Examination of the Nature of the ABC Effect

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Recently it has been shown by exclusive and kinematically complete experiments that the appearance of a narrow resonance structure in double-pionic fusion reactions is strictly correlated with the appearance of the so-called ABC effect, which denotes a pronounced low-mass enhancement in the \( \pi\pi \)-invariant mass spectrum. Whereas the resonance structure got its explanation by the \( d^*(2380) \) dibaryonic resonance, a satisfactory explanation for the ABC effect is still pending. In this paper we discuss possible explanations of the ABC effect and their consequences for the internal structure of the \( d^* \) dibaryon.

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INTRODUCTION

Recently it was demonstrated by the WASA-at-COSY collaboration and the SAID data analysis group that there is a resonance pole at \((2380 \pm 10) - i (40 \pm 5) \) MeV in the \( ^3D_3 - ^3G_3 \) coupled partial waves of \( np \) scattering \([1,2]\). This finding matches perfectly with the \( I(J^P) = 0(3^+) \) resonance structure observed at \( \sqrt{s} = 2.37 \) GeV with a width of 70 MeV in the total cross section of the double-pionic fusion reactions \( pn \to d \pi^0 \pi^0 \) and \( pn \to d \pi^+ \pi^- \) \([4,5]\). Having revealed the pole in the \( np \) scattering amplitudes means that this resonance structure constitutes a genuine s-channel resonance in the system of two baryons. It has been denoted since then by \( d^*(2380) \) following the nomenclature used for nucleon excitations.

Follow-up measurements of the non-fusion reactions \( pn \to pp \pi^0 \pi^- \) \([6]\) and \( pn \to pn \pi^0 \pi^0 \) \([7]\) with the WASA detector at COSY showed that also these reactions, which are partially of isoscalar character, show the \( d^*(2380) \) resonance in agreement with expectations based on isospin coupling.

In addition, WASA measurements revealed that \( d^*(2380) \) is also present in the double-pionic fusion reactions to the helium isotopes \( pd \to ^3\text{He} \pi^0 \pi^0 \), \( pd \to ^3\text{He} \pi^+ \pi^- \), \( dd \to ^4\text{He} \pi^0 \pi^0 \) and \( dd \to ^4\text{He} \pi^+ \pi^- \) \([8,9]\). This means that obviously \( d^*(2380) \) is stable enough to survive also in a nuclear surrounding. This conclusion is supported by the appearance of a dilepton enhancement (DLS puzzle) in heavy-ion collisions \([10,11]\).

In 1960 Abashian, Booth and Crowe \([12]\) found out that the \( \pi\pi \)-invariant mass spectrum in the double-pionic fusion reaction \( pd \to ^3\text{He} \pi^\pi \) exhibits a pronounced low-mass enhancement. Subsequent measurements showed that this enhancement also persists in the fusion reactions to \( d \) and \( ^4\text{He} \) \([13,23]\), if the produced pion pair is of isoscalar nature. Since there was no plausible explanation for this effect it got named after the initials of the authors of the first publication on that issue.

The recent exclusive and kinematically complete WASA measurements, which were carried out at CELSIUS and later-on at COSY, confirmed the previous findings, which had been obtained by merely inclusive single-arm magnetic spectrometer and low-statistics bubble-chamber measurements, respectively. Moreover, the new measurements discovered a strict correlation between the appearance of the ABC effect and the appearance of the \( d^*(2380) \) resonance structure in the total cross sections of the fusion reactions to \( d \), \( ^3\text{He} \) and \( ^4\text{He} \), if these reactions were associated with the production of an isoscalar pion pair \([4,6,8,11]\).

In contrast to these findings no ABC effect was observed in the non-fusion reactions \( pn \to pp \pi^0 \pi^- \) and \( pn \to pn \pi^0 \pi^0 \) despite of the appearance of \( d^*(2380) \) in these reactions. For the first reaction the non-appearance of the ABC effect is easily understood, since in this case the pions of isovector pion pair must be in relative p-wave suppressing thus any low-mass enhancement. For the second reaction there is no such obvious reason.
HYPOTHESES FOR ITS EXPLANATION

From the Dalitz plots of the double-pionic fusion reactions [4, 6, 9, 11], we know that \( d^*(2380) \) decays predominantly via the \( \Delta \Delta \) system in the intermediate state – with the two \( \Delta \)s being in relative \( s \)-wave. This is in accordance with meanwhile numerous theoretical work about this resonance [22, 36].

