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SPIN EFFECTS IN $pd \to {}^3\mathrm{He}X$ REACTION

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It is shown that the two-step model of the reaction $pd \to {}^3\mathrm{He}\ X$ (X = η, η', ω, ϕ), involving the subprocesses $pp \to d\pi^+$ and $\pi^+ n \to Xp$ allows to explain the form of energy dependence of experimental cross sections above the thresholds under assumption that the singlet part of the $pp \to d\pi^+$ amplitude dominates. The spin-spin asymmetry for the reaction dp $\to {}^3\mathrm{He}X$ has been found to be ~ -1 in the forward-backward approximation.

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Reactions $pd \to {}^3\mathrm{He}X$, 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 $\eta-{}^3\mathrm{He}$ system is discussed in the literature [2,3]. 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-Iizuka rule violation [4]. The experimental investigation of the reaction dp $\to {}^3\mathrm{He}\phi$ is proposed [5] in Dubna to check the hypothesis of polarized strangeness content of nucleon [4]. Thus the investigation of conventional (nonexotic) mechanisms of the reaction in question is of great importance.

An important role of intermediate pion beam in the reaction $pd \to {}^3\mathrm{He}\eta$ was displayed in Ref.[6]. As was mentioned for the first time in Ref. [7], at the threshold of the reaction $pd \to {}^3\mathrm{He}\eta$ the two-step mechanism including two

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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 ^{3}He 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 $\theta_{c.m.} \sim 90^\circ$. For the ω, η' and ϕ 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 $pd \to {}^3\mathrm{He}\eta$ reaction was developed in Refs. [3,8]. Recently in Ref.[9] was found that the two-step model can describe the form of the threshold cross section of $pd \to {}^3\mathrm{He}X$ reaction as a function of the mass of produced meson $X = \eta, \omega, \eta', \phi$. The absolute value was underestimated by overal normalization factor about 2.4. However, the above threshold behaviour of cross sections was not investigated in spite of available experimental data [10] and the spinobservables are not discussed.

In this work the two-step model [3] is extended for the production of η, ω, η' and ϕ mesons above the thresholds (at the final c.m.s momenta p^* about several hundred MeV/c). From the description of the energy dependence of the cross section above threshold we conclude that the singlet amplitude in spin structure of process $pp \to d\pi^+$ dominates. On this basis we predict the spin-spin correlation for the reaction dp $\to^3$ HeX at the energy region of the proposed Dubna experiment [5].

In general case the cross section of the reaction dp $\to {}^3$HeX with polarized colliding particles is too cumbersome. Let us consider at first the spinaveraged cross section. In the two-step model it can be present in the following formally separable form

$$\frac{d\sigma}{d\Omega} = R_S K |\mathcal{F}(P_0, E_0)|^2 \frac{d\sigma}{d\Omega}(pp \to d\pi^+) \frac{d\sigma}{d\Omega}(\pi^+ n \to Xp), \tag{1}$$

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 vertex function $d{+}p \to {}^3$He). The formfactor $\mathcal{F}(P_0, E_0)$ in Eq. (5) can be expressed through the S- and D- components of the nuclei wave function φ_l by the following integrals

$$\mathcal{F}_{Lll'}(P_0, E_0) = \frac{1}{4\pi} \int_0^\infty j_L(P_0 r) \exp{(iE_0 r)} \varphi_l^\tau(r) \varphi_{l'}^d(r) r \; dr; \tag{2}$$

the normalization integral $\int_0^\infty [\varphi_0^2(r) + \varphi_2^2(r)] r^2 dr$ equals to 1 for the deuteron and $S_{pd}^\tau = 1.5$[11] for the ^{3}He. The variables E_0 and P_0 are defined in [3]. In comparison with Ref. [8] we do not use the linear approximation in Fermi momenta of nucleons but take into account this dependence exactly. In the S-vawe approximation we have $\mathcal{F}(P_0, E_0) = \mathcal{F}_{000}$.

