Exclusive measurement of the $pp \rightarrow nn\pi^+\pi^+$ reaction at 1.1 GeV

The CELSIUS/WASA Collaboration

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Abstract. First exclusive data for the $pp \rightarrow nn\pi^+\pi^+$ reaction have been obtained at CELSIUS with the WASA detector setup at a beam energy of $T_p = 1.1$ GeV. Total and differential cross-sections disagree with theoretical calculations, which predict the $\Delta\Delta$ excitation to be the dominant process at this beam energy. Instead, the data require the excitation of one of the nucleons to a higher-lying Δ state, preferably the $\Delta(1600)P_{33}$, to be the leading process.

1 Introduction

Two-pion production in nucleon-nucleon collisions connects $\pi\pi$ dynamics with baryon and baryon-baryon degrees of freedom. Among the various reaction channels, the $pp \rightarrow nn\pi^+\pi^+$ reaction is special, since the direct excitation of N^* resonances and their subsequent decay into the $\pi^+\pi^+$ channel is excluded by isospin. Hence it was expected that in the energy region considered here only the $\Delta\Delta$ process would play the dominant role. Indeed, the detailed calculations from the Valencia group [1] predict the $\Delta\Delta$ excitation to be the leading process at energies $T_p > 1$ GeV. However, in a recent isospin decomposition of the total cross-sections for the various $NN\pi\pi$ exit channels we

have shown [2] that this assumption is inconsistent with the experimental total cross-sections.

Due to the particular selectivity of the $pp \rightarrow nn\pi^+\pi^+$ reaction only $I = 3/2$ single resonance excitations can contribute. Therefore, we proposed [2] that the excitation of a higher-lying Δ state, like, *e.g.*, the $\Delta(1600)P_{33}$, might be the leading process in this channel, since the $\Delta(1232)P_{33}$ state in general does not decay by emission of two pions. Only if the $\Delta(1232)P_{33}$ resonance is excited above its two-pion emission threshold, which is above its nominal pole mass, its decay process $\Delta \rightarrow \Delta\pi \rightarrow N\pi\pi$ is kinematically allowed. This situation is treated in theoretical calculations as a special case of the $\Delta\Delta$ process (see graph (9) in fig. 1 of ref. [1]). According to ref. [1] its contribution of the full $\Delta\Delta$ process is very small.

A more recent theoretical study [3] of two-pion production in NN collisions includes additional processes,

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such as, *e.g.*, nucleon pole terms. That way, good agreement is obtained with the total cross-section data for the $pp \rightarrow nn\pi^+\pi^+$ channel. However, at the same time the $pp \rightarrow pp\pi^0\pi^0$ cross-section is massively overestimated for $T_p > 1\text{GeV}$.

2 Experiment

In order to shed more light onto this conflicting situation and since there exist no differential cross-sections at all for this channel, we have undertaken exclusive measurements of the $pp \rightarrow nn\pi^+\pi^+$ reaction at $T_p = 1.1\text{GeV}$ using the WASA detector [4] with the hydrogen pellet target system at the CELSIUS storage ring of the Theodor Svedberg Laboratory in Uppsala. The detector has nearly full angular coverage for the detection of charged and uncharged particles. A side-view cross-section is shown in fig. 1.

The forward detector part consists of a thin-walled window plastic scintillator hodoscope (FWC) at the exit of the scattering chamber, followed by straw tracker (FPC), plastic scintillator quirl (FTH), forward range hodoscope (FRH) consisting of four layers with 24 trapezoidal segments each and, finally, the forward interleaving (FRI) and veto hodoscopes (FVH).

The central detector comprises in its inner part a thin-walled superconducting solenoid (SCS) containing a mini-drift chamber (MDC) for tracking and in its outer part a plastic scintillator barrel (PSB) surrounded by a scintillator electromagnetic calorimeter (SEC) consisting of 1012 CsI (Na) crystals. The positively charged pions were detected and identified in the central detector.

Neutrons were detected in the forward detector. They were identified by the requirement of having no signal in the thin-walled window hodoscope, straw tracker and quirl, however, a signal due to recoil protons in the range hodoscope. If the forward going recoil protons were produced within the first three layers of the FRH, then these recoil protons could also be detected in the succeeding Forward Range Interleaving (FRI) hodoscope [5], which provides a more detailed angular information for the primary neutrons.

The trigger was set to two charged particles in the central detector and two neutron candidates in the forward detector. A neutron candidate was identified by having an energy deposit (by recoil protons) of more than 40 MeV in a segment of the FRH with simultaneously zero hits in the preceding thin-walled detectors FWC, straw tracker and FTH.

