ABC effect in double-pionic nuclear fusion and a pn resonance as its possible origin*

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Abstract A short overview over the ABC phenomenon is given, which is known since 50 years without any satisfactory explanation. On the basis of new exclusive and kinematically complete data obtained with the WASA detector at COSY we show that this phenomenon is linked with a resonant energy dependence in the total cross section of isoscalar double-pionic fusion processes. This resonance structure is connected with the baryon-baryon system, in particular with the pn and ΔΔ systems, however, has a mass, which is 90 MeV below the nominal ΔΔ threshold and a width of only 70 MeV, i.e., five times smaller than expected from a conventional t-channel ΔΔ scenario.

Key words ABC effect, baryon-baryon resonance, double-pionic fusion, isoscalar resonance

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1 Introduction

The experimental program of WASA-at-COSY deals with the production of meson and baryon systems by initial nucleon-nucleon collisions as well as with the subsequent decay of such systems [1]. This provides also the possibility to study experimentally the formation of exotic states in the production of few-nucleon systems. A long-standing and yet unsolved problem in few-body systems is the so-called ABC-effect, which has been a puzzle since 50 years. It deals with double-pionic fusion reactions leading to bound few-nucleon systems.

The acronym ABC stands for an unexpected enhancement at low masses in the invariant ππ mass spectrum $M_{\pi\pi}$ first observed by Abashian, Booth and Crowe [2] in the double pionic fusion of deuterons and protons to ^{3}He. Follow-up experiments [3–13] revealed this effect to be of isoscalar nature with regard to the ππ system and to happen only in cases, where the two-pion production process leads to a bound nuclear system. With the exception of low-statistics bubble-chamber measurements all previous experiments carried out on this issue have been inclusive measurements conducted preferentially with single-arm magnetic spectrometers for the detection of the emitted fused nuclei.

Initially the low-mass enhancement had been interpreted as an unusually large ππ scattering length or as evidence for the σ meson [2]. Since the effect occured particularly strong at beam energies corresponding to the excitation of two Δs in the nuclear system, the ABC effect was interpreted later on by a t-channel ΔΔ 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 [14–19].

This contribution concentrates on the ABC-effect in the most basic system, the pn→ $d\pi^0\pi^0$ reaction, where new exclusive high-statistics measurements have been carried out with WASA@COSY.

2 Experimental results

Single and multi-pion production as well as η, ω, η′ and K production in nucleon-nucleon collisions have been studied systematically in recent years at the proton storage rings CELSIUS and COSY [1]. In two-pion production initiated by nucleon-nucleon collisions the single-nucleon excitation is favored at energies close to threshold. Since single-Δ excitation in

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nucleon-nucleon collisions produces only single-pion production to first order, this excitation is highly suppressed in two-pion production. On the contrary, the excitation of the Roper resonance and its subsequent decay into N$\pi\pi$ channels is not hindered and hence dominates the near-threshold $\pi\pi$ production. In fact, the respective measurements conducted at CELSIUS/WASA [20–22] with the WASA detector setup [23] and at COSY-TOF [24] give results for the Roper resonance properties, which agree well with most recent results from analyses of photo- and pion-induced reactions [25].

At higher energies double-nucleon excitations take over. For $T_\mathrm{p} > 1$ GeV the $\Delta\Delta$ excitation gets the dominant process as can be observed in the respective differential cross section for the Nπ invariant masses. In Refs. [26–29] it is demonstrated that all pp initiated two-pion production channels pp$\pi^0\pi^0$, pp$\pi^+\pi^-$, nn$\pi^+\pi^+$ and pn$\pi^+\pi^0$ may be reasonably well described by Roper, $\Delta\Delta$ and possibly $\Delta(1600)$ excitations in the course of the two-pion production process. The latter excitation plays only a major role in the nn$\pi^+\pi^+$ channel. Note that all these channels have total isospin one.

However, we find strong disagreement with such predictions in the case of an isoscalar two-pion production leading to a nuclear bound system in the final state. This observation leads us again to the long-standing puzzle of the so-called ABC-effect.

From the first exclusive and kinematically complete double-pionic fusion measurements of solid statistics conducted at CELSIUS/WASA a number of remarkable features emerged:

1) In the $\pi\pi$ invariant mass distributions of the investigated reactions pn $\rightarrow$ d$\pi^0\pi^0$ [30, 31], pd$\rightarrow{}^3$He$\pi^0\pi^0$ [32], pd$\rightarrow{}^3$He$\pi^+\pi^-$ [32], dd$\rightarrow{}^4$He$\pi^0\pi^0$ [33] and dd$\rightarrow{}^4$He$\pi^+\pi^-$ [33] no significant high-mass enhancement is seen – contrary to what was recorded in inclusive measurements with single-arm magnetic spectrometers and also contrary to the theoretical predictions based on the t-channel $\Delta\Delta$ process.

