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Measurement of the $pn \to pp\pi^0\pi^-$ reaction in search for the recently observed resonance structure in $d\pi^0\pi^0$ and $d\pi^+\pi^-$ systems

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Exclusive measurements of the quasifree $pn \to pp\pi^0\pi^-$ reaction have been performed by means of pd collisions at $T_p = 1.2$ GeV using the wide angle shower apparatus (WASA) detector setup at the cooler synchrotron COSY (Institut für Kernphysik, Jülich). Total and differential cross sections have been obtained covering the energy region $\sqrt{s} = (2.35$–$2.46)$ GeV, which includes the region of the ABC effect and its associated resonance structure. No ABC effect, i.e., low-mass enhancement is found in the $\pi^0\pi^-$-invariant mass spectrum, in agreement with the constraint from Bose statistics that the isovector pion pair can not be in relative s wave. At the upper end of the covered energy region t-channel processes for Roper, $\Delta(1600)$ and $\Delta\Delta$ excitations provide a reasonable description of the data, but at low energies the measured cross sections are much larger than predicted by such processes. Adding a resonance amplitude for the resonance at $m = 2.37$ GeV with $\Gamma = 70$ MeV and

$I(J^P) = 0(3^+)$ observed recently in $pn \to d\pi^0\pi^0$ and $pn \to d\pi^+\pi^-$ reactions leads to an agreement with the data also at low energies.

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I. 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 this reaction [1–3]. The ABC effect denoting a huge low-mass enhancement in the $\pi\pi$ invariant mass spectrum is observed to happen if the initial nucleons or light nuclei fuse to a bound final nuclear system and if the produced pion pair is isoscalar. Since, at present, no quantitative understanding of this phenomenon has been available, it has been named after the initials of Abashian, Booth, and Crowe, who first observed it in the inclusive measurement of the $pd \to {}^3$HeX 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 $\sqrt{s} = 2.37$ GeV is situated about 90 MeV below $\sqrt{s} = 2m_\Delta$, the peak position of the conventional t-channel $\Delta\Delta$ process, and has a width of only 70 MeV, which is about three times narrower than this process. From the Dalitz plots of the $pn \to d\pi^0\pi^0$ reaction it is concluded that this resonance must decay nevertheless via the intermediate $\Delta^+\Delta^0$ system into its final $d\pi^0\pi^0$ state.

If this scenario is correct, then also the $pn \to pp\pi^0\pi^-$ reaction should be affected by this resonance, since this channel may proceed via the same intermediate $\Delta^+\Delta^0$ system. From isospin coupling we expect that the resonance effect in the $pp\pi^0\pi^-$ system should be half that in the $np\pi^0\pi^0$ system. And from the estimations in Refs. [5,6] 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 some background due to conventional t-channel Roper and $\Delta\Delta$ excitations, we estimate the peak resonance contribution in the $pp\pi^0\pi^-$ system to be in the order of 100 μb.

In the following we will demonstrate that in this particular reaction the resonance is not correlated with the ABC effect for two reasons. First, the isovector $\pi\pi$ system here is not in relative s wave, but in relative p wave. And second, in case of unbound nucleons in the final state the form factor introduced for the description of the ABC effect in Ref. [1] does not act on the pions primarily, but on the nucleons.

Henceforth we will denote the resonance structure by d^*, following its notation in Refs. [7,8], where a resonance with the same quantum numbers has been predicted at just about the mass, where we see this particular resonance structure. Actually, the first prediction of such a resonance dates back to Dyson and Xuong [9] (D_{03} in their nomenclature) postulating a mass amazingly close to the one we observe now. Also, a very recent fully relativistic three-body calculation of Gal and Garzilaco [10] finds this resonance at exactly the position we observe. For a recent review of the dibaryon issue see Ref. [11].

Since in the reaction of interest here the pion pair is produced in the ρ channel, it provides also unique access to the question of whether this resonance can contribute to ρ production and thus to e^+e^- production in np collisions. Known as the so-called DLS puzzle, the dilepton production at $T_p \approx 1.2$ GeV is strongly enhanced in the mass range $0.3 \leqslant M_{e^+e^-} \leqslant 0.6$ GeV$/c^2$ compared to what is expected from a conventional reaction scenario, whereas the pp induced dilepton production is in agreement with it [12]. As a possible solution of this puzzle, e^+e^- production via the d^* resonance has been proposed [13]. In fact, first simulations of this resonance scenario are very promising [14], if the d^* production in the $pp\pi^0\pi^-$ channel turns to be, indeed, in the order of 100 μb.

