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TWO STEP MECHANISM OF $\eta, \eta', \omega, \phi$-MESON PRODUCTION IN $pD \rightarrow {}^3\mathrm{He}X$ REACTION

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Двухступенчатый механизм образования
η, η', ω, ϕ-мезонов в реакции $pD \rightarrow {}^3\text{He}X$

Дифференциальные сечения реакций $pD \rightarrow {}^3\text{He}X$, где $X = \eta, \eta', \omega, \phi$, вычислены на основе двухступенчатого механизма, включающего подпроцессы $pp \rightarrow d\pi^+$ и $\pi^+n \rightarrow Xp$. Показано, что модель хорошо описывает форму имеющихся данных по экспериментальным сечениям как функцию начальной энергии при импульсах мезона в с.ц.м. $p^* = 0,4 - 1$ ГэВ/с для η и при $p^* = 0 - 0,5$ ГэВ/с для ω-мезона, а также отношения $R(\eta'/\eta)$ и $R(\phi/\omega)$. Абсолютная величина сечений очень чувствительна к спиновой структуре элементарных амплитуд и в приближении «вперед-назад» оказывается ниже данных на общий фактор ~3 для η, η' и 5–7 — для ϕ, ω.

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Two Step Mechanism of η, η', ω, ϕ-Meson Production
in Reaction $pD \rightarrow {}^3\text{He}X$.

The differential cross sections of $pD \rightarrow {}^3\text{He}X$ reactions, where $X = \eta, \eta', \omega, \phi$, are calculated on the basis of a two-step mechanism involving subprocesses $pp \rightarrow d\pi^+$ and $\pi^+n \rightarrow Xp$. It is shown that this model describes well the form of available experimental cross sections as a function of initial energy at the final c.m.s. momentum $p^* = 0.4 - 1$ GeV/c for the η and at $p^* = 0 - 0.5$ GeV/c for the ω-meson as well as the ratios $R(\eta'/\eta)$ and $R(\phi/\omega)$. The absolute value of the cross section is very sensitive to the spin structure of the elementary amplitudes and in the forward-backward approximation is underestimated by an overall factor of about 3 for η, η' and 5–7 for ϕ, ω.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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1. Reactions $pD \to^3 HeX$, 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 η meson production was observed near the threshold [1]. In this respect the possible existence of quasi-bound states in the $\eta -^3 He$ system is discussed in the literature [2]- [4]. Thirdly, production of the η, η', ϕ mesons, whose wave functions contain valence strange quarks, raises a question concerning strangeness of the nucleon and the mechanism of Okubo-Zweig-Izuki rule violation [5],[6]. Finally, the preliminary experimental data on η' и ϕ meson production in the reactions $pD \to^3 He\eta'$ and $pD \to^3 He\phi$ near the thresholds are available at present [7] at meson c.m.s. momenta $p^* \sim 20\ MeV/c$. Besides, new experimental data on the $pD \to^3 He\omega$ reaction were obtained recently in Ref. [8]. In this connection the mechanism of the reactions in question seems to be very important.

2. The first attempt to describe the reaction $pD \to^3 He\eta$ on the basis of the three-body [9] mechanism displayed an important role of intermediate pion beam in this process. As was mentioned for the first time in Ref. [10], at the threshold of the reaction $pD \to^3 He\eta$ the two-step mechanism including two subprocesses $pp \to d\pi^+$ and $\pi^+ n \to \eta p$ 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 η meson production in respect to the proton beam is $\theta_{c.m.} \sim 90^o$. The two-step model of the $pD \to^3 He\eta$ reaction is

developed in Refs. [3], [11]. For the ω, η' and ϕ mesons the velocity matching takes place above the corresponding thresholds only at $\theta_{c.m.} \sim 50^o - 90^o$ depending on the meson mass and energy of the incident proton. Thus, the two step mechanism correspond to the Feynman graph in Fig.1 may be assumed to play an important role

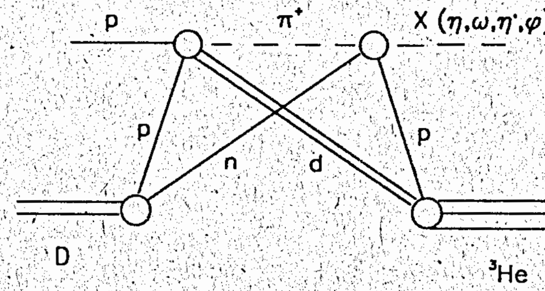

Figure 1: Two-step mechanism of the reaction $pD \to^3 HeX$.

