MENU 2007
11th International Conference
on Meson-Nucleon Physics and
the Structure of the Nucleon
September10-14, 2007
IKP, Forschungzentrum Jülich, Germany

σ CHANNEL LOW-MASS ENHANCEMENT IN DOUBLE-PIONIC FUSION – IS A DIBARYON RESONANCE THE REASON FOR THE ABC EFFECT?

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Abstract

The ABC effect - a puzzling low-mass enhancement in the $\pi\pi$ invariant mass spectrum - is known from inclusive measurements of two-pion production in nuclear fusion reactions. First exclusive measurements carried out at CELSIUS-WASA for the fusion reactions to d and ^{3}He in the final state reveal this effect to be a σ channel phenomenon associated with the formation of a $\Delta\Delta$ system in the intermediate state. The total cross sections obtained for the $pn \to d\pi^0\pi^0$ reaction exhibit a resonance-like behavior. Both this intriguing energy dependence and the differential distributions for the $\pi^0\pi^0$ channels can be well described, if a quasibound state in the $\Delta\Delta$ system leading to a resonance in the pn and $d\pi^0\pi^0$ systems is assumed.

1 Introduction

The ABC effect - first observed by Abashian, Booth and Crowe [1] - in the double pionic fusion of deuterons and protons to ^{3}He, stands for an unexpected enhancement at low masses in the $M_{\pi\pi}$ spectrum. Follow-up experiments [2–11] revealed this effect to be of isoscalar nature and to show up in cases, when the two-pion production process leads to a bound nuclear system. With the exception of low-statistics bubble-chamber measurements [4, 8] all experiments conducted on this issue have been inclusive measurements carried out preferentially with single-arm magnetic spectrographs for the detection of the fused nuclei.

Initially the low-mass enhancement had been interpreted as an unusually large $\pi\pi$ scattering length and evidence for the σ meson, respectively [1]. Since the effect showed up particularily clearly at beam energies corresponding to the excitation of two Δs in the nuclear system, the ABC effect was interpreted lateron by a $\Delta\Delta$ excitation in the course of the reaction process leading to both a low-mass and a high-mass enhancement in isoscalar $M_{\pi\pi}$ spectra [12–16]. In fact, the missing momentum spectra from inclusive measurements have been in support of such predictions. It has been shown [17] that these structures can be enhanced considerably in theoretical calculations by including ρ exchange and short-range correlations.

2 Experiment

In order to shed more light on this issue, exclusive measurements of the reactions $pd \to pd\pi^0\pi^0$ (T_p = 1.03 and 1.35 GeV) and $pd \to {}^3\mathrm{He}\pi\pi$ (T_p = 0.893 GeV) have been carried out in the energy region of the ABC effect

at CELSIUS using the 4π WASA detector setup including the pellet target system [18]. The selected energies are close to the maximum of the ABC effect observed in the respective inclusive measurements. The $pd \to pd\pi^0\pi^0$ reaction proceeds as quasifree $pn \to d\pi^0\pi^0$ reaction with a spectator proton of very small four-momentum. Since all ejectiles except of the spectator have been measured, the spectator momentum has been reconstructed by kinematical fits with three overconstraints. The experimental results on the $pd \to {}^3\mathrm{He}\pi^0\pi^0$ and $pd \to {}^3\mathrm{He}\pi^+\pi^-$ reactions have been published already elsewhere [20, 21].

3 Experimental results

Results of our measurements are shown in Figs. 1 - 4. Fig.1 shows the Dalitz plot of the squares of invariant masses $M_{d\pi^0}$ versus $M_{\pi^0\pi^0}$ for the quasifree reaction process $pn \to d\pi^0\pi^0$ at a nominal beam energy of $T_p =$ 1.03 GeV. Note that due to Fermi motion of the nucleons in the target deuteron the quasifree reaction process proceeds via a continuum of effective collision energies in the range 0.94 - 1.18 GeV with according kinematical smearing in the differential distributions. This smearing may be reduced strongly by dividing the data into narrow bins of effective collision energy at the cost of statistics. In Fig.1 the Dalitz plot for the quasifree $pn \to d\pi^0\pi^0$ reaction is shown both for data and Monte Carlo (MC) simulation of a model description discussed in the next section. Note that the measurements cover practically the full phase space.

