TWO STEP MECHANISM OF $\eta$, $\eta'$, $\omega$, $\phi$ MESON PRODUCTION IN $pD \rightarrow ^3 HeX$ REACTION

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Abstract

The differential cross sections of $pD \rightarrow ^3 HeX$ reactions, where $X = \eta$, $\eta'$, $\omega$, $\phi$, are calculated on the basis of a two-step mechanism involving the subprocesses $pp \rightarrow d\pi^+$ and $\pi^+ n \rightarrow Xp$. It is shown that this model describes well the form of energy dependence of available experimental cross sections at the final c.m.s. momentum $p^* = 0.4-1 GeV/c$ for the $\eta$ and at $p^* = 0 - 0.5$ GeV/c for the $\omega$ meson as well as the ratios $R(\eta'/\eta)$ and $R(\phi/\omega)$. The absolute value of the cross section is underestimated by an overall normalization factor of about 3 for $\eta$, $\eta'$ and by nearly one order of magnitude for $\omega$ and $\phi$. The spin-spin correlations are predicted for the reaction $\vec{Dp} \rightarrow ^3 HeX$ in the forward-backward approximations for the elementary amplitudes.

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1. Reactions $pD \rightarrow ^3HeX$, where $X$ means a meson heavier than the pion, are of great interest for several reasons. Firstly, high momentum transfer ($\sim 1$ GeV/c) to the nucleons takes place in these processes. Secondly, unexpected strong energy dependence of $\eta$ meson production was observed near the threshold [1]. In this respect the possible existence of quasi-bound states in the $\eta - ^3He$ system is discussed in the literature [2]-[4]. Thirdly, production of the $\eta, \eta', \phi$ mesons, whose wave functions contain valence strange quarks, raises a question concerning strangeness of the nucleon and the mechanism of Okubo-Zweig-Iizuka rule violation [5], [6]. As a result of this discussion the experimental investigation of the reaction $\vec{D}p \rightarrow ^3He\phi$ is proposed [7] in Dubna. Finally, the preliminary experimental data on $\eta', \phi$ meson production in the reactions $pD \rightarrow ^3He\eta'$ and $pD \rightarrow ^3He\phi$ near the thresholds are available at present [8] at meson c.m.s. momenta $p^* \sim 20$ MeV/c. New experimental data on the $pD \rightarrow ^3He\omega$ reaction were obtained recently in Ref. [9] above the threshold. In this connection the mechanism of the reactions in question seems to be very important.

2. The first attempt to describe the reaction $pD \rightarrow ^3He\eta$ on the basis of the three-body [10] mechanism displayed an important role of intermediate pion beam in this process. As was mentioned for the first time in Ref. [11], at the threshold of the reaction $pD \rightarrow ^3He\eta$ the two-step mechanism including two subprocesses $pp \rightarrow d\pi^+$ and $\pi^+n \rightarrow \eta p$ is favoured. The advantage of this mechanism is that at the threshold of this reaction and zero momenta of Fermi motion in the deuteron and $^3He$ nucleus the amplitudes of these subprocesses are practically on the energy shells. It is easy to check, that this peculiarity (the so called velocity matching or kinematic miracle) takes place above the threshold too, if the c.m.s. angle $\theta_{c.m.}$ of the $\eta$ meson production in respect to the proton beam is $\theta_{c.m.} \sim 90^\circ$. For the $\omega, \eta'$ and $\phi$ mesons the velocity matching takes place above the corresponding thresholds only at $\theta_{c.m.} \sim 50^\circ - 90^\circ$ depending on the meson mass and energy of the incident proton.

The two-step model of the $pD \rightarrow ^3He\eta$ reaction was developed in Refs. [3], [12]. Progress in comparison with the microscopic model [10] was the comprehension of the very important role of final state interaction in the $\eta - ^3He$ system near the threshold. Recently Fäldt and Wilkin [13] found that the two-step model can describe the form of the threshold cross section of $pD \rightarrow ^3HeX^0$ reaction as a function of the mass of produced meson $X^0 = \eta, \omega, \eta', \phi$. New points of present work are following. (i) We extend the two-step model [3] for the production of $\eta, \omega, \eta'$ and $\phi$ mesons above the thresholds ( at the final c.m.s momenta $p^*$ about several hundred MeV/c). Previously, only $\eta$ meson production was investigated above the threshold by Laget and Lecolley in the microscopic model. (ii) We consider in more general form than in Ref. [13] the influence the spin effects.
particular, we predict the pD spin-spin correlation for the reaction \( \vec{D}\vec{p} \rightarrow ^3\text{He}X \) at the energy region of the proposed Dubna experiment \[7\].

