Abashian-Booth-Crowe Effect in Basic Double-Pionic Fusion: A New Resonance?

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We report on an exclusive and kinematically complete high-statistics measurement of the basic double-pionic fusion reaction $pn \rightarrow d\pi^0\pi^0$ over the full energy region of the ABC effect, a pronounced low-mass enhancement in the $\pi\pi$-invariant mass spectrum. The measurements, which cover also the transition region to the conventional t-channel $\Delta\Delta$ process, were performed with the upgraded WASA detector setup at COSY. The data reveal the Abashian-Booth-Crowe effect to be uniquely correlated with a Lorentzian energy dependence in the integral cross section. The observables are consistent with a narrow resonance

with $m = 2.37$ GeV, $\Gamma \approx 70$ MeV and $I(J^P) = 0(3^+)$ in both pn and $\Delta\Delta$ systems. Necessary further tests of the resonance interpretation are discussed.

The nature of the Abashian-Booth-Crowe (ABC) effect, which denotes a pronounced low-mass enhancement in the $\pi\pi$-invariant mass spectrum of double-pionic fusion reactions, has been a puzzle all the time since its first observation 50 years ago [1]. Follow-up experiments revealed this effect to be correlated with the production of an isoscalar pion pair. Previous interpretations were based on the mutual excitation of the two colliding nucleons into the $\Delta(1232)$ resonance by meson exchange (*t*-channel $\Delta\Delta$ process), which leads to both a low-mass and a high-mass enhancement in isoscalar $M_{\pi\pi}$ spectra [2–5], in line with the momentum distributions from inclusive measurements.

For the reactions $pn \rightarrow d\pi^0\pi^0$ [6], $pd \rightarrow {}^3\text{He}\pi\pi$ [7] and $dd^4\text{He}\pi\pi$ [8] the first exclusive double-pionic fusion measurements of solid statistics carried out at CELSIUS/WASA firmly established the presence of a pronounced low $\pi\pi$-mass enhancement. In addition, the first reaction showed a peculiar resonancelike behavior in the energy dependence of the total cross section [6]—indicative of a resonance in pn and $\Delta\Delta$ systems at a mass roughly 90 MeV below $2m_\Delta$ and a width much smaller than expected from the conventional *t*-channel $\Delta\Delta$ excitation process.

On the other hand, in the *isovector* reactions $pp \rightarrow NN\pi\pi$ no evidence for a significant ABC effect is found [9–11]—including the limiting case of a fusion to a quasibound pp pair in an *s* wave [11,12]. In all these cases the observables are well accounted for by Roper and *t*-channel $\Delta\Delta$ processes.

In order to investigate this issue in a comprehensive way we measured the basic *isoscalar* double-pionic fusion process $pn \rightarrow d\pi^0\pi^0$, exclusively over the almost complete phase space with orders of magnitude higher statistics than obtained previously [6]. The experiment was carried out with the upgraded WASA detector setup [13] at COSY via the reaction $pd \rightarrow d\pi^0\pi^0 + p_{\text{spectator}}$ using proton beam energies of $T_p = 1.0$, 1.2 and 1.4 GeV. Because of Fermi motion of the nucleons in the target deuteron the quasifree reaction proceeds via a range of effective collision energies with overlapping regions 2.22 GeV $\leq \sqrt{s} \leq 2.36$ GeV (triangles in Fig. 2), 2.33 GeV $\leq \sqrt{s} \leq 2.44$ GeV (dots) and 2.42 GeV $\leq \sqrt{s} \leq 2.56$ GeV (squares). The emerging deuterons were registered in the forward detector of WASA and identified by the $\Delta E - E$ technique. The photons from the π^0 decay were detected in the central detector.

That way four-momenta were measured for all particles of an event—except for the very low-energetic spectator proton, which did not reach any detector element. Since the reaction was measured kinematically overdetermined, the spectator momentum could be reconstructed and kinematic

fits with 3 overconstraints performed for each event. From the complete kinematic information available also the relevant total energy in the pn system could be reconstructed for each event individually.

The absolute normalization of the data has been obtained by a relative normalization to quasifree η, $\pi^+\pi^0$ and $\pi\pi$ production measured simultaneously with the same trigger.

