactions (1) and (3).

As a great achievement of such an analysis, the results of [9] can be put forward. It is known that in reaction (1) there is an intense peak in the region of the sum of the $N\Delta(1232)$ masses, $\sqrt{s} \approx 2.15$ GeV [10], which was explained by partial wave analysis by three dominant transitions: $^1D_2$, $^3F_3$, and $^3P_2$ [11]. When analyzing the ANKE-COSY data, a similar peak was detected in reaction (3), approximately in the same energy region. Accordingly, using the results of [10, 11] and partial wave analysis, it was explained by two interfering resonance transitions: $^3P_2$ and $^3P_0$ [9]. Moreover, the second resonance transition $^3P_0$ was observed for the first time in this analysis. For reaction (1), in addition to the first peak, there is a second peak at the energy of $\sqrt{s} \approx 3$ GeV, the nature which remains less clear. The previously published ANKE-COSY data [12] also indicate the possibility of the existence of a similar second peak in reaction (3). The current analysis of the differential cross section (3) performed in the energy range of $T_{\text{beam}} =$ 1.5–2.5 GeV will give new data for further interpretation of the second peak.

2. Experimental setup and measurements

The measurements were carried out using an ANKE spectrometer [13] at the COSY-Jülich synchrotron. The experimental setup is shown in Fig. 1.

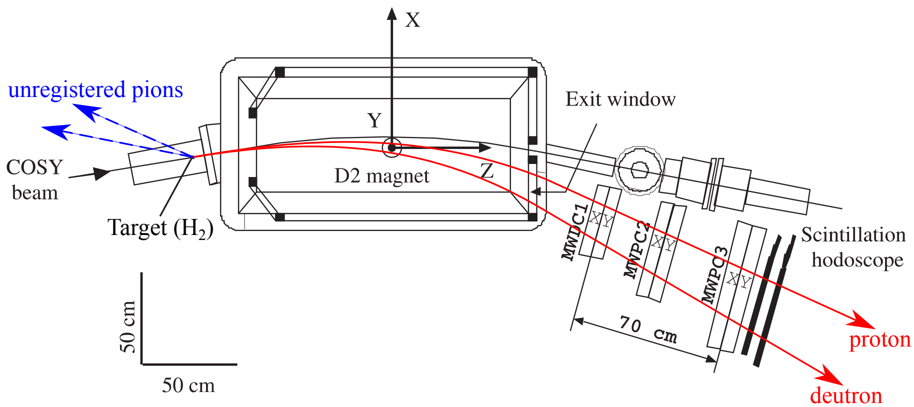

Fig. 1. Forward detector of the ANKE spectrometer.

Charged particles formed by the interaction of a proton beam with a hydrogen cluster–jet target [14] pass through an analyzing magnet, 3 blocks of multi-wire chambers, and 2 planes of scintillation hodoscopes.

The first step in the identification of our reaction was the selection of two coincident protons among all the detected pairs of positively charged particles. The scintillation hodoscope allowed measurement of the difference between the times of flight from the target to the detector for two recorded particles. Assuming the masses of the particles and using the measured momenta and trajectories of the particles, we can also calculate this time difference. If our assumption was correct, then these two values would coincide. With time resolution better than 0.2 ns, the comparison of this value with that calculated from the measured particle momenta and trajectories led to a very good identification of proton pairs (see Fig. 2).

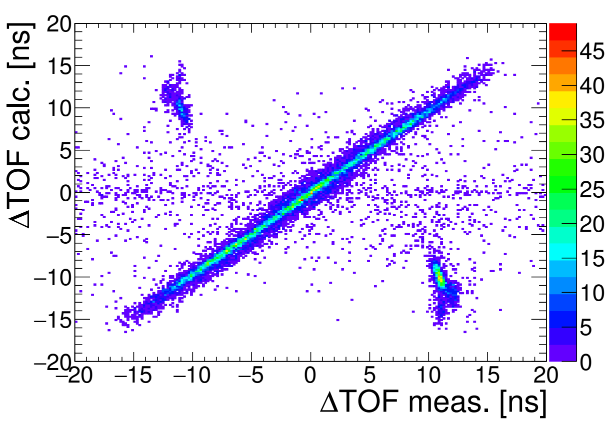

Fig. 2. The calculated time-of-flight difference *vs.* the measured one.

After selecting candidates for the $pp \to ppX$ reaction, information about the momenta of both final protons allows one to reconstruct the complete kinematics of the process based on each event. Only pairs of protons with an excitation energy of $E_{pp} < 3$ MeV were selected. Then candidates were selected for further processing using the missing mass criterion. Events located in the pion peak area were accepted for further processing, adjusted for a small contribution from the background of multi-meson production.

To obtain physical results in terms of $\mathrm{d}\sigma/\mathrm{d}\Omega$, we used the luminosity estimated by the $pp \to pp$ process, for which $\mathrm{d}\sigma/\mathrm{d}\Omega$ are already known.

3. Results

To estimate the angular dependence of the differential cross section, the events were divided into four intervals by θ_{pp}: 0–5°, 5–10°, 10–15°, 15–20°, and fitted by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(0)\left(1 + k\sin^2\theta_{pp}^{\mathrm{cm}}\right) , \tag{5}$$

where the first parameter $\mathrm{d}\sigma/\mathrm{d}\Omega(0)$ is a differential cross section at zero angle, the second one k is a slope parameter (see Fig. 3).