The efficiency of the neutron detection was determined by means of the $pp \rightarrow pn\pi^+$ reaction, which was identified by detecting p and π^+ in the central detector yielding a kinematically complete measurement. From the knowledge of the four-vectors for p and π^+ the four-momentum and with it the direction of the emitted neutron could be reconstructed. Comparison of the expected hits in the forward detector with actually identified neutron events provides the desired information on the efficiency, which in this way was determined to be about 25%. This value agrees well with the value obtained by MC simulations

Fig. 1. Side-view cross-section of the WASA detector: The Superconducting Solenoid (SCS) and the iron yoke for the return path of magnetic flux is shown shaded. Plastic scintillators are situated in the Plastic Scintillator Barrel (PSB), Forward Window Counters (FWC), Forward Trigger Hodoscope (FTH), Forward Range Hodoscope (FRH), Forward Range Intermediate Hodoscope (FRI), Forward Veto Hodoscope (FVH) and Backward Veto Counters (BVC). Cesium iodide scintillators are situated in the Scintillator Electromagnetic Calorimeter (SEC). Proportional wire drift tubes, straws, make up the Mini Drift Chamber (MDC) and the Forward Proportional Chambers (FPC).

of the detector neutron efficiency. Since the efficiency of the WASA detector for the detection of a neutron pair is therefore only about 6%, the accumulated statistics in the $pp \rightarrow nn\pi^+\pi^+$ channel is consequently much smaller than that obtained typically for the other two-pion production channels at comparable luminosity.

In principle, the $nn\pi^+\pi^+$ events can be easily separated from events of other reactions as soon as two π^+ particles in an event have been identified reliably. The most dangerous events to be properly discriminated are $pn\pi^+$ events, where the neutron hits the forward detector, p and π^+ are registered in the central detector with the proton being misidentified in the subsequent data analysis as π^+ . At the same time there must be a fake neutron signal in the forward detector in addition to the real neutron hit in order to simulate the two-neutron trigger condition. It is true that this scenario per se has a very low probability, however, the $pp \rightarrow pn\pi^+$ cross-section of about 20 mb is the largest inelastic cross-section at the energies of interest here, more than two orders of magnitude larger than the $pp \rightarrow nn\pi^+\pi^+$ cross-section. Hence, a reliable π^+ identification is of crucial importance.

The p/π^+ discrimination in the central detector is done three-fold by using information from i) the minidrift chamber in the magnetic field, which measures the particle momentum p , ii) the plastic scintillator barrel PSB, which gives the particle's energy loss information ΔE and iii) the electromagnetic calorimeter, which gives the information of the particle's residual energy E . These informations give rise to three scatterplots of p versus E , p versus ΔE and ΔE versus E , which are shown in fig. 2 for events satisfying the trigger condition of two charged hits in the central

Fig. 2. Separation of positive pions from protons in the central detector. Events satisfying the trigger condition of two charged hits in the central detector are shown. They are plotted in 2D plots of deposited energy in PSB *versus* that in CsI crystals (top), of the deposited energy in PSB *versus* the particle momentum measured by the minidrift chamber (middle) and of the deposited energy in the CsI crystals *versus* the particle momentum measured by the minidrift chamber (bottom). The drawn lines give the cuts used for separating pions from protons. These separation lines are the result from many WASA runs at different incident energies.

detector. In all three plots we can clearly separate between pion and proton bands. A particle is identified as pion, if its position is within the pion band indicated in fig. 2 by the drawn lines in each of these plots. These lines for separating pions from protons are the result from many WASA runs at different incident energies. Figure 3 shows the situation for the trigger condition of two charged hits in the

Fig. 3. The same as fig. 2, but for the trigger condition of two charged hits in the central detector in combination with two neutron candidates in the forward detector.

central detector in combination with two neutron candidates in the forward detector. We see that already, due to this trigger condition, most of the protons are removed. The remaining part is removed by the cuts indicated in the plots.

In a MC simulation injecting two million $pn\pi^+$ events on the detector just 50 events passed the trigger and analysis criteria. However, all of these events were finally rejected by the subsequent kinematic fit (see below). From this we conclude that the surviving data sample is free of any sizeable background. Note that background originating from other single- and double-pion production processes is still much lower than that originating from the $pp \rightarrow pn\pi^+$ reaction.

