Implications of the ABC Resonance Structure on Elastic Neutron-Proton Scattering

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Abstract

In recent WASA-at-COSY measurements of the basic double-pionic fusion reactions \( pn \rightarrow d \pi^0 \pi^0 \) and \( pn \rightarrow d \pi^+ \pi^- \) a narrow resonance structure with \( I(J^P) = 0(3^+) \) in the total cross section has been found. If this constitutes a \( s \)-channel resonance in the \( pn \) system, then it should cause distinctive consequences in \( pn \) scattering. The magnitude of the decay width into the \( pn \) channel is estimated and the expected resonance effects in integral and differential \( pn \) scattering observables are presented. The inclusion of the resonance improves the description of total cross section data. For the analyzing power a characteristic energy dependence is predicted, which should allow a crucial experimental check of the resonance hypothesis.

Keywords: ABC resonance, \( pn \) scattering

1. Introduction

The so-called ABC-effect, which constitutes a peculiar low-mass enhancement in the invariant mass of an isoscalar pion pair produced in a double-pionic fusion reaction, has been a puzzle all the time since its first discovery fifty years ago by Abashian, Booth and Crowe [1]. Recent WASA-at-COSY experiments [2, 3] on the basic double-pionic fusion to deuterium established a tight correlation between the appearance of the ABC effect and a narrow Lorentzian energy dependence with mass \( m = 2.37 \text{ GeV} \) and width \( \Gamma = 70 \text{ MeV} \) in the integral cross sections of the reactions \( pn \rightarrow d \pi^0 \pi^0 \) and \( pn \rightarrow d \pi^+ \pi^- \), isoscalar part. The differential distributions are consistent with a \( I(J^P) = 0(3^+) \) assignment to this resonance-like structure. In addition the experimental Dalitz plots point to a \( \Delta \Delta \) excitation in the intermediate state. Hence we consider the following reaction scenario for the interpretation of the data:

\[ pn \rightarrow R \rightarrow \Delta \Delta \rightarrow (NN\pi\pi)_{I=0}, \]  

(1)

where \( R \) denotes a \( s \)-channel resonance in \( pn \) and \( \Delta \Delta \) systems. By this scenario we explicitly neglect a possible direct decay \( R \rightarrow NN\pi \). Note that an intermediate \( N\Delta \) configuration is excluded by isospin.

In this paper we consider the possible decay channels of such a resonance in the scenario of eq. (1). In particular we estimate the partial decay width into the elastic \( pn \) channel and calculate the effect of such a resonance onto the \( pn \) scattering observables.

2. Decay channels and widths

The cross section of the isoscalar two-body resonance process \( pn \rightarrow R \rightarrow \Delta \Delta \) is given by

\[ \sigma_{pn \rightarrow \Delta \Delta} = \frac{4\pi}{k_i^2} \frac{2J+1}{(2s_p+1)(2s_n+1)} \frac{m_R^2 \Gamma \Gamma_f}{(s-m_R^2+\Gamma^2)^2}, \]  

(2)

where \( k_i \) denotes the initial center-of-mass momentum. With \( J = 3 \) and \( s_p = s_n = 1/2 \) the peak cross section at \( \sqrt{s} = m_R = 2.37 \text{ GeV} \) (\( k_i = 0.72 \text{ GeV/c} \)) is then

\[ \sigma_{pn \rightarrow \Delta \Delta(\text{peak})} = \sigma_0 \frac{\Gamma \Gamma_f}{\Gamma^2} \]  

(3)

with

\[ \sigma_0 = 16.4 \text{ mb} \ (\text{unitarity limit}). \]  

(4)

Since we also have

\[ \Gamma = \Gamma_i + \Gamma_f, \]  

(5)

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we get from (3) and (5):
\[
\Gamma_i = \Gamma(\frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{\sigma_{pn-\Delta\Delta}(\text{peak})}{\sigma_0}}).
\] (6)

To estimate \(\sigma_{pn-\Delta\Delta}(\text{peak})\) consider the total cross sections of all channels, where the isoscalar \(\Delta\Delta\) system can decay into:

