η- and η'-meson production in the reaction $pn \to dM$ near threshold

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Abstract

The two-step model with π, ρ and ω exchanges taken into account is applied to investigate the reactions $pn \to d\eta$ and $pn \to d\eta'$ near the corresponding thresholds. The existing experimental data on the reaction $pn \to d\eta$ are analyzed and predictions for the cross section of the reaction $pn \to d\eta'$ are presented. It is found that π- as well as ρ-meson exchanges yield significant contributions in both reactions. Furthermore, the effect of the ηN final-state interaction is studied. It is shown that an ηN-scattering length of Re $a_{\eta N} \leq 0.3$ fm is sufficient to reproduce the observed enhancement of the $pn \to d\eta$ cross section close to threshold.

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Recently, the total cross section of the reaction $pn \to d\eta$ has been measured close to threshold at CELSIUS in Uppsala [1,2]. These data are remarkable for a variety of reasons: E. g., they reveal that an older estimate yielding a rather large near-threshold production cross section for the reaction $pn \to d\eta$ [3,4] is definitely ruled out [2]. Furthermore, they show that the production cross section very close to threshold is significantly enhanced over the expectation

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for a two-body phase-space behaviour [2], indicating the presence of a strong final-state interaction.

Though there is a large body of theoretical papers about the reaction $pp \to pp\eta$ only a few of them have also dealt with aspects of the near-threshold $pn \to d\eta$ and $pn \to (pn)_{I=0}\,\eta$ production [3–7]. Moreover, all of them rely on the old and now obsolete data point of Ref. [3]. Thus, in the following we want to present a timely re-analysis of this reaction utilizing now the new data from CELSIUS. In particular, we are going to present results of a microscopic calculation of the $pn \to d\eta$ cross section within the framework of the two-step model (TSM), previously applied to the description of the Pontecorvo reactions $\bar{p}d \to pM$ (see, e.g., Ref. [8] and references therein). We start from the π exchange contribution to the η-meson production and study the relevance of other production mechanisms such as the ρ and ω exchange. Furthermore, we investigate the effect of the final-state interaction between the η meson and the nucleons employing an optical-potential model as well as a multiple scattering approach. Finally, as an application of our model, we present predictions for the cross section of the reaction $pn \to d\eta'$ near threshold.

In the TSM the reaction $pn \to dM$ proceeds in two steps: i) the initial nucleons produce an η or η' meson (denoted as M) via virtual π-, ρ- or ω-meson exchange; ii) the proton and neutron form a deuteron in the final state (see Fig. 1).

The amplitude which describes the contribution of the π^0 exchange can be written in the form

$$T^{\pi}_{pn\to dM}(s,t,u) = A^{\pi}_{pn\to dM}(s,t) + A^{\pi}_{pn\to dM}(s,u)\ , \tag{1}$$

where M is the pseudoscalar meson η or η'. $s = (p_1+p_2)^2$, $t = (p_3-p_1)^2$, and $u = (p_3-p_2)^2$ where p_1, p_2, p_3, and p_4 are the 4-momenta of the proton, neutron, M-meson and deuteron, respectively. Treating the nucleons inside the deuteron nonrelativistically, the two terms on the right hand side of Eq. (1) are given by (see, e.g., Ref. [9])

$$A^{\pi}_{pn\to dM}(s,t) = \frac{f_\pi}{m_\pi}\varphi^T_{\lambda_2}(\vec{p}_2)\ (-i\sigma_2)\vec{\sigma}\cdot\vec{M}^{\pi}(\vec{p}_1)\ \vec{\sigma}\cdot\vec{\epsilon}^{\,*}_d\ \varphi_{\lambda_1}(\vec{p}_1)\ \times A_{\pi^0 N\to MN}(s_1,t)\ , \tag{2}$$

$$A^{\pi}_{pn\to dM}(s,u) = \frac{f_\pi}{m_\pi}\varphi^T_{\lambda_1}(\vec{p}_1)\ (-i\sigma_2)\vec{\sigma}\cdot\vec{M}^{\pi}(-\vec{p}_1)\ \vec{\sigma}\cdot\vec{\epsilon}^{\,*}_d\ \varphi_{\lambda_2}(\vec{p}_2)\ \times A_{\pi^0 N\to MN}(s_1,u)\ , \tag{3}$$

where $\vec{\epsilon}_d$ is the polarization vector of the deuteron and φ_λ the spinors of the nucleons in the initial state. f_π is the πNN coupling constant, for which we use the value $f_\pi^2/(4\pi) = 0.08$. Furthermore we have

$$\vec{M}^\pi(\vec{p}_1) \; = \sqrt{2\,m} \int (\vec{k} + \vec{p}_1)\, \Phi_\pi(\vec{k}, \vec{p}_1) \Psi_d(\vec{k})\, \frac{\mathrm{d}^3 k}{(2\pi)^{3/2}} \; , \tag{4}$$

$$\Phi_\pi(\vec{k}, \vec{p_1}) = \frac{F_\pi(q^2)}{q^2 - m_\pi^2} \; , \tag{5}$$

with the kinematics

$$\begin{aligned} q^2 \;\; &= m_\pi^2 - \delta_0(\vec{k}^2 + \beta(\vec{p}_1)) - 2\vec{p}_1\vec{k}, \;\; \vec{q} = \vec{k} + \vec{p}_1 \; , \\ \beta(\vec{p}_1) &= (\vec{p}_1^{\,2} + m_\pi^2 - T_1^2)/\delta_0 \; , \;\; \delta_0 = 1 + T_1/m, \;\; T_1 = \sqrt{\vec{p}_1^{\,2} + m^2} - m \; . \end{aligned}$$