both in η meson production above the threshold and in the case of heavier mesons. Indeed, according to the experimental data [8] the matrix element of the $pD \to^3 He\omega$ reaction $\theta_{c.m.} = 90^o$ as a function of momentum p^* exhibits behaviour similar to that of the $\pi^+ p \to \omega n$ reaction [12]. The investigation of this assumption is the aim of this work.

3. Proceeding from the 4-dimensional technique of nonrelativistic graphs one gets the following expression for the amplitude of the $pD \to^3 HeX$ reaction in the framework of the two-step model Ref.[3]

$$A(pD \to^3 HeX) = C\frac{\sqrt{3}}{2m}A_1(pp \to d\pi^+)A_2(\pi^+ n \to Xp)\mathcal{F}(P_0, E_0), \quad (1)$$

where A_1 and A_2 are the amplitudes of the $pp \to d\pi^+$ and $\pi^+ n \to Xp$ 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

$$\mathcal{F}(P_0, E_0) = \int \frac{d^3q_1}{(2\pi)^3} \frac{d^3q_2}{(2\pi)^3} \frac{\Psi_D(\mathbf{q}_1)\Psi_\tau^*(\mathbf{q}_2)}{E_0^2 - (\mathbf{P}_0 + \mathbf{q}_1 + \mathbf{q}_2)^2 + i\epsilon}. \quad (2)$$

Here $\Psi_D(\mathbf{q}_1)$ is the deuteron wave function and $\Psi_\tau(\mathbf{q}_2)$ is the ^3He wave function in momentum space for the $d+p$ channel; E_0 and $\mathbf{P}_0$ are the energy and momentum of the intermediate π meson at zero Fermi momenta in the nuclear vertices $\mathbf{q}_1 = \mathbf{q}_2 = 0$:

$$E_0 = E_X + \frac{1}{3}E_\tau - \frac{1}{2}E_D, \quad \mathbf{P}_0 = -\frac{2}{3}\mathbf{P}_\tau - \frac{1}{2}\mathbf{P}_D, \quad (3)$$

where E_j is the energy of the j-th particle in c.m.s., $\mathbf{P}_D$ and $\mathbf{P}_\tau$ are the relative momenta in the initial and final states respectively $|\mathbf{P}_\tau| \equiv p^*$. In comparison with [11] we do not restrict ourselves to the linear approximation over $\mathbf{q}_1$ and $\mathbf{q}_2$ in the π meson propagator and take into account the dependence on Fermi momenta exactly. It results in faster decreasing $|\mathcal{F}(P_0, E_0)|$ with increasing mass of the meson produced than in Ref.[11].

Amplitude (1) is related to the differential cross section of the $pD \rightarrow ^3HeX$ reaction by the following expression

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2}\frac{1}{s_{pd}}\frac{|\mathbf{P}_\tau|}{|\mathbf{P}_D|}|A(pD \rightarrow ^3HeX)|^2 = \frac{|\mathbf{P}_\tau|}{|\mathbf{P}_D|}|f(pD \rightarrow ^3HeX)|^2, \quad (4)$$

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 $\mathbf{q}_1$ and $\mathbf{q}_2$ at the point $\mathbf{q}_1 = \mathbf{q}_2 = 0$ 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

$$\frac{d\sigma}{d\Omega} = R_S K |\mathcal{F}(P_0, E_0)|^2 \frac{d\sigma}{d\Omega}(pp \rightarrow d\pi^+) \frac{d\sigma}{d\Omega}(\pi^+n \rightarrow Xp) \quad (5)$$

where K is the kinematic factor defined according to Eq. (21) in Ref. [3] for the differential cross section developed in a spinless approximation. 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 $A_1(pp \rightarrow d\pi^+)$ and $A_2(\pi^+n \rightarrow Xp)$. The analysis is simpler at the angles $\theta_{c.m.} = 0°$ and 180°. In this case the production of pseudoscalar meson $\pi^+n \rightarrow Xp$ in the forward-backward direction is described by only one invariant amplitude. The processes $pp \rightarrow d\pi^+$ and $\pi^+n \rightarrow \omega(\phi)p$ are determined by two forward-backward invariant amplitudes a_i and b_i according to the following expressions [14]

$$\hat{A}_1(pp \rightarrow d\pi^+) = a_1\mathbf{en} + ib_1\sigma[\mathbf{e}\times\mathbf{n}], \quad (6)$$