- (i) \(d\pi^0\pi^0\) and \(d\pi^+\pi^-\):
  Due to isospin rules we expect
  \[
  \sigma_{d\pi^0\pi^0}(I = 0) = 2 \sigma_{d\pi^+\pi^-},
  \]
  however, due to the isospin violation in the pion mass, the available phase space is somewhat smaller for charged pion production than for the production of the lighter neutral pions. In Ref. [3] it has been shown that this results in a resonance cross section, which is lower by about 20 % in case of the \(d\pi^+\pi^-\) channel. Hence we have
  \[
  \sigma_a := \sigma_{d\pi^0\pi^0} + \sigma_{d\pi^+\pi^-} \approx 2.6 \sigma_{d\pi^+\pi^-}.
  \] (8)

The peak cross section of the \(pn \rightarrow d\pi^0\pi^0\) reaction at \(\sqrt{s} = 2.37\text{ GeV}\) has been measured to be 0.27 mb [3]. This includes the contributions of the \(t\)-channel \(\Delta\Delta\) and Roper excitations. Accounting for this background effect the pure resonance cross section in this channel amounts to about 0.24 mb, i.e.:

\[
\sigma_a \approx 0.6\text{ mb.}
\] (9)

- (ii) \(n\pi^0\pi^0\), \(n\pi^+\pi^-\) and \(pp\pi^0\pi^-\) - only \(I = 0\) part:

  In a recent paper [4] Füldt and Wilkin present an estimate of the resonance cross section in the \(pn \rightarrow pp\pi^0\pi^0\) reaction. According to their calculation based on final state interaction theory the expected peak cross section in the deuteron breakup channel \(pp\pi^0\pi^0\) is about 85% that of the non-breakup channel \(d\pi^0\pi^0\), i.e. about 0.2 mb. Very recently also Albaladejo and Oset [5] estimated the expected resonance cross sections in \(pn \rightarrow pp\pi^0\pi^0\) and \(pn \rightarrow pp\pi^+\pi^-\) using a more elaborate theoretical procedure. Their result for the \(pn \rightarrow pp\pi^0\pi^0\) channel is compatible with that from Ref. [4].

Next we consider the \(pp\pi^0\pi^-\) channel. Though both the \(pp\) pair and the \(\pi^0\pi^-\) pair are isovector pairs, they may couple to \(I = 0\) in total. Hence the isoscalar resonance may also decay into the isoscalar part of the \(pp\pi^0\pi^-\) channel. In fact, the decay of the resonance into the \(pp\pi^0\pi^-\) channel proceeds via the same intermediate \(\Delta^+\Delta^0\) system as the \(d\pi^0\pi^0\) channel does. From isospin coupling we expect that the resonance decay into the \(pp\pi^0\pi^-\) system should be half that into the \(n\pi^0\pi^0\) system. And since from the estimates in Ref. [4] we expect the resonance effect in the \(n\pi^0\pi^0\) system to be about 0.20 mb, we estimate the peak resonance contribution in the \(pp\pi^0\pi^-\) system to be in the order of 0.1 mb. In fact, a recent measurement [6] of this channel by WASA-at-COSY is in agreement with such a resonance contribution in the total cross section at \(\sqrt{s} = 2.37\text{ GeV}\).

The resonance effect in the isoscalar part of the \(n\pi^0\pi^-\) channel is composed of the configurations, where either both \(np\) and \(\pi^+\pi^-\) pairs couple each to \(I = 0\) or both pairs each to \(I = 1\). The latter case provides the same situation as the \(pp\pi^0\pi^-\) channel. Hence we have

\[
\sigma_{np\pi^0\pi^-}(I = 0) \approx 2\sigma_{np\pi^+\pi^-} + \sigma_{pp\pi^0\pi^-},
\]

\[
\sigma_b := \sigma_{np\pi^0\pi^-} + \sigma_{np\pi^+\pi^-} + \sigma_{pp\pi^0\pi^-}
\approx 0.5\text{ mb} + 0.2\text{ mb} + 0.1\text{ mb}
\approx 0.8\text{ mb.}
\] (11)

We note that our estimate for the resonant \(pn \rightarrow pn\pi^0\pi^-\) cross section is in agreement with that of Ref. [5].

