Exclusive Measurements of $pp \to d\,\pi^+\pi^0$: Double-Pionic Fusion without *ABC* Effect
(CELSIUS/WASA Collaboration)

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Exclusive measurements of the reaction $pp \to d\pi^+\pi^0$ have been carried out at $T_p = 1.1$ GeV at the CELSIUS storage ring using the WASA detector. The isovector $\pi^+\pi^0$ channel exhibits no enhancement at low invariant $\pi\pi$ masses, i. e. no ABC effect. Therefore this most basic isovector double-pionic fusion reaction qualifies as an ideal test case for the conventional t-channel $\Delta\Delta$ excitation process. Indeed, the obtained differential distributions reveal the conventional t-channel $\Delta\Delta$ mechanism as the appropriate reaction process, which also accounts for the observed energy dependence of the total cross section. This is an update of a previously published version – see important note at the end of the article.

1. Introduction

Double-pionic fusion has been an intriguing reaction all the time since Abashian, Booth and Crowe[1] discovered the so-called ABC effect nearly 50 years ago. The ABC effect stands for an unexpected low-mass enhancement in the spectrum of the invariant $\pi\pi$ masses $M_{\pi\pi}$. It is named after the initials of the authors of the first publications on this effect observed in the double pionic fusion of deuterons and protons to ^{3}He. Follow-up experiments [2,3,4] revealed this effect to show up in cases, when the two-pion production process leads to a bound nuclear system. Since the effect was not observed in $pd \to {}^3$H$\pi^+\pi^0$ data [1,2], this finding has been taken as evidence that the ABC effect might be restricted to the scalar-isoscalar $\pi\pi$ channel (σ channel). With the exception of low-statistics bubble-chamber measurements all

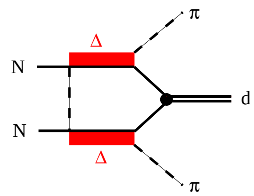

Figure 1. Graph of the double-pionic fusion process via t-channel $\Delta\Delta$ excitation in the intermediate state.

early experiments conducted on this issue have been inclusive measurements carried out preferentially with single-arm magnetic spectrographs for the detection of the fused nuclei.

Theoretically the ABC effect has been interpreted [2,3,4,5,6,7,8] by t-channel $\Delta\Delta$ excitation in the course of the reaction process (see Fig. 1) leading to both a low-mass and a high-mass enhancement in isoscalar $M_{\pi\pi}$ spectra. In fact, the missing momentum spectra from inclusive measurements have been in support of such predictions.

However, recent exclusive measurements of the isoscalar double-pionic fusion reactions $pn \to d\pi^0\pi^0$, $pd \to ^3$He$\pi\pi$ and $dd \to ^4$He$\pi\pi$ [9,10,11,12, 13] covering practically the full reaction phase space exhibit no significant high-mass enhancement, only a very pronounced low-mass enhancement. Also the new data on the most basic double-pionic fusion reaction for the ABC effect – the reaction $pn \to d\pi^0\pi^0$ – point to an isoscalar s-channel resonance as origin of the ABC-effect, which couples to pn and $\Delta\Delta$ channels, has a mass of about 90 MeV below the nominal $\Delta\Delta$ threshold of $\sqrt{s} = 2m_\Delta$ and a width of only ≈ 50 MeV [13]. The latter is much smaller than that expected from a conventional $\Delta\Delta$ system, which has a width of about twice the Δ width. i.e. ≈ 230 MeV.

If this interpretation is true, then double-pionic fusion leading to isovector final states is not expected to exhibit the ABC-effect. Rather one expects agreement with the conventional $\Delta\Delta$ t-channel excitation (Fig. 1). Also since due to Bose symmetry the isovector $\pi^+\pi^0$ system must be in odd relative angular momentum, i. e. in practice in relative p-wave to each other, there should be no low-mass enhancement in the $M_{\pi^+\pi^0}$ spectrum. Hence the $pp \to d\pi^+\pi^0$ reaction represents an important test case both for the current understanding of the ABC effect as a purely isoscalar phenomenon and for the interpretation of all other double-pionic fusion processes as a conventional t-channel $\Delta\Delta$ process. We note that this mechanism by itself is of key interest, since it constitutes the basic double excitation process in the NN system. Surprisingly it has not yet been tested in detail by exclusive and kinematically complete measurements. In a recent study [14] of total cross sections of the non-fusion channels $pp \to NN\pi\pi$ it has been shown that Roper and $\Delta\Delta$ excitations are the predominant two-pion production processes. For a detailed study of the latter the isovector $\pi\pi$ channel is particularly favorable, since there the competing Roper excitation is heavily suppressed [14,15].