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

where $\mathbf{n}$ is the unity vector along the incident proton beam, $\mathbf{e}$ is the polarization vector of the spin 1 particle $(d, \omega, \phi,)$, σ denotes the Pauli matrix. Taking into account Eqs.(6,7) and using the $S-$wave approximation for the nuclear wave functions we have found the following expressions for the forward-backward spin factor R_S 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

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

$$\times\left[\frac{1}{2}(|a_1|^2 + 2|b_1|^2)(3|a_2|^2 + 2Re(a_2^* b_2) + |b_2|^2)\right]^{-1}, \quad (9)$$

for the vector mesons, where $\gamma = |b_2|^2 + 2Re(a_2^* b_2)$. According to Ref. [14], at the threshold of η meson production $T_p \sim 0.9$ GeV one has $|b_1|/|a_1| \sim 0.1$, therefore it allows one to put $R_0 = 1/3$. In the case of vector mesons one can obtain the value $R_1 = 1/3$, for example, at $b_1 = 0$, $a_1 \neq 0$ and $a_2 = b_2$ or $b_2 = 0, a_2 \neq 0$. However, the experimental data on the spin structure of the $pp \to d\pi^+$ and $\pi^+ n \to \omega(\phi)p$ amplitudes at energies $T_p \geq 1400 MeV$ are not available. Thus, it is impossible at present to find the exact absolute magnitude of the cross sections, thereby for the definition the numerical calculations are present below at $R_0 = R_1 = 1$.

The numerical calculations are performed using the RSC wave function of the deuteron [15]. The parametrization [16] 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, Ψ_τ, in the channel $d + p$. The value $S_{pd}^\tau = 1.5$ is taken for the deuteron spectroscopic factor in ^3He [17]. The numerical results are obtained in the S - wave approximation. According to our calculations,

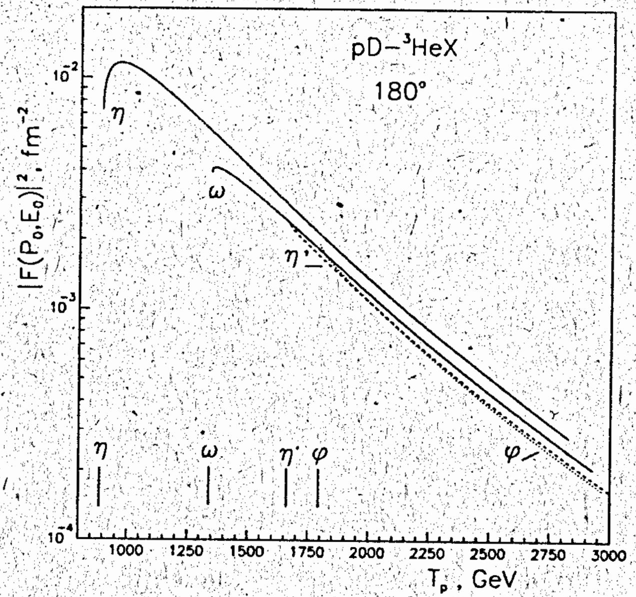

Figure 2: Calculated modulus squared of form factor $|\mathcal{F}_{000}(P_0, E_0)|^2$ (2,10) as a function of kinetic energy of the proton in lab. system T_p for η, η', ω, ϕ meson production at $\theta_{c.m.} = 180^0$.

the contribution of the $D-$ component of the deuteron and ^3He to the modulus squared of the form factor $|\mathcal{F}(P_0, E_0)|^2$ is less than ~ 10 %. In the $S-$ wave approximation form factor (2) takes the following form

$$\mathcal{F}_{000}(P_0, E_0) = \frac{1}{4\pi}\int_0^\infty j_0(P_0 r)\exp(iE_0 r)\varphi_d(r)\varphi_\tau(r) r\, dr. \quad (10)$$

The parametrization [18] is used here for the differential cross section of the $pp \to d\pi^+$ reaction. The experimental data on the total cross section of the reactions $\pi^+ n \to p\eta(\eta', \omega, \phi)$ are taken from Ref. [19] 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 η, η', ω, ϕ mesom 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 $pD \rightarrow ^3He X$ 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 $\pi^+ n \rightarrow Xp$ amplitudes.

