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Abashian-Booth-Crowe resonance structure in the double pionic fusion to ^{4}He

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Exclusive and kinematically complete high-statistics measurements of the double pionic fusion reaction $dd \to {}^4\mathrm{He}\pi^0\pi^0$ have been performed in the energy range 0.8–1.4 GeV covering thus the region of the Abashian-Booth-Crowe 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 the cooler synchrotron at Forshungszentrum Julich GmbH. Similar to the observation in the basic $pn \to d\pi^0\pi^0$ reaction, the data reveal a correlation between the ABC effect and a resonancelike energy dependence in the total cross section. The maximum occurs at $m = 2.37$ GeV $+ \; 2m_N$, i.e., at the same position as in the basic reaction. The observed resonance width $\Gamma \approx 160$ 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 Booth, Abashian, and Crowe [1], who observed this effect for the first time in a single-arm magnetic spectrometer measurement of the $pd \rightarrow {}^3\mathrm{He}X$ 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 resonancelike 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]. The situation is also remarkable insofar as no nonconventional processes have been observed in pp, i.e., *isovector*-induced two-pion reactions. The general situation of the two-pion production in nucleon-nucleon collisions is reviewed in Ref. [5].

Observation of pronounced ABC effects has also been reported from recent exclusive measurements of fusion reactions to He isotopes: $pd \rightarrow {}^3\mathrm{He}\pi^0\pi^0$ and $\pi^+\pi^-$ [6] as well as $dd \rightarrow {}^4\mathrm{He}\pi^0\pi^0$ and $\pi^+\pi^-$ [7]. If the hypothesis of a pn resonance causing the ABC effect is correct, then we should also observe a resonancelike 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.

If true that such a bosonic dibaryon resonance survives in a nuclear surrounding, then this may have a significant impact on the equation of state for nuclear matter as needed for a deeper understanding of, e.g. the evolution of compressed nuclear matter in the course of heavy-ion collisions or in compact stars—see, e.g., Refs. [8–10]. Bosons are not Pauli-blocked and as such allow for higher densities under the same energy or pressure conditions.

In order to investigate this issue in a comprehensive way we measured the energy dependence of the *isoscalar* double pionic fusion process $dd \rightarrow {}^4\mathrm{He}\pi^0\pi^0$ with the WASA detector including a deuterium pellet target [11,12] at the cooler synchrotron at Forschungszentrum Julich GmbH (COSY) and by 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 [13–15], was covered.

The trigger for a valid event was just a single track in the forward detector of WASA with high thresholds in its first layers, in order to suppress fast protons and deuterons. The data rate was at moderate 2 kHz. The selection criteria were a single He track in the forward detector and four neutral hits in the central detector.

The emerging ^{4}He particles were identified by the ΔE-E technique. The photons from the π^0 decay were detected and identified in the central detector [11]. 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 six overconstraints for the kinematic fit of an event. From the three possible combinations to reconstruct the four-momenta of the two pions out of four photon signals the one with the smallest χ^2 has been selected [16,17].

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

The absolute normalization of the data was obtained by a relative normalization to the $dd \rightarrow {}^3\mathrm{He}n$ reaction measured simultaneously with the same trigger. Our results for this reaction in turn have been calibrated to the values of Ref. [18]. The error bars shown in Fig. 1 (solid, statistical; dotted, systematic) are dominated by the systematic uncertainties involved in this procedure [16].

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. Figure 1 exhibits the measured energy dependence of the total cross section. 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 [14,19,20]. The latter include both the $\pi^0\pi^0$ and the $\pi^+\pi^-$ production channels. Because 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 [14,19,20] have been divided by three in Fig. 1, to be comparable to our data, which contain only the $\pi^0\pi^0$ channel. The data point at $\sqrt{s} = 4.06$ GeV is derived from a 0° measurement assuming isotropy. Because we measure strongly anisotropic ^{4}He angular distributions even at the lowest energies, we expect the total cross section to be much lower than that quoted in Ref. [20].

