

THRESHOLD MESON PRODUCTION IN NUCLEON-NUCLEON COLLISIONS*

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A brief overview on recent model calculations for near threshold pion production in nucleon-nucleon collisions is given. Results from our own investigations of the reactions $pp \rightarrow pp\pi^0$ and $pn \rightarrow d\pi^0$ are presented. Direct production, heavy meson exchange and pion rescattering are taken into account. For the latter a T-matrix obtained from a microscopic model of the πN interaction is employed. We obtain a significant contribution from rescattering, but not enough to describe the data for $pp \rightarrow pp\pi^0$. The missing production rate can be provided by heavy meson exchanges. For the first time the effect of off-shell rescattering is investigated for the reaction $pn \rightarrow d\pi^0$. Isoscalar rescattering in combination with isovector rescattering is able to describe the s-wave production data. We confirm that heavy meson exchanges are negligible in this reaction.

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1. Introduction

Recent advances in accelerator technology have opened new perspectives in nuclear physics [1]. The possibility of doing experiments with internal targets in storage rings together with the tool of beam cooling have made it feasible to study particle production processes extremely close to their thresholds and with unprecedented accuracy. Such data have been eagerly awaited by theorists. In the proximity of the threshold the production processes are determined by only a few amplitudes and therefore a theoretical interpretation of them should be simple but at the same time also rather informative.

The reaction $NN \rightarrow NN\pi$ is of particular interest because it constitutes the dominant inelastic process in the NN interaction. For the pion

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production at threshold a large momentum transfer of typically 370 MeV/c between the nucleons is required. This corresponds to NN separations of roughly 0.5 fm. Consequently the study of the pion production process can provide us with information about the short-range part of the NN interaction. Since the pion can rescatter on the nucleon before it is emitted it could be also possible to learn something about the off-shell properties of the πN interaction. Furthermore the reaction $NN \rightarrow NN\pi$ can serve as a testing ground for theoretical models of meson production which can then be applied to the production of other, heavier mesons such as η , η' or ϕ .

Over the last few years several near-threshold experiments for various charge channels of the reaction $NN \rightarrow NN\pi$ were performed. The reaction $pp \rightarrow pp\pi^0$ was measured at the Cyclotron Facility of the Indiana University (IUCF) [2, 3], at TRIUMF [4], and more recently also in Uppsala [5]. Data on $pp \rightarrow d\pi^+$ were provided by the TRIUMF group [6], by the GEM collaboration at COSY in Jülich [7] and by IUCF [8]. Finally, there are measurements on the reactions $pn \rightarrow d\pi^0$ [9], $pn \rightarrow pp\pi^-$ [10], and $pp \rightarrow pn\pi^+$ [11]. Many of the data are taken at values of η (the maximum center-of-mass momentum of the produced pion divided by the pion mass, q_{\max}^π/m_π) below 0.5. This corresponds to bombarding energies of less than 50 MeV above threshold.

TABLE I

Allowed partial waves near threshold for the reactions $pp \rightarrow pp\pi^0$ and $pn \rightarrow d\pi^0$. The notation $^{2S+1}L_J$ is used for the NN states. l_π is the angular momentum of the pion relative to the NN system. $|i\rangle$ and $|f\rangle$ denote the initial and final states, respectively.

	$pp \rightarrow pp\pi^0$	$pn \rightarrow d\pi^0$
	$ f\rangle = ^1S_0 l_\pi\rangle$	$ f\rangle = (^3S_1 - ^3D_1) l_\pi\rangle$
$l_\pi = 0$	$ i\rangle = ^3P_0\rangle$	$ i\rangle = ^3P_1\rangle$
$l_\pi = 1$	-	$ i\rangle = ^1S_0\rangle, ^1D_2\rangle$

At such energies very close to threshold the angular momentum L_{NN} in the final NN system as well as the angular momentum $l_{\pi(NN)}$ of the pion with respect to the NN pair is restricted to the values 0 and 1. Conservation laws for the angular momentum, isospin, and parity, and the Pauli principle

limit the number of possible partial wave amplitudes further. The allowed partial waves under the restrictions $L_{NN} = 0$ and $l_\pi = 0, 1$ are summarized in Table I for the reactions $pp \rightarrow pp\pi^0$ and $pn \rightarrow d\pi^0$. These partial waves will give the dominant contributions to the pion production at threshold. NN states with $L_{NN} = 1$ are much less important since the interaction in these partial waves is comparatively weak. Note that there is no entry for the $l_\pi = 1$ contribution in case of $pp \rightarrow pp\pi^0$. This means that (p-wave) pion production via the Δ (1236) resonance, which plays a major role in other meson production reactions, is strongly suppressed in this particular channel.

