

ABC Resonance Structure in the Double-Pionic Fusion to ${}^4\text{He}$

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Exclusive and kinematically complete high-statistics measurements of the double pionic fusion reaction $dd \rightarrow {}^4\text{He}\pi^0\pi^0$ have been performed in the energy range 0.8 - 1.4 GeV covering thus the region of the ABC effect, which denotes a pronounced low-mass enhancement in the $\pi\pi$ -invariant mass spectrum. The experiments were carried out with the WASA detector setup at COSY. Similar to the observation in the basic $pn \rightarrow d\pi^0\pi^0$ reaction, the data reveal a correlation between the ABC effect and a resonance-like energy dependence in the total cross section. The maximum occurs at $m = 2.37 \text{ GeV} + 2m_N$, *i.e.* at the same position as in the basic reaction. The observed resonance width $\Gamma \approx 160 \text{ MeV}$ can be understood from broadening due to Fermi motion of the nucleons in

initial and final nuclei together with collision damping. Differential cross sections are described equally well by the hypothesis of a pn resonance formation during the reaction process.

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The ABC effect denotes a pronounced low-mass enhancement in the $\pi\pi$ -invariant mass spectrum of double-pionic fusion reactions and is named after Abashian, Booth and Crowe [1], who observed this effect for the first time in a single-arm magnetic spectrometer measurement of the $pd \rightarrow {}^3\text{He}X$ reaction. Recent exclusive and kinematically complete measurements of the basic $pn \rightarrow d\pi^0\pi^0$ reaction revealed the ABC effect to be strictly correlated with a resonance-like structure at a mass of 2.37 GeV in the integral cross section [2, 3]. The data are consistent with a $I(J^P) = 0(3^+)$ assignment for this resonance structure [3, 4].

Observation of pronounced ABC effects has also been reported from recent exclusive measurements of fusion reactions to He isotopes: $pd \rightarrow {}^3\text{He}\pi^0\pi^0$ and $\pi^+\pi^-$ [6] as well as $dd \rightarrow {}^4\text{He}\pi^0\pi^0$ and $\pi^+\pi^-$ [7]. If the hypothesis of a pn resonance causing the ABC effect is correct, then we should also observe a resonance-like energy dependence of the total cross section in all these cases. In such a scenario the reaction would be driven by an active pn pair as in the basic double-pionic fusion reaction, but with the difference that there are now one or two spectator nucleons which merge with the active ones to the final He isotope.

In order to investigate this issue in a comprehensive way we measured the energy dependence of the *isoscalar* double-pionic fusion process $dd \rightarrow {}^4\text{He}\pi^0\pi^0$ with the WASA detector including deuterium pellet target [8] at COSY (FZ Jülich) using deuteron beam energies in the range $T_d = 0.8 - 1.4$ GeV. That way the full energy range, where the ABC effect was observed in previous inclusive single-arm magnetic spectrometer measurements [9–11], was covered.

The emerging ${}^4\text{He}$ particles were registered in the forward detector of WASA and identified by the ΔE -E technique. The photons from the π^0 decay were detected in the central detector [5]. Consequently four-momenta were measured for all emitted particles of an event. Together with the condition that two pairs of the detected photons have to fulfill the π^0 mass condition we have 6 overconstraints for the kinematic fit of an event.

Reaction particles have been detected over the full solid angle with the exception of those ${}^4\text{He}$ ejectiles (lab angles $< 3^\circ$), which escaped in the beam-pipe.

The absolute normalization of the data was obtained by a relative normalization to the $dd \rightarrow {}^3\text{He}n$ reaction measured simultaneously with the same trigger. Our results for this reaction in turn have been calibrated to the values of Ref. [12]. The error bars shown in Fig. 1 (solid: statistical; dotted: systematic) are dominated by