The $\pi^0\pi^0$ channel, which is free of any isospin I=1 contributions, exhibits a pronounced low-mass enhancement (ABC effect) in the $M_{\pi^0\pi^0}$ spectrum both in the fusion process to the deuteron and in the one leading to ^{3}He [20, 21]. Fig. 2 depicts the spectra of the invariant masses $M_{\pi^0\pi^0}$ and $M_{d\pi^0}$ for the quasifree $pn \to^d \pi^0\pi^0$ reaction at the beam energy $T_p = 1.03$ GeV. We note in passing that in the ${}^3\mathrm{He}\pi^+\pi^-$ channel the threshold enhancement is observed [20] too, however, somewhat less pronounced. The reason for this is that this channel contains also isovector contributions - as may be seen [22] by the small shifts between the Δ peaks in the $M_{^3He\pi^+}$ and $M_{^3He\pi^-}$ spectra [20, 21]. However, the main point is that in these spectra we see that indeed two Δs are excited simultaneously in this reaction, which supports the hypothesis of the excitation of a $\Delta\Delta$ system in the course of the double pionic fusion process. .

Angular distributions are shown in Fig. 3 for the quasifree $pn \to d\pi^0\pi^0$ reaction. For the ^{3}He cases they are given in Refs. [20,21]. The distribution of the opening angle $\delta_{\pi^0\pi^0}$ between the two pions in the overall center-of-mass