2. Models for threshold pion production: a brief history

Essentially all recent theoretical investigations on pion production near threshold build up on the model proposed by Koltun and Reitan in 1966 [12]. In this model two production mechanisms are considered: (i) direct production of a pion, depicted in Fig. 1a, (ii) production of a pion which first scatters off the other nucleon before emission, as shown in Fig. 1b. The former is usually called Born term whereas the latter is referred to as rescattering term. This model was utilized by Miller and Sauer in 1991 [13] to analyze the first set of high precision data of the reaction $pp \rightarrow pp\pi^0$ near threshold that became available from IUCF [2]. Surprisingly, it turned out that such a model grossly underestimates the empirical cross section [13]. Only the predicted energy dependence of the cross section, which in this model is determined essentially by phase-space factors and the pp final-state interaction, was found to be in agreement with the IUCF data [3].

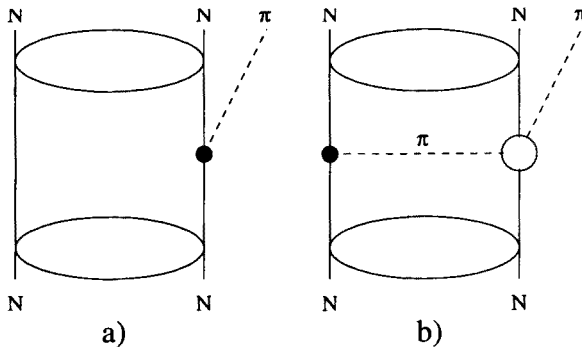


Fig. 1. Pion production mechanisms included in the model by Koltun and Reitan: (a) direct pion emission, (b) pion rescattering.

We want to remark that in this model the πN interaction occurring in the rescattering diagram is approximated by the πN (s-wave) scattering length. In the reaction $pp \rightarrow pp\pi^0$ only the isoscalar component of the πN s-wave interaction is present. Since the corresponding scattering length is almost zero due to chiral constraints, it means that the contribution from the rescattering process is practically negligible [13].

In 1992 Niskanen extended this model by including in addition pion rescattering in the πN p-wave via the Δ (1236) isobar (*c.f.* Fig. 2) [14]. Furthermore, he allowed for an energy dependence in the s-wave rescattering term [15]. These improvements roughly doubled the predicted $pp \rightarrow pp\pi^0$ cross section, but Niskanen's results still underestimate the IUCF data by a factor of 3.6. Another new production mechanism was introduced by

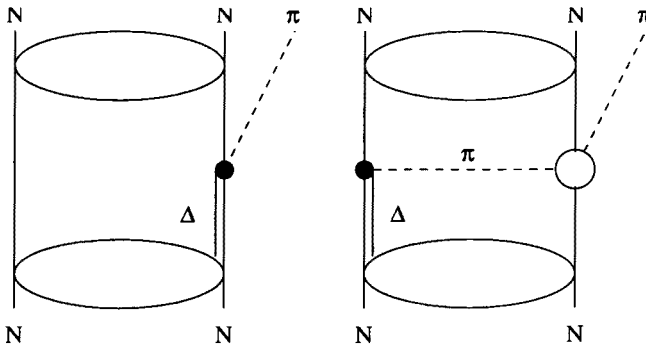


Fig. 2. Pion production via Δ excitation.

Lee and Riska in 1993 [16]. These authors considered effects from meson-exchange currents due to the exchange of heavy mesons, as shown in Fig. 3. It was found that the resulting contributions (in particular the one of the σ meson) enhance the pion production cross section by a factor of 3–5 [16, 17] and thus eliminate most of the underprediction found in earlier investigations. Consequently, at that time it seemed that the reaction $pp \rightarrow pp\pi^0$ near threshold is essentially understood.

However, in 1995 Hernández and Oset presented an alternative explanation for the missing strength in the π^0 production close to threshold [18]. These authors took into account the off-shell properties of the πN amplitude in the evaluation of the rescattering diagram. Since the isoscalar s-wave πN off-shell amplitude can be much larger than its on-shell value at threshold (which is more or less zero, as mentioned before) it turned out that the contribution from rescattering is now considerably enhanced. Indeed it was demonstrated in Ref. [18] that direct production and rescattering alone are also sufficient in order to reproduce the empirical $pp \rightarrow pp\pi^0$ cross section.

