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Measurement of the $np \to np\pi^0\pi^0$ reaction in search for the recently observed $d^*(2380)$ resonance

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ABSTRACT

Exclusive measurements of the quasi-free $np \to np\pi^0\pi^0$ reaction have been performed by means of dp collisions at $T_d = 2.27$ GeV using the WASA detector setup at COSY. Total and differential cross sections have been obtained covering the energy region $\sqrt{s} = (2.35\text{–}2.46)$ GeV, which includes the region of the ABC effect and its associated $d^*(2380)$ resonance. Adding the d^* resonance amplitude to that for the conventional processes leads to a reasonable description of the data. The observed resonance effect in the total cross section is in agreement with the predictions of Fäldt and Wilkin as well with those of Albadajedo and Oset. The ABC effect, *i.e.* the low-mass enhancement in the $\pi^0\pi^0$-invariant mass spectrum, is found to be very modest – if present at all, which might pose a problem to some of its interpretations.

1. Introduction

Recent data on the basic double-pionic fusion reactions $pn \to d\pi^0\pi^0$ and $pn \to d\pi^+\pi^-$ demonstrate that the so-called ABC effect is tightly correlated with a narrow resonance structure in the total cross section of these reactions [1–3]. The ABC effect denoting a huge low-mass enhancement in the $\pi\pi$ invariant mass spectrum is observed to occur, if the initial nucleons or light nuclei fuse to a bound final nuclear system and if the produced pion pair is isoscalar. The effect has been named after the initials of Abashian, Booth and Crowe, who first observed it in the inclusive measurement of the $pd \to {}^3\text{He}X$ reaction more than fifty years ago [4].

The resonance structure with $I(J^P) = 0(3^+)$ [1] observed in the $pn \to d\pi\pi$ total cross section at $\sqrt{s} \approx 2.38$ GeV is situated about 80 MeV below $\sqrt{s} = 2m_\Delta$, the peak position of the conventional t-channel $\Delta\Delta$ process, which is also observed in this reaction. The resonance structure has a width of only 70 MeV, which is about three times narrower than the conventional process. Nevertheless, from the Dalitz plot of the $pn \to d\pi^0\pi^0$ reaction it is concluded that this resonance decays via the intermediate $\Delta^+\Delta^0$ system (at least predominantly) into its final $d\pi^0\pi^0$ state. In the $pn \to pp\pi^0\pi^-$ reaction the resonance has been sensed, too [5], though in this case, there is no ABC effect associated with the resonance. In consequence it has no longer be called ABC resonance, but d^* – adopting the notation of the predicted so-called "inevitable dibaryon" [6] with identical quantum numbers.

By subsequent quasifree polarized $\vec{n}p$ scattering measurements, it has been demonstrated that there is a resonance pole in the coupled ${}^3D_3$–${}^3G_3$ partial waves corresponding to the d^* resonance structure in mass, width and quantum numbers [7,8] – supporting thus its s-channel character.

If the scenario of a s-channel resonance in the np system is correct, then also the $np \to np\pi^0\pi^0$ reaction should be affected by this resonance, since this channel may proceed via the same intermediate $\Delta^0\Delta^+$ system as the $np \to d\pi^0\pi^0$ and $pn \to pp\pi^0\pi^-$ reactions do. From a simple isospin point of view we expect the resonance effect in the $np\pi^0\pi^0$ system to be identical in size to that in the $d\pi^0\pi^0$ system. From more refined estimates in Refs. [9,10], which account also for differences in phase space, we expect the resonance effect in the $np\pi^0\pi^0$ channel to be about 85% of that in the $d\pi^0\pi^0$ system. Since the peak resonance cross section in the latter is 270 μb [3] sitting upon background due to conventional t-channel Roper and $\Delta\Delta$ excitations, we estimate the peak resonance contribution in the $np\pi^0\pi^0$ system to be in the order of 200 μb.

2. Experiment

Since there exist no data at all for the $np \to np\pi^0\pi^0$ channel, we have investigated this reaction experimentally with the WASA detector at COSY (FZ Jülich) by using a deuteron beam with an energy of $T_d = 2.27$ GeV impinging on a hydrogen pellet target [11,12]. By exploiting the quasi-free scattering process $dp \to np\pi^0\pi^0 + p_{spectator}$, we cover the full energy range of the conjectured resonance. In addition, the quasi-free process in inverse kinematics gives us the opportunity to detect also the fast spectator proton in the forward detector of WASA.

The hardware trigger utilized in this analysis required at least two charged hits in the forward detector as well as two neutral hits in the central detector.

The quasi-free reaction $dp \to np\pi^0\pi^0 + p_{spectator}$ has been selected in the offline analysis by requiring two proton tracks in the forward detector as well as four photon hits in the central detector, which can be traced back to the decay of two π^0 particles. That way, the non-measured neutron four-momentum could be reconstructed by a kinematic fit with three over-constraints, which derive from the conditions for energy and momentum conservation and the π^0 mass. The achieved resolution in $\sqrt{s}$ was about 20 MeV.

