Two-Pion Production in Nucleon-Nucleon Collisions and the ABC Effect - Approaching a Puzzle by Exclusive and Kinematically Complete Measurements

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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 collisions, where it always showed up, if the participating nucleons fused to a bound nuclear system in the final state. The first exclusive measurements on the ABC effect have been carried out very recently at CELSIUS-WASA for the fusion reactions leading to $d$, $^{3}$He and $^{4}$He nuclei in the final state. The data analyzed so far for the fusion processes to $d$ and $^{3}$He reveal this effect to be a $\sigma$ channel phenomenon associated with the formation of a strongly attractive $\Delta\Delta$ system. The data for the strictly isospin-selective double-pionic fusion to $^{4}$He, where we expect the largest effect, are currently still analyzed. All inclusive data on this system are well described by our model, too. This case also constitutes the heaviest nuclear system, where exclusive measurements of double-pionic fusion can be carried out with present-day instruments. Surprisingly, the $pp \rightarrow pp\pi^{0}\pi^{0}$ reaction in the $\Delta\Delta$ region is observed to also show a ABC-like low-$\pi\pi$ mass enhancement, a phenomenon, which deserves special attention.

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, 3, 4] 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 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 $\sigma$ meson, respectively. Lateron the ABC effect has been interpreted by $\Delta\Delta$ 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. In fact, the missing momentum spectra from inclusive measurements have been in support of such predictions. It has been shown [5] that these structures can be enhanced considerably in theoretical calculations including $\rho$ exchange. In this case even the basic reaction $pp \rightarrow pp\pi\pi$ with no bound state in the exit channel should exhibit a double-hump structure
in the $M_{\pi\pi}$ spectrum for incident energies in the $\Delta\Delta$ region.

2 Exclusive Measurements at CELSIUS-WASA

In order to shed more light on this issue exclusive measurements of the reactions $pp \rightarrow NN\pi\pi$ (at several energies), $pn \rightarrow d\pi^0\pi^0$ ($T_p = 1.1$ GeV), $pd \rightarrow ^3\text{He}\pi\pi$ ($T_p = 0.893$ GeV) and $dd \rightarrow ^4\text{He}\pi\pi$ ($T_p = 1$ GeV) have been carried out in the energy region of the ABC effect at CELSIUS using the 4$\pi$ WASA detector setup including the pellet target system.

The $dd \rightarrow ^4\text{He}\pi\pi$ reaction could be measured only with modest statistics in the very last experimental run before the final shutdown of the CELSIUS ring. The latter data are currently analyzed by the Uppsala group.

For the other reactions quoted above there are already first results. Those on the $pd \rightarrow ^3\text{He}\pi^0\pi^0$ and $pd \rightarrow ^3\text{He}\pi^+\pi^-$ reactions have been published already \cite{6}. As an example of the experimental performance and the ability of particle identification we show in Fig.1 a $\Delta$E-$E$ scatterplot for particles registered in the forward detector of the WASA-setup \cite{8} in a run with proton beam and deuteron pellet target.

$^3\text{He}$ particles, deuterons and protons have been detected in the forward detector and identified by the $\Delta$E-$E$ technique using corresponding informations from quirl and range hodoscope, respectively. In order to suppress the vast background of fast protons and other minimum ionizing particles already on the trigger level, appropriate $\Delta$E thresholds have been set on the window hodoscope acting as a first level trigger in case of the $^3\text{He}$ run.

Charged pions and gammas (from $\pi^0$ decay) have been detected in the central detector. This way the full four-momenta have been measured for all particles of an event allowing thus kinematic fits with 4 overconstraints in case of $\pi^+\pi^-$ production and 6 overconstraints in case of $\pi^0\pi^0$ production \footnote{In case of $pn \rightarrow d\pi^0\pi^0$, which has been measured as a quasifree reaction in $pd$ collisions, a kinematic fit with only 3 overconstraints was applicable, since the spectator proton had not been measured}.