Therefore it seems likely that the appearance of the ABC effect is correlated with the appearance of the \( \Delta \Delta \) system in the intermediate state and that way also with the internal structure of \( d^*(2380) \).

One of the first attempts to explain the ABC effect was its connection with the conventional \( t \)-channel \( \Delta \Delta \) excitation, a schematic diagram of which is depicted in Fig. 1(a). As pointed out already by Risser and Shuster [37], such an excitation causes a double-hump structure of the \( \pi \pi \)-invariant mass spectrum with enhancements both at low and high masses relative to phase space. If the center-of-mass energy \( \sqrt{s} \) is below the mass \( 2m_{\Delta} \), then the low-mass enhancement dominates. If it is above \( 2m_{\Delta} \), then the high-mass enhancement dominates. Since the mass of \( d^*(2380) \) is 80 MeV below \( 2m_{\Delta} \), the low-mass enhancement is expected to dominate in the region of \( d^*(2380) \).

Fig. 2 exhibits the \( \pi^0 \pi^0 \)-invariant mass \( (M_{\pi^0 \pi^0}) \) spectrum at resonance in the \( pn \rightarrow d^0 \pi^0 \pi^0 \) reaction, where the background from conventional processes is small compared to the resonance signal. Black solid circles denote the measurement from Ref. [4]. The yellow shaded histogram represents the pure phase-space spectrum for comparison – and the dashed curve is obtained, if we calculate the process

\[
\text{pn} \rightarrow d^*(2380) \rightarrow \Delta \Delta \rightarrow d^0 \pi^0
\]

as depicted schematically in Fig. 1(b).

**Description of the \( d^*(2380) \) Resonance Process**

The \( s \)-channel resonance process outlined in eq. (1) and depicted in Fig. 1(b) is described by the transition amplitude

\[
M_R(m_p, m_n, m_d, \hat{k}_1, \hat{k}_2) = M_R^0 \Theta_R(m_p, m_n, m_d, \hat{k}_1, \hat{k}_2),
\]

where the function \( \Theta \) contains the substate and angular dependent part, and

\[
M_R^0 = D_R \ast D_{\Delta_1} \ast D_{\Delta_2}.
\]

Here \( D_{\Delta} \) denotes the \( \Delta \) propagator

\[
D_{\Delta} = \frac{\sqrt{m_{\Delta} M_{\pi\pi}/q_{\pi\pi}^2}}{M_{\pi\pi}^2 - m_{\Delta}^2 + im_{\Delta} \Gamma_{\Delta}}
\]

and

\[
\Gamma_{\Delta}(q_{\pi\pi}^2) = \gamma(q_{\pi\pi}^2)^3 \frac{R^2}{1 + R^2(q_{\pi\pi}^2)^2}
\]

with \( \gamma = 0.74 \), \( R = 6.3 \text{GeV/}c^{-1} \) and \( q_{\pi\pi}^2 \) denoting the decay momentum of the pion in the \( \Delta \) system [37].

If we write \( D_R \) in form of a Breit-Wigner amplitude, then we have

\[
M_R^0 = \frac{m_{\pi\pi} \Gamma_{\Delta}}{s - m_R^2 + im_R \Gamma_R} D_{\Delta_1} D_{\Delta_2}
\]

with mass \( m_R \approx 2.38 \text{ GeV} \) and width \( \Gamma_R(s = m_R^2) \approx 70 \text{ MeV} \).
≡ 3D_3 \rightarrow \hat{G}_3 \text{ coupled partial waves between } p \text{ and } n \text{ in the initial system }^{[3]}.