- (iii) \(pp\pi^0\pi^-\) and \(n\pi^0\pi^-\) (I=0 part):

  The isoscalar part of single-pion production is not well known. Recent work [7, 8] suggests a maximum isoscalar cross section at \(\sqrt{s} = 2.30\text{ GeV}\) with an indication of some steep decline thereafter. At our resonance energy there are no data at all. Independent of this it is very hard to construct a process, where the intermediate \(\Delta\Delta\) system decays by emission of a single pion only. In such a case one of the \(\Delta\) excitations must be de-excited by pion exchange with the other \(\Delta\). However, the formation of an intermediate \(N\Delta\) state is isospin forbidden – as already mentioned in the introduction. Also, the condition \(J^P = 3^-\) is very hard to fulfill in such a scenario. Hence we conclude that any decay of the resonance \(R\) into these single-pion channels must be small compared to the favored decays into the two-pion channels.
We note, however, that we discuss here two extreme situations. Actually, the true solution may be in-between the two extreme waves allowing for a mixing of both components. I.e., the initial partial waves for the formation of the resonance $R$ are the initial partial waves for the elastic decay width due to the resonance excitation in $\pi^-\pi^+$ channels. This solution is at obvious variance with SAID.

Before we continue to discuss the consequences of the resonance hypothesis for the $pn$ scattering observables, we shortly want to discuss the situation for the case that the spin-parity of the resonance would have been $J^P = 1^+$. As discussed in Ref. [2] a $\Delta\Delta$ system in relative $s$-wave in the intermediate state could in principle have $J^P = 1^+$ or $3^+$. In the $J^P = 1^+$ case we would get the unitarity limit $\sigma_\Delta = 7.0 \text{ mb}$ and using the estimate of Fälldt and Wilkin [4] the estimated cross section for $J^P = 1^+$ exceeds the sum of the SAID inelastic cross sections in the $\Delta\Delta$ partial waves. Taking this limiting case would result in $\Gamma_j = \Gamma / 2 = 35 \text{ MeV}$ and $\sigma_{n\pi} = 1.75 \text{ mb}$. As already demonstrated by Fälldt and Wilkin [4] the estimated cross section for $J = 1$ exceeds the sum of the SAID inelastic cross sections in the $\Delta\Delta$ partial waves.

In general the decay widths of a resonance are momentum dependent. This is important, if we consider the resonance not only at its resonance mass – as done above – but also over a wider range of energies, as we will do now in the following. The momentum dependence is particularly significant for the numerator of the resonance amplitude, where the elastic decay width enters linearly and is highly momentum dependent due to the $D$- and $G$-wave character, respectively of the relevant partial waves. Following Ref. [11] we parameterize the elastic width due to the resonance excitation in the $^1L_3$ partial wave as follows:

$$\Gamma(q) = \Gamma(q_R) \frac{q^2}{q_R^{2L+1}} \frac{\delta^2 + \delta'^2}{\delta^2 + \delta'^2}.$$  \hfill (15)
spectrum. Since \( q_{\Delta\Delta} = q_{\pi\pi} \) when neglecting the Fermi motion of the nucleons, this form-factor is reflected directly in the high-mass region. Fitting the cutoff parameter \( \Lambda \) of this monopole form-factor to the data in the \( M_{\pi\pi} \) spectrum results \([2]\) in

\[
\Lambda \approx 0.16 \text{ GeV}/c \quad (18)
\]
corresponding to a length scale of \( r = \frac{\hbar}{\sqrt{2} \Lambda} \approx 2 \text{ fm} \).

The total width of the resonance is then given by

\[
\Gamma_R(s) = \Gamma_i + \sum \Gamma_f = \Gamma(q) + \gamma_R \quad (19)
\]

\[
\int dm^2_1 dm^2_2 |q_{\Delta\Delta}|^2 |D_{\Delta\Delta}(m^2_1) D_{\Delta\Delta}(m^2_2)|^2,
\]
where the integral runs over all possible \( q_{\Delta\Delta} \) and \( N\pi \)-invariant mass-squared \( m^2_1 \) \( (m^2_2) \) forming the systems \( \Delta_1 \) and \( \Delta_2 \), respectively \([13]\).