In order to facilitate comparison with the previous inclusive measurements \cite{2} we display in Fig. 2 lego and contour plots of lab angle versus lab energy of the $^3\text{He}$ particles detected in the forward detector - before kinematic fit and any demand on other particles in the event. Whereas for single $\pi^0$ production $^3\text{He}$ particles have been registered only in a very limited angle and energy range of phase space, the $^3\text{He}$ particles stemming from $\pi\pi$ production have been detected over the full kinematical range up to $^3\text{He}$ angles $\Theta_{^3\text{He}} \leq 90^\circ$. Since we demand the $^3\text{He}$ particles to reach the range hodoscope they need to have kinetic energies of more than 200 MeV in order to be registered and
Figure 1: $\Delta$E-E scatterplot for particles recorded in the WASA Forward Detector during a run with proton beam and deuterium pellet target at $T_p = 0.895$ GeV. The hyperbolic bands for $p$, $d$ and $^3$He particles (bottom to top) are clearly separated \cite{ref1}. Note the log scale in the scatterplot.

Figure 2: 3D and contourplots of lab angle $\Theta_{^3He}^{lab}$ versus lab energy $T_{^3He}^{lab}$ for $^3$He particles measured in the forward detector. The dash-dotted lines give $\Theta_{^3He}^{cm} = 22.5^\circ, 45^\circ, 67.5^\circ, 90^\circ$. The dashed lines indicate the contours of missing masses $MM_{^3He} = 0.135, 0.27, 0.4, 0.5$ GeV. From Ref. \cite{ref2}. 
safely identified. Hence for $^3$He cms angles larger than 90° the phase space is no longer fully covered in this measurement.

In Fig. 2 the band for single $\pi^0$ production is seen to be well separated from the continuum for $\pi\pi$ production. Also immediately evident is a large accumulation of events near the kinematic limit for $\pi\pi$ production, i.e. in the region corresponding to small invariant $\pi\pi$ masses. Since the detector efficiency is approximately constant over the corresponding phasespace region in Fig. 2, this feature obviously is in accord with a strong ABC enhancement present in these data.

3 Results from Exclusive Measurements at CELSIUS-WASA

The $\pi^0\pi^0$ channel, which is free of any isospin I=1 contributions, exhibits in all cases a low-mass enhancement in the $M_{\pi\pi}$ spectra. In Fig. 3 the situation is shown for the reactions $pd \rightarrow ^3\text{He}\pi^0\pi^0$ and $pd \rightarrow ^3\text{He}\pi^+\pi^-$ at $T_p = 0.895$ GeV. The chosen energy is in the region, where the ABC effect is expected to be at maximum as deduced from the inclusive measurements on this reaction system[2]. For the $\pi^0\pi^0$ channels associated with a bound deuteron [9] or an unbound $pp$ system [10] in the final nuclear system the situation is similar, see Figs. 4 and 7.

For the $\pi^+\pi^-$ channel, which may contain isovector contributions, the observed threshold enhancements show up much less pronounced in case of $^3$He and even are absent in case of the unbound $pp$ system in the final state.

From the angular distribution in the $\pi\pi$ subsystem we see that the threshold enhancement is of scalar nature[6, 7].

The $\pi\pi$ low-mass enhancements observed now in the exclusive data for the $\pi^0\pi^0$ channels turn out to be much larger than predicted in previous $\Delta\Delta$ calculations[11, 12, 13]. At the same time the data do not exhibit any high-mass enhancement as predicted by the same calculations and as suggested by the inclusive measurements. As anticipated already in Ref. [4] the high-mass bump observed in inclusive spectra appears to be associated with $\pi\pi\pi$ production and I=1 contributions rather than with the isoscalar $\pi\pi$ production.

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 is provided by a strong $\Delta\Delta$ attraction, which is able to describe the exclusive data for d and $^3$He fusion as well as the inclusive spectra for double-
Figure 3: Results from the exclusive measurements of the reactions $pd \rightarrow ^3\text{He}\pi^0\pi^0$ (top) and $pd \rightarrow ^3\text{He}\pi^+\pi^-$ (bottom) at $T_p = 0.895$ GeV. Left: Spectra of the $\pi\pi$ invariant mass $M_{\pi\pi}$. Right: Spectra of the $^3\text{He}\pi$ invariant masses $M_{^3\text{He}\pi^0}$ (solid dots), $M_{^3\text{He}\pi^+}$ (open crosses) and $M_{^3\text{He}\pi^-}$ (filled triangles). The shaded areas show the pure phase space distributions (left: normalized to touch the data; right: normalized to the total cross section of the data). Solid and dashed curves give $\Delta\Delta$ calculations with and without $\Delta\Delta$ interaction, respectively [6, 7]. Note that in these calculations no collision damping is taken into account, which may be the reason, why the observed structure in the $^3\text{He}\pi$ invariant masses is larger than the calculated $\Delta$ width.