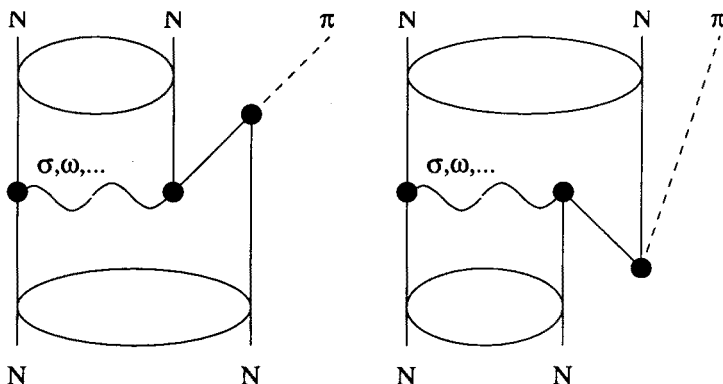


Fig. 3. Mechanisms for pion production: Heavy meson exchanges

Yet another aspect was added to this controversial situation by two recent investigations based on chiral perturbation theory [19, 20]. In these studies a considerable cancellation between the contributions from direct production and rescattering is observed. Then one is essentially left with only contributions from rather short-ranged mechanisms such as heavy meson exchanges - which, however, are not sufficient for describing the experiment [20].

3. The $pp \rightarrow pp\pi^0$ reaction

In the following two sections we will report on our own investigations of the reaction $NN \rightarrow NN\pi$ [21]. The main novelty in these calculations is that a realistic meson-theoretical model of the πN interaction [22] is employed for the evaluation of the rescattering contributions. We present results for the channels $pp \rightarrow pp\pi^0$ and (in the next section) $pn \rightarrow d\pi^0$. We consider only the lowest partial waves in the outgoing channel, *i.e.* the pp pair is taken to be in the 1S_0 and the pion is in an s-wave relative to the nucleon pair or the deuteron, respectively. Our calculations are carried out in momentum space. Distortions in the initial and final NN states are taken into account. The Bonn potential OBEP [23] is used for the NN interaction. The Coulomb interaction is included following the method described in Ref. [21]. The model is developed in the framework of time ordered perturbation theory. Therefore it is consistent with the interactions in the NN - and πN systems which were likewise derived in time ordered perturbation theory [23, 22].

In our model calculation of the reaction $NN \rightarrow NN\pi$ we consider contributions from the direct pion production, from s-wave pion rescattering

and from the heavy-meson-exchange (HME) production mechanism.

3.1. The direct pion production

Following previous investigations we use pseudo-vector coupling for the πNN vertex. This leads to the following structure for the pion production vertex,

$$M_{fi} \propto \sqrt{\frac{\epsilon_p \epsilon_{p'}}{E_p E_{p'}}} \left[\vec{\sigma} \cdot (\vec{p} - \vec{p}') - \omega_q \vec{\sigma} \cdot \left(\frac{\vec{p}}{\epsilon_p} + \frac{\vec{p}'}{\epsilon_{p'}} \right) \right], \quad (1)$$

where \vec{p} (\vec{p}') is the incoming (outgoing) nucleon momentum, and $\epsilon_p = E_p + M$ with the nucleon energy $E_p = \sqrt{M^2 + \vec{p}^2}$. $\omega_q = \sqrt{m_\pi^2 + \vec{q}^2}$ is the energy of the pion with momentum $\vec{q} = \vec{p} - \vec{p}'$.

In earlier calculations [12–14, 16, 17] several approximations are applied in the evaluation of the production amplitude. The energies E_p , $E_{p'}$ and ω_q are replaced by the respective masses in Eq. (1) and usually the first term in Eq. (1) is omitted altogether. Furthermore, the reduced mass of the pion relative to the NN system is replaced by the pion mass m_π in the kinematical relations. This increases the allowed maximum pion momentum q_{\max}^π (for a fixed energy) and enlarges the phase space.

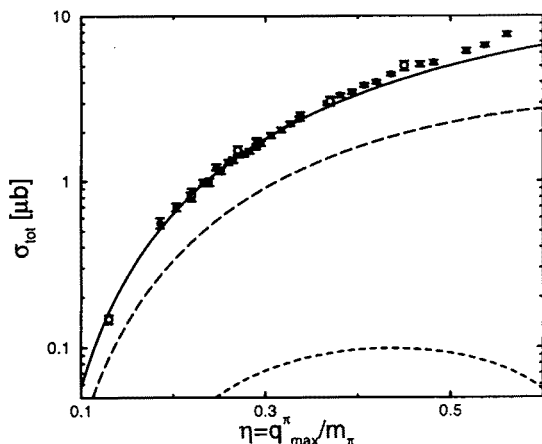


Fig. 4. Total cross section for the reaction $pp \rightarrow pp\pi^0$. The dashed line shows the results for direct production only. Adding rescattering yields the long dashed line. Including also contributions from heavy meson exchanges leads to the solid line. The data are from Refs. [3] (filled circles) and [5] (open circles).