The total cross section data exhibit a very pronounced resonancelike 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}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

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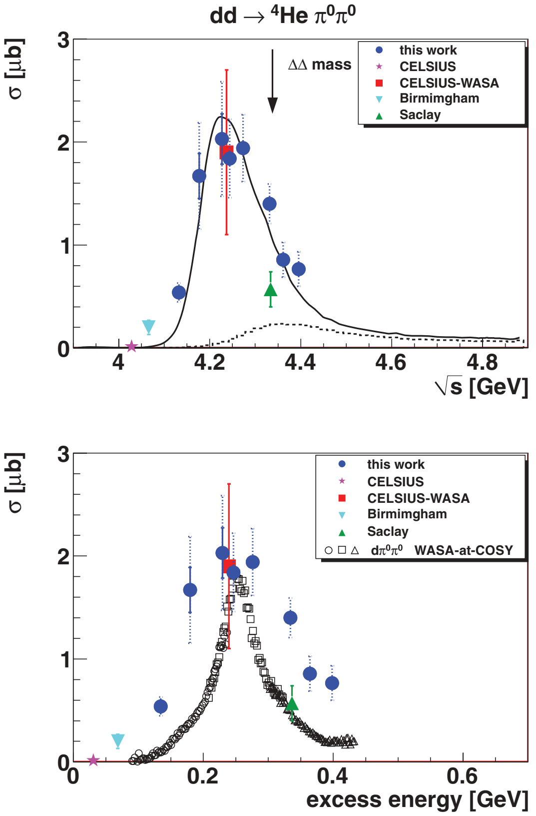

FIG. 1. (Color online) Top: Total cross section of the $dd \to {}^4\mathrm{He}\pi^0\pi^0$ reaction in dependence of the center-of-mass energy $\sqrt{s}$. Results of this work (solid circles) are compared to results from a previous exclusive measurement at CELSIUS/WASA [7] (square) as well as inclusive measurements at CELSIUS [19] (star), Birmingham [20] (inverted triangle), and Saclay [14] (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 the initial and final nuclei. Bottom: Same as above, but now compared to the results for the basic $pn \to d\pi^0\pi^0$ (open symbols) reaction scaled down by a factor of 240.

^{4}He and the initial deuterons. As in the basic channel this peaking occurs about 80 MeV above the observed maximum in the total cross section.

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

Figure 2 shows the Dalitz plots of the invariant mass squared $M^2_{{}^4\mathrm{He}\pi^0}$ versus $M^2_{\pi^0\pi^0}$ 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 the horizontal direction, in the region of the Δ excitation, as it prominently shows up in the $M_{{}^4\mathrm{He}\pi^0}$ 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 borderline. 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 [13–15] suggest and as it was also predicted by model calculations [21] specifically designed for the ^{4}He case.

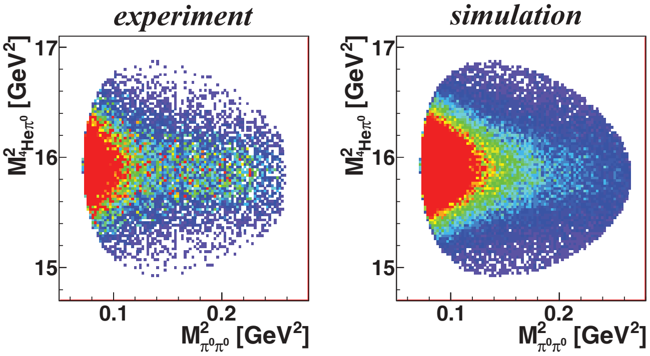

FIG. 2. (Color online) Dalitz plot of $M^2_{{}^4\mathrm{He}\pi^0}$ versus $M^2_{\pi^0\pi^0}$ at the energy of the peak cross section ($\sqrt{s} = 4.24$ GeV). Left: Data (highest $M^2_{\pi^0\pi^0}$ values cut by the beam pipe, see text). Right: Calculation for an s-channel pn resonance with $m = 2.37$ GeV and $\Gamma = 124$ MeV including the Fermi motion of the nucleons in the initial and final nuclei.

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 cms is shown. Because $\Theta_{\pi^0\pi^0} = 180^\circ - \Theta_{{}^4\mathrm{He}}$ and because 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}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 $\Theta_{\pi^0}^{\pi^0\pi^0}$ 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 $pn \to d\pi^0\pi^0$ 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. Because 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 an s-wave pion pair, which is in relative d-wave to the ^{4}He system. At high $\pi^0\pi^0$ invariant masses the situation is just reversed. In this picture the deuteronlike np pair resulting from the $\Delta\Delta$ decay merges with the passive np pair to the ^{4}He ground state.