The results of calculations of the differential cross sections are presented in Fig.3 in comparison with the experimental data [7] at $\theta_{c.m.} = 180^0$. For the η' and ω mesons the experimental data [20] at $T_p = 3$ GeV and $\theta_{c.m.} = 60^0$ are available. It follows from Fig.3,*a* that the calculated cross section for the η meson production at the energies sufficiently higher than the threshold $T_p \geq 1.3$ GeV ($p^* = 0.4 \div 1.0$ GeV/c) is in qualitative agreement with the experimental data in form of energy dependence at $\theta_{c.m.} = 180^0$. As was mentioned above, the strong discrepancy between the calculations and the experimental data near the threshold of η meson production are connected with strong final state interaction because of excitation of the nucleon resonance $N^*(1535)$ and possible formation of a quasi-bound state in the $\eta - ^3He$ system. According to our calculations (Fig.3,*b*), the cross section of the η' 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 $R_0 = 1$

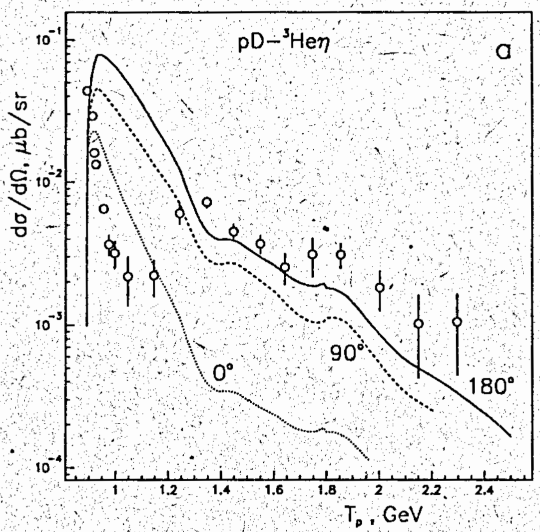

Figure 3: Differential cross sections of the $pD \rightarrow ^3He\eta(\eta', \omega, \phi)$ reactions as a function of lab. kinetic energy of proton T_p. The curves show the results of calculations at $R_S = 1$ for different angles $\theta_{c.m.}$. *a* - $pD \rightarrow ^3He\eta$: 0° (dots), 90° (dashes), 180° (full line), circles (○) are experimental data Ref. [1] at $\theta_{c.m.} = 180^0$; *b* - $pD \rightarrow ^3He\eta'$; $\theta_{c.m.} = 180^0$ (full), $\theta_{c.m.} = 60^0$ (dashed); the circles are experimental data: ○ - $\theta_{c.m.} = 180^0$ Ref. [7]; ● - $\theta_{c.m.} = 60^0$ Ref.[20]; *c* - the same as *b* but for the reaction $pD \rightarrow ^3He\omega$; *d* - the same as *b* but for the reaction $pD \rightarrow ^3He\phi$.

as for the η meson. As one can see from Fig.4, the shape of the modulus squared $|f|^2$ of the $pD \rightarrow ^3He\omega$ reaction amplitude as a function of momentum p^* agrees properly with the form observed in experimental data [8] in the range $p^* = 0 \div 500$ MeV/c. To describe the absolute magnitude of the cross section (Fig.3,*c*) in this range one needs the normalization factor $\sim 3/R_1$ whereas at $T_p = 3$ GeV for $\theta_{c.m.} = 60^o$ [20] the corresponding factor is $\sim 0.5/R_1$. The cross