Finally, we note that this basic two-pion production reaction has been looked at so far only by low-statistics bubble-chamber measurements. As a result there exist no data on differential observables, just total cross sections at a few energies [15–17]. Therefore not only from the aspect of resonance search does it appear desirable to collect high-quality data for this reaction channel, but also from the more general aspect of investigating to what extent this reaction channel can be understood by conventional reaction mechanisms, which have been shown to work well for all -induced two-pion production channels; see the discussion section below.

II. EXPERIMENT

In order to investigate this reaction in more detail experimentally, we have analyzed a pd run at $T_p = 1.2$ GeV taken in 2009 with the wide angle shower apparatus (WASA) detector facility at the cooler synchrotron COSY (Institut für Kernphysik, Jülich) using a deuterium pellet target [18,19]. The hardware trigger utilized in this analysis required at least one charged hit in the forward detector as well as two neutral hits in the central detector.

The quasifree reaction $pd \to pp\pi^0\pi^- + p_{\text{spectator}}$ has been selected by requiring two proton tracks in the forward detector, an π^- track in the central detector, as well as two photons originating from a π^0 decay. That way the nonmeasured proton spectator four-momentum could be reconstructed by a kinematic fit with two over-constraints.

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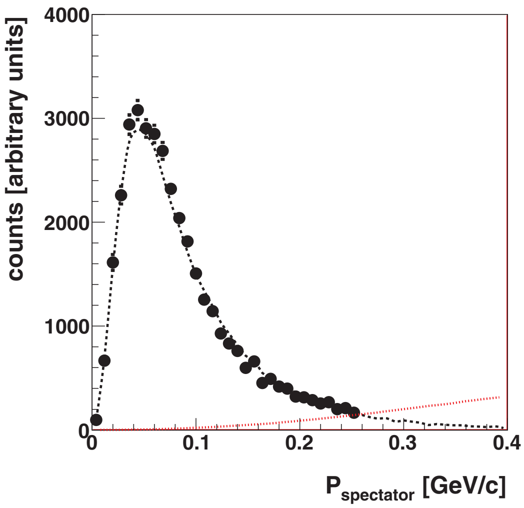

FIG. 1. (Color online) Distribution of the spectator proton momenta in the $pd \to pp\pi^0\pi^- + p_{\text{spectator}}$ reaction. Data are given by solid dots. The dashed line shows the expected distribution for the quasifree process based on the CD Bonn potential [20] deuteron wave function. For comparison the dotted line gives the pure phase-space distribution as expected for a coherent reaction process: it extends up to momenta of 1.5 GeV/c and peaks around 0.7 GeV/c. For the data analysis only events with $p_{\text{spectator}} < 0.16$ GeV/c have been used.

In Fig. 1 the reconstructed spectator momentum distribution is shown in comparison with a Monte-Carlo (MC) simulation of the quasifree $pd \to pp\pi^0\pi^- + p_{\text{spectator}}$ process. The good agreement provides confidence that the data indeed reflect a quasifree process. As in Ref. [1] we only use spectator momenta $p_{\text{spectator}} < 0.16$ GeV/c for the further data analysis. This implies an energy range of $2.35 \leqslant \sqrt{s} \leqslant 2.46$ GeV being covered due to the Fermi motion of the nucleons in the target deuteron. This energy range corresponds to laboratory incident energies of $1.07 < T_p < 1.36$ GeV.

In total a sample of about 42 000 good events have been selected. The requirement that the two protons have to be in the angular range covered by the forward detector and that the π^- and the gammas resulting from π^0 decay have to be in the angular range of the central detector reduces the overall acceptance to about 25%. 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 section. Since the acceptance is substantially below 100%, the efficiency corrections are not fully model independent. The error bars in Fig. 2 and the hatched grey histograms in Figs. 3–9 give an estimate for systematic uncertainties due to the use of different models with and without d^* resonance hypothesis for the efficiency correction.

The absolute normalization of the data has been achieved via the simultaneous measurement of the quasifree single-pion production process $pd \to pp\pi^0 + n_{\text{spectator}}$ and comparison of its result to previous bubble-chamber results for the $pp \to pp\pi^0$ reaction [21,22]. That way the uncertainty in the absolute normalization of our data is that of the previous $pp \to pp\pi^0$ data, i.e., in the order of 20%.