For the reconstruction of the two π^0 particles out of the four γ quanta, all combinations have been considered and the optimal combination has been chosen, where both of the reconstructed $\gamma\gamma$-invariant masses $M_{\gamma\gamma}$ are closest to the nominal π^0 mass. For all selected events this leads to a narrow peak in the two-dimensional plot of $M_{\gamma\gamma}$ versus $M_{\gamma\gamma}$, see, *e.g.* Fig. 2 in Ref. [13]

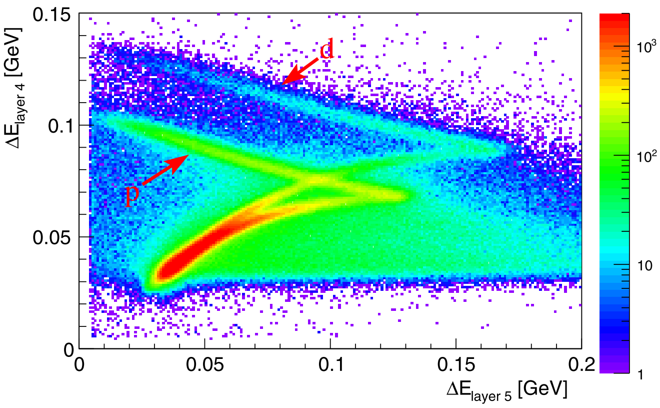

Fig. 1. Plot of the energy loss $\Delta E_{layer\ 4}$ of particles in layer 4 of the segmented Range Hodoscope versus that in layer 5 ($\Delta E_{layer\ 5}$). The bands of stopped and punch-through protons and deuterons are indicated.

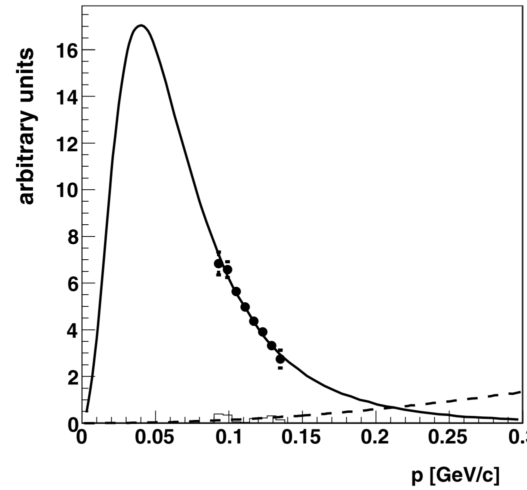

Fig. 2. Efficiency corrected distribution of the spectator proton momenta in the $dp \to np\pi^0\pi^0 + p_{spectator}$ reaction within the WASA acceptance, which allows the detection of the spectator proton only for lab angles larger than three degrees. In addition, the constraint for the suppression of breakup events has been applied (see text). Data are given by solid circles. The hatched histogram (visible at the bottom of the figure) gives the estimated systematic uncertainty due to the incomplete coverage of the solid angle. The solid line shows the expected distribution for the quasifree process based on the CD Bonn potential [15] deuteron wavefunction. For comparison, the dashed line gives the pure phase-space distribution as expected for a coherent reaction process.

and Fig. 3 in Ref. [14]. With this procedure the combinatorial background is very small, in the order of a few percent.

The charged particles registered in the segmented Forward Detector of WASA are identified by use of the $\Delta E - E$ energy loss method. For its application in the data analysis, all combinations of signals stemming from the five layers of the Forward Range Hodoscope are used. As an example, Fig. 1 shows the plot of the energy loss in layer 4 versus that in layer 5. As can be seen, deuterons and protons can be well separated in general.

A difficulty emerges from deuterons, which originate from the $np \to d\pi^0\pi^0$ reaction and which partly also break up while passing the detector. Since in the energy loss plots used for particle identification proton and deuteron bands do have some small but finite overlaps, deuterons cannot be separated completely from np pairs stemming from the $np \to np\pi^0\pi^0$ reaction. To suppress such misidentified events we require the angle between emitted neutron and proton to be larger than five degrees and also their energies to be in the expected range. Nevertheless, a Monte Carlo (MC) simulation of the $np \to d\pi^0\pi^0$ reaction, which is known experimentally and also can be modeled very well [1], shows that we have to expect still a contamination of about 5% in the spectra of the $np \to np\pi^0\pi^0$ reaction. In Figs. 2–7 the observables are shown with the MC-generated contamination events already subtracted. In the pn invariant-mass spectrum M_{pn}, where the contamination shows up most pronounced, this concerns only the first two bins (Fig. 7).