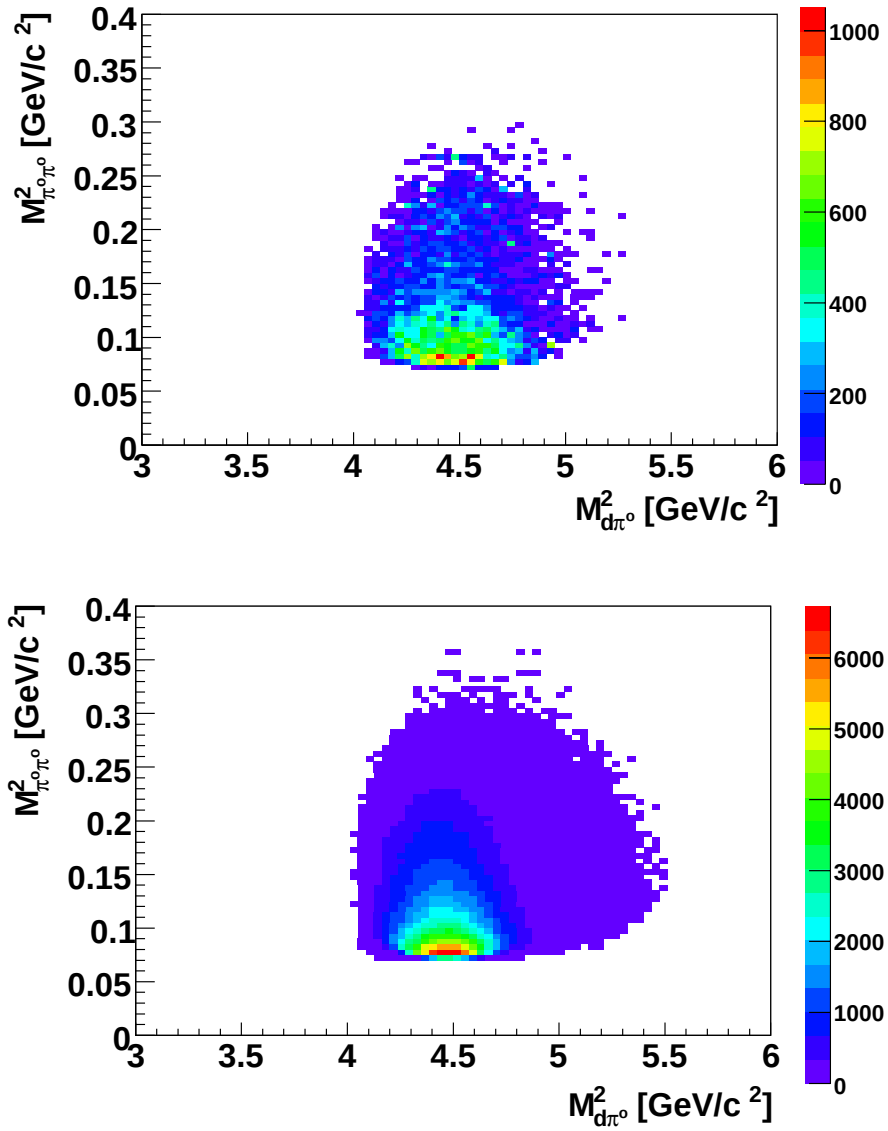

Figure 1: Dalitz plot of the invariant mass distributions for $M_{d\pi^0}$ versus $M_{\pi^0\pi^0}$ for the quasifree reaction process $pn \rightarrow d\pi^0\pi^0$ in the range O.94 - 1.18 GeV of effective collison energies. Top: data, bottom: MC simulation of a quasibound state in the $\Delta\Delta$ system leading to a resonance in the pn and $d\pi^0\pi^0$ systems.

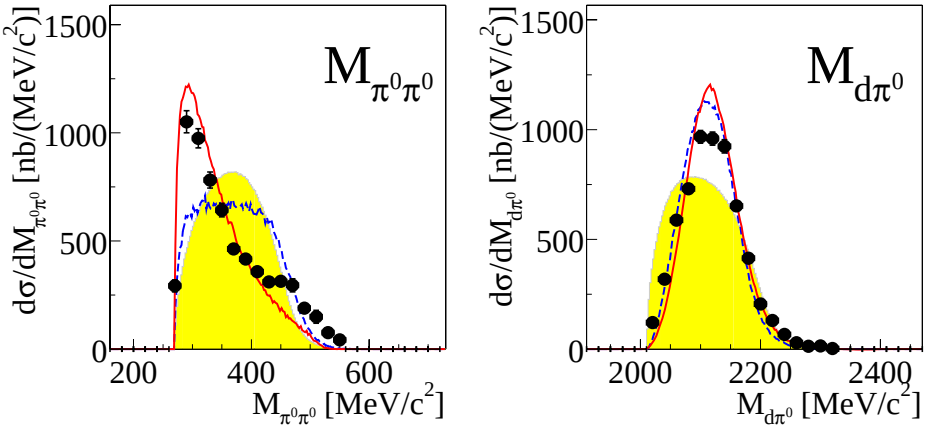

Figure 2: Distributions of the invariant masses $M_{\pi^0\pi^0}$ and $M_{d\pi^0}$ from the exclusive measurement of the quasifree $pn \to d\pi^0\pi^0$ reaction at a beam energy $T_p = 1.03$ GeV. The shaded areas show the pure phase space distributions. Solid and dashed curves give $\Delta\Delta$ calculations with and without the assumption of a quasibound state in the $\Delta\Delta$ system leading to a resonance in the pn and $d\pi^0\pi^0$ systems.

system (cms) peaks at small angles, in particular if we select events with $M_{\pi^0\pi^0} \leq 0.34$ GeV/c^2. This means that the low-mass enhancement is associated with pions leaving the interaction vertex in parallel. The distributions of the deuteron polar angles $\Theta_d^{d\pi^0\pi^0}$ in the overall cms (i.e. the full $d\pi^0\pi^0$ system) and of the pion polar angles $\Theta_{\pi^0}^{\pi^0\pi^0}$ and $\Theta_{\pi^0}^{d\pi^0}$ in $d\pi^0$ and $\pi^0\pi^0$ subsystems, respectively, are symmetric about 90° and anisotropic. The anisotropy observed for the latter (not shown in Fig. 2) corresponds just to the one expected from Δ decay. The anisotropy in the π^0 angular distribution in the $\pi\pi$ subsystem signals some admixture from higher partial waves. It gets strongly reduced, if we consider only data with $M_{\pi^0\pi^0} \leq 0.34$ GeV/c^2, i.e. in the region of the low-mass enhancement. From this we deduce that the threshold enhancement (ABC-effect) is of scalar nature.

