Isoscalar off-shell effects in threshold pion production from pd collisions

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We test the presence of pion-nucleon isoscalar off-shell effects in the $pd\rightarrow\pi^+t$ reaction around the threshold region. We find that these effects significantly modify the production cross section and that they may provide the missing strength needed to reproduce the data at threshold.

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I. INTRODUCTION

Pion production from nucleon-induced reactions has the potential to probe the nuclear phenomena at short distance since it involves processes transferring large momenta to the target nucleus. But the pion also *mediates* the nuclear force; hence meson production (or absorption) plays a fundamental role in hadron dynamics because it may reveal facets of meson-baryon couplings, and of meson-exchange processes in general, which would remain hidden otherwise.

In absence of reliable calculations on meson dynamics within an interacting multinucleon context, one has to rely on the determination of the reaction mechanisms which dominate the process. Even so, the analysis of the process is complicated by the fact that a general treatment of the reaction mechanisms reveals the occurrence of many terms, and one is forced to introduce further assumptions in order to reduce the number of terms to a few, tractable ones. This reduction clearly introduces ambiguities making it more difficult to extract informations about the nuclear wave function at short distances, or about the modifications of the hadron interactions because of the presence of other nucleons. The situation is somewhat simplified if we consider nucleon-induced production close to the pion threshold, since there the s-wave mechanisms of the elementary $NN\rightarrow\pi NN$ inelasticities dominate, while the p-wave mechanisms (including the isobar degrees of freedom) can be treated as corrections.

In the past decade, with the aim to clarify the nature of the elementary $NN\rightarrow\pi NN$ s-wave inelasticities, a great deal of experimental and theoretical activity has been made in pion production from NN collision at energies close to threshold. The situation has been recently reviewed by Meyer [1]. Advances in experimental techniques allowed to measure in particular the reaction $pp\rightarrow\pi^o pp$ cross-section very close to threshold. This reaction filters the s-wave πN coupling in the isoscalar channel. Standard theory including the one-body term and isoscalar rescattering constrained by the πN scattering lengths underestimated the cross section by a factor of 5. Unexpectedly, there have been two theoretical explanations for this discrepancy, not just one. The enhancement in the cross section can be explained by invoking short-range nucleon-nucleon effects [2], where the important effects can be simulated by σ and ω exchanges [3]. The explanation is appealing, since in this case the pion field couples with the two-nucleon axial charge operators, and this coupling provides an explicit link to the inner part of the nucleon-nucleon interaction, which is notoriously difficult to disclose. But the results have been entirely explained by resorting also to an off-shell enhancement of the isoscalar πN amplitude [4].

The calculation by Hernández and Oset employs an s-wave rescattering diagram where the isoscalar amplitude is described by the combined effect of a strong short-range repulsion and a medium range attraction of similar strength, where the repulsion is represented by a contact term and the attractive part is parameterized by means of a σ-exchange diagram. Originally, this representation has been derived with dispersion theoretic methods by analyzing the experimental data on pion-nucleon scattering with discrepancy functions [5]. Subsequently, the fit in Ref. [5] has been reinterpreted as being generated by a sigma-exchange term plus a u-channel term including $\bar{N}$ exchange (or virtual $N\bar{N}$ creation) and other short-range contributions [6,7].

That s-wave pion production/absorption is governed by off-shell effects has been known for quite a few years [8,6]. Hachenberg and Pirner used a field theoretical description for πN scattering in s wave based on the linear σ model and on pseudoscalar πNN interaction. This combination results in a large cancellation between the σ-exchange diagram and the nucleon Born terms. The cancellation however breaks down producing an enhancement when one pion leg is off-mass shell, as happens when the pion rescatters before being absorbed. On the contrary, in the isovector channel the cancellation occurs more efficiently off-shell, producing a suppression of the charge-exchange interaction. Thus, the relative importance of the isospin odd and even channels is reversed because of the off-shell extrapolation. Yet, another off-shell extrapolation has been considered in Ref. [9], derived from a field theoretic model of the πN interaction which has been developed at Jülich [10]. This approach is similar in spirit to the model developed by Hachenberg and Pirner, but here the meson exchanges in the scalar and vector channels are derived from correlated 2π exchanges. The rescattering diagram of Ref. [9] has a less pronounced off-shell enhancement with respect to both πN models of Refs. [10] and [4], and one must introduce here two-nucleon short-range mechanisms such as those mediated by σ and ω exchange in order to reproduce the total cross section for $pp\rightarrow pp\pi^o$ at threshold. Finally, the problem of the off-shell extrapolation for the pion rescattering mechanism has been considered also in the more systematic framework of chiral-perturbation theory