Fig. 4. Energy dependence of the total cross-section for the $pp \rightarrow nn\pi^+\pi^+$ reaction. Open symbols denote previous bubble chamber measurements [6, 7]. The arrow gives the upper limit obtained at COSY-TOF [8] and the filled circle represents the experimental result of this work. The dotted line shows $\Delta\Delta$ calculations as used for the description of the $pp \rightarrow pp\pi^0\pi^0$ reaction [9]. The dashed line represents calculations of the $\Delta(1600) \rightarrow \Delta\pi$ process and the solid line gives the coherent sum of both processes.

The efficiency and acceptance correction of the full data has been performed with Monte Carlo simulations of the detector setup and performance. The absolute normalization of the data was achieved by normalizing to elastic scattering data —measured simultaneously with the $pp \rightarrow nn\pi^+\pi^+$ data.

With the four-vectors of the two pions and the directions of the two neutrons we have measured the $pp \rightarrow nn\pi^+\pi^+$ events with two kinematic overconstraints. Thus the data were subjected to a corresponding kinematic fit.

Due to the fact that we observe neutrons only in the forward detector, whereas π^+ particles are detected only in the central detector, the phase-space coverage is not complete. We estimate the systematic uncertainties due to this deficiency by using for detector response and acceptance corrections various model calculations for $\Delta\Delta$ and $\Delta(1600)$ excitations —see the next section. The thus estimated systematic uncertainties are given by the dark-shaded histograms in figs. 5 and 6.

3 Results

The energy dependence of the total cross-section is displayed in fig. 4. The total cross-section value from this work has been published already in ref. [2] in connection with the isospin decomposition of two-pion produc-

tion data. It is in good agreement with previous bubble-chamber data from KEK [6], however, a factor of five larger than predicted by the Valencia calculations [1]. This huge discrepancy was the primary reason to introduce the excitation of a higher-lying Δ state as a possible explanation in ref. [2].

To better understand this discrepancy, we have to discuss shortly the situation in the $pp\pi^0\pi^0$ channel. The total cross-section of the $pp \rightarrow pp\pi^0\pi^0$ reaction keeps rising from threshold up to $T_p \approx 1$ GeV, where it levels off until 1.2 GeV. Thereafter it continues steeply rising until 1.5 GeV, where it finally levels off again —see figs. 1 and 3 in ref. [2]. As has been demonstrated there, the low-energy structure is due to the Roper resonance [10], whereas the renewed rise at higher energies can be associated with the dominance of the $\Delta\Delta$ excitation [9, 11]. Since the latter describes both total and differential cross-sections for the $pp\pi^0\pi^0$ channel quite well for $T_p > 1$ GeV, a possibly faulty description of the $\Delta\Delta$ process is very unlikely as reason for the failure of the theoretical prediction in the $nn\pi^+\pi^+$ channel.

In a recent theoretical study, where interference terms are neglected, Xu Cao *et al.* [3] demonstrate that the total $nn\pi^+\pi^+$ cross-section may be well described by inclusion of nucleon-pole and other terms not considered in the Valencia model [1]. However, at the same time the $pp\pi^0\pi^0$ channel cross-section is overestimated by partly more than an order of magnitude for energies $T_p > 1$ GeV, where the $\Delta\Delta$ excitation plays the dominant role. Since we achieved a good phenomenological description of the data in this channel [9] by use of a modified version of the Valencia model, we prefer to stick with the latter model description in search of a consistent description for all $NN\pi\pi$ channels. That way, we exactly know what to expect for the differential distributions in the $nn\pi^+\pi^+$ channel from the $\Delta\Delta$ process, in order to be consistent with the differential distributions observed in the $pp\pi^0\pi^0$ channel. Also, in ref. [9] we have demonstrated that the differential data for the $pp \rightarrow pp\pi^0\pi^0$ channel in the region of the $\Delta\Delta$ excitation are not well described by ref. [1], which assumes ρ exchange to be dominant for this process. However, with π exchange as the leading process good agreement with the data is found. This is in accordance with the finding of ref. [3] that ρ exchange is of minor importance.

Figures 5 and 6 show a selection of six differential cross-sections: the differential distributions for invariant masses $M_{\pi^+\pi^+}$, M_{nn} , $M_{n\pi^+}$, $M_{nn\pi^+}$ and $M_{n\pi^+\pi^+}$ and the opening angle between the two pions $\delta_{\pi^0\pi^0}$ in the center-of-mass system (cms).