Finally we show in Fig. 4 the energy dependence of the total cross section of the double-pionic fusion to Deuterium. Depicted are the results for the $pn \to d\pi^+\pi^-$ reaction from bubble chamber measurements at DESY [4] and JINR [8] together with our preliminary results from measuring the quasifree $pn \to d\pi^0\pi^0$ reaction at two incident energies, which have been binned into narrow ranges of effective collison energies providing thus four entries at lower energes and two entries at higher energies. Since $\pi^+\pi^-$ and $\pi^0\pi^0$ channels are related by an isospin factor of two, we have plotted our results in Fig.4

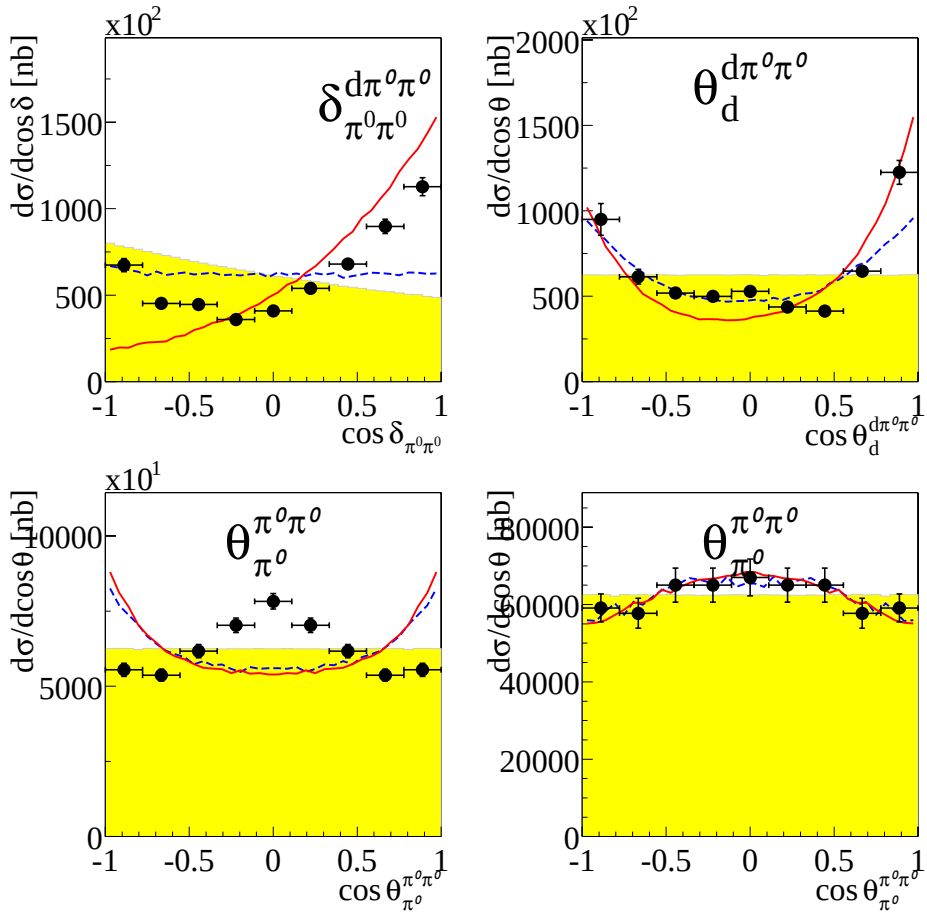

Figure 3: Angular distributions in the quasifree reaction $pn \rightarrow d\pi^0\pi^0$ at the nominal beam energy of T_p =1.03 GeV for the opening angle $\delta^{d\pi^0\pi^0}_{\pi^0\pi^0}$ between the two pions, the angle of the deuteron $\Theta^{d\pi^0\pi^0}_{d}$ - all in the overall cms of the $d\pi^0\pi^0$ system - as well as the pion angle $\Theta^{\pi^0\pi^0}_{\pi^0}$ in the $\pi^0\pi^0$ subsystem (Jackson frame), respectively. This angular distribution is plotted also with the constraint $M_{\pi^0\pi^0} < 0.34$ GeV/c^2 (bottom, right). The shaded areas show the pure phase space distributions. Solid and dashed curves give $\Delta\Delta$ calculations with and without the assumption of a quasibound state in the $\Delta\Delta$ system leading to a resonance in the pn and $d\pi^0\pi^0$ systems.

by multiplying them by this isospin factor, in order to make them directly comparable to the $\pi^+\pi^-$ results.

4 Discussion and Interpretation of Experimental Results

The $\pi\pi$ low-mass enhancements observed in the exclusive data for the $\pi^0\pi^0$ channels turn out to be much larger than predicted in previous $\Delta\Delta$ calculations [12, 14, 16]. As an example we show by the dashed lines in Figs.2 and 3 and by dotted lines in Fig. 4 calculations in the model ansatz of Ref. [12], where we additionally included the pion angular distribution in Δ decay and the Fermi smearing of the nucleons