(χPT) [11]. The main feature here is that the rescattering diagram, once extrapolated off-shell, produce a negative interference with the one-body term, thus yielding a cross section substantially smaller than the measured ones. In this case the inclusion of heavy meson-exchange effect does not solve the discrepancy. However, in another chiral-perturbation approach based on full momentum-space treatment [12], the rescattering diagram was shown to be larger by a factor of 3, thus leading to a substantial increase at threshold. More recently, the χPT approach has been carried further on by considering pion loop diagrams which might simulate σ-exchange phenomena, with the finding that these higher order contributions provide important improvements, but questioning at the same time the convergence properties of the power counting expansion for the specific reaction under consideration [13].

The three-nucleon system is a richer testing ground for studies of pion production and scattering. The addition of just one nucleon increases the complexity of the reaction which involves now the simplest nontrivial multinucleon system where it is possible to test the fundamental $NN \to \pi NN$ process and, at the same time, to solve the accurately the nuclear dynamics with Faddeev methods. Applications of Faddeev methods to pion production/absorption started very recently with studies centered around the Δ resonance [14,15] and herein we apply the same technique of Ref. [15] to study pion production at threshold. Besides the obvious difficulty of performing calculations with three nucleons instead of two, one encounters here the additional difficulty that for the $pd \to \pi^+ t$ reaction one must include from the start the effect of p-wave mechanisms, on top of the s-wave ones. This contrasts with the findings for the two-nucleon case, where the effect of the p-wave mechanisms (including the Δ), tends gradually to zero in approaching the threshold limit. The effect of this difference can be immediately perceived in the differential production cross section, since for NN collision the angular dependence evolves gradually with energy, while in the case of pd collisions it exhibits a remarkable s- and p-wave interference in the threshold region, with strong forward-backward asymmetry [16].

In this work, we have centered our study on the effects due to the s-wave rescattering processes, taking into account both isoscalar and isovector components and their interference to the p-wave mechanism (containing also the Δ degrees of freedom). We have in particular taken into account the off-shell effects in the isoscalar channel by following the same prescription suggested in Ref. [4] to explain the size of the excitation function for the $pp \to pp\pi^o$ process. It is important to stress that there are still large uncertainties inherent to this off-shell extrapolation, and such calculations should be repeated possibly also with other off-shell extensions. Moreover, other production mechanisms here omitted should be possibly included in the calculation, at least those mechanisms which proved to have relevant interference effects in NN collisions. But to implement the production mechanisms in a three-nucleon process is not a trivial task and needs to be done gradually.

At present stage, where we believe that the importance of the off-shell effects in s-wave pion production from NN collisions has been fairly well established by various groups, it is clearly of great relevance to consider the consequences of such effects on more complex reactions. Herein we provide the results obtained when calculating off-shell effects in pd collisions.

II. THEORY

The production mechanisms are constructed starting from the following effective pion-nucleon couplings:

$$\mathcal{L}_{\rm int} = \frac{f_{\pi NN}}{m_\pi}\overline{\Psi}\gamma^\mu\gamma^5\vec{\tau}\Psi\cdot\partial_\mu\vec{\Phi} - 4\pi\frac{\lambda_I}{m_\pi^2}\overline{\Psi}\gamma^\mu\vec{\tau}\Psi\cdot[\vec{\Phi}\times\partial_\mu\vec{\Phi}] - 4\pi\frac{\lambda_O}{m_\pi}\overline{\Psi}\Psi[\vec{\Phi}\cdot\vec{\Phi}]. \quad (1)$$

The first term represents the gradient coupling to the isotopic axial current, while the second denotes the coupling to the isovector nucleonic current, and the last is the pion-nucleon coupling in the isoscalar channel.