The consequences of these approximations were studied by us in a recent paper [21]. It turned out that a more correct treatment of the direct pion production mechanism reduces its contribution to the $pp \rightarrow pp\pi^0$ cross section by a factor of 2 and it also modifies the energy dependence of the cross section. In the present calculation there is a further reduction of the cross section as compared to comparable previous investigations which is due to the employed NN interaction model. (We will comment on the sensitivity to the NN interaction later.) Indeed the pion production cross section resulting from the Born term alone is in our case about a factor 20 smaller than the experiment (cf. the dashed line in figure 4) whereas only a factor of about 5 is missing by, *e.g.*, the model of Miller and Sauer [13].

3.2. Pion rescattering

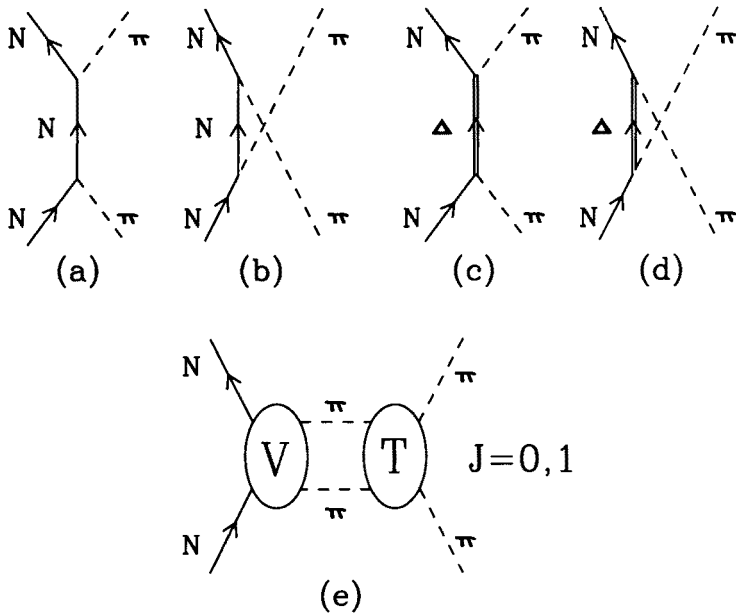


Fig. 5. Graphs included in the πN interaction model

The second pion production mechanism we take into account is pion rescattering (Fig. 1b). In the model of Koltun and Reitan the πN scattering

amplitude is derived from a phenomenological effective Hamiltonian [12]

$$H = 4\pi \frac{\lambda_1}{m_\pi} \bar{\Psi} \vec{\phi} \cdot \vec{\phi} \Psi + 4\pi \frac{\lambda_2}{m_\pi^2} \bar{\Psi} \vec{\tau} \Psi \cdot \vec{\phi} \times \partial_0 \vec{\phi}, \quad (2)$$

where λ_1, λ_2 are fixed by the (empirical) S_{11} and S_{31} pion nucleon scattering lengths. The isovector term (proportional to λ_2) does not contribute to the reaction $pp \rightarrow pp\pi^0$ because of isospin constraints. Since the isoscalar part is very small ($\lambda_1 = 0.005$ according to Höhler *et al.* [24]; $\lambda_1 = -0.0013$ following Arndt *et al.* [25]) it has usually been found that the rescattering contribution to the $pp \rightarrow pp\pi^0$ cross section obtained from the effective Hamiltonian in Eq. (2) is more or less negligible [13, 17, 16].

It is well known that the smallness of the isoscalar s -wave πN on-shell amplitude is due to a strong cancellation between different isospin amplitudes. The situation is rather different for the corresponding off-shell amplitude — which is actually the quantity that enters into the evaluation of the rescattering diagram (Fig. 1b). In order to account for these off-shell properties appropriately we employ in our investigation a microscopic meson-exchange model of the πN interaction which has been constructed recently in Jülich [22]. This model includes the conventional (direct and crossed) pole diagrams involving the nucleon and the Δ -isobar; the meson exchanges in the scalar (σ) and vector (ρ) channels are derived from correlated 2π exchange (figure 5). Further details about this model can be found in Ref. [22].

Here we use a slightly modified version where the form factors are energy-independent and the antibaryon contributions have been left out. These modifications are made to allow an extrapolation of the model to negative energies as required in the present three-particle context. After readjustment of its free parameters this model yields a good description of low-energy πN scattering, comparable to the results shown in Ref. [22]. The resulting s -wave scattering lengths are $a_1 = 0.173m_\pi^{-1}$ and $a_3 = -0.084m_\pi^{-1}$ leading to a value of $\lambda_1 = -0.001$ which is in agreement with the value given in Ref. [17]. The half-off-shell T -matrix produced by this model at πN threshold is shown in Fig. 6.