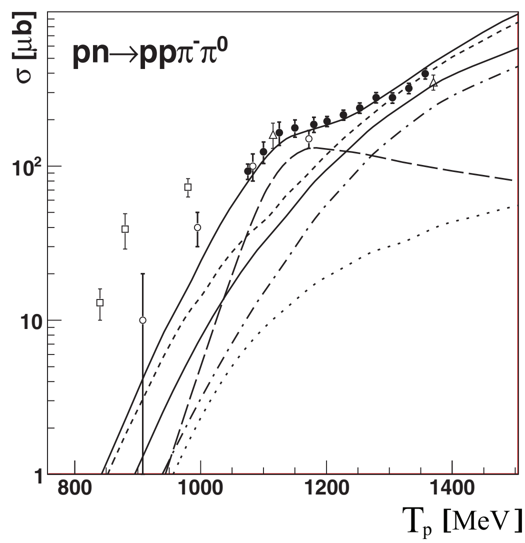

FIG. 2. (Color online) Total cross sections for the $pn \to pp\pi^0\pi^-$ reaction. The results of this work are shown by the full circles together with their error bars, which include both statistical and systematic uncertainties as given by Table I. Previous bubble-chamber measurements from KEK [15] are displayed by open circles, those from NIMROD at RAL [16] by open triangles, and those from Gatchina [17] by open squares. The original Valencia model calculations are shown by the dot-dot-dot-dashed curve. Contributions from Roper excitation and its decay into $N^* \to \Delta\pi$ are given by the dotted line and those from the t-channel $\Delta\Delta$ process by the dash-dotted line. The modified Valencia model calculation is shown by the short-dashed line. The solid curve shows the result, if the s-channel d^* resonance amplitude is added. The d^* contribution itself is given by the long-dashed curve.

III. 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 I.

TABLE I. Total cross sections obtained in this work for the $pn \to pp\pi^0\pi^-$ reaction in dependence of the center-of-mass energy $\sqrt{s}$ and the proton beam energy T_p. Systematic uncertainties are given as obtained from MC simulations for the detector performance assuming various models for the reaction process.

$\sqrt{s}$ (MeV)	T_p (MeV)	σ_{tot} (μb)	$\Delta\sigma_{\text{stat}}$ (μb)	$\Delta\sigma_{\text{sys}}$ (μb)
2.35	1.075	93	2	11
2.36	1.100	124	3	20
2.37	1.125	165	3	29
2.38	1.150	177	3	23
2.39	1.186	186	3	21
2.40	1.201	195	3	15
2.41	1.227	215	3	17
2.42	1.253	238	3	18
2.43	1.279	278	4	21
2.44	1.305	277	5	21
2.45	1.331	320	6	25
2.46	1.357	397	9	31

Figure 2 exhibits the energy dependence of the total cross section. The result of this work is given by the full circles and compared to previous bubble-chamber measurements from KEK (open circles) [15], NIMROD at RAL (open triangles) [16], and Gatchina (open squares) [17]. The latter are known to give much too high cross sections; see, e.g., the $pp\pi^+\pi^-$ channel [23]. Hence we will disregard them for the following discussion. In the overlap region our data agree well with the bubble-chamber results from KEK and RAL. The data exhibit a smooth energy dependence of a monotonically rising cross section with no particular evidence for a narrow resonance structure in the region of the ABC effect around $T_p = 1.13$ GeV. However, at closer inspection the data indicate some kind of plateau in just this region.

The data are first compared to theoretical calculations in the framework of the Valencia model [24], which incorporates non-resonant and resonant t-channel processes for two-pion production in NN collisions. Resonance processes concern here the excitation and decay of the $\Delta\Delta$ system as well as the excitation of the Roper resonance and its subsequent decay either directly into the $N\pi\pi$ system or via the $\Delta\pi$ system. Compared to the original Valencia calculations [24] the present calculations have been tuned to describe quantitatively the isovector two-pion production reactions $pp \to NN\pi\pi$ [23], in particular the $pp\pi^0\pi^0$ [25] and $nn\pi^+\pi^+$ [26] channels by the following modifications:

(i) relativistic corrections for the Δ propagator as given by Ref. [27],
(ii) strongly reduced ρ-exchange contribution in the t-channel $\Delta\Delta$ process—in agreement with calculations from Ref. [28],
(iii) reduction of the $N^* \to \Delta\pi$ amplitude by a factor of 2 in accordance with $pp \to pp\pi^0\pi^0$ and $pp \to pp\pi^+\pi^-$ measurements close to threshold [29–32] as well as in agreement with the analysis of photon- and pion-induced pion production on the nucleon [33],
(iv) inclusion of the t-channel excitation of the $\Delta(1600)P_{33}$ resonance.

The latter modification was necessary, in order to account for the unexpectedly large $pp \to nn\pi^+\pi^+$ cross section [26]. The predictive power of these modifications has been demonstrated by its successful application to the recent $pp \to pp\pi^0\pi^0$ data obtained with WASA at COSY at $T_p =$ 1.4 GeV [34].