Experiments devoted to the isovector double-pionic fusion are very sparse. For the $pd \to ^3$H$\pi^+\pi^0$ reaction there are just two single-arm magnetic spectrometer measurements providing inclusive momentum spectra at just one or two angle settings [1,2]. Experimental information on the $pp \to d\pi^+\pi^0$ reaction is available solely from bubble chamber measurements [16,17] of very low statistics with no information on differential observables. Hence an exclusive measurement of solid statistics and covering most of the relevant phase space appears to be crucial for the most basic isovector double-pionic fusion reaction, in order to settle the issue of the ABC effect in the isovector $\pi\pi$ channel as well as to have a clear-cut test case for the conventional t-channel $\Delta\Delta$ process.

2. Experiment

In order to investigate this particular issue with detailed experimental information we have carried out exclusive measurements of the $pp \to d\pi^+\pi^0$ reaction at $T_p = 1.1$ GeV, i. e. in the energy region of ABC effect and $\Delta\Delta$ excitation.

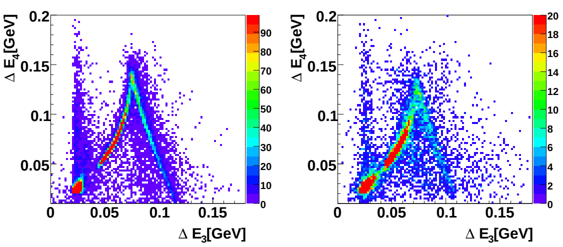

Figure 2. Energy deposit in the third plane of the forward range hodoscope versus that in the fourth plane after application of neural net constraints due to the other ΔE-E combinations in the multi-layer forward detector. The triangle-like pattern shows deuterons, which stop (right wing) or punch through (left wing) the 4^{th} layer of the forward range hodoscope. Left: Monte-Carlo simulation, right: data.

The experiment was performed at the CELSIUS ring at Uppsala using the 4π WASA detector setup including the pellet target system [18].

Deuterons and π^+ particles were detected in the forward detector and identified by the ΔE-E technique using corresponding informations from the quirl and range hodoscopes, respectively. Since both quirl and range hodoscope consist of several detector layers each, the energy loss method can be applied for the particle identification. For this ΔE-E method all possible two-layer combinations have been used. Most efficiently this can be done by a neural net, which has been trained by Monte Carlo simulations of the detector performance [9,19]. Fig. 2 shows as an example the combination energy loss $\Delta E3$ in the 3^{rd} hodoscope layer versus the energy loss $\Delta E4$ in the 4^{th} layer after application of constraints by neural net techniques, which clean the spectrum from the large proton background. Aside from minimum ionizing particles showing up at the lower left corner of Fig. 2 the deuteron band shows up clearly. The gammas from π^0 decay were detected in the central detector.

Since in the experiment d, π^+ and π^0 have been identified and since their kinetic energies and scattering angles were measured, the full four-momentum information about all ejectiles of an $pp \to d\pi^+\pi^0$ event has been obtained. Together with the additional constraint that the two detected gammas have to give the π^0 mass we have thus 5 overconstraints for the subsequent kinematical fit.

Acceptance and efficiency corrections have been performed with Monte Carlo simulations of the detector performance in an iterative procedure starting with the use of pure phase space distributions and ending with a model, which provides a satisfactory description of the data (solid lines in Figs. 4 - 6) assuring thus internal consistency of the procedure.

The absolute cross section was determined by normalization relative to the $pp \to pp\pi^0$ reaction, which was measured simultaneously with the same hardware trigger. As a result we obtain a total cross section of 0.092(15) mb. The uncertainty mainly originates from the large scatter in the literature values [17] for the total cross section of the $pp \to pp\pi^0$ reaction in the energy region of interest.