In Fig. 2, the measured efficiency and acceptance corrected spectator momentum distribution is shown in comparison with a MC simulation of the quasifree $dp \to np\pi^0\pi^0 + p_{spectator}$ process. Due to the beam-pipe, ejectiles can only be detected in the WASA forward detector for lab angles larger than three degrees. The good agreement between data and simulation provides confidence that the data indeed reflect a quasifree process. Systematic uncertain-

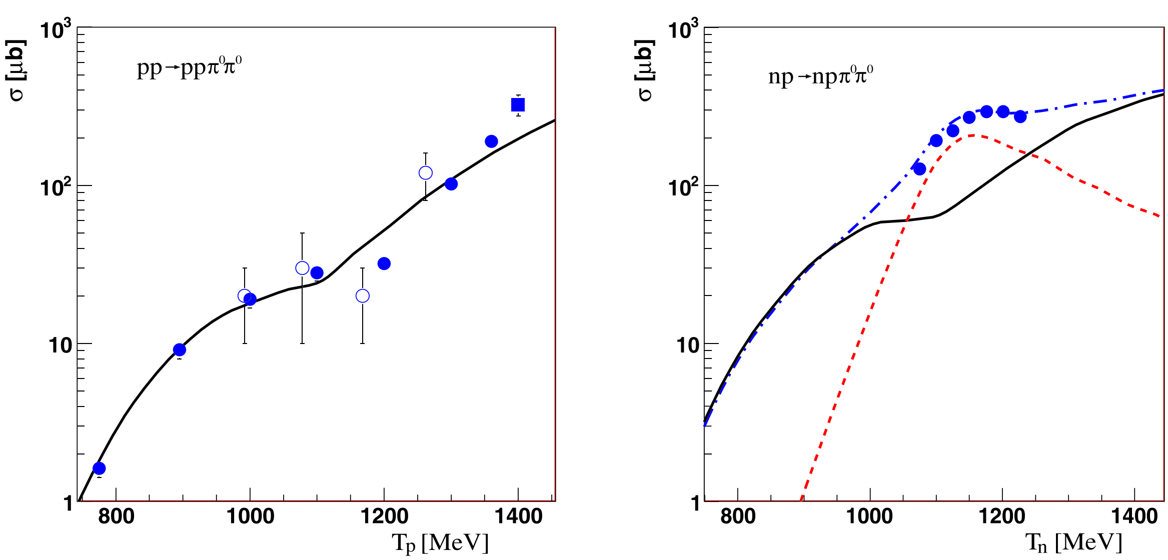

Fig. 3. (Color online.) Total cross sections for the reactions $pp \to pp\pi^0\pi^0$ (left) and $np \to np\pi^0\pi^0$ (right). The results of this work are shown by the full circles in the right figure. Statistical and systematic uncertainties (Table 1) are smaller than the symbol size. The uncertainty in the absolute normalization in the order of 20% is not shown. Previous WASA results on the $pp\pi^0\pi^0$ channel are shown by full circles [18] and full square [14], respectively, in the left figure, previous bubble-chamber measurements from KEK [16] by open circles. The modified Valencia model calculation is shown by the solid lines. The dash-dotted curve shows the result, if the s-channel d^* resonance amplitude is added. The d^* contribution itself is given by the dotted curve.

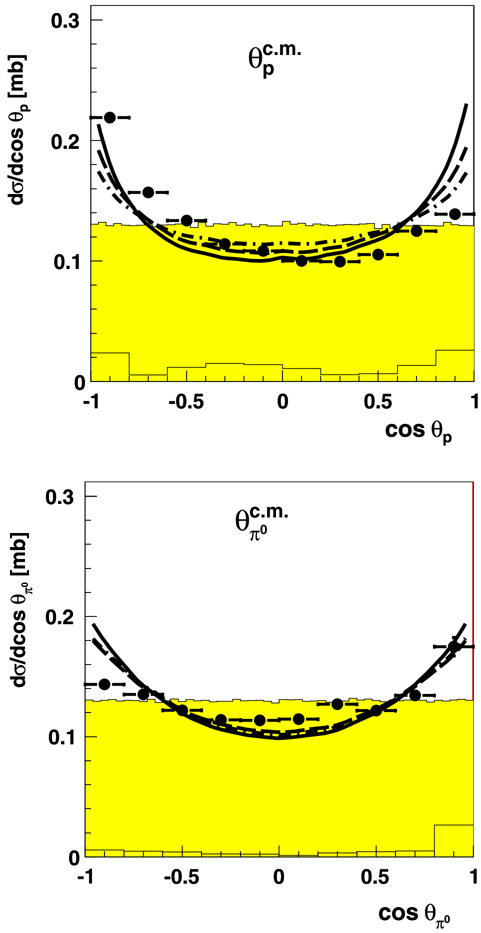

Fig. 4. (Color online.) Distributions of the c.m. angles $\Theta_p^{c.m.}$ (top) and $\Theta_{\pi^0}^{c.m.}$ (bottom) for the $pn \to np\pi^0\pi^0$ reaction at $T_n = 1.135$ GeV. Since the data are shown without separation into $\sqrt{s}$ bins, they correspond to the average over the energy region covered by the quasifree collision process, which is 2.35 GeV $< \sqrt{s} <$ 2.41 GeV (1.07 GeV $< T_n <$ 1.23 GeV). Filled circles represent the experimental results of this work. The hatched histograms give estimated systematic uncertainties due to the incomplete coverage of the solid angle. The shaded areas denote phase-space distributions. The solid lines are calculations with the modified Valencia model. The dashed (dash-dotted) lines shows the result, if the d^* resonance amplitude with (without) inclusion of the $\Delta\Delta$ vertex function [1] is added. Note that in the bottom panel dashed and dash-dotted curves lie practically on top of each other. All calculations are normalized in area to the data.