Though these modifications significantly affect the differential distributions, their effect on the total cross section of the $pn \to pp\pi^0\pi^-$ reaction is predominantly just in absolute scale; compare the dot-dot-dot-dashed line in Fig. 2 with the short-dashed one. The dot-dashed line in Fig. 2 denotes the t-channel $\Delta\Delta$ process and the dotted line the t-channel Roper excitation with subsequent $N^* \to \Delta\pi$ decay.

We note by passing that in the energy region of interest the pp final state interaction is not of importance; see, e.g., the M_{pp} spectrum in Fig. 6, top left of Ref. [25], where the solid line shown there exhibits only a tiny enhancement at threshold due to the pp final state interaction.

The original Valencia calculations give cross sections that are substantially below the data at all energies. The modified calculations provide a reasonable description of the data at high energies—mainly due to the inclusion of the $\Delta(1600)$ excitation—but also fail largely at energies below 1.3 GeV, where they predict cross sectionsthat are too small by as much as a factor of 4. Since such a large failure has not been observed in pp-induced, i.e., isovector two-pion channels—and since there is no t-channel resonance process known that could feed this low-energy region—the reason for this striking failure must be in a low-energy two-pion production process, which is not taken into account in the Valencia model and which does not have much influence on the well measured pp-initiated two-pion production channels.

In Ref. [28] it has been shown that the so-called nucleon-pole term could possibly be such a process. According to their calculations it provides the largest contribution close to threshold in the $pn \to pp\pi^0\pi^-$ reaction. Still, its contribution is far too low to account for these discrepancies here.

We conclude that this failure points to an important isoscalar reaction component, which is not included in the t-channel treatment of two-pion production. It is intriguing that this failure appears to be largest in the energy region where the ABC effect and its associated resonance in the total cross section have been observed in the isoscalar part of the double-pionic fusion to deuterium. Hence we add tentatively the amplitude of this resonance at M = 2.37 GeV and $\Gamma =$ 70 MeV to the conventional amplitude. According to the consideration in the Introduction we have chosen a peak cross section of 100 μb for this resonance contribution. It is amazing how well the resulting curve (solid line in Fig. 2) describes the data. Adjusting the resonance contribution to the data requires a peak cross section in the range of 90–130 μb, depending on the systematic uncertainties associated with our values for the total cross section.

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 $M_{\pi^0\pi^-}$, $M_{p\pi^-}$, M_{pp}, $M_{pp\pi^0}$ as well as the differential distributions for the center-of-mass (cm) angles for protons and pions, namely Θ_p^{cm}, $\Theta_{\pi^0}^{cm}$, and $\Theta_{\pi^-}^{cm}$. These distributions are shown in Figs. 3–9, with each of them plotted for four energy bins: $2.35 < \sqrt{s} < 2.36$ GeV (a), $2.365 < \sqrt{s} < 2.375$ GeV (b), $2.40 < \sqrt{s} < 2.41$ GeV (c), and $2.44 < \sqrt{s} < 2.45$ GeV (d). The second region is chosen to cover just the peak region of the d^* resonance structure observed in the $pn \to d\pi^0\pi^0$ reaction.

In all cases we find only a gradual change in the shapes of the differential distributions. At all energies the invariant mass distributions are significantly different from pure phase space distributions (shaded areas in Figs. 3–9). At the highest energy bin the observed invariant mass distributions follow closely the shapes expected from the $\Delta\Delta$ process. This gets particularly clear in the $M_{p\pi^-}$ (see Fig. 4) and $M_{p\pi^0}$ (not shown) spectra, where pronounced peaks due to the Δ excitation develop; compare corresponding spectra in the $pp \to pp\pi^0\pi^0$ channel [25]. Actually all spectra are qualitatively similar in shape to those obtained in the $pp \to pp\pi^0\pi^0$ channel with the exception of the $M_{\pi\pi}$ spectra (Fig. 3). These observations are understandable by the fact that on the one hand the $\Delta\Delta$ process is the leading process at high energies in both channels, but on the other hand the $\pi\pi$ systems have different relative angular