In Eqs. (4) and (5) $\Psi_d(\vec{k})$ is the deuteron wave function, $F_\pi(q^2)$ the form factor at the πNN vertex and m the nucleon mass. Note that the amplitude $\vec{M}^\pi$ corresponds to the exchange of a neutral π meson only (see the left diagrams in Fig. 1). To take into account also the charged pion exchange we have to multiply amplitude (1) with an isospin factor (which is equal to 3).

The form factor $F_\pi(q^2)$ is taken to be of monopole type with a cutoff mass $\Lambda_\pi = 0.8$ GeV/c, in line with recent QCD lattice calculations [10] and other information [11]. The D-wave part of the deuteron wave function gives only a small contribution and can be savely neglected. This was demonstrated in Ref. [8] for the case of the reaction $\bar{p}d \to Mn$ where the same structure integrals (4) for π, ρ and ω exchanges occur. Note that the property $\vec{M}^\pi(-\vec{p}_1) = -\vec{M}^\pi(\vec{p}_1)$ ensures the correct behaviour of the amplitude (1) under permutations of the initial nucleons. The amplitude should be symmetric in the isoscalar state.

Near threshold only the S-wave part of the amplitude of the elementary reaction $\pi N \to MN$ should be of relevance for the production amplitude $T_{pn\to dM}$. It can be obtained from the experimental S-wave cross section through the relation

$$|A_{\pi^0 N\to MN}(s_1,t)|^2 = |A_{\pi^0 N\to MN}(s_1,u)|^2 = 8\pi s_1 \frac{p_\pi^{\rm cm}}{p_M^{\rm cm}} \sigma_{\pi^- p\to Mn} \tag{6}$$

where s_1 is the square of the c.m. energy in the Mn system. The values of these S-wave cross sections that we used in our calculation are
$\sigma_{\pi^- p\to\eta n} = (21.2 \pm 1.8) p_{\rm cm}^M \; \mu$b and $\sigma_{\pi^- p\to\eta' n} = (0.35 \pm 0.03) p_{\rm cm}^M \; \mu$b
($p_{\rm cm}^M$ in MeV/c). They are extracted from the data given in Ref. [12].

The total cross sections resulting from the π-exchange contribution (with Λ_π = 0.8 GeV/c) are shown in Figs. 2 and 3 (dashed curves) as a function of the c.m. excess energy $Q = \sqrt{s} - m_3 - m_4$. The data points for η production (Fig. 2) are taken from [1,2].

Evidently pion exchange alone cannot describe the η-production cross-section data. Of course, we could have simply adjusted the cutoff mass in the pion form factor in such a way that we reproduce the data. But it goes without saying that the exchange of heavier mesons should also be considered as well as effects of the initial- and final-state interactions.

In order to obtain a direct estimate of the contributions from the ρ and ω exchanges we calculated them in the framework of the TSM using the vector-dominance model (VDM) prediction for the amplitude $\rho N \to \eta(\eta')N$ and assuming that $A_{\omega N\to\eta(\eta')N} \approx A_{\rho^0 N\to\eta(\eta')N}$. We derive the S-wave $\gamma N \to \eta N$ amplitude from the Mainz data at $E_\gamma = 716$ MeV [13] where the differential cross section of the reaction $\gamma p \to \eta p$ is isotropic. In the case of η' we take the $\gamma p \to \eta' p$ cross section of about 1 – 1.5 μb at $E_\gamma = 1.5$ GeV from Ref. [14]. According to Ref. [14] the differential cross section of the reaction $\gamma p \to \eta' p$ at this energy is almost isotropic. In the actual evaluation of the amplitudes we use the coupling constants γ_ρ and γ_ω of Ref. [15]. The $VN \to MN$ amplitudes for longitudinal polarization of the vector mesons V are taken to be the same as the transversal ones. Defining the cross section averaged over the V-meson polarizations as $\mathrm{d}\sigma/\mathrm{d}\Omega = (p_f^{\rm cm}/p_i^{\rm cm})|f|^2$ we obtain the values $|f|^2 = 720$ μb/sr and 60 – 90 μb/sr for the reactions $\rho^0 p \to \eta p$ and $\rho^0 p \to \eta' p$, respectively. Those numbers should be compared with 360 and 9.8 μb/sr for the reactions $\pi^0 p \to \eta p$ and $\pi^0 p \to \eta' p$, respectively.