2) Measurements of the most basic double-pionic fusion process, the pn$\rightarrow$ d$\pi^0\pi^0$ reaction, reveal a peculiar resonance-like behavior [30, 31] in the energy dependence of the total cross section, which indicates a resonance in pn and $\Delta\Delta$ systems at a mass roughly 100 MeV below the nominal $\Delta\Delta$ threshold at the mass of twice the Δ mass. Even more astonishingly, the observed width of this resonance structure is much smaller than expected from a conventional t-channel $\Delta\Delta$ excitation process, which gives a width of twice the Δ width.

3) Contrary to the situation in the isoscalar double-pionic channels the isovector double-pionic fusion process pp$\rightarrow$ d$\pi^+\pi^0$ does not exhibit any ABC effect [34, 35]. This is not unexpected, since Bose symmetry excludes relative s-waves in the isosvector $\pi\pi$ system. And the allowed relative p-wave suppresses any strength at low invariant $\pi\pi$ masses. Therefore this channel is very well suited as crucial test for the conventional t-channel $\Delta\Delta$ process. Indeed, this process describes both the observed differential distributions and the energy dependence of the total cross section.

In order to shed more light onto this issue we have measured the double-pionic fusion processes to D, ^{3}He and ^{4}He exclusively over practically the full phase space at WASA@COSY with orders of magnitude higher statistics than in the previous measurements.

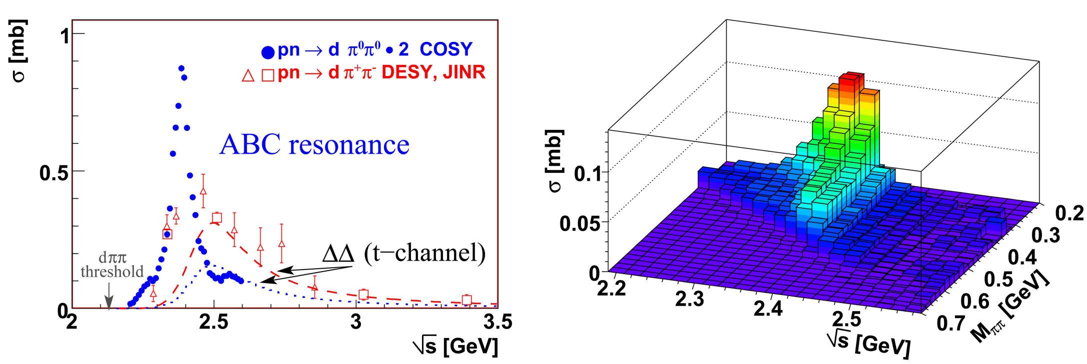

Fig. 1. Left: Energy dependence of the total cross section for the pn$\rightarrow$ d$\pi\pi$ reaction from threshold up to $\sqrt{s}$=3.5 GeV. Data for the d$\pi^+\pi^-$ channel are from JINR Dubna [9] (squares) and DESY [5] (open triangles). The results of this work for the $\pi^0\pi^0$ channel are scaled by the isospin factor of two and are given by the full circles. Dashed and dotted lines represent t-channel $\Delta\Delta$ calculations for $\pi^+\pi^-$ and $\pi^0\pi^0$ channels, respectively. Right: Energy dependence of the $\pi^0\pi^0$ invariant mass $M_{\pi^0\pi^0}$ shown by a 3D-plot of $M_{\pi^0\pi^0}$ versus $\sqrt{s}$. From Ref. [36].

For the most basic fusion process, the one leading to deuterium, first results [36] from the data analysis are now available, see Fig. 1: At the right-hand side of the figure the spectrum of the $\pi^0\pi^0$-invariant mass $M_{\pi^0\pi^0}$ is shown in dependence of total energy in the center-of-mass system $\sqrt{s}$. Our data exhibit a striking low-mass enhancement, however, no striking high-mass enhancement predicted by conventional $\Delta\Delta$ calculations. In addition, the total cross section (Fig. 1, left-hand side) exhibits a narrow resonance-like structure – again in contradiction to the conventional t-channel $\Delta\Delta$ process (dotted curve for the $\pi^0\pi^0$ channel - and dashed curve for the $\pi^+\pi^-$ channel). As we see from Fig. 1, the ABC-effect, i.e. the low-mass enhancement in the $\pi\pi$-mass spectrum is present only at energies $\sqrt{s}$ within this narrow resonance structure. This structure in the total cross section has its maximum about 90 MeV below the $\Delta\Delta$ threshold, i. e. twice the Δ mass. Even more spectacular is the narrow width of only 70 MeV, which is five times smaller than twice the Δ width, which is the width expected from the conventional t-channel $\Delta\Delta$ excitation. Indeed, describing this structure by a s-channel resonance ansatz leads to a surprisingly good description of both the total and the differential distributions including the ABC effect in the $M_{\pi^0\pi^0}$ spectra [31].

Such a baryon-baryon resonance has been predicted by various quark-model calculations [37–42], some of which even predict this resonance to be a member of a dibaryon multiplet.

Since the ABC effect is observed also for double-pionic fusion processes to heavier nuclei [6–11, 32, 33, 43], we conclude that this resonance is obviously robust enough to survive even in the nuclear medium.

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