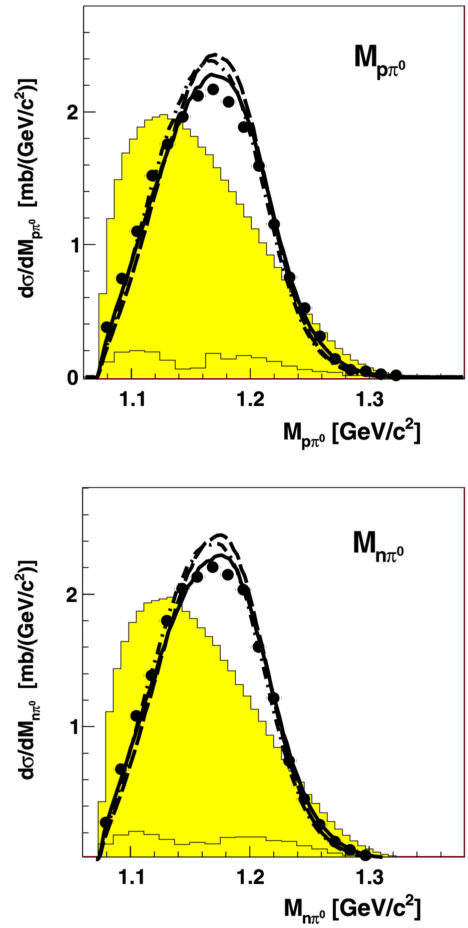

Fig. 5. (Color online.) Same as Fig. 4 but for the distributions of the invariant masses $M_{p\pi^0}$ (top) and $M_{n\pi^0}$ (bottom).

ties due to efficiency and acceptance corrections are very small. They are shown as hatched histogram, barely visible at the bottom line of Fig. 2. The constraint for the suppression of breakup events (see above) causes the maximum accepted spectator momentum to be $<$ 0.14 GeV/c fulfilling the spectator momentum condition used in previous works [1,3,7]. This implies an energy range of 2.35 GeV $\le \sqrt{s} \le$ 2.41 GeV being covered due to the Fermi motion of the nucleons in the deuteron. This energy range corresponds to incident lab energies of 1.07 GeV $< T_n <$ 1.23 GeV.

In total a sample of about 24 000 good events has been selected. The requirement that the two protons have to be in the angular range covered by the forward detector and that the gammas resulting from π^0 decay have to be in the angular range of the central detector reduces the overall acceptance to about 7%. The total reconstruction efficiency including all cuts and kinematical fitting has been about 1%. Efficiency and acceptance corrections of the data have been performed by MC simulations of reaction process and detector setup. For the MC simulations model descriptions have been used, which will be discussed in the next chapter. Since WASA does not cover the full reaction phase space, albeit a large fraction of it, the corrections are not fully model independent. The hatched grey histograms in Figs. 2, 4–7 give an estimate for systematic uncertainties due to the use of different models with and without d^* resonance hypothesis for the efficiency correction. Compared to the uncertainties in these corrections, systematic errors associated with modeling the reconstruction of particles are negligible.

The absolute normalization of the data has been performed by the simultaneous measurement of the quasi-free single pion production process $dp \to pp\pi^0 + n_{spectator}$ and its comparison to previous bubble-chamber results for the $pp \to pp\pi^0$ reaction [16, 17]. That way, the uncertainty in the absolute normalization of our data is essentially that of the previous $pp \to pp\pi^0$ data, *i.e.* in the order of 20%.

3. Results and discussion

In order to determine the energy dependence of the total cross section we have divided our data sample into 10 MeV bins in $\sqrt{s}$. The resulting total cross sections together with their statistical and systematic uncertainties are listed in Table 1.

Fig. 3 exhibits the energy dependence of the total cross section for the $np \to np\pi^0\pi^0$ reaction (right) in comparison to that of the $pp \to pp\pi^0\pi^0$ reaction (left). The previous WASA results [18,14] and the ones of this work are given by the full circles. They are compared to previous bubble-chamber measurements from KEK (open circles) [16] in case of the $pp\pi^0\pi^0$ channel.