3. Proceeding from the 4-dimensional technique of nonrelativistic graphs one gets the following expression for the amplitude of the \( pD \rightarrow ^3\text{He}X \) reaction in the framework of the two-step model corresponding to the Feynman graph in Fig.1 Ref.[3]

\[
A(pD \rightarrow ^3\text{He}X) = C\frac{\sqrt{3}}{2m} A_1(pp \rightarrow d\pi^+)A_2(\pi^+n \rightarrow Xp)F(P_0, E_0),
\]

(1)

where \( A_1 \) and \( A_2 \) are the amplitudes of the \( pp \rightarrow d\pi^+ \) and \( \pi^+n \rightarrow Xp \) processes respectively, \( m \) means the nucleon mass, \( C = 3/2 \) is the isotopic spin factor taking into account the sum over isotopic spin projections in the intermediate state. This factor is the same for all isoscalar mesons \( X \) under discussion. The form factor has the form

\[
F(P_0, E_0) = \int \frac{d^3q_1}{(2\pi)^3} \frac{d^3q_2}{(2\pi)^3} \frac{\Psi_D(q_1)\Psi^*_\tau(q_2)}{E^2_0 - (P_0 + q_1 + q_2)^2 + i\epsilon}.
\]

(2)

Here \( \Psi_D(q_1) \) is the deuteron wave function and \( \Psi^*_\tau(q_2) \) is the \(^3\text{He} \) wave function in momentum space for the \( d+p \) channel; \( E_0 \) and \( P_0 \) are the energy and momentum of the intermediate \( \pi \) meson at zero Fermi momenta in the nuclear vertices \( q_1 = q_2 = 0 \):

\[
E_0 = E_X + \frac{1}{3} E_\tau - \frac{1}{2} E_D, \quad P_0 = -\frac{2}{3} P_\tau - \frac{1}{2} P_D,
\]

(3)

where \( E_j \) is the energy of the \( j \)-th particle in c.m.s., \( P_D \) and \( P_\tau \) are the relative momenta in the initial and final states respectively \( |P_\tau| \equiv p^* \). In comparison with [12] we do not restrict ourselves to the linear approximation over \( q_1 \) and \( q_2 \) in the \( \pi \) meson propagator and take into account the dependence on Fermi momenta exactly. It results in faster decreasing \( |F(P_0, E_0)| \) with increasing mass of the meson produced than in Ref.[12].

Amplitude [11] is related to the differential cross section of the \( pD \rightarrow ^3\text{He}X \) reaction by the following expression

\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s_{pd}} \frac{|P_\tau|}{|P_D|} |A(pD \rightarrow ^3\text{He}X)|^2 = \frac{|P_\tau|}{|P_D|} |f(pD \rightarrow ^3\text{He}X)|^2,
\]

(4)

where \( \sqrt{s_{pd}} \) is the invariant p+D mass. The amplitudes \( A_1(pp \rightarrow d\pi^+) \) and \( A_2(\pi^+n \rightarrow X) \) are similarly related to the corresponding cross sections. When deriving Eq. (1) one factored the amplitudes of elementary subprocesses \( A_1 \) and \( A_2 \) outside the integral sign over \( q_1 \) and \( q_2 \) at the point \( q_1 = q_2 = 0 \) and then replaced them to the amplitudes of the corresponding free processes. Neglection of the off-energy-shell effects is expected to be correct at the velocity matching conditions. Taking into account the off-shell and Fermi motion effects in the optimal approximation [13] one obtains numerical results very close
to the approximation (1) if the energy dependence of the cross sections of elementary processes is smooth enough.