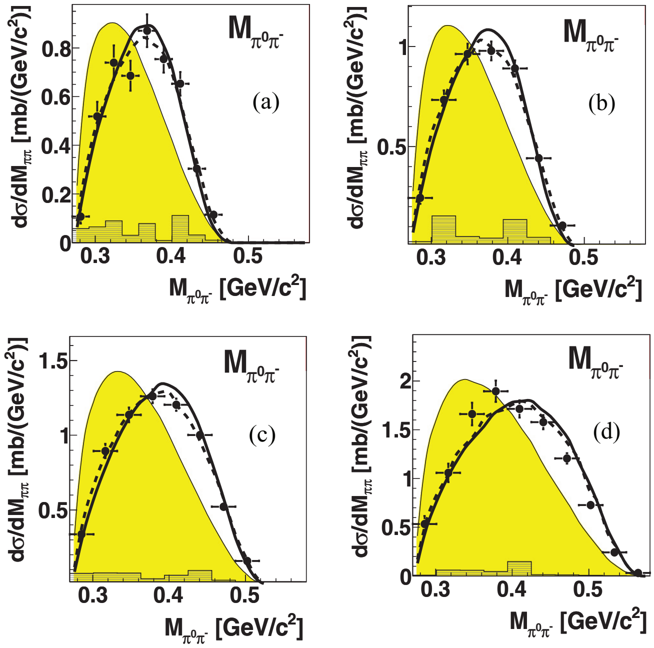

FIG. 3. (Color online) Distribution of the $\pi^0\pi^-$ invariant mass $M_{\pi^0\pi^-}$ for the $pn \to pp\pi^0\pi^-$ reaction at $2.35 < \sqrt{s} < 2.36$ GeV (a), $2.365 < \sqrt{s} < 2.375$ GeV (b), $2.40 < \sqrt{s} < 2.41$ GeV (c), and $2.44 < \sqrt{s} < 2.45$ GeV (d) corresponding to beam energy bins $1.07 < T_p < 1.10$ GeV, $1.11 < T_p < 1.14$ GeV, $1.20 < T_p < 1.23$ GeV and $1.30 < T_p < 1.33$ 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 dashed lines are calculations with the modified Valencia model. The solid lines show the result if the d^* resonance amplitude is added. All calculations are normalized in area to the data.

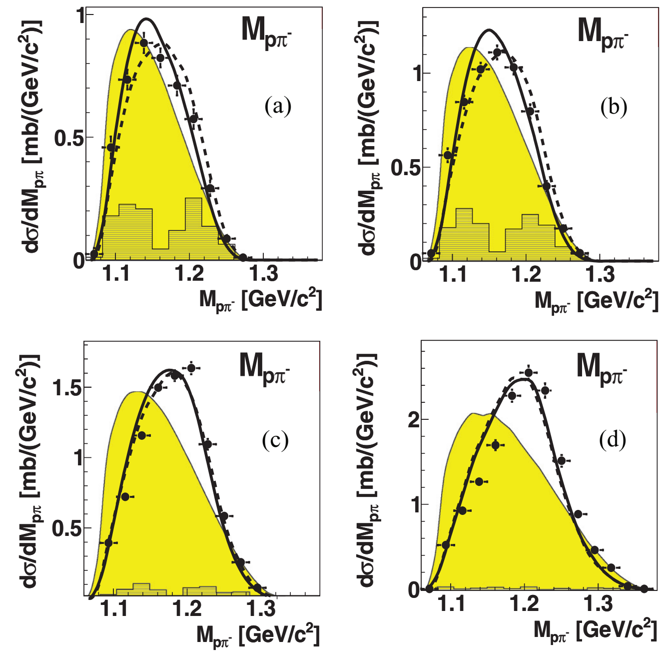

FIG. 4. (Color online) Same as Fig. 3 but for the distributions of the invariant masses $M_{p\pi^-}$.

momenta in these cases due to Bose symmetry. Whereas the isoscalar $\pi^0\pi^0$ system is in relative s wave, the isovector $\pi^0\pi^-$ system has to be in relative p wave. The p-wave condition favors large relative momenta between the pions and hence causes a suppression of intensity at low $\pi\pi$ masses and an enhancement at large masses compared to phase space, and that is what is indeed observed in the $M_{\pi^0\pi^-}$ spectra.

From Fig. 5 we see that the observed M_{pp} spectra exhibit distributions that are substantially narrower then the corresponding phase-space distributions. Obviously large relative momenta between the two protons are suppressed in the reaction of interest. Again the situation is very similar to that in the $pp\pi^0\pi^0$ channel and may be traced to the dominant $\Delta\Delta$ contribution. The modified Valencia calculations reproduce these spectra very well (dashed curves in Fig. 5).

The $M_{pp\pi^0}$ spectra (Fig. 6) peak at $M = M_\Delta + M_p$ as expected for a $pp\pi^0$ subsystem within the $\Delta\Delta$ excitation process.

The proton angular distributions exhibit a strongly anisotropic shape in agreement with a peripheral reaction process (Fig. 7). Also the pion angular distributions exhibit a pronounced anisotropy; see Figs. 8 and 9. Both for protons and pions the anisotropy is significantly larger than observed in the $pp\pi^0\pi^0$ channel. In the latter the two pions can be in relative s wave, whereas here in the $pp\pi^0\pi^-$ channel they have to be in relative p wave.