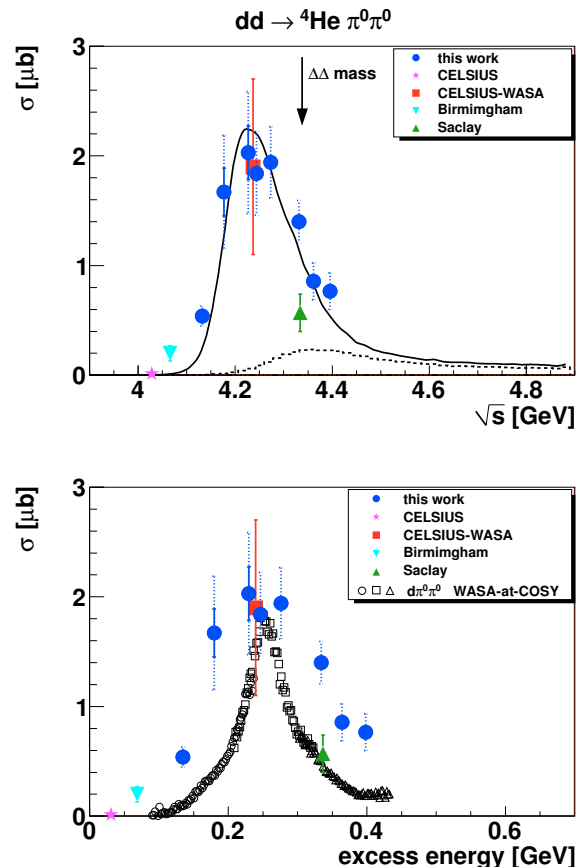


FIG. 1: **Top:** Total cross section of the $dd \rightarrow {}^4\text{He}\pi^0\pi^0$ reaction in dependence of the center-of-mass energy \sqrt{s} . Results of this work (solid circles) are compared to results from a previous exclusive measurement at CELSIUS/WASA [7] (square) as well as inclusive measurements at CELSIUS [14] (star), Birmingham [15] (inverted triangle) and Saclay [10] (triangle). The drawn lines represent a conventional t -channel $\Delta\Delta$ calculation [3] (dotted, scaled arbitrarily) as well as a calculation for an s -channel pn resonance [3] with $m = 2.37$ GeV and $\Gamma_{pn} = 124$ MeV (solid, normalized to the data) including the Fermi motion of the nucleons in initial and final nuclei. **Bottom:** Same as above, but now compared to the results for the basic $pn \rightarrow d\pi^0\pi^0$ (open symbols) reaction scaled down by a factor of 240.

the systematic uncertainties involved in this procedure [13].

The data obtained with WASA-at-COSY are in reasonable agreement with the only other exclusive measurement performed at CELSIUS at $T_d = 1.03$ GeV [7].

Results are shown in Figs. 1 - 4. Fig. 1 exhibits the measured energy dependence of the total cross section.

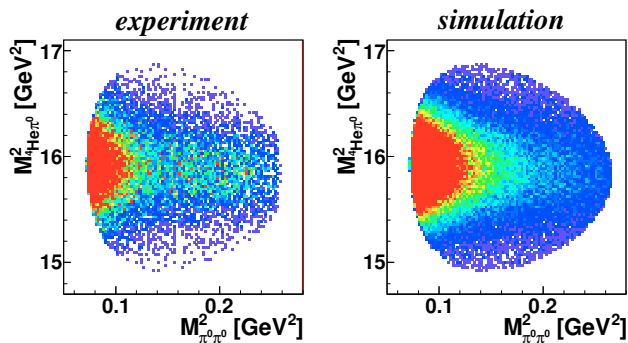


FIG. 2: Dalitz plot of $M_{4He\pi^0}^2$ versus $M_{\pi^0\pi^0}^2$ at the energy of the peak cross section ($\sqrt{s} = 4.24$ GeV). **Left:** data (highest $M_{\pi^0\pi^0}^2$ values cutted due to beam pipe, see text), **right:** calculation for an s -channel pn resonance with $m = 2.37$ GeV and $\Gamma = 124$ MeV including the Fermi motion of the nucleons in initial and final nuclei.