The cross section can be always present in the following formally separable form

$$\frac{d\sigma}{d\Omega} = R_S K |\mathcal{F}(P_0, E_0)|^2 \frac{d\sigma}{d\Omega}(pp \to d\pi^+) \frac{d\sigma}{d\Omega}(\pi^+n \to Xp)$$

(5)

where $K$ is the kinematic factor defined according to Eq. (21) in Ref. [3] for the differential cross section developed in a spinless approximation. Indeed the factor $K$ from Ref.[3] is multiplied here by factor $(9/8)^2$ in order to obtain the correct normalization condition for the the vertex function $d + p \to ^3He$.

The additional factor $R_S$ in Eq.(5), which is absent in Ref.[3], takes into account spins and generally depends on mechanism of the reaction. It is important to remark that the approximation (1) does not lead generally to the condition $R_S = const$ because of complicated spin structure of the amplitudes $A_1(pp \to d\pi^+)$ and $A_2(\pi^+n \to Xp)$. The analysis is simpler at the angles $\theta_{c.m.} = 0^o$ and $180^o$. In this case the production of pseudoscalar meson $\pi^+n \to Xp$ in the forward-backward direction is described by only one invariant amplitude. The processes $pp \to d\pi^+$ and $\pi^+n \to \omega(\phi)p$ are determined by two forward-backward invariant amplitudes $a_i$ and $b_i$ according to the following expressions

$$\hat{A}_1(pp \to d\pi^+) = a_1 e n + i b_1 \sigma [e \times n], \quad (6)$$

$$\hat{A}_2(\pi^+n \to p\omega) = a_2 e \sigma + b_2 (\sigma n)(e \sigma), \quad (7)$$

where $n$ is the unity vector along the incident proton beam, $e$ is the polarization vector of the spin 1 particle $(d, \omega, \phi, \cdot)$, $\sigma$ denotes the Pauli matrix. According to our numerical calculations, the contribution of the $D-$ component of the nuclei wave functions to the modulus squared of the form factor $|\mathcal{F}(P_0, E_0)|^2$ is less than $\sim 10 \%$ for the deuteron and less $\sim 1 \%$ for $^3He$. Using the $S-$ wave approximation for the nuclear wave functions and taking into account Eqs.(6,7) we have found the following expressions for the spin factor $R_S$ of the spin averaged cross section in the two-step model

$$R_0 = \frac{1}{3} \left( \frac{1}{2}|a_1|^2 + \frac{2}{3}|b_1|^2 - \frac{2}{3} Re(a_1 b_1^*) \right) \left[ \frac{1}{2}|a_1|^2 + |b_1|^2 \right]^{-1} \quad (8)$$

– for the pseudoscalar mesons and

$$R_1 = \frac{1}{3} \left[ \frac{1}{2}|a_1|^2(3|a_2|^2 + \gamma) + \frac{2}{3}(|a_2|^2 + \gamma) Re(a_1 b_1^*) + \frac{2}{3}|b_1|^2(5|a_2|^2 + \gamma) \right]$$

$$\times \left[ \frac{1}{2}(|a_1|^2 + 2|b_1|^2)(3|a_2|^2 + \gamma) \right]^{-1} \quad (9)$$

\[\text{4}\]
for the vector mesons, where $\gamma = |b_2|^2 + 2Re(a_2^*b_2)$. As it follows from Ref. [10], at the threshold of $\eta$ meson production $T_p \sim 0.9$ GeV one has $|b_1|/|a_1| \sim 0.1$, therefore it allows one to put $R_0 = 1/3$ [12], [13]. Unfortunately, the experimental data on the spin structure of the $pp \rightarrow d\pi^+$ and $\pi^+n \rightarrow \omega(\phi)p$ amplitudes at energies $T_p \geq 1400$ MeV are not available. Thus, the exact absolute magnitude of the spin factors and the cross sections is rather questionable. We have found numerically from Eqs. (8-9) that the values are not available. Thus, the exact absolute magnitude of the spin factors and the cross sections is arbitrary. An remarkable peculiarity of the condition $|a_1| \gg |b_1|$ is that in this case the spin factor for vector mesons $R_1$ does not depend on the behaviour of amplitudes $a_2$ and $b_2$ and in accordance with Eq. (3) equals to $R_1 = 1/3$. This value is very close to the maximal one $R_{s}^{max} = 4/9$. As it will be shown below the assumption $|a_1| \gg |b_1|$, which provides the condition $R_0 = R_1 = \frac{1}{3} =$ const, is compatible with main features of the observed cross sections for $\eta, \omega$ and $\eta'$ meson production. The numerical calculations are present below at $R_0 = R_1 = \frac{1}{3}$.