bound in the final nucleus. Contrary to these predictions the data also do not exhibit any high-mass enhancement that had been supported by the inclusive measurements, too. As suspected already in Ref. [9] the high-mass bump observed in inclusive spectra rather turns out to be associated with $\pi\pi\pi$ production and I=1 contributions.

Since on the one hand the available $\Delta\Delta$ calculations obviously fail, but on the other hand the data clearly show the $\Delta\Delta$ excitation in their $M_{N\pi}$ spectra, a profound physics piece appears to be missing. Such a missing piece may be provided by a strong $\Delta\Delta$ attraction or even a boundstate condition, as we demonstrated in Refs. [20, 21, 23, 24]. With these assumptions we are able to describe the exclusively measured data for d and ^{3}He fusion as well as the inclusive spectra for double-pionic fusion to ^{4}He amazingly well without modification of the $\Delta\Delta$ interaction parameters. For the boundstate case we request the distribution of the relative momentum of the two Δs to follow that of a Hulthen type distribution. For the scattering case we take the Migdal-Watson [25, 26] ansatz for final state interactions with the $\Delta\Delta$ scattering length as a paramter, which is adjusted for an optimal description of the data. Using an effective range of 2 fm, i.e. in the region of corresponding NN values, we find two aquivalent solutions for the $\Delta\Delta$ scattering length of -16 fm and +10 fm, respectively. The first value means that the interaction is strongly attractive and close to the one for isovector NN scattering, the second solution means that there is even a bound $\Delta\Delta$ state. All these cases provide very similar descriptions of the observables and hence can not be discriminated by the present data base. However, these calculations still predict an energy dependence of the total cross section, which is only slightly steeper than that of $\Delta\Delta$ calculations without mutual interaction, i.e., inconsistent with the total cross section data in Fig. 4.