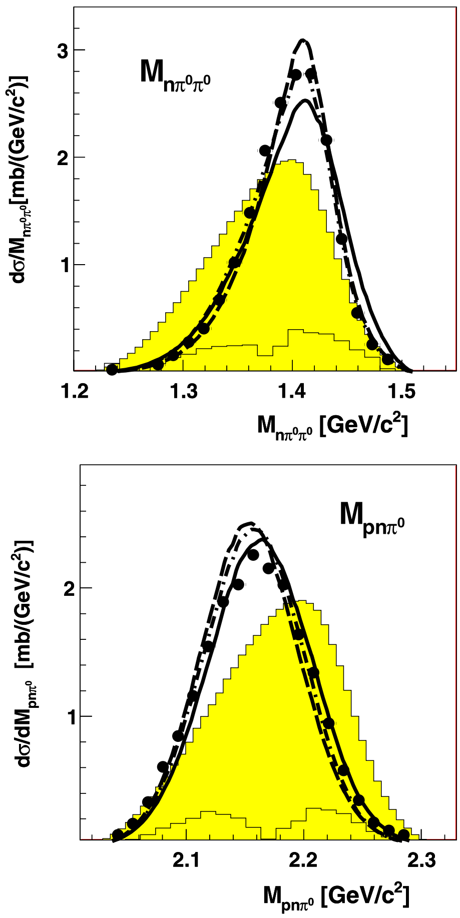

Fig. 6. (Color online.) Same as Fig. 4 but for the distributions of the invariant masses $M_{n\pi^0\pi^0}$ (top) and $M_{pn\pi^0}$ (bottom).

In case of the $np\pi^0\pi^0$ channel, there exist no dedicated data from previous investigations. However, there are some connected data from the PINOT experiment at Saclay, where the inclusive reactions $pp \to \gamma\gamma X$ and $pd \to \gamma\gamma X$ were measured at $T_p = 1.3$ and 1.5 GeV [19]. By excluding the two-photon invariant mass regions corresponding to single π^0 or η production, the remaining two-photon events populating the combinatorial background are likely to originate from $\pi^0\pi^0$ production. By using this feature, a measure of the ratio of the cross sections $pn \to pn\pi^0\pi^0 + d\pi^0\pi^0$ to $pp \to pp\pi^0\pi^0$ has been obtained. This leads to a crude estimate for the $pn \to pn\pi^0\pi^0$ cross section to be larger than the $pp \to pp\pi^0\pi^0$ cross section by roughly a factor of two – in qualitative support of our results from the exclusive measurements [20].

In Fig. 3, we compare the data to theoretical calculations in the framework of the Valencia model [21], which incorporates both non-resonant and resonant t-channel processes for two-pion production in NN collisions. The t-channel resonance processes of interest here concern first of all the excitation of the Roper resonance and its subsequent decay either directly into the $N\pi\pi$ system or via the $\Delta\pi$ system as well as the excitation and decay of the $\Delta\Delta$ system. Deviating from the original Valencia calculations [21], the present calculations have been tuned to describe quantitatively the isovector two-pion production reactions $pp \to NN\pi\pi$ [18], in particular the $pp\pi^0\pi^0$ [22] and $nn\pi^+\pi^+$ [23] channels by the following modifications:

- relativistic corrections for the Δ propagator as given by Ref. [24],

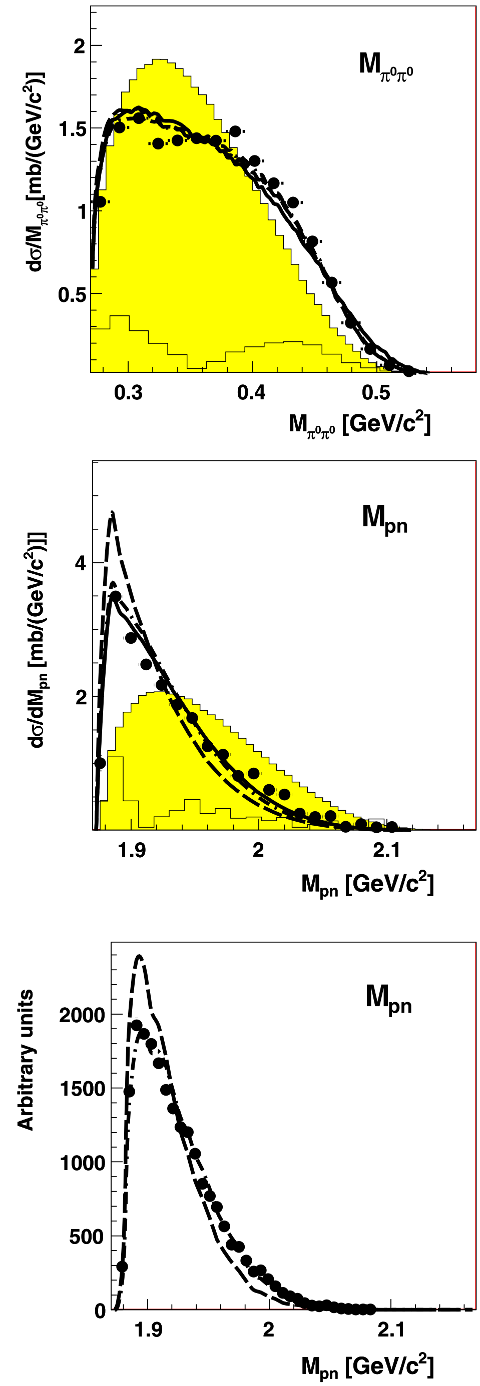

Fig. 7. (Color online.) The same as Fig. 4, but for the distribution of the invariant masses $M_{\pi^0\pi^0}$ (top) and M_{pn} (middle). The bottom panel shows the raw M_{pn} spectrum without efficiency and acceptance corrections.