3. Results and Discussion

Results from the measurements are shown in Figs. 3 - 6. Fig. 3 displays the Dalitz plots of $M^2_{d\pi^0}$ versus $M^2_{\pi^+\pi^0}$ as well as of $M^2_{d\pi^0}$ versus $M^2_{d\pi^+}$. In the data there is no evidence for the presence of the ABC effect, *i. e.* for a $\pi\pi$ low-mass enhancement. Nevertheless the data deviate substantially from phase space, in particular in the region of the Δ excitation in $d\pi^0$ and $d\pi^+$ systems. Since we observe this excitation simultaneously in both systems as revealed in the respective Dalitz plot and especially in its projections, we see here evidence for the ΔΔ excitation in the intermediate system — as it is also borne out by comparison to the Monte-Carlo (MC) simulation of the t-channel ΔΔ excitation mechanism.

In its simplest form given by the pioneering ansatz of Risser and Shuster [5] the t-channel ΔΔ excitation (Fig. 1) is described by a t-channel pion exchange followed by two Δ prop-

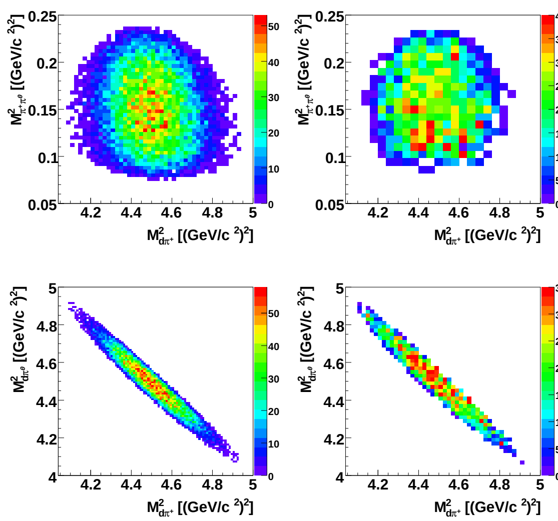

Figure 3. Dalitz plots of the invariant mass squares $M^2_{d\pi^0}$ versus $M^2_{\pi^+\pi^0}$ (**top**) and $M^2_{d\pi^0}$ versus $M^2_{d\pi^+}$ (**bottom**) for the $pp \to d\pi^+\pi^0$ reaction at $T_p = 1.1$ GeV. **Left**: MC simulation of the model description, which corresponds to the solid lines in Figs. 4 - 6, **right**: data.

agators and the condition that the two nucleons are constrained in their phase space by the deuteron boundstate condition. In the isoscalar $\pi\pi$ channel, where the ABC effect shows up, the two pion-nucleon p-waves resulting from the decay of the two Δs couple either to relative s-waves (σ-channel) or d-waves between the two pions. Due to Bose symmetry the isovector $\pi^+\pi^0$ system must be in relative p-wave to each other (ρ channel), *i. e.* the two pion-nucleon p-waves emerging from the decay of the two Δ states lead also to a relative p-wave in the $\pi\pi$ system. This is accomplished best if associated with a nucleon spinflip. Hence the isovector-channel operator $\vec{\sigma} * (\vec{k_1}\ x\ \vec{k_2})$ as given in Refs. [8,15], where $\vec{\sigma}$ denotes the Pauli nucleon-spin operator and $\vec{k_1}$ and $\vec{k_2}$ are the momenta of the outgoing pions, should be the appropriate operator for describing the isovector $\pi\pi$ production in $pp \to d\pi^+\pi^0$.