In fact, the clue to the true nature of the ABC effect may be provided by

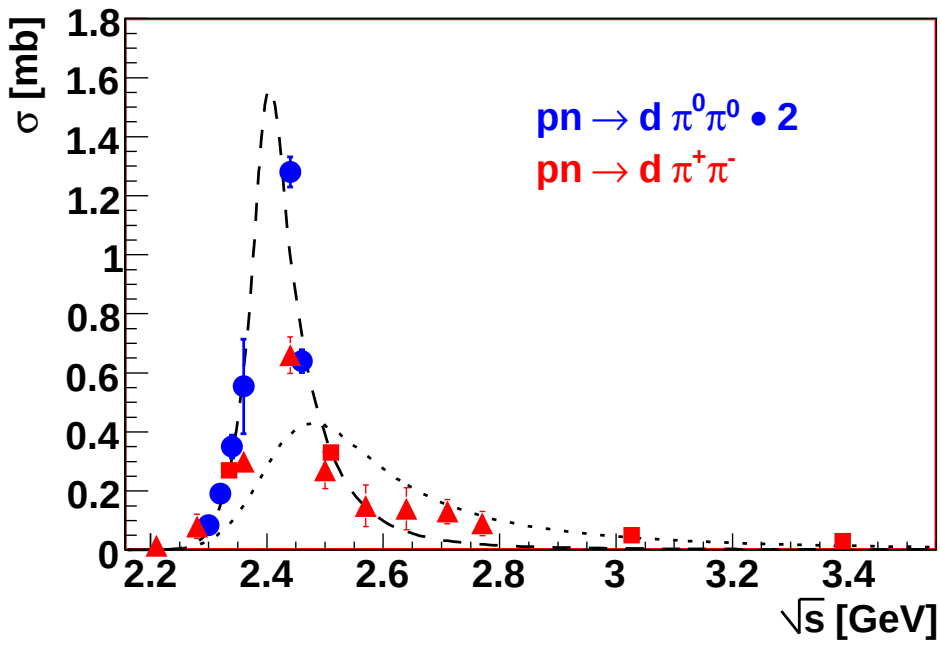

Figure 4: Energy dependence of the $pn \to d\pi\pi$ reaction with preliminary results of this work for the $\pi^0\pi^0$ channel (quasi-free measurements at two incident energies) and results for the $\pi^+\pi^-$ channel from Ref. [8](squares) and Fig. 2c of Ref. [4] (triangles). Dashed and dotted lines represent calculations with and without the assumption of a quasibound state in the $\Delta\Delta$ system leading to a resonance in the pn and $d\pi^0\pi^0$ systems.

the intriguing energy dependence of the double-pionic fusion in the isoscalar channel. On the one hand the isovector fusion channel $pp \to d\pi^+\pi^0$, which shows **no** ABC effect [27] despite a clear $\Delta\Delta$ excitation signal in its differential spectra, exhibits an energy dependence [28] in its total cross section close to the dotted curve in Fig. 4. On the other hand the isoscalar fusion channel exhibits a much steeper energy-dependence resembling that of a pronounced resonance excitation with a width of roughly 100 MeV or even below, i.e. much smaller than twice the Δ width expected from usual $\Delta\Delta$ calculations. As is also borne out by the data in Fig. 4 the cross section maximum at $\sqrt{s} \approx 2.41$ GeV means that the resonance mass is below twice the Δ mass pointing to a quasibound state in the isoscalar $\Delta\Delta$ system, which not only can decay into the pn system, but also into the isoscalar $d\pi\pi$ system, because the Δ decay width is larger then the binding of this state.

In fact, the Migdal-Watson ansatz with its dependence on the relative momentum $q_{\Delta\Delta}$ between the two Δs can be easily upgraded to a Breit-Wigner term with a $q_{\Delta\Delta}$ dependent width. Adjusting the width parameters to a correct reproduction of the $M_{\pi^0\pi^0}$ differential distribution leads not only to a quantitative description of all differential data (solid curves in Figs. 2 and 3 as well as Dalitz plot in Fig.1) but also to a quantitative description of the energy dependence of the total cross section (dashed curve in Fig. 4) by providing automatically the correct width needed for the description of the total cross section data.

Since the model calculations for a quasibound state in the $\Delta\Delta$ system, which assume the decay into this system to proceed via relative s-waves between the two Δs, describe the measured angular distributions very well, the spin-parity assignment to this isoscalar intermediate state has to be either $J^P = 1^+$ or 3^+ taking into account that the two-fermion system has to be in an antisymmetric state.

Acknowledgments

We acknowledge valuable discussions with E. Oset, C. Wilkin, Ch. Hanhart, A. Sibirtsev, L. Alvarez-Ruso, A. Kaidalov, L. Dakhno and V. Anisovitch on this issue. This work has been supported by BMBF (06TU201, 06TU261), COSY-FFE, DFG (Europ. Graduiertenkolleg 683), Landesforschungsschwerpunkt Baden-Württemberg and the Swedish Research Council. 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).

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