- strongly reduced ρ-exchange contribution in the t-channel $\Delta\Delta$ process – in agreement with calculations from Ref. [25],
- reduction of the $N^* \to \Delta\pi$ amplitude by a factor of two in agreement with the analysis of photon- and pion-induced pion production on the nucleon [26] and in agreement with $pp \to pp\pi^0\pi^0$ and $pp \to pp\pi^+\pi^-$ measurements close to threshold [27–30] as well as readjustment of the total Roper excitation according to the results of the isospin decomposition of the $pp \to NN\pi\pi$ cross sections [18],
- inclusion of the t-channel excitation of the $\Delta(1600)P_{33}$ resonance.

Table 1
Total cross sections obtained in this work for the $np \to np\pi^0\pi^0$ reaction in dependence of the center-of-mass energy $\sqrt{s}$ and the neutron beam energy T_n. Systematic uncertainties are given as obtained from MC simulations for the detector performance assuming various models for the reaction process. The uncertainty in the absolute normalization in the order of 20% is not included.

$\sqrt{s}$ [MeV]	T_n [MeV]	σ_{tot} [μb]	$\Delta\sigma_{stat}$ [μb]	$\Delta\sigma_{sys}$ [μb]
2.35	1.075	127	6	12
2.36	1.100	192	9	20
2.37	1.125	222	11	22
2.38	1.150	269	13	27
2.39	1.176	293	14	29
2.40	1.201	295	14	29
2.41	1.227	272	13	27

The latter modification was necessary, in order to account for the unexpectedly large $pp \to nn\pi^+\pi^+$ cross section [23]. The predictive power of these modifications has been demonstrated by its successful applications to the recent $pp \to pp\pi^0\pi^0$ data at $T_p = 1.4$ GeV [14] and to the $pn \to pp\pi^0\pi^-$ reaction [5].

Final state interaction (FSI) in the emitted NN system has been taken into account in the Migdal and Watson [31,32] factorized form.

The NN FSI is by far strongest in the isovector $^1S_0$ pn state and less strong in $^1S_0$ pp and $^3S_1$ pn states as apparent from the scattering lengths in these systems. At energies above 1 GeV the t-channel $\Delta\Delta$ process is the dominating one. Isospin decomposition of its contribution to the total $np \to np\pi^0\pi^0$ cross section [33,34,18] shows that in this process the $^1S_0$ final state is much less populated than the isoscalar $^3S_1$ state. The situation is somewhat different in the near-threshold region, where the Roper excitation process dominates. In this process, equal amounts of pn pairs are emitted in $^1S_0$ and $^3S_1$ states.

Since the modified Valencia calculations have been tuned to the $pp \to pp\pi^0\pi^0$ reaction, it is no surprise that its total cross section is fairly well described – see left panel in Fig. 3. For the closely related $np \to np\pi^0\pi^0$ reaction, the calculations predict a similar energy dependence, but an absolute cross section, which is larger by roughly a factor of two – whereas the data are larger by more than an order of magnitude – see Fig. 3, right panel.

As an independent check of these calculations we may perform an isospin decomposition of cross sections using the formulas given in Refs. [33,34] and the matrix elements deduced from the analysis of the pp induced two-pion production [18]. As an result of such an exercise we get agreement with the modified Valencia calculation within roughly 30%.

As we see from Fig. 3, the experimental cross sections obtained in this work for the $np \to np\pi^0\pi^0$ reaction are three to four times larger than predicted. This failure points to an important reaction component not included in the t-channel treatment of two-pion production. It is intriguing that we deal here with the energy region where the d^* resonance has been observed both in np scattering [7] and in the isoscalar part of the double-pionic fusion to deuterium [1,3]. Also it has been shown that the description of the $pn \to pp\pi^0\pi^-$ cross section improves greatly in this energy region, if this resonance is included [5]. Hence we add also here the amplitude of this resonance to the conventional amplitude. According to the predictions of Fäldt and Wilkin [9] as well as Albaladejo and Oset [10], its contribution at the resonance maximum should be about 200 μb (dotted curve in Fig. 3) as discussed in the introduction. It is amazing, how well the resulting curve (dash-dotted line in Fig. 3) describes the data. Of course, it is a pity that there are no data outside the energy region covered by our data. In particular at energies below 1 GeV and above 1.3 GeV, *i.e.* outside the resonance region, such data would be very helpful to examine experimentally the reliability of the predictions for the t-channel contributions.

When binned into $\sqrt{s}$ bins of 10 MeV, the different distributions do not exhibit any particular energy dependence in their shapes – which is of no surprise, since the energy region covered in this measurement is dominated by the d^* resonance as evident from the discussion of the total cross section. Hence we refrain from showing the differential distributions for single $\sqrt{s}$ bins. We rather show them unbinned, *i.e.*, averaged over the full energy range of the measurement, which has the advantage of better statistics and less systematic uncertainties due to potential binning artifacts.