The data obtained with WASA-at-COSY are in good agreement with those obtained previously [6,14] at CELSIUS, however, of much better statistics and precision. Results are shown in Figs. 1–5. In the overlap regions of the 3 measured energy ranges the data agree within their uncertainties, particularly in absolute magnitude within the normalization errors. Figure 1 exhibits the momentum distribution obtained for the spectator proton. It is found to be consistent with that for a quasifree process. In order to minimize contributions from possible nonquasifree processes we only use data with $p_{\text{spectator}} < 0.16$ GeV/c.

Figure 2 shows the energy dependence of the total cross section. It exhibits a very pronounced Lorentzian shaped energy distribution reminiscent of a resonance. The width of this structure is 4 times smaller than that of a conventional $\Delta\Delta$ excitation process with a width of about $2\Gamma_\Delta$. Also, the peak cross section is about 80 MeV below the nominal mass of $2m_\Delta$. The cross section for the *t*-channel $\Delta\Delta$ process as given in Fig. 2 by the dotted line is derived by isospin relations from the known $pp \rightarrow d\pi^+\pi^0$ cross section [9] assuming the absence of initial
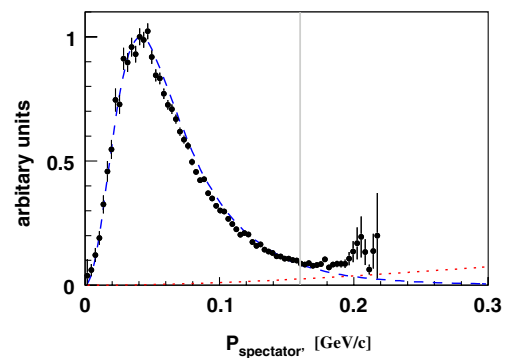

FIG. 1 (color online). Distribution of the spectator proton momenta in the $pd \rightarrow d\pi^0\pi^0 + p_{\text{spectator}}$ reaction. Data are given by solid dots. The dashed line shows the expected distribution for the quasifree process based on the CD Bonn potential [19] deuteron wave function. For comparison the dotted line gives the pure phase-space distribution as expected for a coherent reaction process. It extends up to momenta of 1.5 GeV/c and peaks around 0.7 GeV/c. For the data analysis only events with $p_{\text{spectator}} < 0.16$ GeV/c (vertical line) have been used.
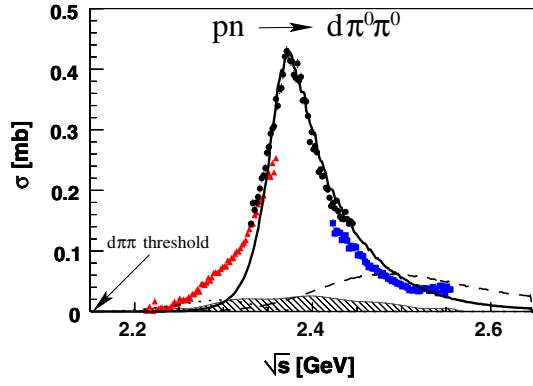
FIG. 2 (color online).   Total cross sections obtained from this experiment on $pd \to d\pi^0\pi^0 + p_{spectator}$ for the beam energies $T_p = 1.0$ GeV (triangles), 1.2 GeV (dots), and 1.4 GeV (squares) normalized independently. Shown are the total cross section data after acceptance, efficiency and Fermi motion corrections. The hatched area indicates systematic uncertainties. The drawn lines represent the expected cross sections for the Roper excitation process (dotted) and the t-channel $\Delta\Delta$ contribution (dashed) as well as a calculation for a s-channel resonance with $m = 2.37$ GeV and $\Gamma = 68$ MeV (solid).

state interactions. Based on Ref. [10] the only other major contribution to this reaction channel should be the Roper excitation process (dashed line based on Ref. [5] with updated $N^* \to \Delta\pi$ branching ratio [15,16]), although there might be other, non—resonant contributions of relevance [17]. It seems that conventional processes contributing to $pn \to d\pi^0\pi^0$ not only are much smaller in magnitude, but also at variance with the energy dependence of the data.