The double-pionic fusion of deuterium to $^4\text{He}$ constitutes the fusion process to the heaviest nucleus, which can be measured exclusively with present-day experimental setups. For exclusive measurements on heavier nuclei high-resolution zero-degree spectrometers directly connected to the vacuum and supplemented by a WASA-like central detector would be required - an instrument, which is not available at present.

The fusion process to $^4\text{He}$ exhibits the biggest ABC effect ever measured in previous inclusive magnetic spectrometer measurements [3]. The $^4\text{He}$ momentum spectrum, which represents the $\pi\pi$ invariant mass spectrum (though
Figure 4: Preliminary results[9] from exclusive measurements of the reaction \( pn \rightarrow d\pi^0\pi^0 \) at \( T_p = 1.05 \) GeV. **Left:** Spectrum of the \( \pi\pi \) invariant mass \( M_{\pi^0\pi^0} \). **Right:** Spectrum of the \( d\pi \) invariant mass \( M_{d\pi^0} \). The shaded areas show the pure phase space distributions, solid and dashed curves give \( \Delta\Delta \) calculations with and without \( \Delta\Delta \) interaction, respectively[7]. Note that in this case no collision damping is expected to occur. Hence the calculated width in the \( M_{d\pi^0} \) spectrum should fit to the observed one - as indeed is the case.

in a nonlinear way), decomposes in this case in nearly two narrow bumps corresponding to low- and high-mass \( \pi\pi \)-enhancements - see Fig. 5, where the experimental momentum spectrum as obtained at Saclay [2] is shown. The solid line displays our prediction with \( \Delta\Delta \) interaction (adjusted in height to the data), whereas the broken lines are from the original paper [14] and denote phase space distributions for two- and three-pion production each adjusted to touch the data. The prediction compares very well with the data with the exception of the high-mass region, where we suspect strong contributions from three-pion production in the inclusive spectra.

Yet another prediction is the energy dependence of the reaction cross section, which should be resonance-like. This is demonstrated in Fig. 6, which on the left shows the situation for the total cross section and on the right the situation of the ABC effect itself. As in the original work on \(^4\)He [14] the latter is taken to be the \( \pi\pi \) low-mass enhancement above phase space, where the latter is adjusted as to touch the data (as displayed in Fig. 5). Again our prediction does remarkably well.

The lecture we are learning here for the \( \pi\pi \) production in few-nucleon systems may possibly serve as a guideline for the microscopic understanding of medium effects in the \( \sigma \) channel and its possible association to chiral restoration.
Figure 5: Experimental $^4$He momentum spectrum for the reaction $dd \rightarrow ^4$He X at $T_d = 1.09$ GeV and $\Theta_{lab} = 0^\circ$ as obtained at Saclay [14]. The solid (red) line displays our prediction with $\Delta\Delta$ interaction (adjusted in height to the data), whereas the broken lines are from the original paper and denote phase space distributions from for two- and three-pion production - each adjusted to touch the data. From Ref. [7]

4 The Basic Reaction Leading to Unbound Final States

For the basic reaction $pp \rightarrow NN\pi\pi$ most of the data have been collected for the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels, which are most easily accessible experimentally. The $\pi^+\pi^+$ and $\pi^+\pi^0$ channels are much harder to access, since they are associated with the production of neutrons.

At low incident energies, i.e., in the threshold region, the data on the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels have been successfully explained by excitation and decay of the Roper resonance [5, 15, 16] - see also the corresponding article [17] in this proceedings - and alternatively also within the concept of chiral dynamics [18].