Hence we have \( \Gamma_i = p_{\text{PN}}^{-1} \), where \( p_i \) and \( L \) denote momentum and orbital angular momentum, respectively, in the initial \( pn \) channel. Since the resonance is far beyond the \( pn \) threshold, the momentum dependence over the comparatively narrow region of the resonance is small and can actually be neglected here.

In the exit channel the resonance decays into the \( \Delta \Delta \) system with a relative \( s \)-wave between the two \( \Delta s \) — as observed in the \( \Delta \) angular distribution (Fig. 5 in Ref. [5]). Therefore we have

\[
\Gamma_{\Delta \Delta} = g_{\Delta \Delta}^2 p_{\Delta \Delta},
\]

where \( p_{\Delta \Delta} \) is the momentum of the \( \Delta \) in the \( \Delta \Delta \) system and which is just half of the momentum transfer \( q_{\Delta \Delta} \) in this system given by

\[
q_{\Delta \Delta} = p_\Delta - p_\Delta = (p_{\vec{N}_1} + p_{\vec{N}_2}) - (p_{\vec{N}_2} + p_{\vec{N}_2}) = (p_{\vec{N}_1} + p_{\vec{N}_2}) - (p_{\vec{N}_2} + p_{\vec{N}_2})
\]

The momentum dependent total width of the resonance is then given by

\[
\Gamma_R(s) = \Gamma_i + \sum \Gamma_f = \Gamma_i(q) + \gamma_R 
\int dm_1^2 dm_2^2 p_{\Delta \Delta} |D_{\Delta \Delta}(m_1^2) D_{\Delta \Delta}(m_2^2)|^2,
\]

where the integral runs over all possible \( q_{\Delta \Delta} \) and \( N\pi \)-invariant mass-squared \( m_1^2 \) \( m_2^2 \) forming the systems \( \Delta_1 \) and \( \Delta_2 \), respectively [3].

The second term in eq. (9) denotes the decays of the resonance via the intermediate \( \Delta \Delta \) system. The quantity \( \gamma_R \) contains the coupling constant \( g_{\Delta \Delta} \) and other constants and is fitted to yield a total width of \( \Gamma_R(s = m_R^2) = 70 \text{ MeV} \).

The angular dependence is obtained from the angular momentum coupling in entrance and exit channels:

\[
s_p + s_n + \vec{L} = \vec{J} = s_{\Delta_1} + s_{\Delta_2} \quad \text{(10)}
\]

with

\[
s_p + s_n = \vec{s}, \quad s_{\Delta_1} = \vec{l}_1 + s_{\vec{N}_1}, \quad s_{\Delta_2} = \vec{l}_2 + s_{\vec{N}_2},
\]

\[
s_{\vec{N}_1} + s_{\vec{N}_2} = s_d.
\]

Here \( s_p, s_n \) and \( s_d \) with \( s_p = s_n = \frac{1}{2} \) and \( s_d = 1 \) denote the spins of \( p, n \) and \( d \). The orbital angular momenta \( \vec{l}_1 \) and \( \vec{l}_2 \) with \( l_1 = l_2 = 1 \) stand for the pion \( p \)-waves originating from \( \Delta \) decay and \( \vec{L} \) is the initial orbital angular momentum between the incident proton and neutron.

Eq. (10) assumes that we have \( s \)-wave between the two \( \Delta s \) in the intermediate state — in agreement with observation, as mentioned already above.

If the coordinate system is chosen to be the standard one with the \( z \)-axis pointing in beam direction (implying \( m_L = 0 \) and \( (\Theta_i, \Phi_i) = (0, 0) \)), then the function \( \Theta_R(m_p, m_n, m_d, \vec{k}_1, \vec{k}_2) \) defined in eq. (2) is built up by the corresponding vector coupling coefficients and spherical harmonics representing the angular dependence due to the orbital angular momenta involved in the reaction:

\[
\Theta_R(m_p, m_n, m_d, \vec{k}_1, \vec{k}_2) = \sum \left( \frac{1}{2} \frac{1}{2} m_p m_n |1m_s| (1Lm_0|JM) \left( JM |\frac{3}{2} \frac{3}{2} m_1^2 m_2^2 \right) \frac{3}{2} m_1^2 |\frac{1}{2} 1m_1^2 m_1^1 \right) \left( \frac{1}{2} m_2^2 \right) \left( \frac{3}{2} \frac{3}{2} m_1^2 m_2^2 \right) \left( 1m_0 |\frac{3}{2} \frac{1}{2} m_1^2 m_1^2 \right) Y_{20}(0, 0) Y_{1m_1}(\vec{k}_1) Y_{1m_2}(\vec{k}_2).
\]