The amplitudes for the vector-meson exchanges can be written in the form (treating again the nucleons in the deuteron nonrelativistically)

$$\begin{aligned} A^V_{pn\to dM}(s,t) = & \frac{G_V}{2\,m}\varphi^T_{\lambda_2}(\vec{p}_2)(-i\,\sigma_2)\cdot A_{V^0N\to MN}(s_1,t) \;\times \\ & \left\{\vec{M}^V_1(\vec{p}_1)\cdot\vec{\epsilon}^{\,*}_d - i\left[\vec{M}^V_2(\vec{p}_1)\times\vec{\epsilon}^{\,*}_d\right]\cdot\vec{\sigma}\right\}\varphi_{\lambda_1}(\vec{p}_1)\;, \qquad (7) \\ A^V_{pn\to dM}(s,u) = & \frac{G_V}{2\,m}\varphi^T_{\lambda_1}(\vec{p}_1)(-i\,\sigma_2)\cdot A_{V^0N\to MN}(s_1,u) \;\times \\ & \left\{\vec{M}^V_1(-\vec{p}_1)\cdot\vec{\epsilon}^{\,*}_d - i\left[\vec{M}^V_2(-\vec{p}_1)\times\vec{\epsilon}^{\,*}_d\right]\cdot\vec{\sigma}\right\}\varphi_{\lambda_2}(\vec{p}_2)\;, \qquad (8) \end{aligned}$$

where

$$\vec{M}^V_1(\vec{p}_1) = \sqrt{2\,m}\int[(\vec{k}-\vec{p}_1) + \frac{\vec{k}^2-\vec{p}_1^{\,2}}{m_V^2}(\vec{k}+\vec{p}_1) + 2(1+\kappa_V)(\vec{k}+\vec{p}_1)] \;\times$$

$$\Phi_V(\vec{k},\vec{p}_1)\Psi_d^*(\vec{k})\frac{\mathrm{d}^3k}{(2\pi)^{3/2}} \tag{9}$$

and

$$\vec{M}_2^V(\vec{p}_1) = \sqrt{2\,m}\int[(\vec{k}-\vec{p}_1)+\frac{\vec{k}^2-\vec{p}_1^2}{m_V^2}(\vec{k}+\vec{p}_1)]\ \times$$
$$\Phi_V(\vec{k},\vec{p}_1)\Psi_d^*(\vec{k})\frac{\mathrm{d}^3k}{(2\pi)^{3/2}}\ . \tag{10}$$

$\Phi_V(\vec{k},\vec{p}_1)$ is defined by Eq. (5) where m_π^2 should be substituted by m_V^2 etc. G_V is the vector coupling constant and κ_V is the ratio of the tensor and vector couplings. For these coupling constants and for the corresponding vertex form factors we use the values from the full Bonn NN potential [16], i.e. $G_\rho^2/4\pi = 0.84$, $\kappa_\rho = 6.1$, $G_\omega^2/4\pi = 20$, $\kappa_\omega = 0$ and $\Lambda_\rho = 1.4$ GeV/c, $\Lambda_\omega = 1.5$ GeV/c. Note that the amplitudes (7)–(8) should also be multiplied by the isospin factor 3 in the case of ρ exchange.

As far as the initial state interaction (ISI) is concerned it would be, of course, desirable to calculate its effect by means of a realistic model of the NN interaction. However, there are basically no NN potentials available in the literature that are still valid in the energy range where η and, in particular, η' production occurs. Therefore we decided to introduce an overall normalization constant which effectively accounts for the expected reduction of the production cross sections due to the ISI. This constant is adjusted to the data on the reaction $pn \to d\eta$ and then used for calculating predictions for the reaction $pn \to d\eta'$. The latter step is based on the reasonable assumption that the ISI does not change that much in the energy range from the η- to the η'-production threshold.

Alternatively, we employ an estimate for the effect of the ISI that has been presented recently in Ref. [17]. It is based on the assumption that, at the large energies required for the production of heavier mesons, the NN t-matrices are basically constant for (off-shell) momenta not too far away from the on-shell point. In this case the effect of the ISI can be expressed by a simple reduction factor λ that depends only on the NN phase shifts and inelasticities, i.e. [17]

$$\lambda(T_{NN}) = \eta_L(T_{NN})\cos^2\left(\delta_L(T_{NN})\right) + 1/4\left[1-\eta_L(T_{NN})\right]^2\ . \tag{11}$$

In our case the initial pn system is in the $^1P_1$ state. The corresponding phase shifts and inelasticity parameters near the thresholds of η and η' production can be taken from the VA phase-shift analysis [18]. The values at $T_{\rm lab} \approx 1250$ (2400) MeV are $\delta_L(p_1) = -29°(-2.1°)$ and $\eta_L(p_1) = 0.54(0.828)$. This yields a reduction factor of $\lambda_{\rm ISI} = 0.46(0.83)$.