As is well known [17], a good guess for the coupling constants can be obtained from chiral symmetry and PCAC, which constrain the three constants to be of the order

$$f_{\pi NN}/m_\pi \simeq g_A/(2f_\pi), \quad (2)$$

$$4\pi\lambda_I/m_\pi^2 \simeq 1/(4f_\pi^2), \quad (3)$$

$$4\pi\lambda_O/m_\pi \simeq 0, \quad (4)$$

where g_A ($\simeq 1.255$) is the axial nucleonic normalization, and f_π is the pion decay constant ($\simeq 93.2$ MeV). The first condition follows directly from the Goldberger-Trieman relation, while the last two are implied by the Weinberg-Tomozawa ones. Current phenomenological values for $f_{\pi NN}^2/(4\pi)$ can reach values as low as 0.0735 [18], 0.0749 [19], or 0.076 [20], but also values around 0.081 [21] have been considered acceptable. Some years ago common values were centered around 0.078–0.079 [22,23]. Similarly, from the pion-nucleon scattering lengths, λ_I is determined within the range 0.055–0.045, while the weaker isoscalar coupling has typically larger indetermination, ranging from 0.007 to -0.0013 [2,4]. The isovector and isoscalar couplings, when combined with the axial πNN vertex, are the basic ingredients for the two-nucleon s-wave rescattering mechanisms, while the axial-current coupling alone forms the basis for the one-body production process.

The matrix elements for the rescattering process require an off-mass-shell extrapolation of the two constants λ_I and λ_O, since the rescattered pion can travel off-mass-shell. For λ_O we consider the off-shell structure previously employed in the $pp \to pp\pi^o$ process by Hernández and Oset (Ref. [4]) which is based on a parametrization due to Hamilton [5], namely

$$\lambda_O(\tilde{q},\tilde{p})=\lambda_O^{\text{on}} g_O(\tilde{q},\tilde{p})$$
$$=-\frac{1}{2}(1+\epsilon)m_\pi\left(a_{sr}+a_\sigma\frac{m_\sigma^2}{m_\sigma^2-(\tilde{q}-\tilde{p})^2}\right),\quad (5)$$

with $m_\sigma=550$ MeV, $a_\sigma=0.22m_\pi^{-1}$, $a_{sr}=-0.233m_\pi^{-1}$, and $\epsilon=m_\pi/M$. In the threshold limit, $(\tilde{q}-\tilde{p})^2\simeq(\tilde{q}_o-m_\pi)^2-\tilde{\mathbf{q}}^2$, where $\tilde{q}$ is the transferred four-momentum between the two active nucleons. According to previous treatments of the $2N\pi$-production amplitude, the time-component $\tilde{q}_o$ is fixed around $\tilde{q}_o\simeq m_\pi/2$, while the space component $\tilde{\mathbf{q}}$ represents a loop variable and is integrated over.

This form leads to an on-shell value of the order of 0.007. The on-shell value derives from a cancellation between the short-range term, a_{sr}, and the σ-exchange term, a_σ, while off shell the cancellation occurs only partially and thus leads to the off-shell enhancement. The use of a fictious sigma-exchange model should not be considered a crucial aspect of the model, since similar forms (possibly summed over a ‘‘distribution’’ of masses m_σ) can be easily obtained also in theoretical approaches based on subtracted dispersion relations. The approaches based on subtracted dispersion relations such as πN model of Ref. [10] lead indeed to similar off-shell enhancement.