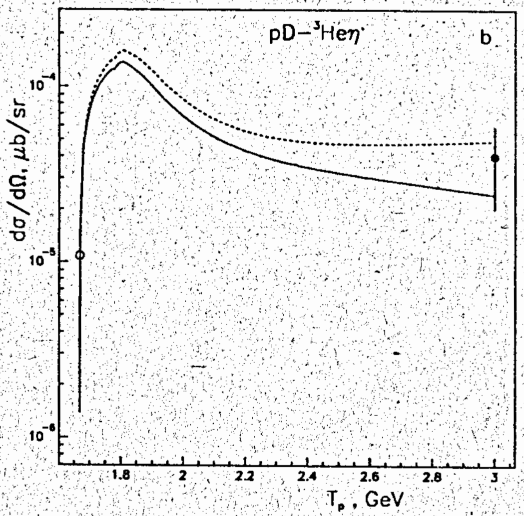

FIG.3,b

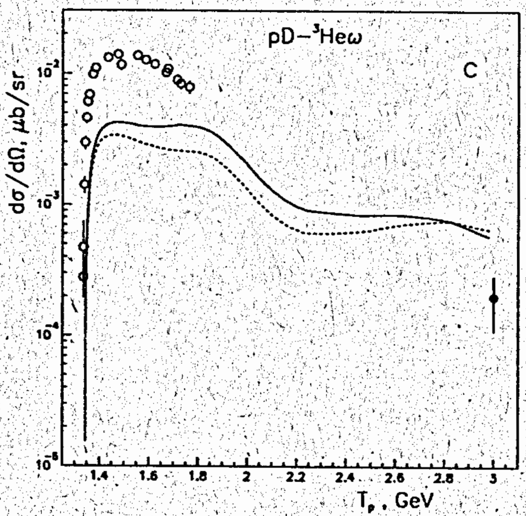

FIG.3,c

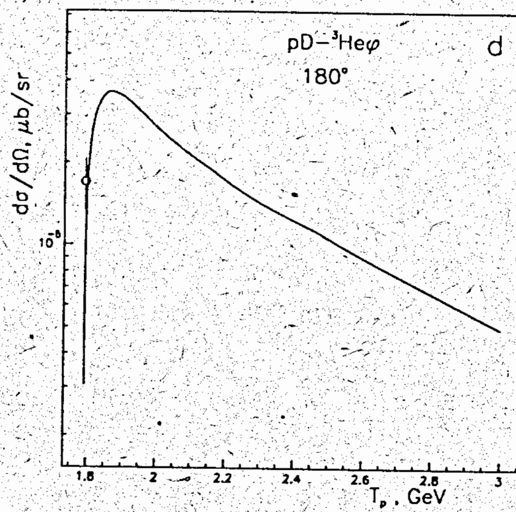

FIG.3,d

section of the $pD \rightarrow^3 He\phi$ reaction predicted by the two-step model is shown in Fig.3, *d*. The only experimental value [7] available near the threshold ($p^* = 24$ MeV/c) of the reaction $pD \rightarrow^3 He\phi$ is approximately twice as high as the calculated one at $R_1 = 1$. It should be noted the ratio $R(\phi/\omega) = |f(pD \rightarrow^3 He\phi)|^2/|f(pD \rightarrow^3 He\omega)|^2$ near the corresponding thresholds predicted by the model $R^{th} = 0.052$ is in good agreement with the experimental value $R^{exp} = 0.07 \pm 0.02$.

5. In conclusion, it should be mentioned that the two step mechanism favoured in the case of η meson production near the threshold and at $\theta_{c.m.} \sim 90^o$ owing to the kinematical velocity matching also turns out to be very important beyond the matching conditions, namely both above the threshold of η meson production and in the cases of η', ω, and ϕ mesons. Despite of its simplicity the two-step model describes fairly well the available experimetal

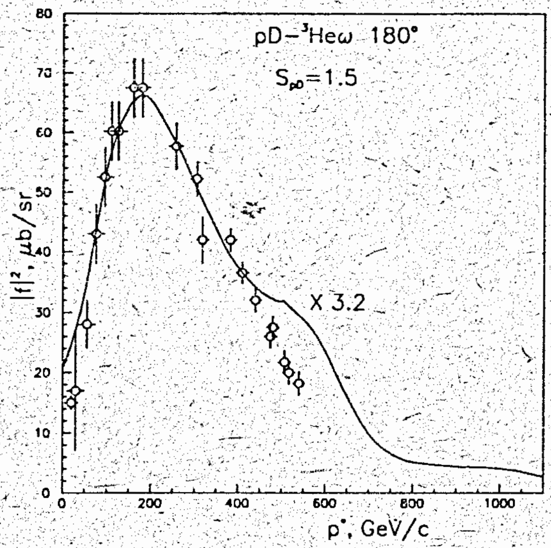

Fig.4: The modulus squared of amplitude (4) of $pD \to ^3 He\omega$ reaction via the c.m.s. momentum of the ω- meson, p^*. The curve is the result of calculation at R=1 (multiplied by factor 3.2), the circles (o) are experimental data [8].