Because 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}He case [16]. There are only two differences. First, the

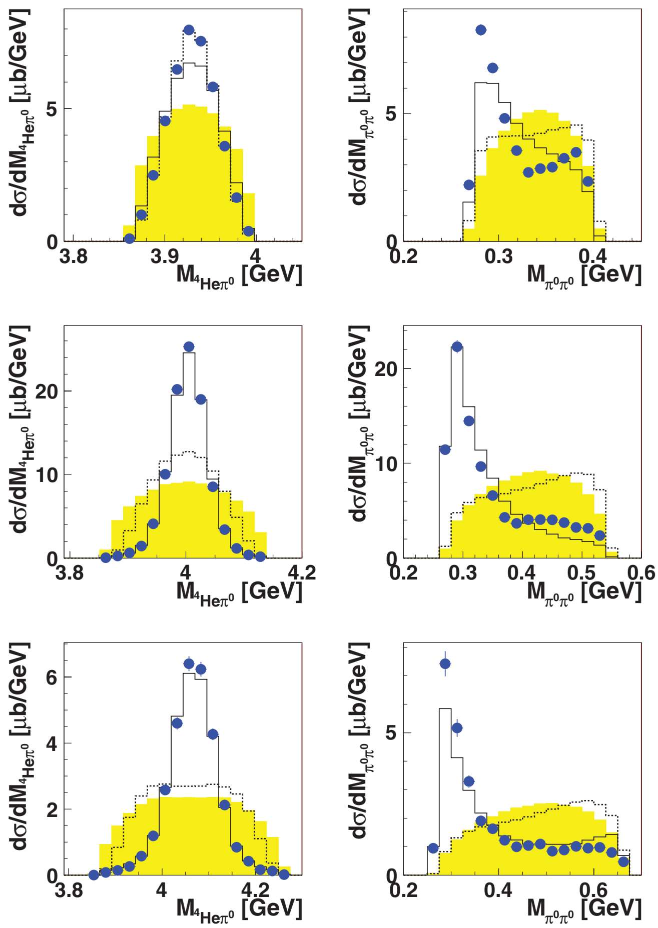

FIG. 3. (Color online) Distributions of $M_{^4\mathrm{He}\pi^0}$ (left) and $M_{\pi^0\pi^0}$ (right) at $\sqrt{s} = 4.13$, 4.27, and 4.40 GeV. The shaded area denotes the phase-space distribution and the solid line a calculation of an s-channel pn resonance with $m = 2.37$ GeV and $\Gamma = 124$ MeV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

nucleons' momenta are smeared due to their Fermi motion in the initial and final nuclei. In particular the Fermi motion in the strongly bound ^{4}He nucleus leads to a substantial smearing of the energy dependence in the total cross section adding nearly 40 MeV to the total width. To understand the full observed width we need in addition a broadening of (124–68) MeV = 56 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 [22]. Second, because the ABC effect appears even more concentrated towards low $\pi^0\pi^0$ momenta in the ^{4}He case, we have to decrease the phenomenological cutoff parameter [3] in the $\Delta\Delta$ vertex function by about a factor of 2. The resulting calculation is shown in Figs. 1–4 by the solid lines providing a reasonable description of the data. Because these calculations are semiclassical Monte Carlo simulations, the cutoff 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.

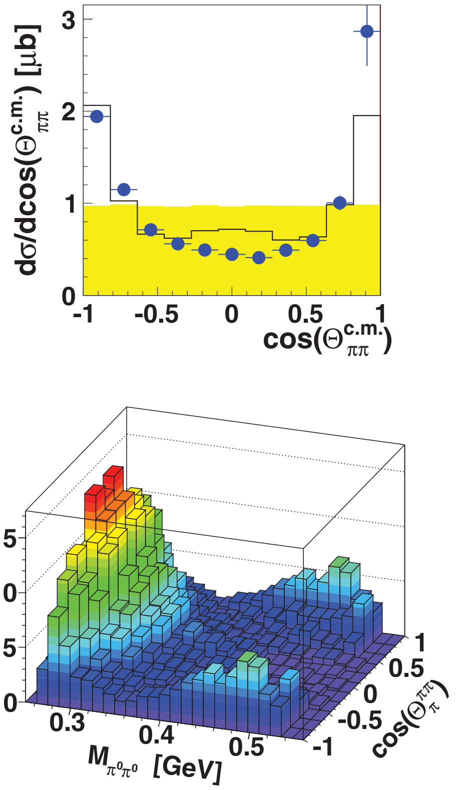

FIG. 4. (Color online) Same as Fig. 3, but for angular distributions at the peak cross section ($\sqrt{s} = 4.27$ GeV). Top: cms distribution of the $\pi^0\pi^0$ system. Bottom: Distribution of the pion angle $\Theta_{\pi^0}^{\pi^0\pi^0}$ in the $\pi^0\pi^0$ subsystem (Jackson frame) in dependence of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

In conclusion, our data on the double pionic fusion to ^{4}He establish the correlation of a resonancelike 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 the initial and final nuclei as well as by 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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