The second term in eq. (18) 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 \( \Gamma_R(s = m^2_R) = 70 \text{ MeV} \).

3. Resonance amplitude in the \( pn \) channel

Knowing now the partial decay width of the resonance \( R \) into the elastic \( pn \) channel we can calculate the resonance effect in this channel by adding the resonance amplitude to the corresponding partial wave amplitude of the energy dependent SAID solution.

The scattering amplitude is given by the T-matrix elements for the \((l, j)\)th partial wave, which are connected to those of the S-matrix by

\[
T_{ij} = \frac{S_{ij} - 1}{2i} \quad (20)
\]
The S-matrix is parameterized usually in the Stapp notation \([14]\)

\[
S_{ij} = \eta_{ij} e^{2i\delta_{ij}} \quad (21)
\]

where \( \delta_{ij} \) denotes the real part of the phase shift in the \((l, j)\)th partial wave and \( \eta_{ij} \) stands for its absorptive part, the inelasticity.

For the full partial wave amplitude in the resonating partial waves \( ^1D_3 \) and \( ^3G_3 \), respectively, we take the product S-matrix approach as used for the SAID analysis of \( \pi N \) scattering \([18]\):

\[
S_{ij} = S^0_{ij}(1 + 2i\frac{m_R \Gamma_i}{m^2_R - s - im_R \Gamma_R} e^{2i\Phi_R}) \quad (22)
\]

where \( S^0_{ij} \) denotes the non-resonating background contribution, for which we take the current SAID SP07 solution.

By doing so we assume that

- the energy-dependent SAID solution is not affected significantly by use of the data in the resonance region \( T_n = (1.0 - 1.3) \text{ GeV} \). Since differential cross section data - as we will demonstrate below - show an insignificant sensitivity to the resonance, the only data of relevance in this region are the analyzing power data at \( T_n = 1.1 \text{ GeV} \). In a global SAID analysis based on a multitude of data such a single data set is not expected to play a significant role.

- the perturbation by the resonance amplitude is small, so that no severe problem with unitarity arises. Multiplication of the Breit-Wigner resonance term with the background S-matrix in the multiplicative S-matrix approach helps to diminish this problem. In case of \( \Phi_R = 0 \) unitarity is conserved by construction, otherwise one needs to check, whether for the resonating partial wave \( \eta \leq 1 \) is still valid.

In the resonance amplitude all values are fixed with the exception of the resonance phase \( \Phi_R \). There are a priori no predictions for this phase between resonance and background amplitudes. Hence it is treated as a free parameter. In the following we use the total \( pn \) cross section data to fix the resonance phase \( \Phi_R \).

4. Resonance effect in \( np \) scattering observables

The total (integral) elastic and reaction \( np \) cross sections are shown in Fig. 1. The solid curves give the current SAID solution and the dotted (dashed) lines the result, if we add the resonance amplitude in the \( ^1D_3 \) \(^3G_3\)
Figure 1: Total (integral) elastic (top) and inelastic (bottom) \( p n \) cross sections in dependence of the incident neutron energy \( T_n \). The two data points are from Besliu et al. [16]. The solid (dotted) lines denote the current SAID solution SP07 [10], the dotted (dashed) lines are the result, if we add the resonance amplitude in the \( 3^3D_3 \) (\( 3^1G_3 \)) partial wave. Note that dotted and dashed curves lie nearly on top of each other, since the total cross sections are not sensitive to the partial waves' orbital angular momenta. The dash-dotted curves are the result, if in the \( 3^1G_3 \) case the inelasticity \( \eta_{ij} \) is constrained to unity, wherever it would exceed unity by adding the resonance amplitude. This concerns only the energy region \( T_n < 1.1 \text{ GeV} \).