Since the relative phases of the different contributions are not known we calculate the cross section of the reaction $pn \to dM$ as the incoherent sum

$$\sigma_{pn\to dM} = N[\sigma^{(\pi)} + \sigma^{(\rho)} + \sigma^{(\omega)}] \ . \tag{12}$$

The dash-dotted curve in Fig. 2 represents the sum $\sigma^{(\pi)} + \sigma^{(\rho)} + \sigma^{(\omega)}$ without correcting for the ISI. This result clearly overestimates the empirical cross section. In order to achieve agreement with the data for the reaction $pn \to d\eta$ at $Q > 10$ MeV the theoretical cross section has to be multiplied by a normalization constant N of 0.68 (see the solid curves in Fig. 2). It is remarkable that this reduction factor is not very different from the value obtained from the estimation of ISI effect based on Eq. (11). We see that as a confirmation of the physics contained in our model being basically correct.

Comparing the dash-dotted with the dashed curve makes clear that we get significant contributions from the exchanges of vector mesons. We want to emphasize that those contributions are primarily due to the ρ exchange. The ω-exchange term is negligibly small and the result without its contribution would be indistinguishable from the full result shown in the figure. As a matter of fact, the magnitude of the ρ-exchange term is even larger than the π-exchange contribution. This is not unreasonable. Actually, recently C. Wilkin has argued [7] that a large ρ exchange might be favourable for explaining the observed large cross section ratio $\sigma_{pn\to pn\eta}/\sigma_{pp\to pp\eta}$ [19]. We would like to stress that the dominance of the ρ exchange over π exchange in our model is not due to the soft form factor used for the latter. Even with a value of $\Lambda_\pi = 1.3$ GeV as used in the full Bonn model ρ exchange would still dominate.

The predictions for the reaction $pn \to d\eta'$ are shown in Fig. 3. The dashed curve shows the cross section when only π exchange is taken into account. The solid and dash-dotted lines include the contributions from ρ and ω exchange. Like in case of η production the ω exchange gives only a rather small contribution. Thus the difference between the dash-dotted and the dashed curves is entirely due to the ρ-exchange contribution. Since there is still a large uncertainty in the experimental value of the $\gamma p \to \eta' p$ cross section (1 μb – 1.5 μb) [14] on which the ρ exchange contribution is based we present calculations employing the lower and upper bounds. The corresponding results (lower and upper solid and dash-dotted curves in Fig. 3) reflect this uncertainty in the input of our model. In any case, the ρ exchange increases the cross section of the reaction $pn \to d\eta'$ by almost a factor of 20–40. This strong enhancement is caused by the rather large $\rho N \to \eta' N$ S-wave amplitude extracted from the experimental $\gamma p \to \eta' p$ cross section. There are indications that the latter reaction is dominated by an $S_{11}(1890)$ resonance, cf. Ref. [14].

Admittedly, the ambiguity involved in the ρ exchange introduce fairly large variations in the predicted cross section. But still one can conclude from our

model calculation that the cross section for the reaction $pn \to \eta' d$ for $Q \approx 30$ MeV should be about 1 μb or even more, and therefore should be measurable at new accelerator facilities such as COSY in Jülich.

Note that the results shown by the solid curves in Fig. 3 were obtained by using the same reduction factor 0.68 for the ISI as in the reaction $pn \to d\eta$. Estimate (11) suggests a slightly smaller reduction of the $pn \to d\eta'$ cross section ($\lambda_{\rm ISI} = 0.83$).

In Fig. 3 we show also the data for the reaction $pp \to pp\eta'$ which are from [20] (open circles) and [21] (filled circles) for comparison. Evidently, near threshold the cross section predicted for the reaction $pn \to d\eta'$ is significantly larger than the cross section of the reaction $pp \to pp\eta'$. This is similar to the case of η production near threshold (see, e.g. [1]) and can be explained by a more favourable isospin factor as well as by the larger phase space in the reaction $pn \to dM$ as compared with the reaction $pp \to ppM$.

It can be seen from Fig. 2 that the experimental cross section for very small excess energies lies above the calculated cross section. In order to demonstrate this more clearly we have divided the data points by the result of our model (solid curve in Fig. 2) and present this ratio in Fig. 4. Then the enhancement of the cross section close to threshold is rather obvious. It is generally believed that this enhancement of the cross section at small excess energies is due to a strong and attractive interaction of the η meson with the nucleons in the final state [2] (a similar enhancement has been also found in the reaction $pp \to pp\eta$ [22]). Therefore, in the following we want to discuss the effect of this final-state interaction (FSI) on the reaction $pn \to d\eta$.

Evidently the enhancement occurs only for $Q \leq 10$ MeV which corresponds to characteristic momenta of $p_3 = p_\eta^{\rm cm}$ below 50 MeV/c. This indicates that the enhancement should be mainly due to the coherent final-state interaction. Therefore one can safely assume that the range of the FSI is much larger than the range of the interaction that is responsible for the production of the η meson. In this case the (S-wave) production amplitude and the (S-wave) FSI can be factorised [23] and the FSI can be taken into account by multiplying the production cross section calculated above with a so-called enhancement factor [23] resulting from the long range ηd interaction.