For the production vertex we take the same pion coupling constant as in the NN potential, namely $f^2/4\pi = 0.0795$. The form factor is chosen to be rather soft. We use a monopole form with a cutoff mass $\Lambda_\pi = 800 \text{ MeV}$ which is in line with recent QCD lattice calculation [26] and other information [27].

Results for the $pp \rightarrow pp\pi^0$ cross section including contributions of the rescattering mechanism are depicted by the long-dashed curve in Fig. 4. The rescattering process increases the cross section by a factor of around

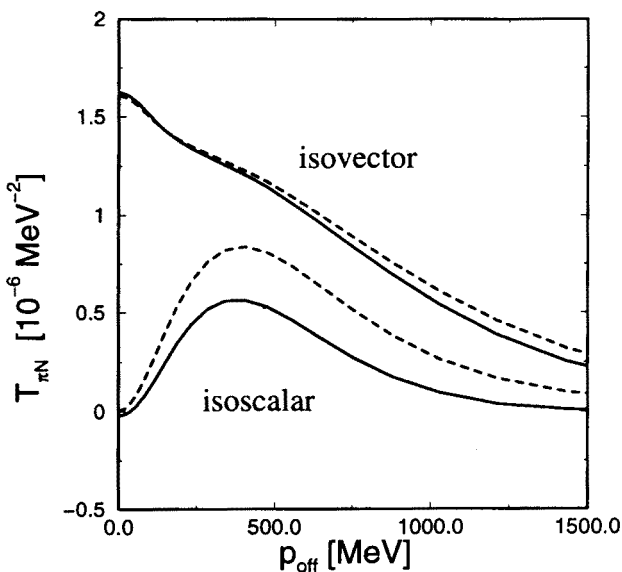


Fig. 6. Half-off-shell πN s -wave T -matrix at threshold. The lower two curves show the isoscalar component of the T -matrix, the upper curves display the isovector component. The solid line denotes the model used in the present calculation whereas the dashed line is the result from model 1 of Ref. [22].

10 compared to the rate for direct production. This is in qualitative agreement with the findings reported in Ref. [18] which, however, are based on phenomenological off-shell extrapolations of the πN amplitude.

3.3. Heavy meson exchanges

As can be seen in Fig. 4 our predictions based on direct pion production plus rescattering underestimate the empirical data [3, 5] by a factor of 2. Evidently further production mechanisms are needed. An obvious option are corrections from meson-exchange currents as proposed by Lee and Riska [16]. Corresponding diagrams are shown in Fig. 3. The results presented in Ref. [16] and the subsequent more thorough investigations by Horowitz and collaborators [17] indicate that only the diagrams involving the σ and ω mesons give rise to an appreciable contribution. Therefore we restrict our calculation to these two mesons. The vertex parameters for the ω exchange are taken over from OBEPT ($g_\omega^2/4\pi = 20$, $\Lambda_\omega = 2000$ MeV). Since the σ meson that is used in one-boson-exchange models of the NN interaction is an effective parameterization of more complex processes like correlated and

uncorrelated $\pi\pi$ -exchange [31] it should be different in the present context involving vertices with antinucleons. Hence we consider the σ coupling constant as a free parameter which is chosen to reproduce the π^0 production cross section close to threshold. With the values $g_\sigma^2/4\pi = 5.7$, $A_\sigma = 1700$ MeV the solid line in Fig. 4 is obtained. It is interesting that the required σ coupling strength is almost identical to the one used in the full Bonn NN model [23].

3.4. Discussion

Obviously the reaction $pp \rightarrow pp\pi^0$ is rather sensitive to the πN off-shell behavior as well as to the short range component of the NN force. However, in order to learn something about either of these features it is necessary to have some constraints on one of them. With regard to the properties of the πN amplitude this seems to be difficult at present. For example, the πN model used in the present calculation as well as the initial model (model 1 of Ref. [22]) yield an equally good fit of the relevant πN phase shifts. However, due to minor differences in their dynamical ingredients (antibaryon contributions are left out in the model applied here), the isoscalar s-wave πN half-off-shell amplitude at threshold is about 50 % larger around the maximum in the initial model (*c.f.* Fig. 6) and accordingly an enhanced contribution from the rescattering mechanism can be expected. Note that the isovector s-wave πN amplitude, which is also shown in Fig. 6, is much less model dependent.

