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Measurement of the $\vec{n}p \to d\pi^0\pi^0$ reaction with polarized beam in the region of the $d^*(2380)$ resonance

WASA-at-COSY Collaboration

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Abstract. We report on a high-statistics measurement of the most basic double-pionic fusion reaction $\vec{n}p \to d\pi^0\pi^0$ over the energy region of the $d^*(2380)$ resonance by use of a polarized deuteron beam and observing the double fusion reaction in the quasifree scattering mode. The measurements were performed with the WASA detector setup at COSY. The data reveal substantial analyzing powers and confirm conclusions about the d^* resonance obtained from unpolarized measurements. We also confirm the previous unpolarized data obtained under complementary kinematic conditions.

1 Introduction

As has been pointed out previously by Harney [1], finite vector analyzing powers $A_y(\Theta)$ arise in reaction processes only, if at least two different partial waves interfere. Hence in case of an isolated s-channel resonance, which is formed by a single partial wave matching to spin and parity of the resonance, the analyzing powers in the resonance region will be vanishing small, if there is no sizeable interfering background from other reaction processes.

Recently, in the reaction $pn \to d\pi^0\pi^0$ a pronounced, narrow resonance structure corresponding to a mass of 2.38 GeV and a width of about 70 MeV has been observed in the total cross section near $\sqrt{s} \approx 2.4\,\text{GeV}$ ($T_p = 1.2\,\text{GeV}$) [2–4]. Its quantum numbers have been determined to be $I(J^P) = 0(3^+)$ [3]. The s-channel character of this resonance has been established recently by polarized $\vec{n}p$ scattering. Inclusion of these new data into the SAID partial-wave analysis produces a pole in the coupled ${}^3D_3$-${}^3G_3$ partial waves at $(2380 \pm 10 - i40 \pm 5)\,\text{MeV}$ [5,6]. Since then this resonance is denoted by $d^*(2380)$.

The $d\pi^0\pi^0$ channel is the d^* decay channel with the smallest amount of background from other reaction processes [3–11]. Nevertheless it has sizeable contributions from t-channel $N(1440)$ and $\Delta\Delta$ excitations. Both of them are very well known from the study of pp-induced two-pion production [4,12–24].

Hence, due to the finite background amplitudes we may expect sizeable analyzing powers A_y in the region of the d^* resonance. Also, they are expected to increase with increasing energy due to the increasing contribution of higher partial waves. Since A_y is composed only of interference terms of partial waves, it is sensitive to even small partial-wave contributions and therefore qualifies as a sensitive spectroscopic tool for the investigation of the d^* resonance region.

2 Exclusive measurements at WASA

In order to investigate this issue in a comprehensive way we measured the basic *isoscalar* double-pionic fusion process $\vec{n}p \to d\pi^0\pi^0$ exclusively and kinematically complete.

The experiment was carried out with the WASA detector setup [25, 26] at COSY via the reaction $\vec{d}p \to d\pi^0\pi^0 + p_{spectator}$ using a polarized deuteron beam at the lab energy $T_d = 2.27\,\text{GeV}$. Since due to Fermi motion of the nucleons in the beam deuteron the quasifree reaction proceeds via a range of effective collision energies, we cover the energy region $2.30\,\text{GeV} < \sqrt{s} < 2.47\,\text{GeV}$.

The emerging deuterons as well as the fast, quasifree scattered spectator protons were detected in the forward detector of WASA and identified by the ΔE-E technique. Gammas from the π^0 decay were detected in the central detector.

That way the full four-momenta were determined for all particles of an event. Since the reaction was measured kinematically overdetermined, kinematic fits with 6 overconstraints could be performed for each event. From the full kinematic information available for each event also the relevant total energy in the np system could be reconstructed for each event individually.

By just having a different trigger these measurements have been obtained in parallel to the ones for np elastic scattering [5,6]. The trigger used for the detection of the $d\pi^0\pi^0$ events required at least one hit in the forward detector and three neutral hits in the central detector.

For details of the experiment, in particular also with respect to the determination of the beam polarization, checks for quasifree scattering and the procedure for deriving A_y from the data, see ref. [6].

For convenience the absolute normalization of the cross section data has been obtained just by relative normalization to the datum of the total cross section at $\sqrt{s} = 2.38\,\text{GeV}$ published in ref. [4].