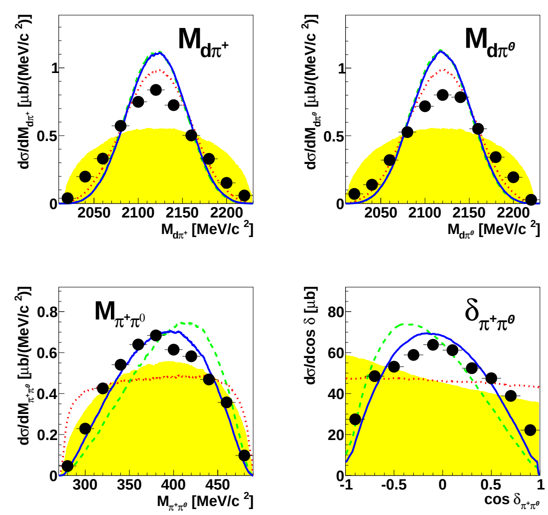

Figure 4. Distributions of the invariant masses $M_{d\pi^+}$ (**top left**), $M_{d\pi^0}$ (**top right**) and $M_{\pi^+\pi^0}$ (**bottom left**) as well as of the cm opening angle between the two pions $\delta_{\pi^+\pi^0}$ (**bottom right**) for the $pp \to d\pi^+\pi^0$ reaction at $T_p = 1.1$ GeV. The solid dots represent the data of this work. The phase space distributions are indicated by the shaded areas. The t-channel $\Delta\Delta$ calculations according to Risser and Shuster [5] are shown by the dotted curves, whereas these calculations supplemented by $\vec{\sigma} * (\vec{k_1}\ x\ \vec{k_2})$ in the reaction amplitude are given by the solid lines. Dashed curves denote calculations for ρ on-shell production.

In Figs. 4 - 6 t-channel $\Delta\Delta$ calculations are shown. The dotted lines denote calculations, where the isovector-channel operator is omitted (*i. e.* as in the t-channel calculations for the ABC effect in the isoscalar channel). The solid lines – and the MC simulations for the Dalitz plots in Fig. 3 – denote calculations, where the isovector-channel operator is applied. The dashed curves finally assume that in the exit channel the $\pi\pi$ final state interaction leads to the formation of a real ρ meson, *i. e.*, these calculations include a Breit-Wigner term (propagator) for the ρ me-

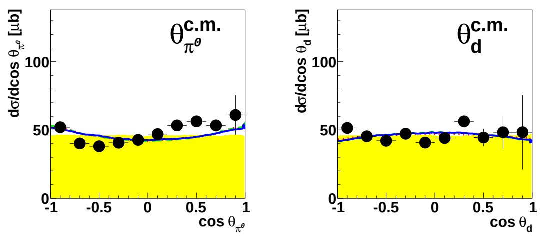

Figure 5. Angular distributions of π^0 and d in the cm system for the $pp \to d\pi^+\pi^0$ reaction at $T_p = 1.1$ GeV. The solid dots represent the data from this work. The phase space distribution is indicated by the shaded area. For the meaning of the curves see caption of Fig. 4. Note that dashed, dotted and solid lines coincide here.

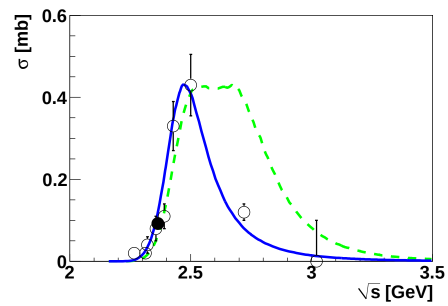

Figure 6. Energy dependence of the total cross section for the $pp \to d\pi^+\pi^0$ reaction. The open dots are from previous measurements [17,16], the solid dot represents the result of this work. For the meaning of the curves see caption of Fig. 4. Note that solid and dotted curves coincide here.

son in addition to the vector-isovector operator. Whereas the latter modification has only a minor impact on the observables, the inclusion of the isovector-channel operator is striking and essential for the description of the data – in particular for the $\pi\pi$ invariant mass and opening angle distributions. All calculations shown in Figs. 4 - 6 have been normalized in absolute scale to the observed total cross section.