The numerical calculations are performed using the RSC wave function of the deuteron [17]. The parametrization [18] of the overlap integral between the three-body wave function of the $^3He$ nucleus and the deuteron is used for the wave function of $^3He$, $\Psi_\tau$, in the channel $d + p$. The value $S_{pd}^\tau = 1.5$ is taken for the deuteron spectroscopic factor in $^3He$ [19]. The numerical results are obtained in the $S$-wave approximation for the spin averaged cross sections and taking into account the D-component of deuteron for spin correlations. The formfactor (2) can be expressed through the S- and D-components of the nuclei wave function $\varphi_l$ by the following integrals

$$\mathcal{F}_{lll}(P_0, E_0) = \frac{1}{4\pi} \int_0^\infty j_L(P_0r) \exp (iE_0r) \varphi_1^l(r)\varphi_0^l(r)r \, dr; \quad (10)$$

the normalization integral $\int_0^\infty [\varphi_0^2(r) + \varphi_2^2(r)]r^2dr$ equals to 1 for the deuteron and $S_{pd}^\tau$ for the $^3He$. In the $S$-wave approximation we have $\mathcal{F}(P_0, E_0) = \mathcal{F}_{0000}$. The parametrization [20] is used here for the differential cross section of the $pp \rightarrow d\pi^+$ reaction. The experimental data on the total cross section of the reactions $\pi^+n \rightarrow \eta(\eta', \omega, \phi)$ are taken from Ref. [21] and the isotropic behaviour of the differential cross section is assumed here. In Fig.2 are shown the results of calculations of the modulus squared of the form factor $|\mathcal{F}_{000}(P_0, E_0)|^2$ for the production of $\eta, \eta', \omega, \phi$ meson at the angle $180^0$ as a function of kinetic energy $T_p$ of the incident proton in the laboratory system. One can see from this figure that the value of $|\mathcal{F}_{000}(P_0, E_0)|^2$ decreases exponentially with increasing $T_p$, and the slope in the logarithmic scale is the same for all mesons in question. It is important to remark that at the definite energy $T_p$ the value of the form factor $|\mathcal{F}_{000}(P_0, E_0)|^2$ is practically the same for all mesons whose production thresholds in the reaction $pD \rightarrow ^3HeX$.
is below $T_p$. Therefore difference in the production probability of different mesons in the two-step model is mainly due to difference of the $\pi^+ n \to X p$ amplitudes.

The results of calculations of the differential cross sections are presented in Fig.3 in comparison with the experimental data at $\theta_{c.m.} = 180^0$ from Refs.\[8\], \[9\] and at $\theta_{c.m.} = 60^0$, $T_p = 3$ GeV from Ref. \[22\]. We do not discuss here the region near the $\eta$ threshold and the related problem of $\eta - ^3 He$ final state interaction which was investigated in detail previously \[3\],\[12\]. It follows from Fig.3,\(a\) that form of energy dependence of the calculated cross section for the $pD \to ^3 He\eta$ reaction at the energies sufficiently higher than the threshold $T_p \geq 1.3$ GeV ($p^* = 0.4 - 1.0$ GeV/$c$) is in qualitative agreement with the experimental data at $\theta_{c.m.} = 180^0$ and in a less degree at $\theta_{c.m.} = 60^0$. To obtain the absolute value of the cross section we need the normalization factor $N = 3$ which is close to $N = 2.4$ found in Ref. \[13\] at the threshold. According to our calculations (Fig.3,\(b\)), the cross section of the $\eta'$ meson production near the threshold ($p^* = 22$ MeV) and at $T_p = 3$ GeV agrees with the experimental data in absolute value at the same factor $N = 3$ as for the $\eta$ meson. As one can see from Fig.4, the shape of the modulus squared $|f|^2$ of the $pD \to ^3 He\omega$ reaction amplitude as a function of momentum $p^*$ agrees properly with the form observed in experimental data \[3\] in the range of $p^* = 0 - 500$ MeV/$c$. It should be noted that the ratio $R(\phi/\omega) = |f(pD \to ^3 He\phi)|^2/|f(pD \to ^3 He\omega)|^2$ near the corresponding thresholds predicted by the model $R^{th} = 0.052$ is in agreement with the experimental value $R^{exp} = 0.07 \pm 0.02$.