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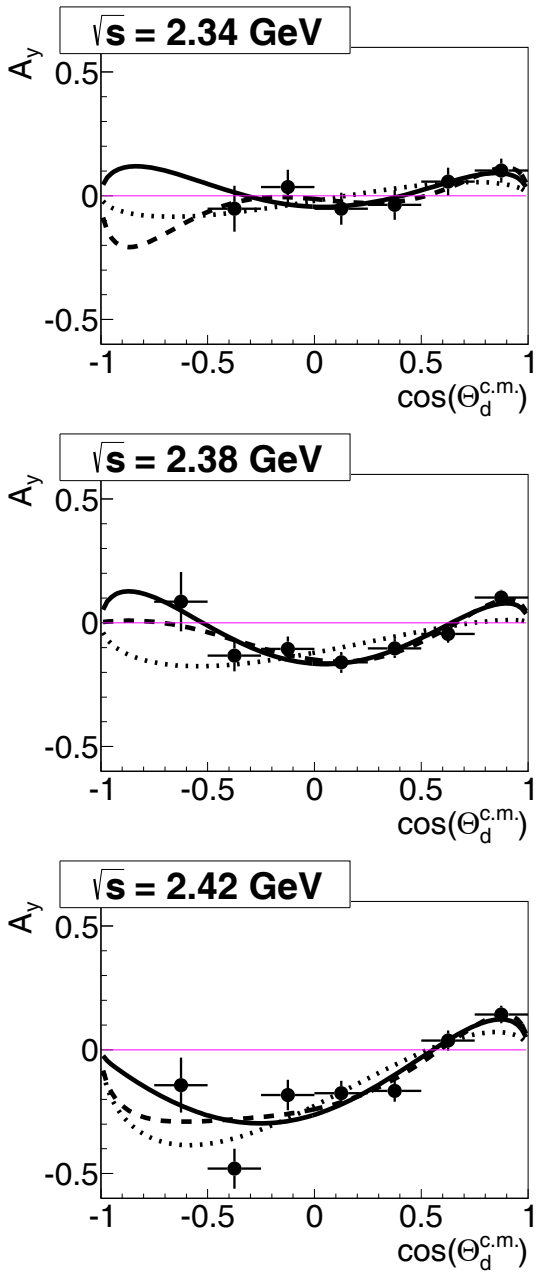

Fig. 1. Analyzing power in dependence of the deuteron scattering angle in the c.m. system for the three energy bins centered at $\sqrt{s} = 2.34\,\text{GeV}$ (top), 2.38 GeV (middle) and 2.42 GeV (bottom). The solid circles denote the experimental results of this work. The dotted lines give a 2-parameter fit to the data by use of eq. (1). The solid lines show the fit results, if a $\sin(3\Theta^{c.m.})$ term is added and the dashed lines a fit, if also a $\sin(4\Theta^{c.m.})$ term is included, see eq. (2).