In the figures, the data are compared to pure phase space distributions (shaded areas in figs. 5 and 6) as well as to calculations (dotted, dashed and solid lines in figs. 4–6), which will be discussed in the following. As a convention, we show in figs. 5 and 6 all theoretical distributions normalized to the experimental cross-section. This is because we are interested here in the shape of the differential distributions. For the comparison with the absolute cross-section see fig. 4.

Fig. 5. Distribution of the $\pi^+\pi^+$ invariant mass $M_{\pi^+\pi^+}$ (left) and the $\pi^+\pi^+$ opening angle $\delta_{\pi^+\pi^+}$ (right) for the $pp \rightarrow nn\pi^+\pi^+$ reaction at $T_p = 1.1$ GeV. Solid dots represent the experimental results of this work. The dark-shaded histograms denote estimated systematic uncertainties. The light-shaded areas denote phase space distributions. The dotted lines show $\Delta\Delta$ calculations as used for the description of the $pp \rightarrow pp\pi^0\pi^0$ reaction [9]. The dashed lines are calculations of the $\Delta(1600) \rightarrow \Delta\pi$ process and the solid lines give the coherent sum of both processes. All calculations are normalized in area to the data.

Fig. 6. Same as fig. 5 but for the distributions of the invariant masses M_{nn} (left top), $M_{n\pi^+}$ (right top), $M_{nn\pi^+}$ (left bottom) and $M_{n\pi^+\pi^+}$ (right bottom).

Though the statistics of the $nn\pi^+\pi^+$ data is limited, the data are still able to discriminate between various scenarios. Whereas the angular distributions not shown here are essentially compatible with phase space, the invariant-mass distributions show substantial deviations from phase space. The measured M_{nn} spectrum appears narrower in its intensity distribution than phase space, whereas its complementary spectrum, the experimental $M_{\pi^+\pi^+}$ spectrum is substantially broader than phase space. This behavior signals the excitation of a system, which requires a large internal energy: When the excited system decays, the internal energy is transferred mainly to its light decay

products, the emitted pions. Also, the $M_{n\pi^+\pi^+}$ distribution is substantially enhanced towards its high-mass end in favor of a higher-lying resonance decaying into the $n\pi^+\pi^+$ system. We note that the nn final-state interaction plays only a very minor role at the beam energy considered here. Its effect shows up only at very small M_{nn} values, see, *e.g.*, fig. 6 in ref. [9].

Next we confront the data with theoretical predictions [1] of the Valencia group and subsequent modifications [9] of the original calculations. In ref. [1] three processes have been considered to feed the $pp \rightarrow nn\pi^+\pi^+$ reaction:

- the $\Delta\Delta$ process, which is considered to be the leading process for $T_p > 1$ GeV;
- the contribution from nonresonant chiral terms according to graphs (1)–(3) in ref. [1], which is expected to be the leading contribution for $T_p < 1$ GeV; and finally
- the contribution from the excitation of the Roper resonance with subsequent single-pion decay and associated nonresonant emission of a second pion, graphs (6)–(7) in ref. [1]. This contribution is the smallest one in the calculations of ref. [1]. Accounting for the finding in ref. [10] that the Roper contribution is largely overestimated for $T_p > 1$ GeV in ref. [1], this contribution should be insignificant for the data discussed here. We note, in passing, that in principle also a double Roper excitation, *i.e.* excitation of the Roper resonance in each of the participating nucleons could feed the $pp \rightarrow nn\pi^+\pi^+$ reaction, however, such a process must be even much rarer than the single Roper process discussed here. This is also true for any process mutually exciting the two nucleons to still higher excited states, since their resonance propagators—having poles at much higher energies—are tiny at the energies of interest here.

The dotted lines in figs. 4–6 show the predictions for the $\Delta\Delta$ process calculated according to ref. [9], which exhibit large deviations from the measured distributions in shape—in particular in the $M_{\pi^+\pi^+}$ and $\delta_{\pi^+\pi^+}$ spectra. For the $M_{\pi^+\pi^+}$ spectrum these calculations predict a low-mass enhancement, which is absent in the data. We note that in the $pp\pi^0\pi^0$ channel exactly such a (moderate) low-mass enhancement is observed. With regard to the $\pi^+\pi^+$ opening angle $\delta_{\pi^+\pi^+}$ these calculations predict preferential parallel and antiparallel emissions of the two pions, which again is not supported by the data.