However, the absolute value of the cross section for vector mesons is essentially smaller than the experimental value. At the threshold ($p^* \sim 20$ MeV/$c$) the normalization factor $N$ for $\omega$- is 5.9 and for $\phi$-meson is 6.6. To describe the absolute magnitude of the cross section in the range of $100$ MeV/$c \leq p^* \leq 400$ MeV/$c$ one needs the normalization factor $N = 9.6$. On the other hand, at $T_p = 3$ GeV for $\theta_{c.m.} = 60^0$ \[22\] the calculated cross section coincides with the experimental value in absolute magnitude.

The above mentioned agreement with the experimental data in form of energy dependence of $\eta,\omega$ (and $\eta'$) and in the ratios $\eta'/\eta, \phi/\omega$ supports the assumption that the spin factors $R_0$ and $R_1$ are approximately constants in the corresponding energy regions. Therefore the assumption $|a_1| \gg |b_1|$ seems to be enough reasonable. It allows us to give the definite prediction for spin-spin correlations in the reaction $\vec{p}\vec{D} \to ^3 HeX$ with polarized deuteron and proton. Using Eqs.\[3\],\[4\] and taking into account the D- component of the deuteron wave function we find under above condition $b_1 = 0$, that the cross section of vector meson production in case of polarized colliding particles can be obtained from
Eq. (5) by the following replacement

\[ R_1 |\mathcal{F}(P_0, E_0)|^2 \rightarrow \frac{1}{3} \left\{ |\mathcal{F}_{000}|^2 (1-P_p \cdot P_D - \sqrt{2} \text{Re}(\mathcal{F}_{000} \mathcal{F}_{202}^*) \left[ P_p \cdot P_D - \frac{3}{2P_0^2} [P_0 \times P_p] \cdot [P_0 \times P_D] \right] \right. \]

\[ + |\mathcal{F}_{202}|^2 \left[ 1 + \frac{1}{4} P_p \cdot P_D - \frac{3}{2P_0^2} [P_0 \times P_p] \cdot [P_0 \times P_D] + \frac{9}{4P_0^4} ([P_0 \times P_p] \cdot P_0)([P_0 \times P_D] \cdot P_0) \right] \}, \]

where \( P_p \) and \( P_D \) are the polarization vectors of the proton and deuteron respectively and the momentum \( P_0 \) is defined in Eq. (3). It is assumed here that the tensor polarization of deuteron is zero. Using this result we obtain for the spin-spin asymmetry the following expression in case \( P_d \perp P_0 \) and \( P_p \perp P_0 \)

\[ \Sigma_1 = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\downarrow\downarrow) + d\sigma(\downarrow\uparrow)} = -\frac{|\mathcal{F}_{000}|^2 - |\mathcal{F}_{202}|^2 - \frac{1}{\sqrt{2}} \text{Re}(\mathcal{F}_{000} \mathcal{F}_{202}^*)}{|\mathcal{F}_{000}|^2 + |\mathcal{F}_{202}|^2}, \]

(12)

where \( d\sigma(\uparrow\uparrow) \) and \( d\sigma(\downarrow\downarrow) \) are the cross sections for parallel and antiparallel orientation of the polarization vectors of the proton and deuteron. We have found numerically from Eq. (12) that near the threshold \( \Sigma_1(\phi) = -0.95 \) and \( \Sigma_1 \) very fast goes to \(-1\) above the threshold. Very similar result is obtained for the \( \omega \) meson: \( \Sigma_1(\omega) = -0.92 \). Neglecting the D-component of the deuteron wave function we obtain one the same result for vector and pseudoscalar mesons: \( \Sigma_1 = \Sigma_0 = -1 \).