Earlier investigations indicated also a considerable sensitivity to the employed NN interaction model. *E.g.*, the results based on the Reid soft-core and the Bonn A (*r*-space version) potentials, respectively, which were presented by Horowitz *et al.* in Ref. [17], differ by almost a factor 2. (Note that such a sensitivity was denied in the abstract of this paper!) We show here results for the Paris NN potential [29] for which, however, a somewhat less pronounced variation is observed. Still its prediction is about 30 % larger than the one for OBEPT (*c.f.* the dashed curve in Fig. 7b). The origin of this sensitivity can be traced to a node in the NN 1S_0 half-off-shell T-matrix occurring at a (off-shell) momentum of around 370 MeV/*c*. This value is more or less identical with the typical momentum transfer between the nucleons at pion production threshold (*cf.* the comments in the Introduction) and consequently with the momentum at which the NN half-off-shell T-matrix is needed for the evaluation of the direct production diagram. This explains why the contribution of the direct pion production is relatively small (*c.f.* Fig. 4). On the other hand it also means that the magnitude of this contribution will depend strongly on the specific position of this node the presence of which is associated with the transition from the

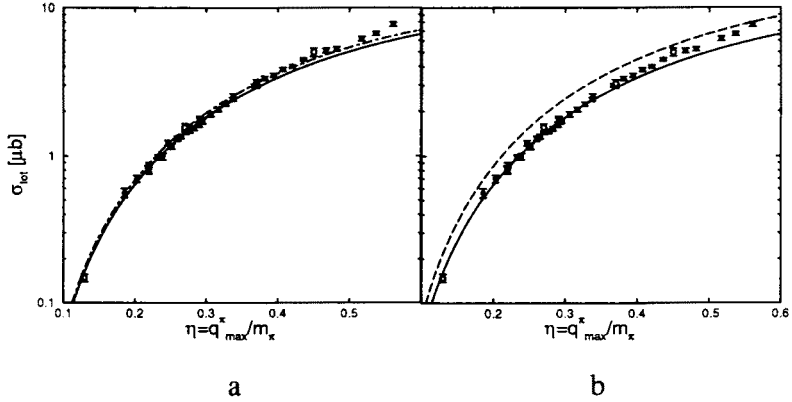


Fig. 7. Sensitivity of the reaction $pp \rightarrow pp\pi^0$ to (a) the πNN form factor and (b) different nucleon-nucleon interactions. The solid line is obtained with OBEPT and $\Lambda_\pi = 800$ MeV. The dashed-dotted line (in (a)) corresponds to $\Lambda_\pi = 1000$ MeV. The dashed line (in (b)) is the result for the Paris NN potential.

intermediate attraction to the short-range repulsion in the NN force.

The evaluation of the rescattering- and HME diagrams involves loop integrations. This means that one averages over the NN half-off-shell T -matrix. Therefore the dependence of their contributions on the employed NN models is much less pronounced.

The sensitivity to the πNN form factor (applied at the pion production vertex of the rescattering diagram) is demonstrated in Fig. 7a. We show results for $\Lambda_\pi = 800$ MeV (used in the present model) and $\Lambda_\pi = 1000$ MeV. The latter value is suggested by a recent study of the πNN form factor in the meson-exchange picture [28]. Obviously variations of the cutoff mass within this range have very little influence on the results.

A possibility to pin down the contributions of the various pion production mechanisms could be provided by a careful study of the energy dependence of the production cross section. In Fig. 8 we show results for the contributions of the direct diagram, rescattering and HME individually, each of them scaled to the data at $\eta = 0.2$. It is evident that the different production mechanisms lead to rather large differences in the predicted energy dependence. Unfortunately, for $\eta > 0.4$ where the differences are becoming more pronounced contributions from (NN) p-waves are presumably no longer negligible. Therefore it is necessary to include these p-waves in the calculations if one wants to reach reliable conclusions [30].

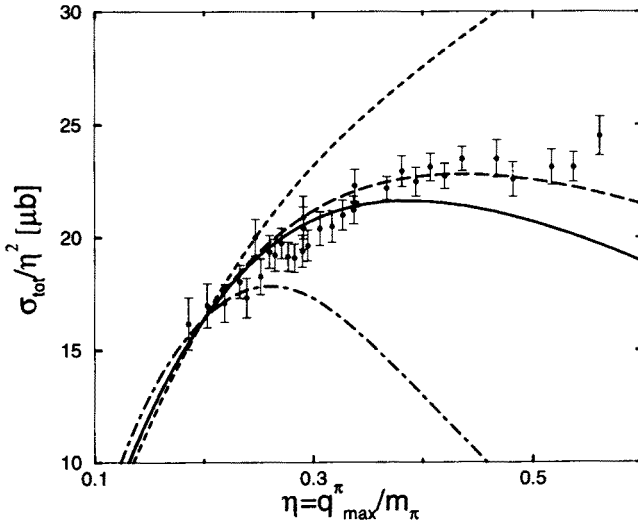


Fig. 8. Energy dependence of the different contributions to the reaction $pp \rightarrow pp\pi^0$. Shown are the direct production (dashed-dotted), rescattering (long dashed) and heavy meson exchanges (dashed), each scaled individually to the data at $\eta = 0.2$. The solid line represents our total result, *c.f.* Fig. 4. Note that the cross section is divided by η^2 .