In the simplest version of this approach the enhancement factor depends only on the ηd scattering length $A_{\eta d}$ (see, e.g., Ref. [24]). Values for this scattering length can be readily found in the literature [25,26]. In the present investigation, however, we adopt the original prescription of Goldberger and Watson [23] where also the ηd wave function in the continuum, $\psi_{p_3}(\vec{r})$, is required. Furthermore, we apply two different approaches for the calculation of the enhancement factor for the reaction $pn \to d\eta$: The optical potential (OP)

method and the Foldy-Brueckner adiabatic approach based on the multiple scattering (MS) formalism (see also Ref. [23]). Note that both these methods have already been used for the calculation of the enhancement factor for the reaction $pd \to {}^3He\ \eta$ (see Refs. [24] and [27], respectively).

Let us first describe the OP method. The optical potential in momentum space can be expressed through the single ηd-scattering term

$$V_{\rm opt}(\vec{q}) = -\frac{2\pi}{\mu}\,\frac{m_d}{m_\eta + m_d}\,[t_{\eta p}(k_{\eta p}) + t_{\eta n}(k_{\eta n})]\rho_d(\vec{q})\ . \tag{13}$$

Here μ is the ηd reduced mass, and $t_{\eta N}$ the ηN t-matrix which is related to the scattering amplitude $f_{\eta N}$ by $t_{\eta N}(k_{\eta N}) = (1 + \frac{m_\eta}{m})\, f_{\eta N}(k_{\eta N})$. Note that we use the scattering length approximation for the latter, i.e. $f_{\eta N}(k_{\eta N}) = ((a_{\eta N})^{-1} - ik_{\eta N})^{-1}$. $k_{\eta N}$ is the modulus of the relative ηN momentum and $\rho_d(\vec{q})$ the deuteron form factor,

$$\rho_d(\vec{q}) = \int {\rm d}^3 r\ \exp\left(i\frac{\vec{q}}{2}\vec{r}\right)|\Psi_d(\vec{r})|^2\ . \tag{14}$$

In the ηd c.m. system $\vec{k}_{\eta N}$ is given by

$$\vec{k}_{\eta N} = \frac{m}{m+m_\eta}\vec{p}_\eta - \frac{m_\eta}{m+m_\eta}\,\frac{\vec{p}_d}{2} = \frac{m+m_\eta/2}{m+m_\eta}\,\vec{p}_3\ . \tag{15}$$

The optical potential (13) is transformed into coordinate space and then the Schrödinger equation is solved numerically yielding the continuum wave function $\psi_{p_3}(\vec{r}_{\eta d})$ as well as the ηd-scattering length. The enhancement factor is simply given by $\lambda^{\rm OP}_{\rm FSI}(p_3) = |\psi_{p_3}(0)|^2$ [23].

In the multiple scattering formalism we use the Foldy-Brueckner adiabatic approximation and start from the ηd wave function defined at fixed coordinates of the proton ($\vec{r}_p$) and the neutron ($\vec{r}_n$) (see Ref. [23] for details):

$$\begin{aligned}\psi_k(\vec{r}_\eta, \vec{r}_p, \vec{r}_n) = {} & \exp\,(i\vec{k}\vec{r}_\eta) \\ & + \frac{t_{\eta p}}{D}\,\frac{\exp\,(ikr_p)}{r_p}\left(\exp\,(i\vec{k}\vec{r}_p) + t_{\eta n}\,\frac{\exp\,(ikr_{pn})}{r_{pn}}\exp\,(i\vec{k}\vec{r}_n)\right) \\ & + \frac{t_{\eta n}}{D}\,\frac{\exp\,(ikr_n)}{r_n}\left(\exp\,(i\vec{k}\vec{r}_n) + t_{\eta p}\frac{\exp\,(ikr_{pn})}{r_{pn}}\exp\,(i\vec{k}\vec{r}_p)\right)\ ,\end{aligned}$$

where

$$D = \left(1 - t_{\eta p}t_{\eta n}\,\frac{\exp\,(2ikr_{pn})}{r_{pn}^2}\right)\ . \tag{16}$$

Here $\vec{r}_{pn} = \vec{r}_p - \vec{r}_n$ and $\vec{k} = \vec{p}_3$ and k, r_{pn}, etc., are the moduli of these vectors. $t_{\eta N}$ is defined in Eq. (13). Then the ηd-scattering length and the enhancement factor follow from

$$A_{\eta d}^{\rm MS} = \frac{m_d}{m_\eta + m_d} \langle \frac{2 t_{\eta N}(k_{\eta N} = 0)}{1 - t_{\eta N}(k_{\eta N} = 0)/r} \rangle \ ,$$
$$\lambda_{\rm FSI}^{\rm MS}(p_3) = |\langle \psi_{p_3}(\vec{r}_\eta = 0, \vec{r}_p = \vec{r}/2, \vec{r}_n = -\vec{r}/2) \rangle|^2 \ .$$

The resulting enhancement factors $\lambda_{\rm FSI}(p_3)$ are plotted in Fig. 4 (upper panel for the multiple scattering formalism and lower panel for the optical potential) for different values of the ηN-scattering lengths given in Table 1. In this Table we also present the calculated values of $A_{\eta d}^{\rm OP}$ and $A_{\eta d}^{\rm MS}$ and compare them with the results of Ref. [26]. Of course, the optical potential model is a questionable approximation for the ηd system. It only gives reasonable values for the ηd scattering length if $a_{\eta N}$ is small so that the first iteration is dominant. For larger $a_{\eta N}$ it might still give a reasonable estimate of $A_{\eta d}$ provided that there is a cancelation between different higher-order iterations.