Figure 2: Total \( p n \) cross section (top) and total isoscalar nucleon-nucleon cross section (bottom) in dependence of the incident neutron (nucleon) energy \( T_n \). Data (solid symbols) below 800 MeV are from Lisowski et al. [17] and above 800 MeV from Devlin et al. [18]. The open symbols represent data from Sharov et al. [19]. The horizontal bars indicate the energy resolution of the incident neutrons. The plotted curves are averaged over these experimental energy resolutions. For the meaning of the curves see caption of Fig. 1. The vertical arrow indicates the position of the ABC resonance structure.
partial wave with phase $\Phi_R = -30^\circ$. As expected from the estimate in eq. (13), the resonance effect is very small in the integral cross sections. In addition there are no data to compare to with the exception of two data points with large uncertainties [14]. The experimental situation improves drastically, however, if we consider the sum of elastic and reaction cross section, i.e., the full total $np$ cross section, which can be accessed by $0^\circ$ transmission measurements.

Fig. 2, top, shows the total $np$ cross section for $T_n = (0.5 - 2)$ GeV. The data (solid symbols) plotted for $T_n < 0.8$ GeV are from Lisowski et al. [17] taken at LAMPF in a high-resolution dibaryon search. The data plotted for $T_n > 0.8$ GeV are from Devlin et al. [18] taken with a neutron energy resolution of $(4 - 20)%$ (horizontal bars in Fig. 2). Also data from Sharov et al. [19] are shown (open symbols), which have larger uncertainties, but are taken with a much superior neutron energy resolution of $(13 - 15)$ MeV. The data exhibit a pronounced jump in the cross section between $T_n = (1.0 - 1.3)$ GeV. This jump is remarkable, since the $pp$ total cross section is completely flat in this energy region. Hence in the isoscalar total nucleon-nucleon cross section $\sigma_{T=0} = 2\sigma_{pn} - \sigma_{pp}$, where the SAID values are used for $\sigma_{pp}$, this jump appears significantly still pronounced (Fig. 2, bottom). The current SAID solution is shown by the solid lines again. Its description of the data is only fair. In particular the observed $s$-shaped increase in the total cross section above 1 GeV is only slightly indicated in the SAID solution.

If we include the resonance amplitude in the $^3D_3$ ($^3G_3$) partial wave with a resonance phase $\Phi_R = 0$, then we obtain a Lorentzian shaped bump in the total cross section around $T_n \approx 1.1$ GeV, which roughly provides the right increase of the cross section in this energy region, but also a fall-off thereafter, which is not in accord with the data. To reproduce the $s$-shaped increase in the total cross section we rather need $\Phi_R \approx -(25 - 45)^\circ$, which provides a destructive interference with the $^3D_3$ ($^3G_3$) background amplitude at energies below the resonance mass and a constructive interference above it. This calculation is shown in Fig. 2 by the dotted (dashed) lines. We see that the resulting $s$-shaped pattern improves significantly the agreement with the data. The calculations are averaged over the energy resolution of the neutron beams (indicated by the horizontal bars in Fig. 2) used in the experiments. This energy smearing is particularly large in the measurements of Devlin et al. [18].

Putting the resonance in either $^3D_3$ or $^3G_3$ partial waves makes no major difference here, since the total cross sections are not sensitive to the partial waves' orbital angular momenta. Slight differences arise from the fact that we have different momentum dependences for $^3D_3$ and $^3G_3$ partial waves — see eq. (15) — and in particular from the fact that the resonance amplitude is multiplied by the background amplitude — see eq. (22), where the real parts of $^3D_3$ and $^3G_3$ phase shifts differ by more than $10^\circ$.

The phase shifts for $^3D_3$ and $^3G_3$ partial waves in the energy region of interest are depicted in Fig. 3. For the $^3D_3$-case the inclusion of the resonance with $\Phi_R \approx -(25 - 45)^\circ$ does not cause problems with unitarity, since the background inelasticity $\eta^B_{43}$ is already much below unity in the energy region of the resonance.