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 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 $\theta_{c.m.} = 0^\circ$ and 180°. 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 [12]

$$\hat{A}_1(pp \to d\pi^+) = a_1 \mathrm{e}\cdot\mathrm{n} + ib_1\vec{\sigma}\cdot[\mathrm{e}\times\mathrm{n}], \tag{3}$$

$$\hat{A}_2(\pi^+n \to p\omega) = a_2 \mathrm{e}\cdot\sigma + b_2(\vec{\sigma}\cdot\mathrm{n})(\mathrm{e}\cdot\mathrm{n}), \tag{4}$$

where n is the unity vector along the incident proton beam, e is the polarization vector of the spin 1 particle $(d,\omega,\phi,)$, σ 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 ~ 1 % for ^{3}He. Using the S-wave approximation for the nuclear wave functions and taking into account Eqs.(3), (4) we have found the following expressions for the spin factor R_S of the spin averaged cross section in the two-step model

$$R_0 = \frac{1}{3}\left(\frac{1}{2}|a_1|^2 + \frac{2}{3}|b_1|^2 - \frac{2}{3}\mathrm{Re}(a_1b_1^*)\right)\left[\frac{1}{2}|a_1|^2 + |b_1|^2\right]^{-1} \tag{5}$$

– for the pseudoscalar mesons and

$$R_1 = \frac{1}{3}\left[\frac{1}{2}|a_1|^2(3|a_2|^2+\gamma) + \frac{2}{3}(|a_2|^2+\gamma)\mathrm{Re}(a_1b_1^*) + \frac{2}{3}|b_1|^2(5|a_2|^2+\gamma)\right]\times$$

$$\times\left[\frac{1}{2}(|a_1|^2+2|b_1|^2)(3|a_2|^2+\gamma)\right]^{-1} \tag{6}$$

for the vector mesons, where $\gamma = |b_2|^2 + 2\mathrm{Re}(a_2^*b_2)$. As it follows from Ref. [12], 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 $R_0 = 1/3$ [8,9]. Unfortunately, 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, the exact absolute magnitude of the spin factors and the cross sections is rather questionable. We have found numerically from Eqs.(5), (6) that the values R_0 and R_1 vary in the range from 1/9 to 4/9 when the complex amplitudes a_i and b_i vary 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.(6) equals $R_1 = 1/3$. 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 η,ω and η' meson production. The numerical calculations are present below at $R_0 = R_1 = \frac{1}{3}$.

The numerical calculations are performed using nuclear wave functions and parametrization for the $pp \to d\pi^+$ reaction like in Ref. [3]. The experimental data on the total cross section of the reactions $\pi^+n \to p\eta(\eta',\omega,\phi)$ are taken from Refs. [13,14] and the isotropic behaviour of the differential cross section is assumed here. 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 results of calculations of the differential cross sections are presented in Figs.1 and 2 in comparison with the experimental data.

Numerical calculations show that under assumption $|a_1| \gg |b_1|$ the two-step model:

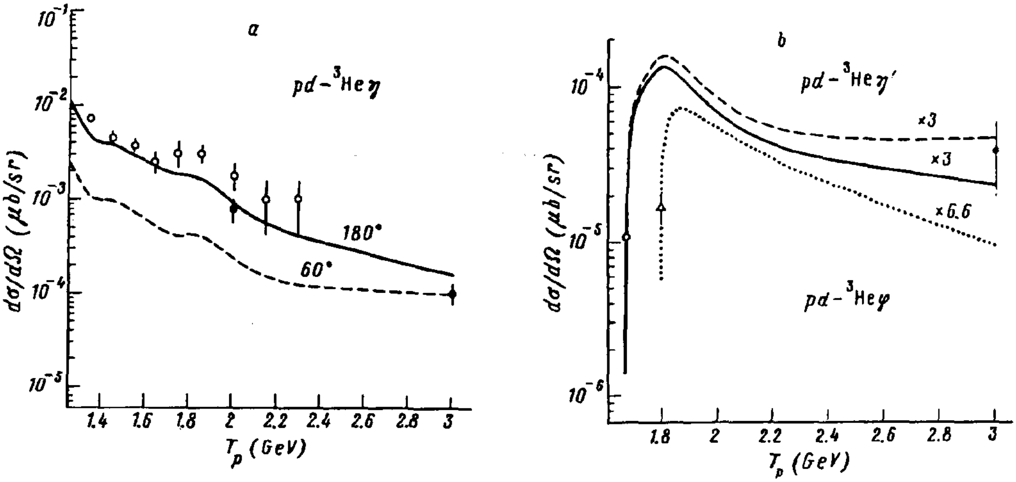

Fig.1. Differential cross sections of the $pd \to ^3$ He$\eta(\omega,\ \eta',\ \phi)$ reactions as a function of lab. kinetic energy of proton T_p. The curves show the results of calculations at $R_S = \frac{1}{3}$ for different angles $\theta_{c.m.}$ multiplied by the appropriate normalization factor N. *a*) $pd \to ^3$ Heη: 180° (full line, $N = 3$), 60° (dashed curve, $N = 3$), circles are experimental data: o - $\theta_{c.m.} = 180°$, Ref.[1]; • - $\theta_{c.m.} = 60°$, Ref.[15]; *b*) $pd \to ^3$ Heη' at $\theta_{c.m.} = 180°$ (full, $N = 3$) and $\theta_{c.m.} = 60°$ (dashed, $N = 3$); the circles are experimental data for the η' production: o - $\theta_{c.m.} = 180°$, Ref. [16]; • - $\theta_{c.m.} = 60°$, Ref.[15]; the dotted line shows the results of calculation for the $pd \to ^3$Heϕ reaction at $\theta_{c.m.} = 180°$ normalized by factor $N = 6.6$ to the experimental point ($\triangle$) from Ref.[16]

(i) describes the shape of the energy dependence of the observed cross sections for the η, η', ω meson production (see Figs.1,2);

(ii) predicts the ratio of modules of the threshold amplitudes squared $R(\phi/\omega) = |f(pd \to ^3 \text{He}\phi)|^2/|f(pd \to ^3 \text{He}\omega)|^2 = 0.52$ in agreement with the experimental value $R^{exp} = 0.07 \pm 0.02$;

(iii) explains the absolute value of the cross section of the reaction $pd \to ^3$ Heω at $T_p = 3$ GeV, $\theta_{c.m.} = 60°$ (this kinematical region corresponds to the matching condition);

(iv) does not contradict within the experimental errors to the experimental data [15] on the absolute value of the cross section of η' production at $T_p = 3$ GeV, $\theta_{c.m.} = 60°$ (this kinematical region corresponds to the matching condition).

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 pd $\to ^3$HeX with polarized deuteron and proton. Assuming the polarization vectors of proton $\mathbf{P}_p$ and deuteron $\mathbf{P}_d$ are perpendicular to the incident beam and the tenzor polarization of the deuteron is zero we obtain for the spin-spin asymmetry the following expression

$$\Sigma_X = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)} = -\frac{|\mathcal{F}_{000}|^2 - |\mathcal{F}_{202}|^2 - \frac{1}{\sqrt{2}}\text{Re}(\mathcal{F}_{000}\mathcal{F}^*_{202})}{|\mathcal{F}_{000}|^2 + |\mathcal{F}_{202}|^2}, \tag{7}$$

where $d\sigma(\uparrow\uparrow)$ and $d\sigma(\uparrow\downarrow)$ are the cross sections for parallel and antiparallel orientation of the polarization vectors of the proton and deuteron. We have found numerically from Eq. (7) that near the threshold $\Sigma_\phi = -0.95$ and Σ_ϕ very fast goes to -1 above the threshold. Very similar result is obtained for the ω meson: $\Sigma_\omega = -0.92$. Neglecting the D-component of the deuteron wave function we obtain