Both the modified Valencia calculations (dashed curves in Figs. 3–9) and those including the d^* resonance (solid curves) provide very similar shapes for the differential distributions in reasonable agreement with the data. This similarity may

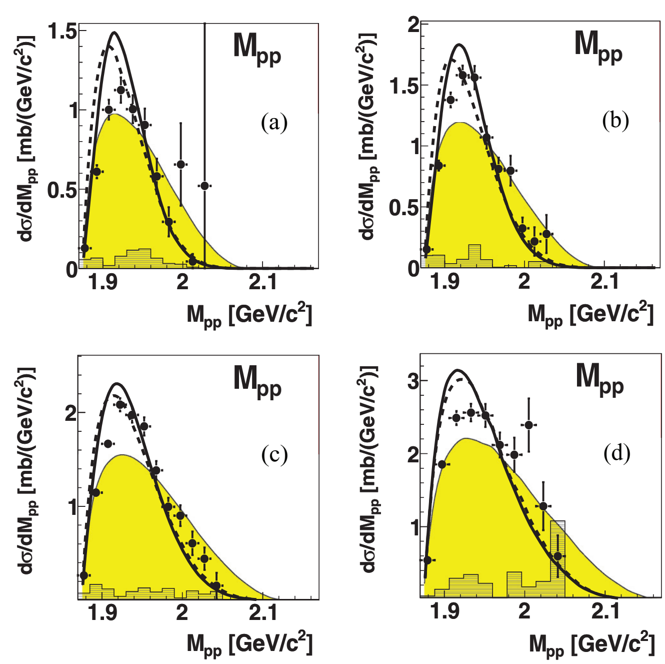

FIG. 5. (Color online) Same as Fig. 3 but for the distributions of the invariant masses M_{pp}.

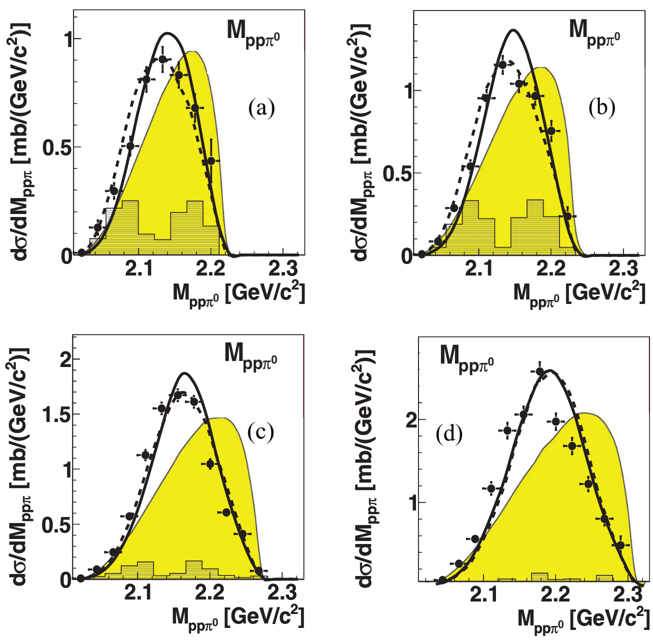

FIG. 6. (Color online) Same as Fig. 3 but for the distributions of the invariant masses $M_{pp\pi^0}$.

appear surprising at first glance and hence needs some detailed consideration.

First, the observed strongly anisotropic proton angular distribution is very close to the one expected for a $J = 3$ resonance; see Ref. [1]. However, it is also equally well accounted for by t-channel pion exchange, which produces a prominent U shape at energies far above the $\pi\pi$ threshold; see also Refs. [25,34].

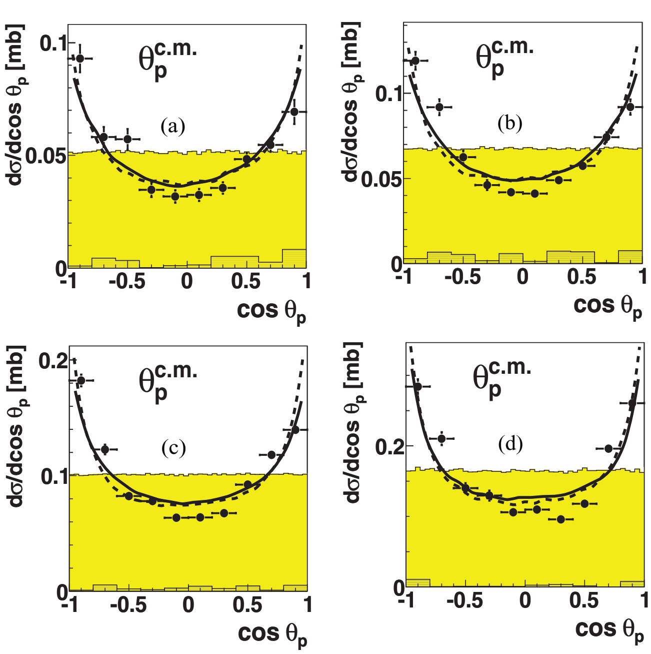

FIG. 7. (Color online) Same as Fig. 3 but for the distributions of the cm angle Θ_p.