The angular distributions for deuterons and pions resulting from eq. (12) are displayed in Fig. 5 of Ref. [5].

The \( p \)-wave pions emerging from the intermediate \( \Delta \Delta \) system can couple to relative \( s \)- and \( d \)-waves. In the first instance, \( d \) and \( \pi \pi \) systems must then be in relative \( d \)-wave to match the requirement for the resonance spin, whereas in the second case \( d \) and \( \pi \pi \) systems have to be in relative \( s \)-wave.

For the \( \pi^0 \pi^0 \)-invariant mass spectrum the calculation of this resonance process is shown by the dashed line in Fig. 2. It gives the proper tendency. However, the produced low-mass enhancement is much too small in comparison to that observed in the data.

We note that a calculation of the \( t \)-channel process depicted in Fig. 1(a) leads to a very similar \( M_{\pi^0 \pi^0} \) distribution. This is not surprising, since at the energy of interest we are much below the nominal \( \Delta \Delta \) threshold of \( 2m_\Delta \), so that also in this case the intermediate \( \Delta \Delta \) system is strongly favored to be in relative \( s \)-wave. Hence the dynamics of the \( \pi^0 \pi^0 \) system observed in the \( M_{\pi^0 \pi^0} \) spectrum appears to be similar.

\[ FF \sim \frac{\Lambda^2}{\Lambda^2 + p_{\Delta \Delta}^2}. \]
If we neglect the Fermi motion of the nucleons within the deuteron, then the nucleon momenta cancel in eq. (8) and we have \( p_\Delta = p_\pi^0\pi^0\), where \( p_\pi^0\pi^0\) is the pion momentum in the \( \pi\pi\) system. Hence this vertex function is directly reflected in the \( M_\pi^0\pi^0\) spectrum causing there the ABC effect by suppression of the high-mass region.

We note in passing that already in the work of Kälbermann and Eisenberg [39] about the ABC effect formfactors had been introduced, but there at the \( \pi NN\) vertices. In Ref. [3] the cutoff parameter \( \Lambda \) had been fitted to the data in the \( M_\pi^0\pi^0\) spectrum (Dalitz plot projection) resulting in \( \Lambda \approx 0.16 \text{ GeV/c} \), which corresponds to a length scale of \( r \approx \frac{h_s}{\Lambda} \approx 2 \text{ fm} \). This result is shown in Fig. 2 by the solid line for the \( M_\pi^0\pi^0\) spectrum. It appears that for this spectrum the calculation exaggerates the low-mass enhancement somewhat. Here, a 20% larger cutoff parameter would give an optimal description.

Though this ansatz accounts very well for the data on the double-pionic fusion reactions to \( d \) (and also to \( ^3\text{He} \) and \( ^4\text{He} \)) [9–12], which are not considered here), there are two disturbing features:

First of all, the cutoff parameter \( \Lambda \) is unusually small. Cutoff parameters used in the description of hadronic reactions are usually three to four times larger.

Second, for non-fusion reactions like \( pn \to pn\pi^0\pi^0\) the vertex function in eq. (2) does not affect primarily the \( M_\pi^0\pi^0\) spectrum, but the \( M_\pi^0\pi^0\) spectrum, since the unbound \( pn \) system is no longer restricted in its relative motion by the deuteron wavefunction. The fact that the vertex function does not influence significantly the \( M_\pi^0\pi^0\) spectrum agrees with the experimental finding that there is no significant ABC effect in this reaction [8]. But the impact of the vertex function on the \( M_\pi^0\pi^0\) spectrum leads to a large enhancement of the low-mass region in the \( M_\pi\pi\) spectrum, which is at variance with the data [8] – see Fig. 3, dashed lines.