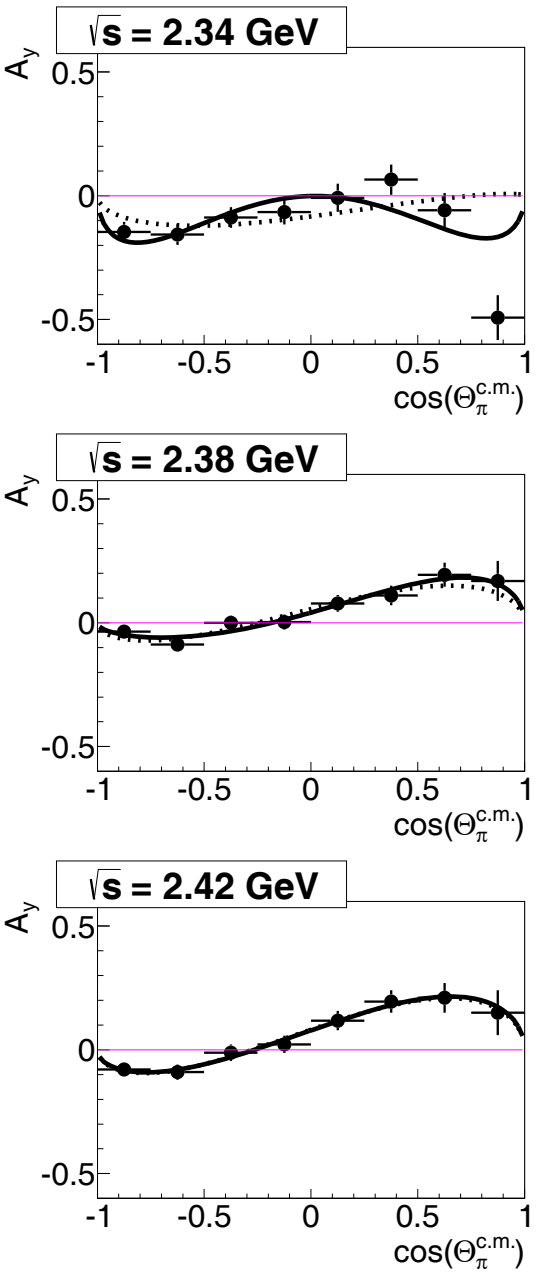

Fig. 2. The same as fig. 1, but for the π^0 scattering angle in the c.m. system. Fits are shown for the 2- and 3-parameter options.

3 Results

3.1 Analyzing powers

The analyzing powers A_y extracted from this experiment are shown in figs. 1–3 in dependence of the center-of-mass (c.m.) scattering angles $\Theta_d^{c.m.}$, $\Theta_{\pi^0}^{c.m.}$ and $\Theta_\Delta^{c.m.}$ of emitted deuteron, π^0 and Δ particles, respectively. The intermediate Δ from the process $d^* \to \Delta^+\Delta^0 \to d\pi^0\pi^0$ has been reconstructed from the 4-momenta of its decay products π^0 and nucleon —the latter by taking half the deuteron momentum, thereby neglecting the small correction due to Fermi motion of the nucleons inside the deuteron. Since the Dalitz plot displayed in fig. 4 of ref. [3] exhibits a Δ excitation band sitting upon no substantial background, no cut on the Δ mass appears to be necessary.

The data have been binned into three energy bins as displayed in figs. 1–3: $\sqrt{s} = 2.30$–$2.35\,\text{GeV}$ with center of gravity at 2.34 GeV, $\sqrt{s} = 2.36$–$2.40\,\text{GeV}$ with centroid at

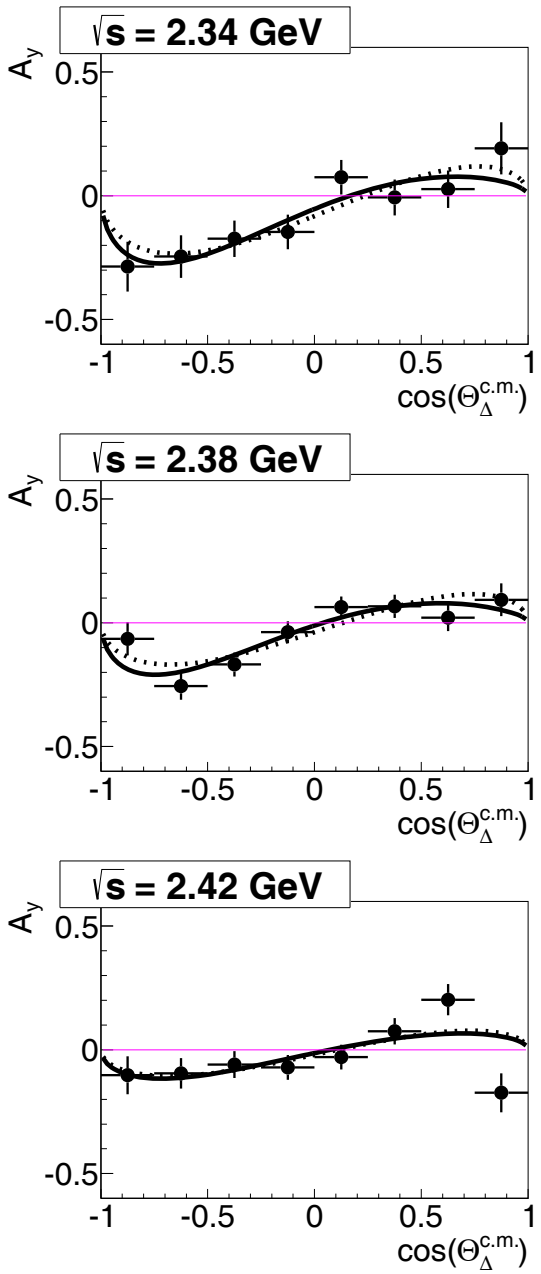

Fig. 3. The same as fig. 2, but for the Δ scattering angle in the c.m. system.