For the $^3G_3$-case the situation is much more delicate, since $\eta^B_{43}$ is still close to unity in the resonance region — with the consequence that the the total $\eta_{43}$ gets slightly above unity for energies below 1.1 GeV. This points to the necessity that the background amplitudes would need to be readjusted, when taking into account the resonance explicitly. Since this would mean a major effort much beyond the scope of this work, where the main emphasis is to demonstrate the basic effect of the resonance on the observables, we demand for simplicity $\eta_{43} = 1$ in the region, where it would exceed unity. (Effectively, this means that we readjust the background inelasticity $\eta^B_{43}$ accordingly.) This constrained calculation is shown in the figures by the dash-dotted lines. As expected, the calculation for the total cross sections falls now speedily back to the SAID solution in energy region below 1.1 GeV, where $\eta_{43}$ is now constrained to unity. As we will show below in Fig. 5, this constraint has only tiny effects on the differential $np$-scattering observables at energies below 1.1 GeV.

After having succeeded in improving the description of the total cross section data substantially by inclusion of the resonance amplitude in $^3D_3$ or $^3G_3$ partial waves, we consider now the resonance effect in the differential observables. In contrast to the situation for the integral cross section, it will make here a substantial difference, whether the resonance is in the $^3D_3$ or the $^3G_3$ partial wave due to the different angular dependences of these partial waves — in particular in the analyzing power $A^\eta$, as we will demonstrate in the following.

Fig. 4 shows the angular distributions of differential cross section $d\sigma/d\cos(\Theta)$, vector analyzing analyzing power $A^D$, and spin correlation coefficients $A^{qqj}$ at $T_n = 1.13$ GeV corresponding to the resonance energy $\sqrt{s} = 2.37$ GeV, where we expect the effect of the resonance on the observables to be largest. At this energy there are only data for the differential cross section at small scattering angles. The solid lines denote the current SAID solution, the dotted (dashed) lines give the result with
Figure 3: Energy dependence of the phase shifts for $^3D_3$ (left) and $^3G_3$ (right) partial waves. The real parts $\delta_l$ are shown at the top, the imaginary parts below either as inelasticity $\eta_l$ (Stapp notation \[14\]) in the middle or as $\rho_l$ phase in the SAID convention \[10, 22\] at the bottom. The solid lines and symbols denote the SAID SP07 energy dependent and single energy solutions, respectively \[10\]. Since the sign of $\rho$ does not enter \[22\], we plot the SAID solution for $\rho$ for both signs. Dotted and dashed curves show the results of including the resonance amplitude in $^3D_3$ and $^3G_3$ partial waves, respectively. The dash-dotted curve results, if in the $^3G_3$ case the inelasticity $\eta_{34}$ is constrained to unity, wherever it would exceed unity by adding the resonance amplitude. This concerns only the energy region $T_n < 1.1$ GeV.

Figure 4: Differential distributions of cross section $d\sigma/d\cos(\Theta)$, vector analyzing power $A_y$ and spin correlation coefficients $A_{00}^j$ at $T_n = 1.13$ GeV corresponding to the resonance energy $\sqrt{s} = 2.37$ GeV. For the meaning of the curves see caption of Fig. 1. For the differential cross section data are plotted for the nearby energies $T_n = 1.118$ GeV \[20\] and $T_n = 1.135$ GeV \[21\].

The resonance amplitude added in the $^3D_3$ ($^3G_3$) partial wave. As expected from the discussion of the integral elastic cross section the resonance effect is tiny in the differential cross section, however, sizably in the polarization observables. It is largest in the analyzing power $A_y$, which solely depends on interference terms. The resonance effects are particularly notable at intermediate angles, where the differential cross section gets smallest. We also see that $^3D_3$ and $^3G_3$ resonance contributions lead to opposite effects there. This provides the opportunity to disentangle these contributions by $A_y$ measurements.