### \( \Delta\Delta \) Final State Interaction

Another attempt to explain the ABC-effect by a final-state interaction (FSI) between the two \( \Delta \)s in the intermediate state dates back to the first WASA measurements on this issue [10, 40].

If we parameterize the \( \Delta\Delta\)-FSI in the Migdal-Watson ansatz [41–43], then we obtain the factor

\[
FSI = 1 + \frac{R^2}{\left( \frac{1}{a_x^2} + \frac{1}{2} p_\pi^0\pi^0 \right)^2 + p_\Delta^2},
\]

(14)

which multiplies the expression for the cross section. Here \( R \) denotes the vertex size, \( r_0 \) the effective range and \( a_x \) the scattering length. For recent values of \( r_0 = 2 \text{ fm} \) and \( R = 1.1 \text{ fm} \) a reasonable description of the \( M_\pi^0\pi^0\) spectrum is achieved with \( a_x \approx 30 \text{ fm} \), see Fig. 4. Numerically the first term in eq. (14) is small compared to the second one and also the finite range term in the denominator of the second term may be neglected. Thus we see that eqs. (13) and (14) both have a similar structure with similar \( p_\Delta \) dependence, i.e. they lead to similar corrections in the differential spectra. However, with eq. (14) we avoid a discussion of an unreasonable cutoff parameter, which is replaced now by some reasonable value for the scattering length. But for the \( np \to np\pi^0\pi^0\) reaction the problem stays essentially the same as in the previous case.

![Figure 3](image-url)

**FIG. 3:** (color online). Differential distributions of invariant masses \( M_{\pi^0\pi^0}\) (a) and \( M_{pn}\) (b) for the \( np \to np\pi^0\pi^0\) reaction. The black solid circles denote data [8] and the yellow shaded area phase-space distributions. The dashed lines give the calculation of the reaction process including the route \( np \to d^{(2380)} \to \Delta\Delta \to np\pi^0\pi^0 \) with use of the vertex function in eq. (13). The solid lines show the result, when instead of the vertex function a \( d\)-wave contribution in the intermediate \( \Delta\Delta \) system is assumed – see text. Note that in the \( M_{\pi^0\pi^0}\) spectrum solid and dashed lines lie nearly on top of each other.
in trying to explain the ABC effect. It assumes that spectrum (dashed lines in Fig. 5).

The enhancement at the with the main route is not enough to reproduce prop-

ession (dotted line in Fig. 5(a)). But its interference 
tively, if a light and narrow σ meson is emitted according to

\[ \sigma \rightarrow \pi \pi \]

Due to \( J^P = 3^+ \) the σ meson and the deuteron have to be in relative d-wave. This means that the transition amplitude of this process should be proportional to the relative momentum squared, i.e. \( A \sim q_{\pi d}^2 \sim (M^2_{\pi d_{\max}} - M^2_{\pi d}) \). This momentum dependence provides a high-mass \( M_{\pi d} \) suppression (dotted line in Fig. 5(a)). But its interference with the main route is not enough to reproduce properly the enhancement at the \( \pi \pi \) threshold (solid line in Fig. 5(a)).

In this ansatz the data are only reproduced quantitatively, if a light and narrow σ meson (\( M_\sigma = 300 \text{ MeV} \), \( \Gamma_\sigma = 100 \text{ MeV} \)) is assumed (solid line in Fig. 5(b)). The strong mass reduction compared to the accepted value \( m_\sigma = 440 \text{ MeV}, \Gamma_\sigma = 544 \text{ MeV} \), in (b) for the values \( m_\sigma = 300 \text{ MeV} \) and \( \Gamma_\sigma = 100 \text{ MeV} \). The solid lines give the coherent sum.