2.38 GeV and $\sqrt{s}$ = 2.41–2.47 GeV centered at 2.42 GeV. The middle one corresponds to the maximum cross section of the d^* resonance, whereas the other two roughly correspond to its half maximum. At the lowest-energy bin the analyzing power in dependence of the deuteron scattering angle is still small. However, substantial A_y values are obtained at the two higher-energy bins.

In the following the description of the data is based on the formalism outlined in ref. [27]. Based on that work A_y angular dependencies have been derived in ref. [17], which can be theoretically expected in pp induced, *i.e.* purely isovector two-pion production, if there are only relative s- and p-waves in the final channel:

$$A_y(\Theta^{c.m.}) = a\sin(\Theta^{c.m.}) + b\sin(2\Theta^{c.m.}) \qquad (1)$$

with the parameters a and b to be adjusted to the data.

For the $pn \to d\pi^0\pi^0$ reaction the situation changes insofar as we deal here with a purely isoscalar channel. In addition d-waves have to be included, in order to allow the formation of $d^*(2380)$. For simplicity we assume the $\pi\pi$ system to be in relative s-wave. At least for the resonance formation this is well justified [3]. Applying the formalism presented in ref. [17] to this situation [28] we again end up with a formal description in terms of $\sin(j\Theta)$:

$$A_y(\Theta^{c.m.}) = \sum p_{j-1}\sin(j\Theta^{c.m.}). \qquad (2)$$

Due to the involvement of d-waves the sum runs now over 4 terms (j = 1,...,4) from $\sin(\Theta^{c.m.})$ until $\sin(4\Theta^{c.m.})$. The weighting parameters $p_0, \ldots, p_3$ to be adjusted to the data have now the following meaning:

$$\begin{aligned} p_0 &= q a_1^* b + p_2, && (sp + pd),\\ p_1 &= q^2 a_2^* r_1 + 4p_3, && (sd + dd),\\ p_2 &= q^3 b r_1^*, && (pd),\\ p_3 &= q^4 r_1^* r_2, && (dd). \end{aligned} \qquad (3)$$

Here q denotes the momentum of the $\pi\pi$ system relative to the deuteron and the strength parameters a_1, a_2, b, r_1 and r_2 stand for the transitions

$$\begin{aligned} a_1&:\ {}^3S_1 \to {}^3S_1 s, && (s),\\ a_2&:\ {}^3D_1 \to {}^3S_1 s, && (s),\\ b&:\ {}^1P_1 \to {}^3S_1 p, && (p),\\ r_1&:\ {}^3D_3 \to {}^3S_1 d, && (d),\\ r_2&:\ {}^3G_3 \to {}^3S_1 d, && (d), \end{aligned} \qquad (4)$$

where on the left-hand side the pn partial wave in the entrance channel is given by its spectroscopic nomenclature. The right-hand side denotes the partial wave of the deuteron together with its angular momentum relative to the $\pi\pi$ system. The interference of these partial waves, which are abbreviated by s, p and d, is indicated in brackets at the right-hand side of eq. (3). Note that in the entrance channel ${}^3S_1$ and ${}^3D_1$ as well as ${}^3D_3$ and ${}^3G_3$ are coupled partial waves. In principle, also the ${}^3S_1$-${}^3D_1$ coupled waves contribute to the ${}^3S_1 d$ configurations. However, for simplicity we omit this contribution, since it is expected to be small compared to the contribution of the d^* resonance.

In order to see how many terms in the expansion (3) are needed by the data, we performed fits with 2, 3 and 4 terms as given in tables 1–3 and shown in figs. 1–3 by the dotted, solid and dashed lines, respectively.