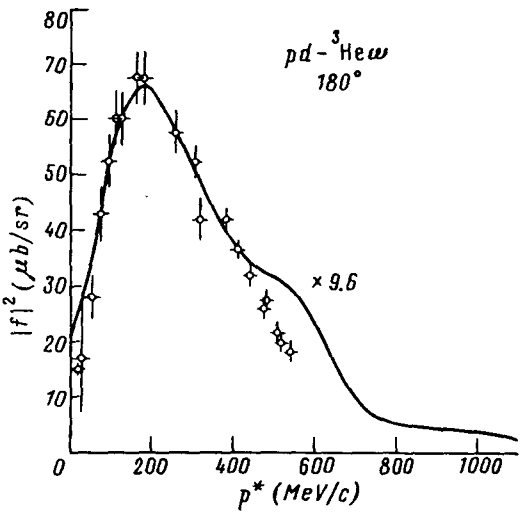

Fig.2. The modulus squared of the amplitude of the $pd \to {}^3\mathrm{He}\omega$ reaction as a function of the c.m.s. momentum of the ω meson, p^*. The curve is the result of calculation at $R_l = \frac{1}{3}$ multiplied by factor $N = 9.6$, the circles (o) are experimental data [10]

one the same result for vector and pseudoscalar mesons: $\Sigma_{\phi,\omega} = \Sigma_{\eta,\eta'} = -1$. It should be noted that the positive value for Σ_ϕ is expected on the basis of $s\bar{s}$ hypothesis [4].

In conclusion, the absolute value of the cross section for vector mesons is essentially smaller than the experimental value. At the threshold ($p^* \sim 20\,\mathrm{MeV/c}$) the normalization factor N for ω- is 5.9 and for ϕ-meson is 6.6. To describe the absolute magnitude of the cross section in the range of $100\,\mathrm{MeV/c} \leq p^* \leq 400\,\mathrm{MeV/c}$ one needs the normalization factor $N = 9.6$ that is essentially larger than the value 2.4 found in Ref.[9] at the threshold. Fairly satisfactory description of the form of the amplitude modulus squared $|f(pd \to {}^3\mathrm{He}\omega)|^2$ and deficiency of the absolute value by an order of magnitude is the main puzzle of this model. The experiments with polarized particles [5] can give a new very important information about the mechanism in question.

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1. J.Berger, M.Boivin, A.Boudard et al., Phys. Rev. Lett. **61**, 919 (1988); P.Berthet et al., Nucl. Phys. **A443**, 589 (1985).
2. C.Wilkin, Phys. Rev. **C47**, R938 (1993).
3. L.A.Kondratyuk, A.V.Lado, and Yu.N. Uzikov, Yad. Fiz. **58**, 524 (1995).
4. J.Ellis, M.Karliner, D.E.Kharzeev, and M.G.Sapozhnikov, Phys. Lett. **B353**, 319 (1995).
5. B.Khachaturov et al. Talk in Int. Symp. DEUTERON-95, Dubna (4-7 July,1995).
6. J.M.Laget and J.F.Lecolley, Phys. Rev. Lett. **61**, 2069 (1988).
7. K.Kilian and H.Nann, Preprint KFA, Juelich,1989.
8. G.Fäldt and C. Wilkin, Nucl. Phys. **A587**, 769 (1995).
9. G.Fäldt and C. Wilkin, Phys. Lett. **B354**, 20 (1995).
10. R.Wurzinger, R.Siebert, J.Bisplinghoff et al., Phys. Rev. **C51**, R443 (1995).
11. R.Schiavilla, V.R.Pandaripande and R.B. Wiringa, Nucl. Phys. **A449**, 219 (1986).
12. J.F.Germond and C.Wilkin, J. Phys. **G16**, 381 (1990).
13. J.Keyne et al., Phys. Rev. **D14**, 28 (1976).
14. V.Flaminnio, W.G.Moorhead, D.R.O.Morrison et al., CERN-HERA, 83-01.
15. H.Brody, E.Groves, R.Van Berg et al., Phys. Rev. **D9**, 1917 (1974).
16. R.Bertini et al. Preprint LNS/Ph/94-16.