For λ_I the extrapolation can be accomplished by invoking ρ-meson dominance and the related Riazuddin-Fayyazuddin-Kawarabayashi-Suzuki identity, which implies (on shell, for $\omega_\pi\to m_\pi$)

$$\frac{\lambda_I^{\text{on}}}{m_\pi^2}=\frac{f_\rho^2}{8\pi m_\rho^2},\quad (6)$$

with the corresponding off-shell extrapolation

$$\lambda_I(\tilde{q},\tilde{p})=\lambda_I^{\text{on}} g_I(\tilde{q},\tilde{p})=\lambda_I^{\text{on}}\frac{m_\rho^2}{m_\rho^2-(\tilde{q}-\tilde{p})^2}\left(\frac{\Lambda_\rho^2}{\Lambda_\rho^2-(\tilde{q}-\tilde{p})^2}\right)^2,\quad (7)$$

where again we use $(\tilde{q}-\tilde{p})^2=(\tilde{q}_o-m_\pi)^2-\tilde{\mathbf{q}}^2$ in the threshold limit.

The production matrix-elements in the nonrelativistic $3N$ space with such couplings are the following:

$$\langle 3N|A^{1\text{B}}|3N,\pi\rangle=\frac{-if_{\pi NN}}{m_\pi}\boldsymbol{\sigma}_2\tilde{\mathbf{p}}[\boldsymbol{\tau}_2]_1^{z_\pi}\times\delta\left(\mathbf{p}'-\mathbf{p}-\frac{6+2\epsilon}{6(2+\epsilon)}\mathbf{P}_\pi\right)\times\delta\left(\mathbf{q}'-\mathbf{q}+\frac{1}{3}\mathbf{P}_\pi\right)\quad (8)$$

for the one-body process,

$$\langle 3N|A_O^{2\text{B}}|3N,\pi\rangle=2i\frac{f_{\pi NN}4\pi\lambda_O}{m_\pi^2}\times\boldsymbol{\sigma}_3\tilde{\mathbf{q}}[\boldsymbol{\tau}_3]_1^{z_\pi}\times\frac{v_{\pi NN}(\tilde{q})g_O(\tilde{q},\tilde{p})}{m_\pi^2+\tilde{\mathbf{q}}^2-\tilde{q}_0^{\,2}}\delta\left(\mathbf{q}'-\mathbf{q}+\frac{1}{3}\mathbf{P}_\pi\right)\quad (9)$$

and

$$\langle 3N|A_I^{2\text{B}}|3N,\pi\rangle=\sqrt{2}i\frac{f_{\pi NN}4\pi\lambda_I}{m_\pi^3}\times\boldsymbol{\sigma}_3\tilde{\mathbf{q}}[\boldsymbol{\tau}_3\times\boldsymbol{\tau}_2]_1^{z_\pi}\times\frac{v_{\pi NN}(\tilde{q})g_I(\tilde{q},\tilde{p})}{m_\pi^2+\tilde{\mathbf{q}}^2-\tilde{q}_0^{\,2}}(\tilde{q}_0+\omega_\pi)\times\delta\left(\mathbf{q}'-\mathbf{q}+\frac{1}{3}\mathbf{P}_\pi\right)\quad (10)$$

for the two-body isoscalar and isovector rescattering, respectively. $v_{\pi NN}(\tilde{q})$ is the hadronic form factor of the πNN vertex, whose structure is governed by the monopole-type cutoff Λ_π. The momenta $\mathbf{p}$ and $\mathbf{q}$ are Jacobi momenta for nucleon 2 in the (2+3) center of mass (c.m.), and nucleon 1 in the (1+2+3) c.m., respectively, while $\mathbf{P}_\pi$ is the pion momentum in the total c.m. Similarly, $\mathbf{p}'$ and $\mathbf{q}'$ are the Jacobi momenta for the three nucleons in the no-pion case. Other relevant pion momenta are

$$\tilde{\mathbf{p}}\simeq\frac{(3+\epsilon)}{3(1+\epsilon)}\mathbf{P}_\pi\quad (11)$$

and

$$\tilde{\mathbf{q}}\simeq\mathbf{p}+\frac{(6+2\epsilon)}{6(2+\epsilon)}\mathbf{P}_\pi-\mathbf{p}'.\quad (12)$$