For the analyzing power in dependence of the deuteron scattering angle the latter two are very close together in the angular regions, which are well covered by data. This means that a 3-parameter fit is already appropriate for a proper description of the data. For the lowest energy,

Table 1. Results of the fits to the analyzing power data in dependence of the deuteron scattering angle by use of eq. (2) with two (2p), three (3p) and four (4p) terms.

$\sqrt{s}$ (GeV)	fit	p_0	p_1	p_2	p_3	χ^2/ndf
2.34	4p	−0.04(10)	0.11(15)	−0.03(13)	0.07(8)	0.9/2
	3p	0.04(5)	−0.01(7)	0.08(6)		1.8/3
	2p	−0.02(4)	−0.07(4)			4.1/4
2.38	4p	−0.07(4)	0.01(6)	0.08(5)	0.03(4)	2.8/3
	3p	−0.04(3)	−0.03(4)	0.12(3)		3.6/4
	2p	−0.12(2)	−0.08(3)			19/5
2.42	4p	−0.20(4)	0.18(6)	0.04(6)	0.04(4)	11/3
	3p	−0.17(4)	0.14(4)	0.09(3)		12/4
	2p	−0.22(3)	0.21(3)			19/5

Table 2. Results of the fits to the analyzing power data in dependence of the π^0 scattering angle by use of eq. (2) with two (2p) and three (3p) terms.

$\sqrt{s}$ (GeV)	fit	p_0	p_1	p_2	χ^2/ndf
2.34	3p	−0.12(3)	0.01(3)	−0.12(3)	20/5
	2p	−0.08(2)	0.06(3)		39/6
2.38	3p	0.06(2)	0.12(2)	0.02(2)	3.6/5
	2p	0.06(2)	0.11(2)		5.1/6
2.42	3p	0.08(2)	0.15(2)	0.00(2)	0.9/5
	2p	0.08(2)	0.15(2)		0.9/6

Table 3. Results of the fits to the analyzing power data in dependence of the Δ scattering angle by use of eq. (2) with two (2p) and three (3p) terms.

$\sqrt{s}$ (GeV)	fit	p_0	p_1	p_2	χ^2/ndf
2.34	3p	−0.10(4)	0.17(4)	−0.04(4)	5.0/5
	2p	−0.08(3)	0.17(4)		6.0/6
2.38	3p	−0.05(2)	0.14(3)	−0.04(3)	7.6/5
	2p	−0.04(2)	0.14(3)		9.9/6
2.42	3p	−0.02(3)	0.09(3)	−0.01(3)	15/5
	2p	−0.02(2)	0.09(3)		15/6

where the data are very close to zero throughout the measured angular range, already the 2-parameter fit is sufficient with providng a χ^2 per degree of freedom (ndf) of unity. The fact that already a 3-parameter fit is sufficient for an appropriate description of the data in the resonance region is in accordance with the new SAID solution, which exhibits the d^* pole predominantly in the ${}^3D_3$-wave and only very weakly in ${}^3G_3$. Hence r_2 got to be small and p_3 negligible compared to p_2. In fact, the resonance term p_2 is highly demanded by the data, as the comparison between dashed and dotted curves demonstrates. Since p_2 enters also in p_0, the latter is also requested by the fit, whereas p_1 turns out compatible with zero within uncertainties at resonance. Therefore, the leading contribution to the analyzing power of the $\Theta_d^{c.m.}$ angular distribution turns out to be the interference of the resonant d-wave with the non-resonant p-wave.

The q-dependence of the parameters makes it plausible that the analyzing power is smallest at the lowest energy $\sqrt{s} = 2.34\,\mathrm{GeV}$ and tends to level off as soon as the resonance maximum is reached. At 2.42 GeV the resonance amplitude is already substantially reduced, however, the q-dependence in p_0 and p_2 counteracts this reduction.

In order to see whether the data are compatible with a resonance behavior in the transition ${}^3D_3 \to {}^3S_1 d$, we may invert the fit results for the parameters p_j in table 1 into the strength pararmeters a_1, a_2, b and r_1 by use of eq. (3). By assuming a Lorentzian energy dependence for r_1 we find the remaining strength parameters to be, indeed, compatible with a monotonic energy dependence, though the substantial uncertainties in the fit parameters p_j given in table 1 do not allow this conclusion to be very stringent.