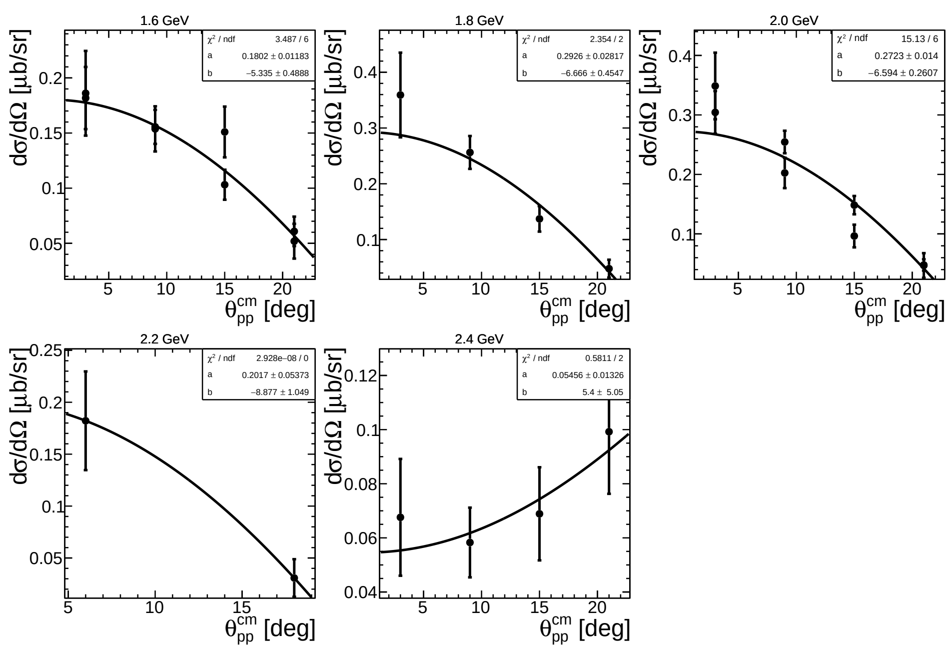

Fig. 3. Angular dependence of differential cross section of the $pp \to \{pp\}_s\pi^0$ reaction.

Figure 4 presents the energy dependence of $\mathrm{d}\sigma/\mathrm{d}\Omega(0)$. It combines data by the WASA Collaboration [15], earlier published ANKE data [9, 12, 16], and the current data.

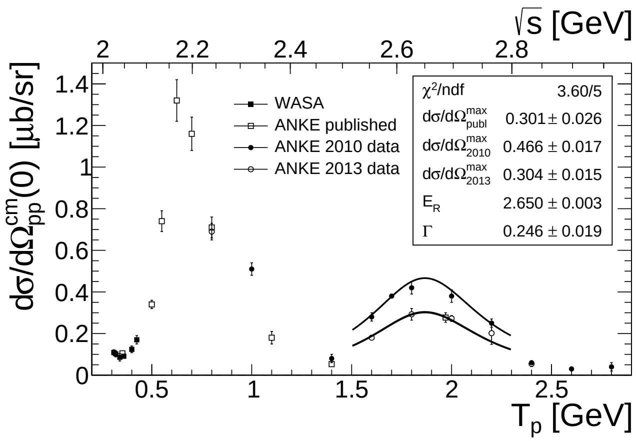

Fig. 4. Differential cross sections at zero angle $\mathrm{d}\sigma/\mathrm{d}\Omega(0)$ for the $pp \to \{pp\}_s\pi^0$ reaction. Full squares are the WASA experimental values from [15], open squares are the previously published ANKE ones from [9, 16], full circles are the ANKE data from [12], and open circles are the current data.

The data of the three runs were approximated by a joint fit, where each set of data was fitted by a Breit–Wigner function

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(0) = \frac{N}{(\sqrt{s} - E_0)^2 + \Gamma^2/4} \,. \tag{6}$$

Here, the average value E_0 and width Γ are common, but the absolute value $\mathrm{d}\sigma/\mathrm{d}\Omega(0)$ for each data set is different. The absolute value of the current data and the early ANKE data [9, 16] are the same, and the data from [12] are quite different. We assume that this is due to a large systematic error of normalization in this run. Nevertheless, it can be seen that with this fit, the average value and width are stable with a good χ^2/n.d.f. These results show that in addition to the peak in reaction (3) around $T_{\mathrm{beam}} \approx 0.65$ GeV that corresponds to the $\Delta(1232)$ resonance, there exists the second peak with a mass of 2.65 ± 0.01 GeV and a width of 0.25 ± 0.02 GeV, similar to the one known for the $pp \to d\pi^+$ reaction.

The slope parameter of the differential cross section (Fig. 5) changes its sign in the area of the second peak, which means that the dynamical mechanism changes in the reaction.

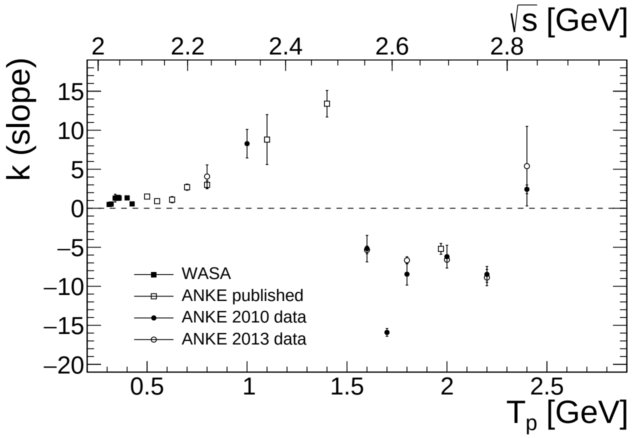

Fig. 5. Slope parameter k of the differential cross section for the $pp \to \{pp\}_s\pi^0$ reaction.

4. Outlook

We plan to conduct a more thorough analysis for some energies in order to reduce the errors of the cross-section value, consider the physical nature of the second peak explaining, which resonant transitions are responsible for the peak, and publish the results.

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