5. In conclusion, the two step mechanism favoured in the case of \( \eta \) meson production near the threshold and at \( \theta_{c.m.} \sim 90^\circ \) owing to the kinematical velocity matching turns out to be very important also beyond the matching conditions, namely both above the threshold of \( \eta \) meson production and in the cases of \( \eta' \), \( \omega \), and \( \phi \) mesons. Despite of its simplicity the two-step model describes fairly well the shape of energy dependence of available experimental data of the cross sections of \( \eta \) and \( \omega \) production as well as the ratios \( \eta'/\eta \) and \( \phi/\omega \) at the thresholds. The absolute value of the cross sections is not described by this model. The most discrepancy was found for the vector mesons. The normalization factor for \( \omega \) meson \( N = 9.6 \) is considerably greater than the value \( N = 2.4 \) established by Fäldt and Wilkin [13] at the thresholds of all mesons under discussion. The reasons for the deficiency in absolute value of the predicted cross section may be the contribution of nondeuteron states in the subprocess \( pp \rightarrow \pi NN \) at the first step and the full spin structure of the elementary amplitudes beyond the approximations (6,7) and (1). For example, the contribution of the two-nucleon state with the spin 0 will modify in a different way the amplitudes of the pseudoscalar and vector meson production in the reaction \( pD \rightarrow^3 HeX \). The experiments with polarized particles [7] can give a new information about the mechanism in question.
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**Figure captions**

Fig.1. Two-step mechanism of the reaction $pD \rightarrow ^3HeX$.

Fig.2. Calculated modulus squared of form factor $|F_{000}(P_0, E_0)|^2$ as a function of kinetic energy of the proton in laboratory system $T_p$ for $\eta$, $\eta'$, $\omega$, $\phi$ meson production at $\theta_{c.m.} = 180^0$.

Fig.3. Differential cross sections of the $pD \rightarrow ^3He\eta(\omega, \eta', \phi)$ reactions as a function of lab. kinetic energy of proton $T_p$. The curves show the results of calculations at $R_S = \frac{1}{3}$ for different angles $\theta_{c.m.}$ multiplied by the appropriate normalization factor $N$.

a - $pD \rightarrow ^3He\eta$: $180^0$ (full line, $N = 3$), $90^0$ (dashed curve, $N = 3$), circles are experimental data: $\bigcirc - \theta_{c.m.} = 180^0$ Ref. [1]; $\bullet - \theta_{c.m.} = 60^0$ Ref. [22];

b - $pD \rightarrow ^3He\eta'$ at $\theta_{c.m.} = 180^0$ (full, N=3) and $\theta_{c.m.} = 60^0$ (dashed, N=3); the circles are experimental data for the $\eta'$ production: $\bigcirc - \theta_{c.m.} = 180^0$ Ref. [8]; $\bullet - \theta_{c.m.} = 60^0$ Ref. [22]; the dotted line shows the results of calculation for the $pD \rightarrow ^3He\phi$ reaction at $\theta_{c.m.} = 180^0$ normalized by factor $N = 6.6$ to the experimental point ($\triangle$) from Ref. [8];

c - the same as b but for the reaction $pD \rightarrow ^3He\omega$ with normalization factor $N = 1$; circles ($\bigcirc$) are the experimental data from Ref. [9].

Fig.4. The modulus squared of the amplitude of the $pD \rightarrow ^3He\omega$ reaction defined by Eq. (4) as a function of the c.m.s. momentum of the $\omega$ meson, $p^*$. The curve is the result of calculation at $R_1 = \frac{1}{3}$ multiplied by factor $N = 9.6$, the circles ($\bigcirc$) are experimental data [3].
Figure 1:
Figure 2:
FIG. 3, a

$pD - ^3He \eta$

$\frac{d\sigma}{d\Omega}, \mu b/\text{sr}$

$T_p, \text{GeV}$

180°

60°
FIG. 3.\textsubscript{c}

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\end{center}
\caption{\(pD-^{3}\text{He} \omega\)}
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Fig. 4