For the $\Theta_{\pi^0}^{c.m.}$ dependence of the analyzing power we may stick with the same ansatz eq. (2), but need to reinterpret the transitions (4) with respect to the partition $d\pi^0$-π^0. With still having the $\pi^0\pi^0$ system coupled to zero, this means that the transitions (s) and (d) both represent configurations, where the π^0 is in relative p-wave to the $d\pi^0$ system, *i.e.* contain also resonance contributions. If we forget the somewhat erratic data point at small angles at $\sqrt{s} = 2.34\,\mathrm{GeV}$, then we observe an approximately constant pattern over the energy region of interest, which can be described sufficiently well by already the first two terms in the expansion eq. (2).

Finally, for the $\Delta\Delta$ partition we expect relative s-waves independent of whether this partition originates from d^* or conventional t-channel excitation, since the considered energies are still below the nominal mass of two Δ excitations. The observed A_y distributions are similar to those for the $d\pi^0$-π^0 partition and hence characterized dominantly by the p_1 contribution.

3.2 Cross sections

By using both the unpolarized and polarized runs of this experiment we may extract also (unpolarized) differential and total cross sections. This is valuable, since we used in this experiment the quasifree pn collision in reversed kinematics covering thus the lab system phase space complementary to what has been obtained in regular kinematics used previously [3].

Figure 4 shows the Θ_d^* angular dependence of the (unpolarized) differential cross section over the energy region $\sqrt{s} = 2.33$–$2.43\,\mathrm{GeV}$ binned into five intervals. The data plotted by the open circles have been obtained in a previous experiment [3] by use of a proton beam hitting a deuterium target in quasifree kinematics. Due to the experimental conditions only the deuteron back-angles could be measured in good quality. Now, with a deuteron beam impinging on a hydrogen target the phase space in the lab system is populated in a complementary way and we may deduce the cross sections preferably at forward angles (solid circles). Note that in fig. 4 the data are plotted at angles mirrored to the way plotted in fig. 5 of ref. [3].

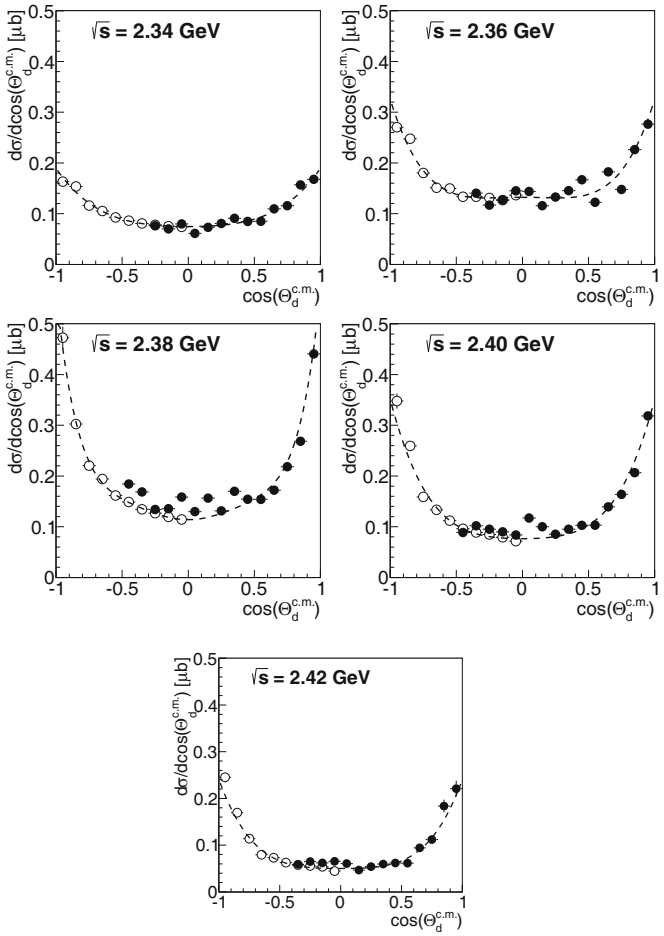

Fig. 4. Deuteron angular distributions across the energy region $\sqrt{s} = 2.33$–$2.43\,\mathrm{GeV}$ binned into five intervals. Open circles denote previous results [3], filled circles this work. The dashed curves give Legendre fits with $L_{max} \leq 6$.