In the actual calculation ranging from threshold up to the Δ resonance the on-shell couplings are further corrected by means of a Heitler-type (or K-matrix) form (η is the pion momentum in pion-mass units)

$$\hat{\lambda}_O\simeq\frac{2}{3}\frac{\lambda_O+\lambda_I}{1+2i\eta(\lambda_O+\lambda_I)}+\frac{1}{3}\frac{\lambda_O-2\lambda_I}{1+2i\eta(\lambda_O-2\lambda_I)},\quad (13)$$

$$\hat{\lambda}_I\simeq\frac{1}{3}\frac{\lambda_O+\lambda_I}{1+2i\eta(\lambda_O+\lambda_I)}-\frac{1}{3}\frac{\lambda_O-2\lambda_I}{1+2i\eta(\lambda_O-2\lambda_I)}.\quad (14)$$

This reduces the rescattering contributions at higher energies but the correction is uninfluential in the threshold limit. On top of these processes, we have included also the two-body mechanism mediated by Δ rescattering,

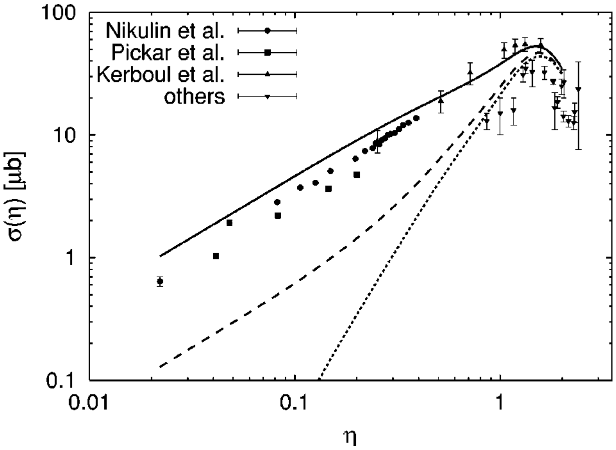

FIG. 1. Production cross section for the $pd\to\pi^+t$ versus η. The dotted line contains the sole p-wave mechanisms. The dashed line includes also πN s-wave rescattering mediated by ρ exchange. The solid line considers in addition the isoscalar off-shell effects. The data are from Refs. [16,32,33]. The remaining data (''others'') have been extracted from a world collection as explained in Ref. [15].

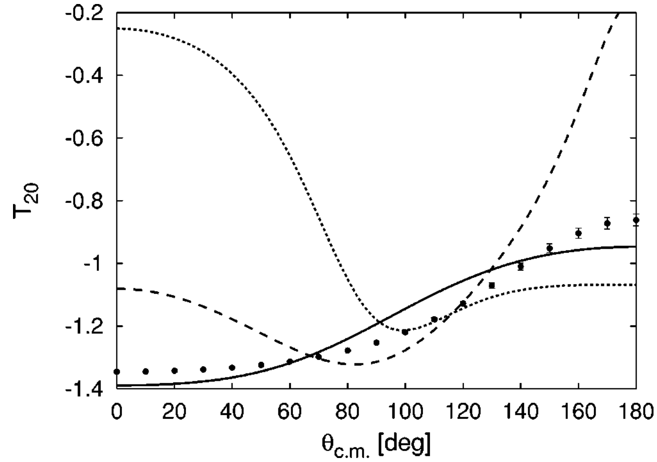

FIG. 2. The deuteron tensor analyzing power T_{20} for $\eta=0.25$. The lines show the same calculations as in Fig. 1. The points are extracted from Ref. [16].

$$\langle 3N|A_{\Delta}^{2\mathrm{B}}|3N,\pi\rangle=\frac{-if_{\pi N\Delta}}{m_{\pi}}\times\frac{V_{N\Delta}(\mathbf{p}',\mathbf{p}_{\Delta})\boldsymbol{S}_2\tilde{\mathbf{p}}[\boldsymbol{T}_2]_1^{z\pi}}{T_{\mathrm{cm}}+M-\mathcal{M}_{\Delta}+p_{\Delta}^2/2\mu_{\Delta}+q'^2/2\nu_{\Delta}}\times\delta\left(\mathbf{q}'-\mathbf{q}+\frac{1}{3}\mathbf{P}_{\pi}\right),\tag{15}$$

since its contribution becomes soon important as the energy increases. The intermediate Δ momentum is defined as

$$\mathbf{p}_{\Delta}\simeq\mathbf{p}+\frac{(6+2\epsilon)}{6(2+\epsilon)}\mathbf{P}_{\boldsymbol{\pi}}.\tag{16}$$