The decomposition of the np-scattering observables into partial wave amplitudes is given in Ref. \[22\]. Accordingly we have for the analyzing power:

$$d\sigma/d\cos(\Theta) \cdot A_y \sim \text{Im}(H_3 + H_5)H_4^* \quad (23)$$
with $H_3$ containing sums over partial wave amplitudes with total angular momenta $j_0 = j = L$, $j_+ = L - 1$ and $j_- = L + 1$. $H_3$ contains terms being proportional either to the Legendre polynomials $P_j$ or to the associated ones $P_j^\ast$. In $H_5$ there are terms only proportional to $P_j$ and in $H_4$ only proportional to $P_j^\ast$. In particular, the structure of $H_4$ for $j = 3$ is as follows:

$$H_4(j = 3) \sim [4(T_{L=4} - 3T_{L=2}) + \sqrt{12}T_{L=3}]P_j^\ast, \quad (24)$$

where the $T$-matrix elements contain the complex phase shifts. We see that a resonance effect in $^3D_3$ and $^3G_3$ enters with opposite sign and is proportional to $P_j^\ast$ in both cases. Hence the resonance effect vanishes at the zeros of $P_j^\ast$, which is the case at $\cos(\Theta) = \pm 1/\sqrt{5} = \pm 0.447$ corresponding to $\Theta = 63.4^\circ$ and $116.6^\circ$. At these angles the predictions with and without resonance in $^3D_3$ or $^3G_3$ cross each other – see Fig. 4, top right. $P_j^\ast$ is maximal at $\cos(\Theta) = \pm \sqrt{11/15} = \pm 0.856$ and minimal at $\cos(\Theta) = 0$. Since at the latter the differential cross section is minimal and much lower than at $\cos(\Theta) = \pm 0.856$ – see Fig. 3, left –, the resonance effect in $A_y$ gets maximal at $\cos(\Theta) = 0$, i.e. at $\Theta = 90^\circ$.

In Fig. 5 we plot the energy dependence of $A_y$ near $\Theta = 90^\circ$, the angular region, where we find the largest resonance effects and where also a large amount of data are available, in particular from neutron-proton scattering experiments at Saclay [23, 24]. Since the angular dependence around $\Theta = 90^\circ$ is small, we plot in Fig. 5 the energy dependence at $\Theta = 83^\circ$, where the situation of available data [23, 24, 25, 26, 27, 28, 29, 30, 31] is more favorable than at $\Theta = 90^\circ$. The meaning of the drawn curves is the same as in Fig. 4. A significant resonance effect shows up within the energy region $T_n = (1.0 - 1.3)$ GeV. The effect is opposite in sign for the resonance residing in $^3D_3$ or $^3G_3$ partial waves. Note also that the calculations with (dashed) and without (dash-dotted) the constraint $\eta_{43} \leq 1$ exhibit only small differences for energies below 1.1 GeV – well within uncertainties of currently available data. This is not unexpected, since according to eqs. (20) - (24) the analyzing power is mainly sensitive to the real part of the phase shift.

5. Conclusions

Summarizing, we have shown that the $I(J^P) = 0(3^\ast)$ resonance structure found in the basic double-pionic fusion process $pn \rightarrow d\pi^0\pi^0$ is consistent with existing $np$ scattering data. The effect of such an $s$-channel resonance is significant in specific $np$ observables. In particular it improves considerably the description of the total cross section beyond 1 GeV. Among the differential observables the vector analyzing power exhibits the largest sensitivity to the resonance. However, for a crucial test of the resonance hypothesis and a meaningful separation of $^3D_3$ and $^3G_3$ resonance contributions high-precision data are needed for the energy region $T_n = (1.0 - 1.3)$ GeV. Such measurements have actually been carried out very recently with the WASA detector at COSY and the data analysis has started. The WASA detector installed at the COSY ring is particularly suited for analyzing power measurements in the intermediate angle region, which – as we have demonstrated here – is of main interest for the search of resonance effects in $np$ scattering.

We finally note that on the issue of the $I(J^P) = 0(3^\ast)$ resonance structure meanwhile a first three-body Faddeev calculation with full relativistic kinematics and based on hadron dynamics has been carried out by Gal and Garzilaco [32]. They find, indeed, a resonance with just these quantum numbers at a mass of 2.36(2) GeV in agreement with the experimental observation.

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