Figure 3 displays the cross section in dependence of the $\pi\pi$-invariant mass $M_{\pi^0\pi^0}$ and the center-of-mass energy $\sqrt{s}$. A pronounced low-mass enhancement is observed in the $M_{\pi^0\pi^0}$ distribution—the ABC effect—but only at energies within the resonance-structure ("ABC region") in the total cross section. Outside this structure the $M_{\pi^0\pi^0}$ distribution gets rather flat.
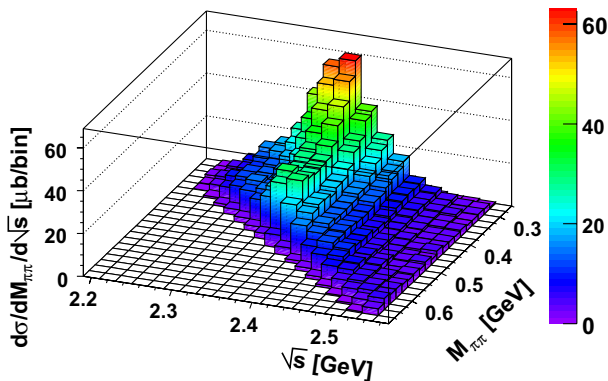

FIG. 3 (color online).   Energy dependence of the cross section as a function of the $\pi^0\pi^0$ invariant mass $M_{\pi^0\pi^0}$ shown by a 3D plot of the cross section versus $M_{\pi^0\pi^0}$ and $\sqrt{s}$.

Figure 4 shows the Dalitz plots of the invariant mass squared $M^2_{d\pi^0}$ versus $M^2_{\pi^0\pi^0}$ for two energies: at the peak cross section ($\sqrt{s} = 2.38$ GeV) and above the ABC region ($\sqrt{s} = 2.50$ GeV). The Dalitz plots exhibit an enhancement in horizontal direction, in the region of the Δ excitation, as it prominently shows up in the $M^2_{d\pi^0}$ projection in Fig. 4, bottom. This feature is consistent with the excitation of a $\Delta\Delta$ system in the intermediate state—from now on we assume this configuration to be realized. Above the ABC region the Dalitz plot displays only gentle maxima both at low and high $\pi\pi$ masses, as predicted by the conventional t-channel $\Delta\Delta$ process [2]. In contrast, at the peak cross section we see a large enhancement at the low-mass kinematic limit of $M^2_{\pi^0\pi^0}$.

Angular distributions allow us to deduce the total angular momentum of the reaction. Within the ABC region the angular distributions stay very similar in shape to those at the peak cross section. Since the deuteron is a loosely bound state the relative momentum of the two nucleons after pion emission must be small and may be neglected relative to the pion momenta. Therefore, from the pion and deuteron momenta the Δ momenta can be reconstructed. Deuteron and Δ angular distributions in the center-of-mass system (c.m.s.) are displayed in Fig. 5. The very low-energetic deuterons going backward in the c.m.s. are not completely covered in our measurements, and thus the systematic uncertainties indicated by the hatched area in Fig. 5 get very large in this region. Within uncertainties the angular distributions are symmetric around 90° as demanded for an isospin conserving reaction in a NN system with definite initial isospin. The Δ angular distribution is
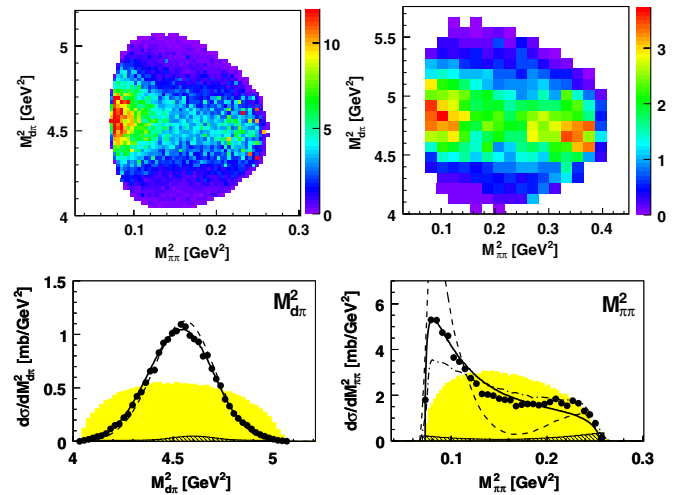