In Eq. (15) μ_{Δ} is the reduced mass of the Δ-N system, while ν_{Δ} is the reduced mass for the N-(ΔN) partition. $T_{\mathrm{c.m.}}$ is the c.m. kinetic energy of the three nucleons in the initial state. The ΔN transition potential is determined by the π plus ρ exchange diagrams, where the pseudoscalar meson provides the typical longitudinal structure to the ΔN transition, i.e., $(\boldsymbol{\sigma}_3\cdot\tilde{\mathbf{q}})(\boldsymbol{S}_2^{\dagger}\cdot\tilde{\mathbf{q}})(\boldsymbol{\tau}_3\cdot\boldsymbol{T}_2^{\dagger})$, while the vector meson generates the transversal contribution $(\boldsymbol{\sigma}_3\times\tilde{\mathbf{q}})(\boldsymbol{S}_2^{\dagger}\times\tilde{\mathbf{q}})(\boldsymbol{\tau}_3\cdot\boldsymbol{T}_2^{\dagger})$. $\mathbf{S}_2$ $(\mathbf{T}_2)$ is the spin (isospin) operator for the $\Delta\leftrightarrow N$ transition. For complete details on the employed transition potential, and for other aspects connected with the isobar mechanism, such as, e.g., the detailed expression for the complex Δ mass $\mathcal{M}_{\Delta}$, we refer to a set of studies performed around the resonance region [24–26]. All amplitudes, Eqs. (8), (9), (10), and (15) must be multiplied in addition by the common factor $1/\sqrt{(2\pi)^3 2\omega_{\pi}}$. Moreover, taking into account Pauli identity, the full one-body mechanism results by multiplying Eq. (8) by the multiplicity factor $\sqrt{3}(1+P)$, while the remaining two-body mechanisms are multiplied by $2\sqrt{3}(1+P)$, where P is the ternary permutator which commutes the $3N$ coordinates cyclically/anticyclically. Combining the P operator with the given mechanisms in $3N$ partial waves is not a trivial task, and numerical treatment of the resulting amplitudes has been a challenge.

The matrix elements are calculated between in and out nuclear states, where the out-state is specified by the three-nucleon bound-state wave function (plus a free pion wave), and the incoming state is determined by the deuteron-nucleon asymptotic channel. For the $3N$ bound state we have taken the triton wave function as has been developed, tested and calculated in Ref. [27]. As two-body input for the three-nucleon equations we used a separable representation [28] of the Paris interaction. This form represents an analytic version of the PEST interaction, originally constructed and applied by the Graz group [29].

We have in addition calculated the relevance of the three-nucleon dynamics in the initial state (ISI) by solving the Faddeev type Alt-Grassberger-Sandhas (AGS) equations [30]. The AGS equations for neutron-deuteron scattering go over into effective two-body Lippmann-Schwinger equations [30] when representing the input two-body T-operators in separable form. The T is represented in separable form using again the above mentioned EST method. Applying the same technique to the π absorption process, an integral equation of rather similar structure is obtained for the corresponding amplitude. The only difference is that the driving term of the n-d scattering equation (i.e., the particle-exchange diagram, the so-called ''Z'' diagram) is replaced by the off-shell extension of the plane-wave pion-absorption amplitude. More details can be found in [15,31] and references therein.