Nevertheless, it is expected that the multiple scattering approach gives a more reliable estimation for $A_{\eta d}$. It is known that the Foldy-Brueckner approach describes the πd-scattering amplitude at low energies quite well (see, e.g., Ref. [32]). The η-meson is certainly somewhat heavier than the pion but its interaction with the nucleons is likewise considerably weaker than the forces in the NN system. Therefore the adiabatic approximation might still be quite reasonable also in the case of ηd scattering. For example, we see from Table 1 that within the MS approach an attractive ηN interaction never yields spurious repulsive results for the ηd system — as it happens for the optical potential and for the first approach used by Green et al. [26]. We want to point out that our results are in rather good agreement with the second approach of Ref. [26] for a wide range of $a_{\eta N}$ values.

The solid curves in Fig. 4 show our results based on the ηN scattering $a_{\eta N} = 0.291 + i\,0.360$ fm derived from η photo-production data [29]. Evidently, they describe the enhancement of the cross section rather well. The dashed and dotted curves correspond to the values $a_{\eta N} = 0.3 + i\,0.3$ fm and $a_{\eta N} = 0.476 + i\,0.279$ fm proposed in Refs. [24] and [27], respectively. The former curve which corresponds to the smaller value of $a_{\eta N}$ still agrees satisfactorily with the data, while the latter one overshoots them. The dash-dotted curve based on $a_{\eta N} = 0.717 + i\,0.263$ fm from a recent analysis of Batinić et al. [31] overestimates the data at $Q \leq 10$ MeV by more than a factor 2. Thus, we conclude that our analysis of the reaction $pn \to d\eta$ close to threshold favours fairly small ηN-scattering lengths, Re $a_{\eta N} \leq 0.3$ fm. The ηd scattering length corresponding to these values are $A_{\eta d} \approx 0.4 + i\,1.2$ fm, cf. Table 1. We would like to point out that the above ηN scattering lengths are considerably below the lowest

value, Re $a_{\eta N} \approx 0.7$ fm, for which an ηd bound state is expected to exist [26]. Finally, we want to call attention to the fact that both employed approaches give very similar results for the enhancement factor. Furthermore, we would like to remark that a recent Faddeev-type calculation of the ηd system testifies that the MS approach is quite reliable for small values of Re $a_{\eta N}$ like those supported by our analysis [33].

In summary, using the two-step model we calculated the cross sections of the reactions $pn \to d\eta$ and $pn \to d\eta'$ near the threshold including π, ρ as well as ω exchange. The ω contribution is found to be rather small. The contribution of the ρ exchange is of comparable magnitude to the one from π exchange in the case of η production and might be even more important for η' production due to the presence of a possible $S_{11}(1980)$ resonance for which the SAPHIR collaboration found strong evidence in the photo production of η' mesons near threshold. Our results agree with the experimental data on η production if we take into account effects from the initial state interaction. We considered also the influence of the final-state interaction using the optical-potential and multiple-scattering approaches. Both methods yield similar results for the enhancement factor. Agreement with the data could be obtained only for ηN interactions with small ηN-scattering lengths, Re $a_{\eta N} \leq 0.3$ fm, i.e. values that are considerable below the lowest value, Re $a_{\eta N} \approx 0.7$ fm, for which an ηd bound state is expected to exist.

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References

[1] H. Calén et al., Phys. Rev. Lett. **79**, 2642 (1997).

[2] H. Calén et al., Phys. Rev. Lett. **80**, 2069 (1998).

[3] F. Plouin, P. Fleury and C. Wilkin, Phys. Rev. Lett. **65**, 690 (1990).

[4] J.-M. Laget, F. Wellers, and J.F. Lecolley, Phys. Lett. B **257**, 254 (1991).

[5] T. Vetter et al., Phys. Lett. B **263**, 153 (1991).

[6] G. Fäldt and C. Wilkin, Nucl. Phys. A **604** 441 (1996).

[7] C. Wilkin, nucl-th/9810047.

[8] L.A. Kondratyuk et al., Yad. Fiz. **61**, 1670 (1998).

[9] L.A. Kondratyuk and M.G. Sapozhnikov, Phys. Lett. B **220**, 333 (1989).

[10] K.F. Liu, S.J. Dong, T. Draper, and W. Wilcox, Phys. Rev. Lett. **74**, 2172 (1995).

[11] S.A. Coon and M.D. Scadron, Phys. Rev. C **23**, 1150 (1981).

[12] D.M. Binnie et al., Phys. Rev. **8**, 2789 (1973).