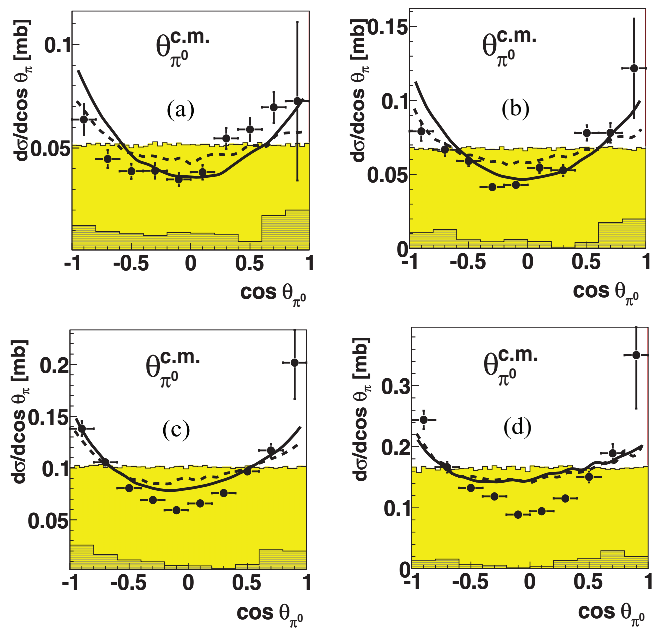

FIG. 8. (Color online) Same as Fig. 3 but for the distributions of the cm angle Θ_{π^0}.

Second, we expect a sizable effect from the dipole form factor at the $\Delta\Delta$ vertex, which was introduced phenomenologically for the description of the ABC effect, i.e., the low-mass enhancement in the $M_{\pi^0\pi^0}$ distribution, in the $pn \to d\pi^0\pi^0$ reaction [1]. Different from the bound nucleus case, where the relative momentum between the two Δs is essentially made up by the relative momentum between the two emerging pions, in the unbound case the relative $\Delta\Delta$ momentum is mainly transferred to the two emerging nucleons: the heavy partners

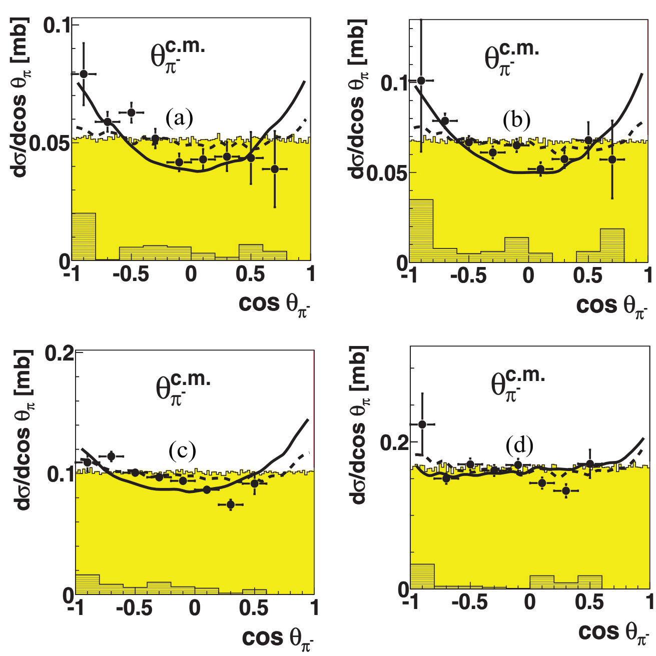

FIG. 9. (Color online) Same as Fig. 3 but for the distributions of the angle Θ_{π^-}.

of the Δ decays. Hence in the case of unbound nucleons in the final state we expect the low-mass enhancement due to this form factor not to be in the $M_{\pi\pi}$ spectrum, but in the M_{pp} spectrum. And this is also what initial calculations with the inclusion of form factor for the d^* resonance show. However, this effect is counterbalanced by the requirement that the two protons have to be in relative p wave, in order to build a s-channel resonance with $J^P = 3^+$. In case of a $d\pi^0\pi^0$ final state this spin-parity can be easily achieved by combining the spin 1 of the deuteron with the p-wave decays of the two Δ states into the $N\pi$ system such that in total we have a $\pi^0\pi^0$ system in relative s wave, which again is in d wave relative to the deuteron. In the case of the $pp\pi^0\pi^-$ channel we have an isovector $\pi^0\pi^-$ system, which by Bose symmetry needs to be in relative p wave. To fulfill the required spin-parity, the pp system can no longer be in relative s wave, but needs to be at least in a relative $^3P_2$ state.