III. RESULTS

To exhibit the relevance of isoscalar off-shell effects for $pd\to\pi^+t$ we have calculated the integral cross section near threshold up to the Δ region. The calculated results are compared with a collection of data from Refs. [16,32,33] and others as explained in Fig. 1. Practically all the experimental data near threshold refer in fact to π^o production from pd collisions, and the comparison has been made assuming iso-

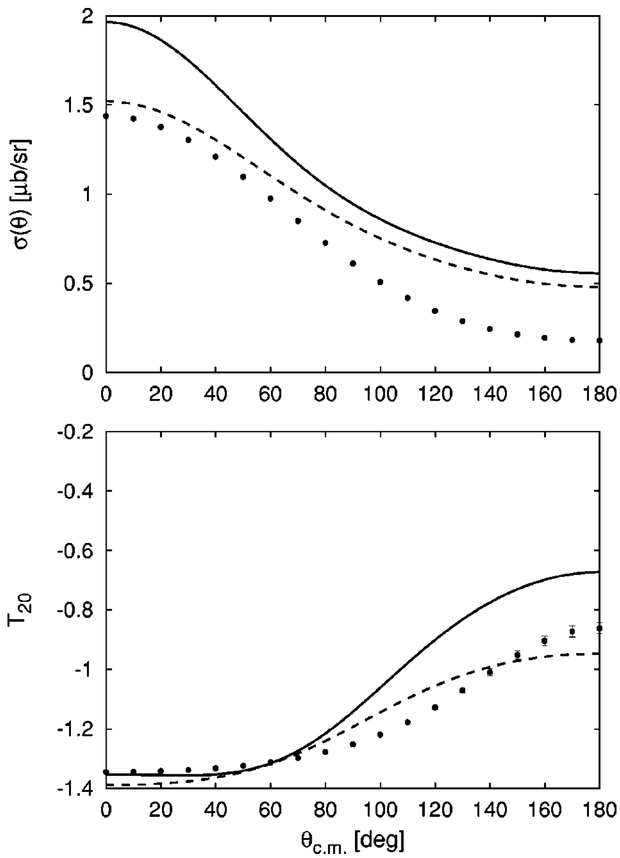

FIG. 3. Effect of $3N$ initial-state correlation at $\eta=0.25$. Differential cross section (T_{20}) is shown on the top (bottom) panel. In both cases the solid line includes the $3N$ ISI effects, while the dashed line has been obtained in plane-wave approximation. The points are extracted from Ref. [16].

spin invariance and hence implying a factor of 2 between the two cross sections. In so doing we have avoided the need to include the effects of Coulomb distortions in the exit channel. Given the complexity of the reaction dynamics which depends upon several contributions, the isoscalar effects have been calculated on top of the other mechanisms we had considered. As explained previously, the model includes also p-wave Δ rescattering, the one-body p-wave term, and the isovector ρ-exchange mechanisms.

The relevant parameters employed herein (cutoffs, coupling constants) have been tested previously against the $pp \to \pi^+ d$ process in Ref. [24]. For the ρ-exchange model we use $\lambda_I = 0.045$ in Eq. (6). The results indicate that the modifications introduced by the isoscalar contributions are significant over the whole range considered, and that the effect is one of the most pronounced at threshold.

Further evidence come from the results exhibited in Fig. 2, where the deuteron tensor analyzing power T_{20} is shown. Details on the formalism for the calculation of polarization observables can be found in Ref. [34]. The points represent a best-fit to experimental data as given in Ref. [16]. The trend of the data is reproduced once both the isovector *and* isoscalar terms are taken into account.

It is clearly important to assess the role of the initial state correlations, since the three-body dynamics between the nucleon and the deuteron could modify the whole picture and undermine the conclusions of this work. For this reason, we have calculated the ISI effects by solving the AGS equations for the $3N$ system using as input a separable representation of the Paris interaction. The same Faddeev-like technique herein employed has been applied previously to pion production at the Δ resonance in Ref. [15]. In Fig. 3 one can examine the role of the $3N$ dynamics in the initial state from the angular dependence of the unpolarized production cross section and from T_{20}, for $\eta = 0.25$. The modifications introduced by the $3N$ dynamics are sizable, but the overall picture does not change drastically. In addition, the $3N$ effects improve the angular dependence of both observables, thus possibly confirming our findings about the importance of the isoscalar off-shell effects.

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