Recently Platonova and Kukulin proposed an alternative explanation of the ABC effect. They consider two possible decay branches for the \( d^*(2380) \) resonance. Hereby they go back to the work of Dyson and Xuong, who based on SU(6) predicted a sextet of non-strange dibaryon states. In that work \( d^*(2380) \) is denoted by \( D_{03} \), where the first index means the isospin and the second one the spin of the dibaryon state.

Kukulin and Platonova assume the main decay of \( D_{03} \) to proceed via the \( D_{12} \) member of the sextet, i.e. \( D_{03} \rightarrow D_{12} \pi \rightarrow d\pi\pi \), where \( D_{12} \) is identified with the \( I(J^P) = 1(2^+) \) state at the \( N\Delta \) threshold. For the numerous discussions, whether the latter constitutes a genuine resonance or not, see e.g. Refs. 45–56. Since in this route \( D_{12} \) and the associated pion have to be in relative p-wave, in order to fulfill the angular momentum requirements of \( D_{03} \), this decay route is practically indistinguishable from the route \( D_{03} \rightarrow \Delta\Delta \rightarrow d\pi\pi \), i.e. both routes give essentially identical results for the \( M_{d\pi\pi} \) spectrum (dashed lines in Fig. 5).

The second decay route constitutes a really new piece in trying to explain the ABC effect. It assumes that a σ meson is emitted according to \( D_{03} \rightarrow d\sigma \). Due to \( J^P = 1^+ \) the σ meson and the deuteron have to be in relative d-wave. This means that the transition amplitude of this process should be proportional to the relative momentum squared, i.e. \( A \sim q_{\pi d}^2 \sim (M^2_{\pi d_{\max}} - M^2_{\pi d}) \). This momentum dependence provides a high-mass \( M_{\pi d} \) suppression (dotted line in Fig. 5(a)). But its interference with the main route is not enough to reproduce properly the enhancement at the \( \pi\pi \) threshold (solid line in Fig. 5(a)).

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Since the \(d^*(2380) \rightarrow NN\) decay is sizable \(^2\) and the Roper resonance \(N^*(1440)\) has the same quantum numbers as the nucleon, one may assume that a \(d^*(2380) \rightarrow N^*(1440)N\) decay might also exist. Due to the spin-parity \(J^P = 3^+\) of the \(d^*(2380)\) resonance one needs to have at least a \(d\)-wave between the nucleon and the Roper resonance, which in the course of its decays \(N^*(1440) \rightarrow N\sigma \rightarrow N\pi\pi\) and \(N^*(1440) \rightarrow \Delta\pi \rightarrow N\pi\pi\) finally must transform to a \(d\)-wave between pion and nucleon pairs, if the nucleons fuse to a deuteron. This can proceed by no means straightforward, since these \(N^*(1440)\) decays end up with a pion pair in relative \(s\)-wave, which is again in relative \(s\)-wave to the final nucleon. Hence another intermediate step is needed, where the orbital angular momentum of \(L = 2\), which initially is between \(N^*(1440)\) and \(N\), is transferred to be finally in between the nucleon pair and the pion pair – with the partners in the pairs being in relative \(s\)-waves. We are not aware of any reasonable rescattering process, which could make such a selective angular momentum transfer. We only note in passing that, if indeed such a process would favor the \(N^* \rightarrow \Delta\pi \rightarrow N\pi\pi\) branch for some reason, then we could reproduce the ABC effect very well by a \(5\%\) admixture. Here the ABC effect by suppressing the high-mass region is due to the \(d\)-wave \(N^*(1440)N\) and \(d\sigma\pi\) vertices. But we emphasize that we do not consider this a realistic option.

\[d\text{-wave } \Delta\Delta \text{ admixture}\]

Having learned in the previous examples that a \(d\)-wave introduces a strong momentum dependence such that the ABC effect may be reproduced, we may consider yet another ansatz, which possibly is more realistic.