That way, i.e., by inclusion of the d^* resonance, we obtain a description for both integral (solid curve in Fig. 2) and differential cross sections (solid curves in Figs. 3–9), which is comparable in quality to what was achieved for the description of the the purely isovector channels $pp\pi^0\pi^0$ and $nn\pi^+\pi^+$.

Concerning the $\Delta\Delta$ vertex form factor, which was introduced for the phenomenological description of the ABC effect in the $pn \to d\pi^0\pi^0$ reaction, we would like to mention an alternative ansatz proposed recently by Platinova and Kukulin [35]. They assume the d^* resonance not only to decay into the $d\pi^0\pi^0$ channel via the route $d^* \to \Delta^+\Delta^0 \to d\pi^0\pi^0$, 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 d wave relative to the deuteron in this decay process, in order to satisfy the resonance condition of $J^P = 3^+$. In consequence the available momentum in the decay process is concentrated in the relative motion between d and σ, leaving 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. That is, the low-mass enhancement (ABC effect) in this model is made by the $d\sigma$ decay branch and not by a form factor as introduced in Ref. [1]. The enhancement in this model is further increased by interference of the $d\sigma$ decay amplitude with the decay amplitude via the $\Delta^+\Delta^0$ system. Applying this scenario to the $pp\pi^0\pi^-$ channel we have in this case no decay branch via the isoscalar σ configuration, since the $\pi^0\pi^-$ pair is purely isovector. Hence the d^* decay into this channel proceeds solely via the $\Delta^+\Delta^0$ system and does not exhibit any low-mass enhancement (ABC effect), neither in the $M_{\pi^0\pi^-}$ nor in the M_{pp} system. This situation corresponds just to a d^* calculation without form factor at the $\Delta^+\Delta^0$ vertex. Since then the p-wave condition for the pp subsystem is no longer counterbalanced by the effect of the form factor, the calculated M_{pp} distribution gets wider and close to phase-space, thus worsening somewhat the agreement with the data.

IV. SUMMARY AND OUTLOOK

The first exclusive and kinematically complete $pn \to pp\pi^0\pi^-$ measurements of solid statistics have been carried out in quasifree kinematics with a proton beam hitting a deuterium target. Utilizing the nucleons' Fermi motion in the deuterium target an energy region of $2.35 < \sqrt{s} < 2.46$ GeV could be covered corresponding to an incident lab energy range of 1.07–1.36 GeV. This energy region also covers the region of the ABC effect and its associated narrow resonance structure around 2.37 GeV. No evidence for a low-mass enhancement (ABC effect) is found in the data for the $\pi^0\pi^-$-invariant mass distribution. Its absence is easily understood from the fact that the isovector $\pi^0\pi^-$ pair has to be in relative p wave and—even more importantly—that in this case of unbound nucleons the form factor introduced for the description of the ABC effect in the $d\pi\pi$ channel causes a low-mass enhancement in M_{pp} and not in $M_{\pi\pi}$. In the latter, however, the impact of the form factor is counterbalanced by the condition that the two protons have to be in relative p wave, in order to reach the $J^P = 3^+$ requirement for the resonance.

The differential data are reasonably well accounted for by conventional t-channel calculations with the modified Valencia model [24–26]. These calculations also give a good description of the total cross section at the highest measured energies. However, at lower energies these calculations fall short by at least a factor of 4 in cross section. Since such a big failure has not been observed in pp-induced reaction channels and since it concerns the low-energy region, where no t-channel resonance processes are known to contribute, it has to be ascribed to an unconventional isoscalar process. One such process is the excitation of the d^* resonance. Its inclusion in the model description for the $pn \to pp\pi^0\pi^-$ reaction leads to a much improved understanding of both differential and total cross section data. The necessary peak cross section of about 100 μb for the d^* contribution agrees very well with expectations.

After the experimental evidence found in the $d\pi^0\pi^0$ and $d\pi^+\pi^-$ channels, the $pp\pi^0\pi^-$ channel is now the third channel, which is consistent with the d^* hypothesis. If true, then this resonance should also been detected in the $pn \to pn\pi^0\pi^0$ reaction and—most importantly—–in pn scattering, the *experimentum crucis*. Data for these reactions have been taken already by the WASA collaboration. Their analysis is in progress.

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