For a four-body final state there are seven independent differential observables. We choose to show in this paper the differential distributions for the invariant masses $M_{\pi^0\pi^0}$, M_{pn}, $M_{p\pi^0}$, $M_{n\pi^0}$, $M_{n\pi^0\pi^0}$ and $M_{pp\pi^0}$ as well as the differential distributions for the center-of-mass (cm) angles for protons and pions, namely $\Theta_p^{c.m.}$ and $\Theta_{\pi^0}^{c.m.}$. These distributions are shown in Figs. 4–7.

All measured differential distributions are markedly different in shape from pure phase-space distributions (shaded areas in Figs. 3–6), but close to the predictions both with (dashed and dash-dotted lines) and without (solid lines) inclusion of the d^* resonance.

The pion angular distribution (Fig. 4) behaves as expected from the p-wave decay of the Δ resonance. And also the proton angular distribution is similarly curved. Both t-channel meson exchange and the $J^P = 3^+$ requirement for d^* formation predict comparable shapes in agreement with the data.

The invariant mass spectra for $M_{p\pi^0}$, $M_{n\pi^0}$, $M_{n\pi^0\pi^0}$ and $M_{pn\pi^0}$ (Figs. 5–6) are characterized by Δ and $N\Delta$ dynamics as they naturally appear in the deexcitation process of an intermediate $\Delta\Delta$ system created either by d^* decay or via t-channel meson exchange.

The M_{pn} and $M_{\pi^0\pi^0}$ spectra (Fig. 7) need a more thorough discussion. The data of the $M_{\pi^0\pi^0}$ spectrum appear to be quite well described by the calculations, which hardly deviate from each other. At small invariant masses though, in the range 0.3–0.4 GeV/c^2, there is an indication of a small surplus of strength. Taken the uncertainties inherent in the data and in the theoretical description, these deviations appear not to be particularly significant. Therefore, if this constitutes a sign of the ABC effect, then it is obviously very small in this reaction. Note that contrary to the situation in the $pn \to pp\pi^0\pi^-$ reaction, where the pion pair has to be in relative p-wave and hence the ABC-effect is absent, the pion pair here is preferentially in relative s-wave allowing thus, in principle, the occurrence of the ABC effect. Hence, the finding that there is no or nearly no ABC effect comes as a surprise at least for some of its interpretations – see, *e.g.* Ref. [35]. This finding is of no surprise, if the ABC effect is described by a formfactor at the $\Delta\Delta$ vertex of the d^* decay [1]. However, then a problem arises with the description of the M_{pn} spectrum, as we discuss in the following.

The M_{pn} spectrum peaks sharply at its low-mass threshold, which is characteristic for a strong np FSI as discussed above. This low-mass peaking is well accounted for by the modified Valencia calculations (solid lines in Figs. 4–7). Inclusion of the d^* resonance as outlined in Ref. [1] (dashed lines) exaggerates the low-mass peaking deteriorating thus the agreement with the data. The reason for this behavior is the formfactor at the $\Delta\Delta$ decay vertex of d^* introduced in Ref. [1] for the description of the ABC effect, *i.e.* the low-mass enhancement in the $M_{(\pi\pi)^0}$ spectra observed in double-pionic fusion reactions. However, as already pointed out in Ref. [5], this formfactor acts only on the $M_{\pi^0\pi^0}$ and $M_{\pi^+\pi^-}$ spectra, if the nucleon pair is bound in a final nuclear system. If this is not the case, then the formfactor acts predominantly on the invariant-mass spectrum of the nucleon pair. This is illustrated by comparison of the calculations including d^* with (dashed) and without (dash-dotted) this formfactor. As we see, the formfactor hardly changes the $M_{\pi^0\pi^0}$ distribution, but shuffles substantial strength in the M_{pn} spectrum to low masses – thus overshooting the observed low-mass enhancement.

Unfortunately, also the model-dependence of the acceptance and efficiency corrections is largest near the low-mass threshold hampering thus a definite statement about a failure of the formfactor ansatz. In order to circumvent this model dependence somewhat, we plot the data in Fig. 7, bottom, before acceptance and efficiency corrections. The calculations shown are now given within the acceptance of the WASA detector. We see that, first of all, the corrections do not change the shape of the distribution profoundly, and second that the calculations with formfactor overshoot the low-mass peak in similar manner as before, whereas the calculations without this formfactor agree again well with the data.

This overshooting indicates that the formfactor introduced in Ref. [1] on purely phenomenological grounds for the description of the ABC effect is possibly at variance with the data for isoscalar two-pion production in non-fusion channels. Hence alternative solutions for this phenomenon may have to be looked for, such as d-wave contributions in the intermediate $\Delta\Delta$ system and/or final nucleon-pair [36,37].