At incident energies above 1 GeV, where the $\Delta\Delta$ mechanism should take
Figure 6: Energy dependence of double pionic fusion, shown here for the reaction $pd \to ^3He \pi^0\pi^0$ as an example. The situation for the $^4He$ case is very similar. The dotted (black) curve denotes phase space, dashed (blue) and solid (red) curves are predictions of $\Delta\Delta$ excitation with and without $\Delta\Delta$ interaction included. **Left:** total cross section with the solid dot denoting the CELSIUS-WASA result \cite{6} and the blue curve being arbitrarily adjusted to it. **Right:** ABC peak, i.e. $\pi\pi$ low-mass enhancement above phase space (where the latter is adjusted to touch the data, see e.g. Figs. 5) at $\Theta_{^3He}^{cm} = 180^\circ$. Comparison of data taken from \cite{14} with predictions of the $\Delta\Delta$ ansatz with interaction included. From Ref. \cite{7}

over, the data for $\pi^+\pi^-$ and $\pi^0\pi^0$ channels change drastically. Indeed this mechanism is identified by observing the simultaneous excitation of $\Delta^{++}$ and $\Delta^0$ in the appropriate $M_{\pi^+\pi^+}$ and $M_{\pi^+\pi^-}$ spectra. However, we observe\cite{19} a phase-space like behavior in the measured $M_{\pi^+\pi^-}$ spectra rather than the predicted\cite{5} double-hump structure. This observation together with the observation that the measured pion angular distributions are flat has led us to the conclusion that obviously the $\Delta\Delta$ system is produced solely in an $I(J^P) = 1(0^+)$ configuration. This is equivalent to the statement that the two-pion production process is dominantly fed by the $^1S_0$ partial wave in the entrance channel. This in turn is consistent with the observation at lower energies, where the there dominating Roper process proceeds via the $^1S_0$ incident partial wave, too.

In the measured $M_{\pi^0\pi^0}$ spectrum on the other hand we find a systematic low-mass enhancement, which is associated with the two pions flying in parallel both in lab and overall center-of-mass systems - as exhibited in the distributions of the $\pi^0\pi^0$ opening angle in Fig.7. This situation is in line with the situation observed in the exclusive measurements of double-pionic fusion processes discussed above for the ABC effect.

We note, however, that in the $pp$ collision case, where the nucleons in
Figure 7: Preliminary results[10] from the exclusive measurements of the reaction $pp \rightarrow pp\pi^0\pi^0$ for $\pi^0\pi^0$ invariant masses $M_{\pi^0\pi^0}$ (left) and opening angles $\delta_{\pi^0\pi^0}$ between the two pions in the overall center-of-mass system (right) at $T_p = 1.0$ GeV (top), 1.1 GeV (middle) and 1.2 GeV bottom). The shaded areas show the corresponding distributions for pure phase space.

the final state stay unbound, the introduction of a $\Delta\Delta$ interaction does not produce any significant $\pi\pi$ low-mass enhancement. For a proper description of the $\pi^0\pi^0$ low-mass enhancement there we possibly have to go back to the original idea [1] of an unusually strong $\pi\pi$ interaction as the origin of the ABC effect. However, as we see only now from the kinematically complete data samples, this unusual $\pi\pi$ interaction cannot be understood to be the same one as studied in the vacuum but rather as a $\pi\pi$ interaction, which obviously is associated with the presence of nearby baryons forming a $\Delta\Delta$ system in the intermediate state.

Yet another interpretation discussed previously in connection with $\pi\pi$ low-mass enhancement and ABC effect, respectively, has been the hypothesis of Bose-Einstein correlations[11, 19], which are expected to show up in case of sources emitting identical bosons in a stochastically independent manner.
However, in such a scenario not only the $\pi^0\pi^0$ channel should exhibit a low-mass enhancement, but the $\pi^+\pi^+$ channel, too. The latter channel is very hard to access, since it is connected with the production of two neutrons, the detection of which is very difficult experimentally. Using the capability of the WASA setup to detect neutrons with some finite efficiency, we have been able to obtain exclusively measured data for the first time for this channel. As a result no special $\pi^+\pi^+$ low-mass enhancement is found there, excluding thus the Bose-Einstein correlation scenario \cite{10}.

So whereas the double-pionic fusion reactions appear to have found a reasonable explanation by the strong attractive force in the $\Delta\Delta$ system, this explanation is not sufficient for the low-mass enhancement in the basic reaction leading to the unbound two-nucleon system, for which an explanation is still pending. However, one can not exclude that such an explanation, if found, might also pertain to fused systems and thus provide an explanation for those as well, providing an alternative to the one presented here.

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