data on the energy dependence of the cross sections of η and η' as well as the ratios η'/η and ϕ/ω. The definite absolute value of the cross section can be obtained when the spin structure of the $pp \to d\pi^+$ and $\pi^+n \to \omega(\phi)p$ amplitudes will be available. We have found numerically from Eqs.(8-9) that the values R_S vary in the range from 1/9 to 4/9 when the complex amplitudes a_1 and b_1 vary arbitrary. Therefore, in the forward-backward approximation for the elementary amplitudes the absolute value of the calculated $\eta(\eta')$ meson production cross section is by factor $\geq 1/R_0^{max} = 2.25$ smaller than the experimental value. In the case of vector mesons the overall normalization factor is $\geq 2/R_1^{max} = 4.5$ for the ϕ and

$\geq 3.2/R_1^{max} = 7.2$ for the ω meson. From the comparison with the spinless approximation ($R_S = 1$) we expect that perhaps one can increase the magnitude of R_S using the full spin-structure of the elementary amplitudes beyond the approximations (6.7) and (1). Another reason for the deficiency in absolute value of the predicted cross section may be the contributuion of nondeuteron states in the subprocess $pp \to \pi NN$ at the first step. 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 $pD \to ^3 HeX$.

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References

[1] J. Berger et al., Phys.Rev.Lett. **61** (1988) 919; P. Berthet et al., Nucl.Phys. **A443** (1985) 589.

[2] C. Wilkin, Phys. Rev. C47 (1993) R938.

[3] L.A. Kondratyuk, A.V. Lado and Yu.N. Uzikov, Yad. Fiz. **57** (1995) 524.

[4] S.Wycech, A.M. Green, J.A. Niskanen, in: Abstr. Book of XV European Few Body Conf. (June 3-4, 1995, Valencia, Spain) p.196; Belyaev V.B. et al. *ibid.*

[5] J.Ellis, M.Karliner, D.E.Kharzeev, M.G.Sapozhnikov. Preprint CERN-TH.7326/94

[6] R.Wurzinger. Preprint LNS/Ph/94-21, 1994.

[7] R.Bertini et al. Preprint LNS/Ph/94-16.

[8] R.Wurzinger, R. Siebert, J.Bisplinghoff et al., Phys.Rev.**C51** (1995) R443.

[9] J.M. Laget, J.F. Lecolley, Phys. Rev. Lett. **61** (1988) 2069.

[10] K. Kilian and H. Nann, Preprint KFA, Juelich.1989.

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

[12] J.Keyne et al., Phys.Rev. **D14** (1976) 28.

[13] S.A. Gurvitz, Phys. Rev. **C22** (1980) 725; S.A. Gurvitz, J.-P. Dedonder and R.D. Amado, Phys. Rev. **C19** (1979) 142;

[14] J.F. Germond and C. Wilkin, J.Phys.**G16** (1990) 381.

[15] G. Alberi, L.P. Rosa and Z.D. Thome , Phys. Rev. Lett. **34** (1975) 503.

[16] M.A.Zusupov, Yu.N. Uzikov and G.A.Yuldasheva, Izv.AN KazSSR,ser. fiz.-mat. N 6. (1986) 69.

[17] R. Schiavilla, V.R. Pandaripanda and R.B. Wiringa, Nucl.Phys. **A449** (1986) 219.

[18] B.G. Ritchie, Phys.Rev. **C44** (1991) 533.

[19] V.Flaminnio, W.G.Moorhead, D.R.O.Morrison et al., CERN-HERA, 83-01.

[20] H.Brody, E.Groves, R.Van Berg et al., Phys.Rev. **D9** (1974) 1917.