Here, in this work, the angles are defined relative to the direction of the initial neutron, whereas in ref. [3] they have been defined relative to the direction of the initial proton.

Since we deal here with a purely isoscalar reaction, the unpolarized angular distributions have to be symmetric about 90° in the cms (Barshay-Temmer theorem [29]). The data are in very good agreement with this requirement. To underline this, we show in fig. 4 fits with an expansion into Legendre polynomials of order 0, 2, 4 and 6, *i.e.* including d-waves between d and $\pi^0\pi^0$ systems and allowing total angular momenta up to $J_{max} = 3$:

$$\sigma(\Theta^{c.m.}) = \sum_{n=0}^{J_{max}} a_{2n}\ P_{2n}(\Theta^{c.m.}), \qquad (5)$$

where the coefficients a_{2n} denote the fit parameters.

In addition to the symmetry about 90° fig. 4 demonstrates that the anisotropy is largest around the maximum of the d^* resonance flattening off below and above. The fact that the angular distribution tends to flatten out towards lower energies is not unexpected, since close to threshold we expect contributions only from the lowest partial waves. The fact that the angular distribution tends to be flatter also at the high energy end of the investigated energy region, is not as trivial. It supports the fact that the high spin $J = 3$ of the d^* resonance requires a unusually large anisotropy of the angular distribution, which is larger than obtained in the conventional t-channel $\Delta\Delta$ process, which gets the dominant mechanism at higher energies and where the $\Delta\Delta$ system may also be in lower angular momentum configurations.

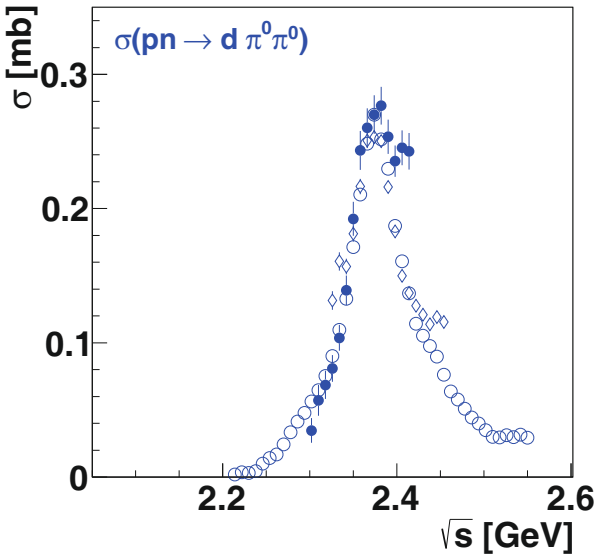

Fig. 5. Energy dependence of the total cross section measured under three different experimental conditions described in refs. [3] (open circles), [4] (open diamonds) and this work (filled circles), see text.

Finally we display in fig. 5 the energy dependence of the total cross section as obtained with three independent measurements under different experimental conditions:

- pn collisions under usual quasifree kinematics with unpolarized beam and without magnetic field in the central part of the WASA detector at three beam energies (open circles [3]),
- pn collisions under usual quasifree kinematics with unpolarized beam, but with magnetic field in the central part of the WASA detector (open diamonds [4]) and
- $\vec{n}p$ collisions under reversed quasifree kinematics with polarized beam and without magnetic field in the central part of the WASA detector (filled circles, this work).

The data of the first and third measurements have been normalized in absolute height to the value obtained in the second measurement [4] for $\sqrt{s} = 2.38\,\mathrm{GeV}$. Within uncertainties the data from all three experiments agree to each other.

4 Summary

We have presented the first measurements of the $\vec{n}p \to d\pi^0\pi^0$ reaction with polarized beam using the quasifree np

collision process under reversed kinematics. The deduced total cross sections are consistent with previous results. The obtained deuteron angular distributions complement the previous results. They clearly show that at resonance the anisotropy is larger than outside.

The measurements exhibit significant analyzing powers in dependence of deuteron and pion angles, which can be understood as being due to the interference of the d^* resonance amplitude with background amplitudes.

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