Similar to the fact that the deuteron groundstate contains a \(d\)-wave admixture, we may postulate also a such one for the intermediate \(\Delta\Delta\) system. The \(d\)-wave \(\Delta\Delta\) amplitude is proportional to \(g_3^2\). So contrary to the ansatz with the \(\Delta\Delta\) vertex function and \(\Delta\Delta\) FSI, respectively, the \(M_{\pi\pi}\) spectrum will be suppressed in particular at small masses, see dotted line in Fig. 6. A destructive interference between \(d\)-wave and \(s\)-wave (dashed line) components will suppress then high \(M_{\pi\pi}\) invariant masses. A \(20\%\) admixture of the \(d\)-wave component on the amplitude level, \textit{i.e.} \(4 - 5\%\) on the cross section level, is sufficient for a reasonable description of the ABC-effect. This means a very similar amount of \(d\)-wave admixture as in the deuteron groundstate. We note that the effect of the deuteron \(d\)-state in these calculations is negligible, since its momentum dependence does not act on the pion pair.

Opposite to the previous cases, this ansatz does not cause a problem in the description of the \(np \rightarrow np\pi^0\pi^0\) reaction. It does neither produce an ABC effect in the \(M_{\pi^0\pi^0}\) spectrum nor a low-mass enhancement in the \(M_{\pi\pi}\) spectrum there. The situation is depicted in Fig. 3, where the data from Ref. \cite{8} are compared with the results of the ansatz with the \(\Delta\Delta\) vertex function (dashed lines) and the ansatz with \(d\)-wave \(\Delta\Delta\) admixture (solid lines). Whereas these calculations lie practically on top of each other in the \(M_{\pi^0\pi^0}\) spectrum, the calculations differ substantially for the \(M_{\pi\pi}\) case. There the calculation with the vertex function strongly overshoots the low-mass region, whereas the \(d\)-wave ansatz is in agreement with the data.

We note that a \(\Delta\Delta\) \(d\)-wave contribution has been predicted in quark model calculations recently \cite{33,34}.

\section*{CONCLUSIONS}

We have discussed several possible reasons for the ABC effect. Most of these hypotheses can be tuned to reproduce qualitatively the low-mass enhancements in the \(M_{\pi\pi}\) spectra of double-pionic fusion reactions. However, only a single one is able to explain simultaneously the non-occurrence of the ABC effect in the non-fusion reaction \(np \rightarrow np\pi^0\pi^0\). This remaining hypothesis concerns a \(d\)-wave admixture in the intermediate \(\Delta\Delta\) system – quite similar to that known from the deuteron ground-state. As already mentioned, a \(d\)-wave admixture has been predicted from quark-model calculations \cite{33,34}. Of course, the description of the \(M_{\pi^0\pi^0}\) spectrum is still not perfect and might require a mixture of some of the proposed options. \textit{E.g.}, a somewhat smaller \(d\)-wave admixture could be combined with a \(\Delta\Delta\) vertex function (or \(\Delta\Delta\) FSI) with a more reasonable cut-off parameter (or scattering length).

Thus the ABC effect in double-pionic fusion reactions together with its absence in non-fusion reactions may
lead to some insight into the internal structure of the $d^*(2380)$ resonance. This is also an important aspect in the photo excitation $\gamma d \rightarrow d^*(2380)$, where the transition formfactor depends on size and internal structure of this resonance state. Dedicated experiments are expected to be conducted at MAMI in near future.

As discussed above, we find it very unlikely that $d^*(2380)$ has a decay branch into $N^+N$. A dedicated experimental test of such a decay would be the investigation of isoscalar single-pion production in the energy region of interest. In addition, investigation of such a decay branch into the $NN\pi$ system can resolve the question, whether the main decay route is $d^*(2380) \rightarrow \Delta\Delta$ or $d^*(2380) \rightarrow D_{12}\pi$ as anticipated in Refs. [28, 29, 41]. Since $D_{12}$ has a sizeable decay branch into $NN$, the route via $D_{12}$ will feed also the $NN\pi$ channel, whereas such a feeding is not possible by an intermediate $\Delta\Delta$ system.

Unfortunately, there are no data at all in this energy region and even at lower energies the data base is not very precise [58]. However, though WASA at COSY has finished data taking, there are still data samples from previous runs available, which – though collected primarily for other reasons – could allow to extract the wanted isoscalar single-pion production. An analysis of such data is in progress.

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