The observed distributions of the invariant masses $M_{d\pi^+}$ and $M_{d\pi^0}$ exhibit clearly the simultaneous excitation of two Δ resonances. Simple t-channel $\Delta\Delta$ calculations without isovector-channel operator (dotted curves in Figs. 4 - 6) reproduce both $M_{d\pi^+}$ and $M_{d\pi^0}$ spectra quite well, however, not the $M_{\pi^+\pi^0}$ spectrum, where they exhibit both a low-mass and a high-mass enhancement – *i. e.* the classically predicted ABC effect for isoscalar channels [5]. Both these features are not observed in our data. These calculations also fail to describe the observed distribution of the opening angle $\delta_{\pi^+\pi^0}$ between the two pions in the center-of- mass (cm) system, see Fig. 4. In contrast, calculations including the isovector channel operator provide a reasonable description of all data (solid lines in Figs. 4 - 6). In particular the $\delta_{\pi^+\pi^0}$ distribution favors the $sin\delta_{\pi^+\pi^0}$ shape predicted by the isovector-channel operator. The further inclusion of a Breit-Wigner term for the production of a real ρ meson in the final state (dashed curves) worsens the agreement with the data substantially.

Fig. 5 displays the angular distributions of d and π^0 in the cm system. Both distributions are compatible with isotropy and also in accordance with the t-channel predictions. Since in this experiment the π^+ particles could be identified uniquely only in the forward detector together with the deuterons, the π^0 particles have been restricted by kinematics to the backward hemisphere in the cm system. Hence the $\Theta_{\pi^0}^{cm}$ distribution is not measured over the full angular range. However, this means no loss of information, since we have identical particles in the initial channel with the consequence that the cm angular distributions have to be symmetric about 90°.

In Fig. 6 finally the energy dependence of the total cross section is plotted. The open dots give the results from previous bubble chamber measurements [16,17]. The solid dot, which is compatible to the previous data within uncertainties, gives the result of this work. The drawn curves represent t-channel calculations in the definitions given above. They have been normalized in absolute scale to the data. Solid and dotted curves coincide in the figure. Their energy dependence is given primarily by the Δ propagators, whereas the k^2 dependence of the reaction amplitude due to the pion double p-waves from the decay of the two Δs is counteracted by the q^{-2} dependence from the pion propagator. This results in a resonance-like structure with a maximum at twice the Δ mass and a width of about twice the Δ width. These calculations give a good account of the experimentally observed energy dependence. In contrast, the calculation assuming the production of a real ρ meson in the exit channel (dashed curve) is far from the experimentally observed energy dependence for $\sqrt{s} > 2.5$ GeV.

4. Conclusions

The first exclusive measurements of the double-pionic fusion reaction to an isovector $\pi\pi$ channel provide differential cross sections, which are in good agreement with a conventional t-channel $\Delta\Delta$ excitation in the intermediate state - though small contributions from other processes may not be excluded. The isovector $\pi^+\pi^0$ channel exhibits no low-mass enhancement, *i. e.* no ABC effect, as indeed expected from the Bose symmetry in the $\pi\pi$ system, which prohibits relative s-waves between π^+ and π^0. The fact that also the experimentally observed energy dependence of the total cross section is well reproduced by the t-channel $\Delta\Delta$ process adds further confidence to the understanding of the double-pionic fusion process in isovector channels. Moreover, it provides the possibility to reliably predict the expected size of the conventional t-channel $\Delta\Delta$ process in the $pn \to d\pi^+\pi^-$ and $pn \to d\pi^0\pi^0$ reactions by use of isospin relations as demonstrated in Ref. [10].

5. Acknowledgments

We acknowledge valuable discussions with L. Alvarez-Ruso, Ch. Hanhart, E. Oset and C. Wilkin. This work has been supported by BMBF (06TU261), Forschungszentrum Jülich (COSY-FFE) and DFG (Europ. Graduiertenkolleg 683). We also acknowledge the support from the European Community-Research Infrastructure Activity under FP6 "Structuring the European Research Area" programme (Hadron Physics, contract number RII3-CT-2004-506078).

6. Important Note

This is an update of the previous arXiv version published in Physics Letters B [20]. The update is based on a reanalysis [21] of the data for the $pp \to d\pi^+\pi^0$ reaction, where it was discovered that the originally published value for the cross section was too low by a factor of about two. This corrected value has been published in an erratum [22].

The differential distributions obtained in this reanalysis and exhibited in Figs. 3 - 5 of this updated version did not change significantly - with the obvious exception in the absolute scale.

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