[13] B.Krusche et al., Z. Phys. A **351**, 237 (1982); Phys. Rev. Lett. **74**, 3736 (1995).

[14] R. Plötzke et al., Phys. Lett. B **444**, 555 (1998).

[15] V.L.E. Eletsky and B.L. Ioffe, Phys. Rev. Lett. **78**, 1010 (1997).

[16] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).

[17] C. Hanhart and K. Nakayama, nucl-th/9809059, Phys. Lett. B, in print.

[18] R. Arndt et al., Virginia Tech Partial-Wave Analysis Facility, http:// said.phys.vt.edu/

[19] H. Calén et al., Phys. Rev. C, in press .

[20] P. Moskal et al., Phys. Rev. Lett. **80**, 3202 (1998).

[21] F. Hibou et al., Phys. Lett. B **438**, 41 (1998).

[22] H. Calén et al., Phys. Lett. B **366**, 39 (1996).

[23] M.L. Goldberger and K.M. Watson, *Collision theory* (John Wiley and Sons, New York 1964).

[24] C. Wilkin, Phys. Rev. C **47** (1993) R938.

[25] S.A. Rakityanski et al., Phys. Lett. B **359**, 33 (1995).

[26] A.M. Green, J.A. Niskanen and S. Wycech, Phys. Rev. C **54**, 1970 (1996).

[27] G. Fäldt and C. Wilkin, Nucl. Phys. **A587**, 769 (1995).

[28] C. Bennhold and H. Tanabe, Nucl. Phys. **A350**, 625 (1991).

[29] B. Krusche, *Proceedings II TAPS Workshop*, ed. by J. Diaz and Y. Schuts (World Scientific, Singapore 1994,), p.310.

[30] M. Batinić et al., Phys. Rev. C **51**, 2310 (1995).

[31] M. Batinić et al., nucl-th/9703023.

[32] V.V. Baru and A.E. Kudryavtsev, Sov. J. Nucl. Phys. **60**, 1475 (1997).

[33] N.V. Shevchenko et al., Phys. Rev. C **58** R3055 (1998).

Table 1
η-deuteron scattering lengths in fm resulting from the optical potential method (OP) and the Foldy-Brueckner approach (MS) as described in the text. 'Green1' and 'Green2' refer to results presented in Ref. [26].

	$a_{\eta N}$	$A_{\eta d}^{\rm OP}$	$A_{\eta d}^{\rm MS}$	$A_{\eta d}^{\rm Green1}$	$A_{\eta d}^{\rm Green2}$
Bennhold-Tanabe [28]	$0.25 + i0.16$	$0.606 + i0.89$	$0.613 + i0.602$	$0.66 + i0.71$	$0.66 + i0.58$
Krusche [29]	$0.291 + i0.360$	$-0.14 + i1.33$	$0.399 + i1.18$	$0.17 + i1.35$	$0.42 + i1.25$
Wilkin [24]	$0.30 + i0.30$	$0.08 + i1.37$	$0.526 + i1.06$	$0.39 + i1.28$	$0.58 + i1.11$
Fäldt [27]	$0.476 + i0.279$	$-0.15 + i2.32$	$1.01 + i1.387$	$0.81 + i2.15$	$1.22 + i1.56$
Batinić [30]	$0.888 + i0.274$	$-2.06 + i1.37$	$1.85 + i2.83$	$-2.90 + i4.12$	$2.37 + i5.79$
Batinić [31]	$0.717 + i0.263$	$-1.94 + i2.31$	$1.62 + i2.11$	–	–

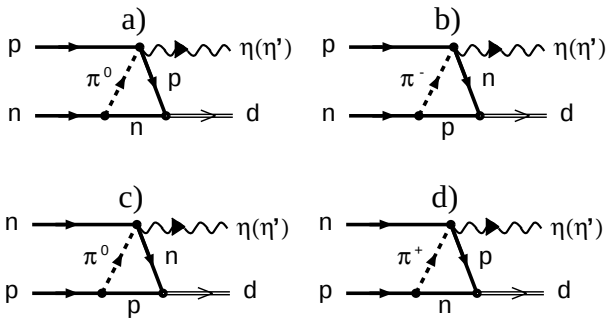

Fig. 1. Diagrams describing the two-step model (TSM). Note that besides the π-exchange contribution also diagrams involving the exchange of the ρ and ω mesons are taken into account.