Another possibility to learn more about the individual production mechanisms is offered by the study of other $NN \rightarrow NN\pi$ processes ($pn \rightarrow d\pi^0$, *etc.*) using the same model (with the same parameters). This is the topic of the next section.

4. The $pn \rightarrow d\pi^0$ reaction

Let us now consider the reaction $pn \rightarrow d\pi^0$ close to threshold. We have calculated the production cross section with the same model and applying the same parameters (for the pion production vertex and the heavy meson exchanges) as for $pp \rightarrow pp\pi^0$. Thus the results, which are shown in Fig. 9, can be considered as real predictions of our model. The cross section generated by the direct production mechanism (Fig. 1a) is extremely small which is due to the known cancellation between the contributions from the deuteron s- and d-wave components [12, 32]. Therefore the corresponding curve cannot be seen in Fig. 9.

The bulk of the cross section is provided by isovector s-wave pion rescat-

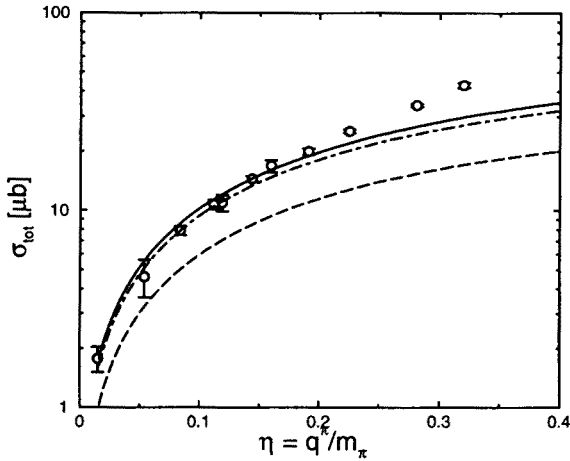


Fig. 9. Total cross section for the reaction $pn \rightarrow d\pi^0$. The dashed line shows the result for direct production plus isovector rescattering. Adding isoscalar rescattering yields the dashed-dotted curve. Including also contributions from heavy meson exchanges leads to the solid line. The data are from Ref. [9].

tering. It accounts for roughly one half of the experimentally observed production rate. However, there is also an important contribution from the isoscalar part of the rescattering process. Indeed it enhances the cross section by about 50 % and brings the result close to the experiments (*c.f.* Fig. 9). Note that this enhancement is entirely due to the fact that the off-shell properties of the πN interaction are taken into account. For the static approximation used, *e.g.*, in Ref. [32] the contribution from the isoscalar channel would be negligible — like in the corresponding $pp \rightarrow pp\pi^0$ case.

The addition of the contributions from heavy meson exchanges leads only to a moderate change in the cross section. This is in contradiction to the results presented in Ref. [32], where the HME contributions almost doubled the cross section. We want to mention, however, that some unjustified assumptions have been made in the aforementioned calculations, which lead to an overestimation of the effect from HME by a factor of 3–4, as has been pointed out by Niskanen recently [33].

Our result starts to deviate from the data at energies around $\eta = 0.25$. We believe that this is due to p-wave contributions which are missing in our model calculation and which set in at much lower energies in the reaction $pn \rightarrow d\pi^0$ than in $pp \rightarrow pp\pi^0$.

The energy dependence of the $np \rightarrow d\pi^0$ cross section near threshold is

commonly parameterized by

$$\sigma_{np} = \frac{1}{2}(\alpha\eta + \beta\eta^3), \quad (3)$$

where the first coefficient, α , is determined by s-wave pion production. Its experimental value has been given by Hutcheon *et al.* to be $\alpha = 184 \pm 5 \pm 13 \mu\text{b}$ [9]. Our model predicts a value of $\alpha = 204 \mu\text{b}$ which lies just outside of the experimental error bars.

The contribution of the individual production mechanisms are specified in Table II. The HME contribution changes α by only $15 \mu\text{b}$ — a value which is in good agreement with the corresponding results obtained by Niskanen [33].