Another alternative involving d-waves has been proposed recently by Platonova and Kukulin [35]. In their ansatz they assume the d^* resonance not only to decay into the $d\pi^0\pi^0$ channel via the route $d^* \to \Delta^+\Delta^0 \to d\pi^0\pi^0$,[7] but also via the route $d^* \to d\sigma \to d\pi^0\pi^0$. Since σ is a spin zero object, it has to be in relative d-wave to the deuteron in this decay process, in order to satisfy the resonance condition of $J^P = 3^+$. In consequence the available momentum in this decay process is concentrated in the relative motion between d and σ leaving thus only small relative momenta between the two emerging pions. Therefore the $M_{\pi^0\pi^0}$ distribution is expected to be peaked at low masses – *i.e.*, the low-mass enhancement (ABC effect) in this model is made by the $d\sigma$ decay branch (in the amount of about 5%) and not by a formfactor as introduced in Ref. [1]. The enhancement in this model is further increased by an interference of the $d\sigma$ decay amplitude with the decay amplitude via the $\Delta^+\Delta^0$ system. It appears straightforward to extend this ansatz also to reaction channels, where the np system is unbound. However, since we hardly observe a low-mass enhancement (ABC effect) in the $M_{\pi^0\pi^0}$ spectrum, much less $d^* \to d\sigma$ contribution is needed here than in the $pn \to d\pi^0\pi^0$ reaction – which possibly poses a consistency problem for this ansatz [35].

Another point of concern with this ansatz is that mass and width of the sigma meson have been fitted to the $pn \to d\pi^0\pi^0$ data in Ref. [35] with the result that $m_\sigma \approx 300$ MeV and $\Gamma_\sigma \approx 100$ MeV. Both values are much smaller than the generally accepted values for the sigma meson [38], which are $m_\sigma =$ (400–550) MeV and $\Gamma_\sigma =$ (400–700) MeV. In Ref. [35] it has been argued that these deviations could be a sign of chiral restoration in the hadronic/nuclear environment – in particular within the six-quark bag. However, any evidence for this hypothesis from other experiments is lacking so far. Whether the enhanced ABC effect observed in the double-pionic fusion to ^{4}He [39] is in support of such an argumentation is an open question.

[7] Actually they consider the decay $d^* \to D_{12}^{++}\pi^0 \to d\pi^0\pi^0$ with D_{12}^{++} being a $I(J^P) = 1(2^+)$ state near the $N\Delta$ threshold, but since the pion emitted in the d^* decay is in relative p-wave to D_{12}, this route is practically indistinguishable from a $d^* \to \Delta^+\Delta^0$ decay at the given kinematic conditions.

4. Conclusions

The $np \to np\pi^0\pi^0$ reaction, for which no dedicated previous data exist, has been investigated by exclusive and kinematically complete measurements. They have been carried out in quasifree kinematics with a deuteron beam impinging on a hydrogen pellet target. Utilizing the nucleons' Fermi motion in the deuteron projectile an energy region of 2.35 GeV $< \sqrt{s} <$ 2.41 GeV could be covered corresponding to an incident lab energy range of 1.07–1.23 GeV. This energy region covers the region of the d^* resonance. The data are in agreement with a resonance contribution of about 200 μb, as predicted by Fäldt and Wilkin [9] as well as by Albaladejo and Oset [10]. The d^* contribution is by far larger than that from conventional processes. Calculations based on conventional t-channel meson exchange underpredict the data by factors three to four and in addition are at variance with the measured energy dependence of the total cross section. Though those calculations have been tuned to two-pion production channels, where d^* does not contribute, they still may have some inherent model dependence. But, even if we assume the associated uncertainty to be as large as 50%, we still arrive at an uncertainty of only 15% for the required d^* contribution, *i.e.* 200 ± 30 μb.

In general, the differential data are reasonably well described by calculations, which include both the d^* resonance and the conventional t-channel processes.

The data do not exhibit any significant low-mass enhancement (ABC effect) in the $\pi^0\pi^0$-invariant mass distribution. Though this is not in disagreement with the phenomenological ansatz of a formfactor at the $d^* \to \Delta\Delta$ decay vertex introduced in Ref. [1], the worsening of the description of the M_{pn} spectrum by use of this formfactor calls possibly for an improved explanation of the ABC effect in connection with the d^* resonance.

After having found evidences for the d^* resonance in the $d\pi^0\pi^0$, $d\pi^+\pi^-$ and $pp\pi^0\pi^-$ channels, the channel investigated here has been one of the two remaining two-pion production channels, where the predicted contributions of the d^* resonance had not yet been checked experimentally. As we have shown now, the data for the $np\pi^0\pi^0$ channel are consistent with the d^* hypothesis and provide an experimentally determined branching of about 12% for the d^* decay into this channel. A preliminary list of decay branches is given in Ref. [40], an update of which is in preparation.

Since d^* has been observed meanwhile also in the elastic channel by polarized $\vec{n}p$ scattering, the only remaining unexplored decay channel is $np\pi^+\pi^-$. This channel has been measured recently at HADES and preliminary results have been presented already at conferences [41–43]. It will be highly interesting, not only to obtain total cross sections for this channel, but also differential distributions. Of particular interest will be the M_{pn} and $M_{\pi^+\pi^-}$ distributions as discussed in this work.

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