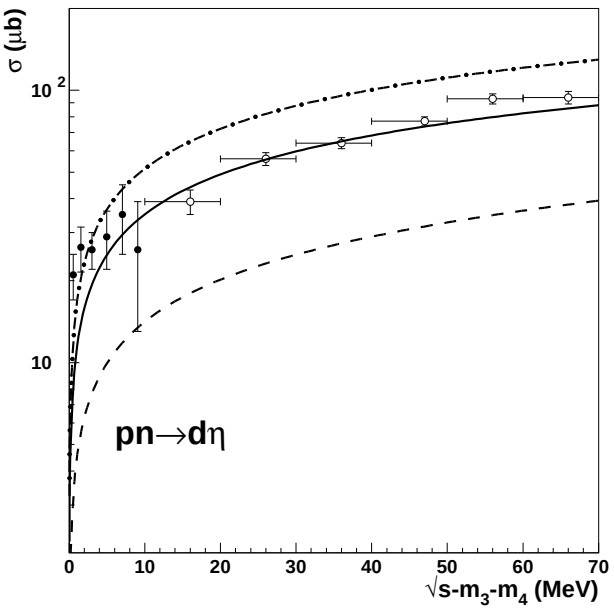

Fig. 2. Cross section of the reaction $pn \to d\eta$ as a function of the c.m. excess energy. The dashed curve shows the result from the π-exchange contribution alone whereas the dash-dotted curve is the sum of π, ρ, and ω exchange. The solid curve represents the results including all contributions (π, ρ, ω) multiplied with a normalization factor $N = 0.68$ in order to take into account effects from the initial state interaction (see text). The data points for are taken from Refs. [1] (open circles) and [2] (filled circles).

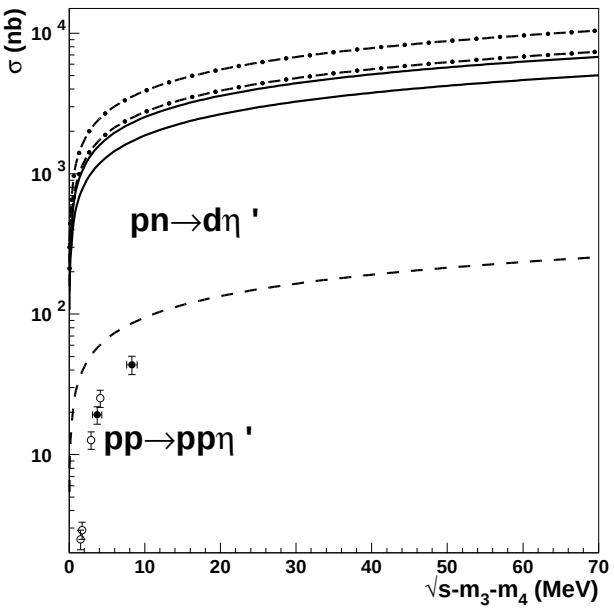

Fig. 3. Cross section of the reaction $pn \to d\eta'$ as a function of the c.m. excess energy. The dashed curve shows the result from the π-exchange contribution alone whereas the dash-dotted curves are the sum of π, ρ, and ω exchange. The solid curves represent the results including all contributions (π, ρ, ω) multiplied with a normalization factor $N = 0.68$ in order to take into account effects from the initial state interaction (see text). The upper and lower solid and dash-dotted curves are the results obtained using the maximal and minimal values of the $\rho^0 p \to \eta' p$ S-wave amplitudes. The data points are from Refs. [20] (open circles) and [21] (filled circles), respectively.

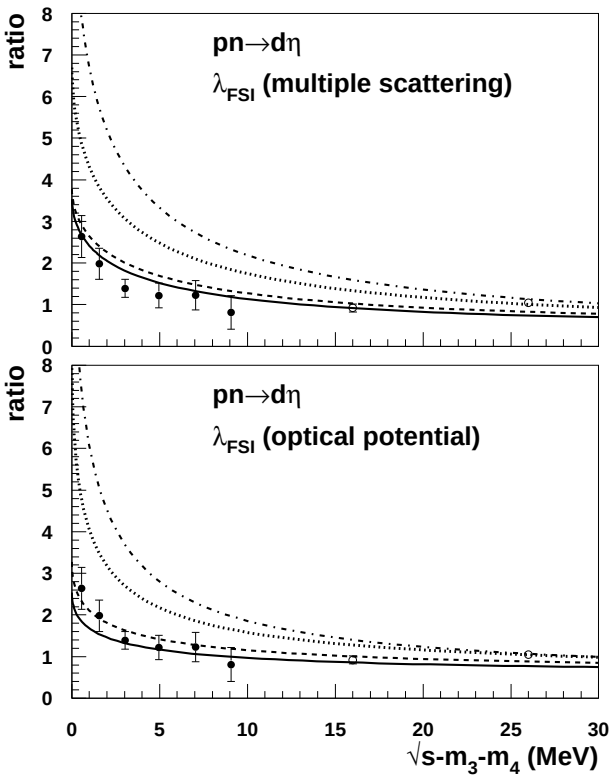

Fig. 4. The enhancement factors $\lambda_{\rm FSI}(p_3)$ for different values of the ηN-scattering lengths as a function of the c.m. excess energy. The solid curves corresponds to the ηN scattering length $a_{\eta N} = 0.291 + i\,0.360$ fm derived from η photo-production data [29]. The dashed and dotted curves correspond to the values $a_{\eta N} = 0.3 + i\,0.3$ fm and $a_{\eta N} = 0.476 + i\,0.279$ fm proposed in Refs. [24] and [27], respectively. The dash-dotted curve is the result for $a_{\eta N} = 0.717 + i\,0.263$ fm, found in a recent analysis of Batinić et al. [31].