FIG. 4 (color online).   Top: Dalitz plots of $M^2_{d\pi^0}$ versus $M^2_{\pi^0\pi^0}$ at $\sqrt{s} = 2.38$ GeV (peak cross section) (left) and at $\sqrt{s} = 2.5$ GeV (right). Bottom: Dalitz plot projections $M^2_{d\pi^0}$ (left) and $M^2_{\pi^0\pi^0}$ (right) axes at $\sqrt{s} = 2.38$ GeV. The curves denote calculations for a s-channel resonance decaying into $\Delta\Delta$ with $J^P = 3^+$ with (solid) and without (dash-dotted) form factor as well as for $J^P = 1^+$ (dashed). Hatched and shaded areas represent systematic uncertainties and phase-space distributions, respectively.
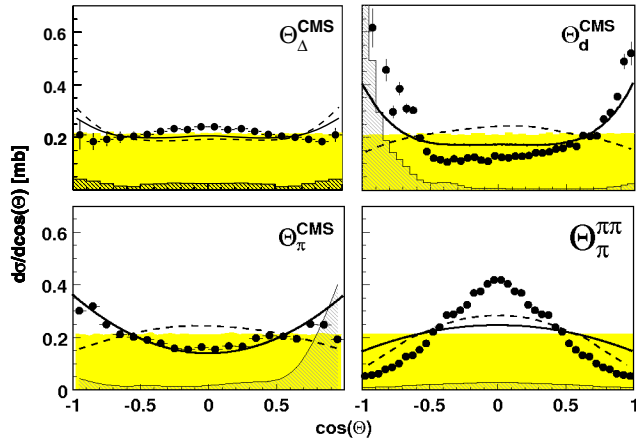
FIG. 5 (color online).   Same as Fig. 4, but for angular distributions at the peak cross section ($\sqrt{s} = 2.38$ GeV). Top: Δ (left) and deuteron (right) c.m.s. distributions, bottom: pion distribution in c.m.s. (left) and Jackson frame (right).

essentially isotropic, consistent with an s—wave in the intermediate $\Delta\Delta$ system. This is not unexpected, since we are largely below the nominal threshold of $2m_\Delta$. Whereas deuteron and pion angular distributions are strongly anisotropic in the ABC region, they get much flatter at higher energies in accordance with the conventional t-channel $\Delta\Delta$ process, which is expected to take over there.

In order to proceed it becomes necessary to properly implement the possible reaction dynamics. We performed a microscopic calculation for an assumed resonance state in a given partial wave to decay via $\Delta\Delta$ in an s wave. After the Δ decays the nucleons merge to form a deuteron. This model allows us to extract the partial wave content of the assumed resonance state.

The final state requires the total isospin to be zero. For an isoscalar $\Delta\Delta$ system in the intermediate state in a relative s wave, antisymmetrization requires $J^P = 1^+$ or 3^+. Hence we confront the data with calculations for an s-channel resonance process $pn \to R \to \Delta\Delta \to d\pi^0\pi^0$ for both spin assignments. With the ingredients described up to here, the $M_{\pi\pi}$ distribution is not yet described well (dash-dotted line in Fig. 4). This discrepancy can be improved by including a $\Delta\Delta$ vertex function. Parameterizing this as a monopole form factor calls for a cut-off scale as small as 0.15 GeV/c^2, close to the mass of the pion. The corresponding fit is shown by solid and dashed lines in Figs. 4 and 5 for $J^P = 3^+$ and 1^+, respectively. Note, if the relative momenta of the nucleons in the deuteron were negligible, the argument of that vertex function would be just the pion relative momentum. This explains the high sensitivity of the $\pi\pi$ spectrum to this quantity. In addition to the $M_{\pi\pi}$ distribution the observed angular distributions for deuterons and pions in the c.m.s. clearly prefer $J = 3$ in the ABC region. The inclusion of background terms, especially the conventional t-channel $\Delta\Delta$ process, further improves the description of the data.

Our data establish the correlation of the narrow resonancelike energy dependence with the long-standing puzzle of the ABC effect. But so far no conventional process has been identified, which can explain this phenomenon. In this situation one might be tempted to assign the signal to an unconventional s-channel resonance with $I(J^P) = 0(3^+)$, $m \approx 2.37$ GeV and $\Gamma \approx 70$ MeV, as already tentatively proposed in Ref. [6]. Note that such a resonance has been postulated by various quark-model calculations, see, e.g., Ref. [18]. With this ansatz together with the above mentioned vertex function we obtain a good description of the data (solid lines in Figs. 2–5) both in their energy dependence and in their differential behavior. However, to firmly establish the existence of such a resonant system further studies are called for to provide a microscopic understanding of the unusually small parameter in the vertex function. In addition, this resonance should be observable also in pn elastic scattering. Although its effect there is estimated to be only a few percent of the total elastic cross section, it should be very prominent in the $J^P = 3^+$ partial waves. The present pn database is very scarce in the relevant energy range. Thus, precise, polarized measurements in this channel are urgently called for, in order to allow for a partial wave analysis.

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