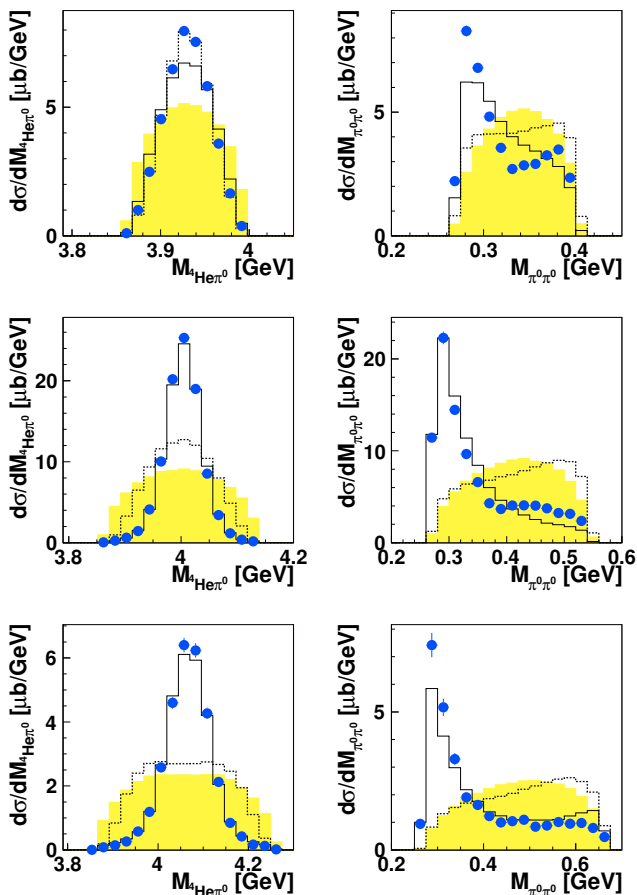


FIG. 3: Distributions of $M_{4He\pi^0}$ (left) and $M_{\pi^0\pi^0}$ (right) at $\sqrt{s} = 4.13, 4.27$ and 4.40 GeV. The shaded area denotes the phase-space distribution and the solid line a calculation of an s -channel pn resonance with $m = 2.37$ GeV and $\Gamma = 124$ MeV including the Fermi motion of the nucleons in initial and final nuclei. The dotted lines give a conventional t -channel $\Delta\Delta$ calculation.

In the upper part the data from this and from previous work are plotted versus the total energy \sqrt{s} in the center-of-mass system (cms). With the exception of the CELSIUS/WASA measurement [7] all other data originate from inclusive single-arm magnetic spectrometer measurements [10, 14, 15]. The latter include both the $\pi^0\pi^0$ and the $\pi^+\pi^-$ production channels. Since both are purely isoscalar reactions, the cross sections of both channels scale like 1:2, if we disregard the isospin violation due to different masses of neutral and charged pions. Therefore the values from the inclusive measurements [10, 14, 15] have been divided by three in Fig. 1. The data point at $\sqrt{s} = 4.06$ GeV is derived from a 0° -measurement assuming isotropy. Since we measure strongly anisotropic ${}^4\text{He}$ angular distributions even at the lowest energies, we expect that actually the total cross section is much lower than quoted in Ref. [15].

The total cross section data exhibit a very pronounced resonance-like energy distribution. In the lower part of Fig. 1 the data are plotted versus the excess energy of the reaction. That way we can directly compare with the total cross section results for the basic $pn \rightarrow d\pi^0\pi^0$ reaction. We see that the cross section maxima coincide in the excess energy, though the width of the structure is much larger in the ${}^4\text{He}$ case. However, it is still substantially smaller than the width of about $2\Gamma_\Delta$ of the conventional t -channel $\Delta\Delta$ process (dotted lines in Fig. 1). This process peaks at about $2m_\Delta + 2m_N - E_B$, where E_B denotes the nucleon binding energy difference between ${}^4\text{He}$ and the initial deuterons. As in the basic channel this occurs about 80 MeV above the observed maximum in the total cross section.

We discuss in the following two invariant mass and two angular distributions, which completely describe the 3-body reaction. The shape of all differential distributions remains rather unchanged over the full energy region measured (cf. Fig. 3).

Fig. 2 shows the Dalitz plots of the invariant mass squared $M_{4He\pi^0}^2$ versus $M_{\pi^0\pi^0}^2$ at the peak cross section ($\sqrt{s} = 4.24$ GeV). The Dalitz plot is very similar to that obtained in the basic reaction. It exhibits an enhancement in horizontal direction, in the region of the Δ excitation, as it prominently shows up in the $M_{4He\pi^0}$ spectra displayed in Fig. 3. This feature is consistent with the excitation of a $\Delta\Delta$ system in the intermediate state – as discussed for the basic reaction [3]. More prominent – and even still much more pronounced than in the basic reaction – we observe here the ABC effect as a significant enhancement at the low-mass kinematic limit of $M_{\pi^0\pi^0}$. Consequently the Dalitz plot is mainly populated along the $\pi\pi$ low-mass border line. The $M_{\pi^0\pi^0}$ distribution is shown on the right side of Fig. 3 for three different beam energies. It clearly exhibits the ABC effect at all measured energies. We note, in passing, that we do not see a particular high-mass enhancement as the inclusive data [9–11] suggest and as it was also predicted by model