TABLE II

Cross section factor α , *c.f.* Eq. (3), for the different production mechanisms.

production mechanism	α [μb]
direct emission	0.2
+ isovector rescattering	120
+ isoscalar rescattering	189
+ heavy meson exchanges	204

In Fig. 10 we compare the results obtained with OBEPT with the ones using the Paris model for the initial- and final state distortions. Evidently the cross section for $pp \rightarrow pp\pi^0$ is rather insensitive to the used NN interaction. This is in agreement with the findings reported by Horowitz in Ref. [32]. At first this is surprising because the deuteron wave function of the s-state (like the 1S_0 in the corresponding $pp \rightarrow pp\pi^0$ case) has also a node around the momentum $q = 370 \text{ MeV}/c$ typical for the threshold kinematics and its position is again slightly different for different NN models. However, the contribution of the direct pion production — which is primarily sensitive to the position of this node — is very small in case of the reaction $pn \rightarrow d\pi^0$ (*c.f.* the discussion above) and therefore variations of it have a very small influence on the total production cross section.

The sensitivity of the $pn \rightarrow d\pi^0$ cross section to the πNN form factor is depicted in Fig. 10a. We see that the variation in the cross section caused by changing the cutoff mass from 800 to 1000 MeV is somewhat larger than for the reaction $pp \rightarrow pp\pi^0$ (Fig. 7a).

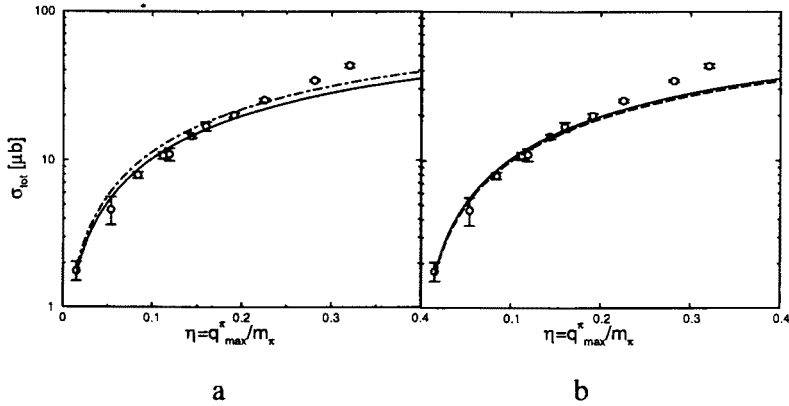


Fig. 10. Sensitivity of the reaction $pn \rightarrow d\pi^0$ to (a) the πNN form factor and (b) different nucleon-nucleon interactions. The solid line is obtained with OBEPT and $\Lambda_\pi = 800$ MeV. The dashed-dotted line (in (a)) corresponds to $\Lambda_\pi = 1000$ MeV. The dashed line (in (b)) is the result for the Paris NN potential.

5. Summary

The hitherto existing investigations on the reaction $pp \rightarrow pp\pi^0$ have shown that the empirical cross section near threshold can be reproduced quantitatively. This could be achieved with contributions from either heavy meson exchanges or from off-shell pion rescattering so that it seemed that the two production mechanisms would exclude each other. Our investigations indicate that they can be combined with each other. Indeed, within our model contributions from πN s-wave rescattering as well as from heavy meson exchanges are necessary in order to obtain agreement with the experiments.

The studies indicate that the production cross section is very sensitive to the short range component of the NN interaction. First of all this is reflected in a dependence of the results on the employed NN model. Secondly, it manifests itself in the potentially large contributions from the HME production mechanism. In addition there is a strong sensitivity to the off-shell behavior of the πN interaction. Unfortunately, the uncertainties inherent in either of those properties make it difficult to disentangle them in a study of the reaction $pp \rightarrow pp\pi^0$.

One possible way out of this dilemma could lie in a careful analysis of the energy dependence of the production cross section. As we have shown,

the different production mechanisms lead to rather pronounced variations. However, here it is necessary to include also p-waves into the calculations before any reliable conclusions can be drawn.

Another possibility to learn more about the individual production mechanisms is offered by the study of other $NN \rightarrow NN\pi$ processes within the same model. For that purpose we looked at the reaction $pn \rightarrow d\pi^0$. Indeed we found that this process is much less sensitive to the short-range part of the NN interaction. There is almost no dependence on the employed NN model and also contributions from HME play only a minor role. The bulk of the $pn \rightarrow d\pi^0$ cross section near threshold is provided by rescattering due to the isovector part of the s-wave πN interaction. However, the contribution of the isoscalar part is significant so that a comparison with the data would definitely allow to obtain constraints on the corresponding off-shell properties. The isoscalar amplitude of the πN model employed in our study enhances the cross section by about 50 % and therefore is responsible for the good agreement of our calculation with the data. Clearly, since pion production mechanisms involving the Δ excitation (which are so far missing in our model) could be also important in the reaction $pn \rightarrow d\pi^0$, as shown by Niskanen, one should be cautious in drawing quantitative conclusions from this result at present.

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