However, exactly these $\Delta\Delta$ calculations give a good description of the $pp \rightarrow pp\pi^0\pi^0$ data as demonstrated in ref. [9]. Assuming the $\Delta\Delta$ process to be the leading process in both $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow nn\pi^+\pi^+$ channels we would have expected similar differential distributions in both channels due to isospin symmetry. Since this is not the case and since also the absolute cross-section in the $nn\pi^+\pi^+$ channel is massively underpredicted by the $\Delta\Delta$ process, we have to consider the possibility that higher-lying Δ resonances play a substantial role in the $pp \rightarrow nn\pi^+\pi^+$ reaction. Hence we consider in the following the process $pp \rightarrow n\Delta^{*++} \rightarrow nn\pi^+\pi^+$, where Δ^* denotes a higher-lying Δ resonance.

Above the $\Delta(1232)P_{33}$ resonance we have as possible $I = \frac{3}{2}$ three- and four-star candidates [12]: $\Delta(1600)P_{33}$ with a width $\Gamma \approx 350$ MeV, $\Delta(1620)S_{31}$ with $\Gamma \approx 150$ MeV and $\Delta(1700)D_{33}$ with $\Gamma \approx 300$ MeV. All three candidates have their largest decay branch into the $N\pi\pi$ channel, dominantly via the $\Delta(1232)P_{33}$. Still higher-lying Δ states have masses beyond 1900 MeV. However, the higher the resonance mass, the less is its excitation probability at our incident energy corresponding to a total cms energy of $\sqrt{s} = 2.37$ GeV = 1.43 GeV + m_N . With the available maximum total energy of 1.43 GeV for the excitation of *one* of the nucleons during the collision process we are well below the pole of any of these candidates. Hence, only the excitation of those candidates is likely, which have a large width, so that they can be excited significantly already at our energy. This makes the $\Delta(1600)P_{33}$ the most likely candidate from the energetic point of view. The matrix elements for the production of these Δ states in nucleon-nucleon collisions have been calculated in ref. [13] with the result that the square of these matrix elements is by far largest for $\Delta(1600)P_{33}$ and $\Delta(1620)S_{31}$ and an order of magnitude smaller for $\Delta(1700)D_{33}$.

From this discussion we see that among the three candidates the $\Delta(1600)P_{33}$ appears to be most suited to contribute to the $pp \rightarrow nn\pi^+\pi^+$ reaction in the energy region of interest here. We note that the recent SAID phase shift analysis [14] finds the pole of the $\Delta(1600)P_{33}$ state to be as low as 1457 MeV, which makes this state even more attractive as a candidate. However, since all three candidates have similar decay characteristics, we will not be able to discriminate them by the differential distributions. We therefore chose the $\Delta(1600)P_{33}$ as the most suited candidate, in order to see what influence such a higher-lying Δ excitation has on the observables.

We calculate the excitation of the $\Delta(1600)P_{33}$ and their subsequent decay $\Delta(1600)^{++} \rightarrow \Delta^+\pi^+ \rightarrow n\pi^+\pi^+$ by modifying graph (9) of ref. [1] accordingly. This calculation is shown by the dashed lines in figs. 5 and 6. They differ from the $\Delta\Delta$ results in particular in the $M_{\pi^+\pi^+}$ and $\delta_{\pi^+\pi^+}$ spectra achieving there good agreement with the data. Finally we superimpose the $\Delta(1600)P_{33}$ and $\Delta\Delta$ processes destructively as required by the isospin decomposition results [2]. Hereby we have adjusted the strength of this process to fit the total cross-section data. This condition makes the $\Delta(1600)P_{33}$ process the dominant process. Hence the resulting full calculation shown by the solid lines gives differential distributions, which are very close in shape to those for the pure $\Delta(1600)$ process (dashed lines)¹. The data are well described by this calculation. Though it is only the $M_{\pi^+\pi^+}$ and $\delta_{\pi^+\pi^+}$ distributions, which per se can clearly discriminate between $\Delta\Delta$ (dotted) and $\Delta(1600)P_{33}$ excitation, the latter one still provides a preferable description (solid lines in figs. 4–6) in all observables.

Summarizing we have presented the first exclusive measurements of the $pp \rightarrow nn\pi^+\pi^+$ reaction. The data show evidence for excitation and decay of a higher-lying Δ resonance. From the arguments given the $\Delta(1600)P_{33}$ appears to be a preferable candidate. That way the description of the differential data can be made consistent with that of the total cross-section and with the description of the data in other channels as required by the isospin decomposition.

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¹ Since we can not discriminate against contributions of the other two candidate resonances $\Delta(1620)S_{31}$ and $\Delta(1700)D_{33}$, the fitted strength of the $\Delta(1600)P_{33}$ process effectively subsumes the contribution of all candidates.