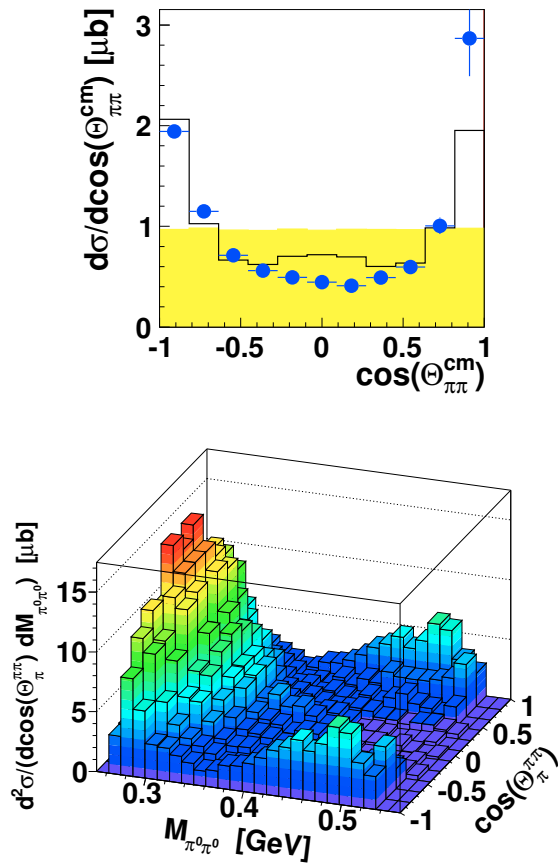


FIG. 4: Same as Fig. 3, but for angular distributions at the peak cross section ($\sqrt{s} = 4.27$ GeV). **Top:** cms distribution of $\pi^0\pi^0$ system, **bottom:** distribution of the pion angle $\Theta_{\pi^0\pi^0}$ in the $\pi^0\pi^0$ subsystem (Jackson frame) in dependence of $M_{\pi^0\pi^0}$.

calculations [16] specifically designed for the ${}^4\text{He}$ case.

In Fig. 4 we show a selection of angular distributions. In the upper part the angular distribution of the $\pi^0\pi^0$ -system in the center-of-mass system (cms) is shown. Since $\Theta_{\pi^0\pi^0} = 180^\circ - \Theta_{{}^4\text{He}}$ and since the particles in the incident channel are identical, the cms angular distribution must be symmetric about 90° and the $\pi^0\pi^0$ -angular distribution is identical to the ${}^4\text{He}$ -angular distribution. The observed angular dependence is similar to the corresponding one in the basic reaction, though significantly more peaked near $\cos\Theta = \pm 1$. At the bottom of Fig. 4 we show the lego plot of the distribution of the pion angle $\Theta_{\pi^0\pi^0}$ in the $\pi^0\pi^0$ -subsystem (Jackson frame) in dependence of $M_{\pi^0\pi^0}$. This angular distribution is somewhat convex curved in the ABC region (low-mass enhancement) as expected from the $pn \rightarrow d\pi^0\pi^0$ reaction. After an intermediate region, where the angular distribution flattens out, it gets very anisotropic at high $M_{\pi^0\pi^0}$ values resembling a d -wave distribution. Since the cms

π^0 -angular distribution (see Ref. [7]) exhibits a p -wave-like dependence as in the basic reaction [3], the following picture emerges from the differential distributions: In the ABC region the pions emerging from the $\Delta\Delta$ intermediate system couple to a s -wave pion pair, which is in relative d -wave to the ${}^4\text{He}$ system. At high $\pi^0\pi^0$ -invariant masses the situation is just reversed. In this picture the deuteron-like np pair resulting from the $\Delta\Delta$ decay merges with the passive np pair to the ${}^4\text{He}$ ground state.

Since the features, which we observe here, are very similar to those observed for the basic double-pionic fusion reaction, we adapt the ansatz used there for the description of the ${}^4\text{He}$ case [13]. There are only two differences: First, the nucleons' momenta are smeared due to their Fermi motion in initial and final nuclei. In particular the Fermi motion in the strongly bound ${}^4\text{He}$ nucleus leads to a substantial smearing of the energy dependence in the total cross section adding nearly 40 MeV in the total width. To understand the full observed width we need in addition a broadening of (124 - 68) MeV, which we ascribe to collision damping of the pn resonance in the nuclear medium – a feature well known, *e.g.*, from Δ excitation in nuclei [17]. Second, since the ABC effect appears even more concentrated towards low $\pi^0\pi^0$ momenta in the ${}^4\text{He}$ case, we have to decrease the phenomenological cut-off parameter [3] in the $\Delta\Delta$ vertex function by about a factor of two. The resulting calculation is shown in Figs. 1 - 4 by the solid lines providing a reasonable description of the data. Since these calculations are semiclassical MC simulations, the cut-off parameter is likely to fudge a number of shortcomings in our simple treatment of the problem. Hence a full quantum mechanical microscopic calculation would be very desirable.

In conclusion, our data on the double-pionic fusion to ${}^4\text{He}$ establish the correlation of a resonance-like energy dependence in the total cross section with the ABC effect in very much the same way as shown for the basic double-pionic fusion reaction to deuterium. A calculation based on the s -channel pn resonance with $I(J^P) = 0(3^+)$, $m = 2.37$ GeV and $\Gamma = 124$ MeV gives a good account of the observed distributions. The enlarged width of the resonance-structure in the total cross section is explained by the Fermi motion of the nucleons in initial and final nuclei as well as collision damping. That way the ABC effect in the double-pionic fusion to nuclei is traced back to a pn resonance, which obviously is strong enough to survive even in the nuclear medium.

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