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THE MECHANISMS OF THE $pD \to {}^3H_\Lambda K^+$ REACTION

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The K^+ meson production in proton-nucleus collisions is of great interest as these reactions allow one to investigate the nuclear structure at short distances between nucleons [1]. The $pD \to^3 H_\Lambda K^+$ reaction is a process with high momentum transfer. So, at the threshold of this reaction ($T_p = 1132 MeV$) initial proton and deuteron have momenta $\sim$ 1 GeV/c in the c.m.s. but in the final state all nucleons are at rest. At the proton kinetic energy in the laboratory system T_p below 1580 MeV the $p + N \to N + \Lambda + K$ process on a free nucleon N at rest is forbidden by the energy-momentum conservation. Therefore the $pD \to^3 H_\Lambda K^+$ reaction in this region occurs either through involving high momentum components of the deuteron wave function when incident proton collides with one of its nucleons (one-step mechanism, Fig. 1 ,a) or by means of active interaction with two nucleons of the deuteron (two-step mechanism, Fig.1,b). It seems less obvious that in the last case the high momentum components of the wave function will be required. In this respect the $pD \to^3 H_\Lambda K^+$ reaction is similar to $pD \to^3 He\pi^0$ [2] and $pD \to^3 He\eta$ [3] reactions for which the two-step mechanism (called a three -body one in literature) was found to dominate [3, 4]. Indeed, the $pD \to^3 H_\Lambda + K^+$ and $pD \to^3 He\eta$ reactions have deeper analogy in the framework of the two-step mechanism with subprocesses $pp \to d\pi^+$ and $\pi^+ n \to \Lambda K^+$ or $\pi^+ n \to p\eta$ respectively. The relation between masses of initial and final particles in these reactions is such that at the corresponding threshold of the reaction as well as for the angles $\theta_{c.m.} \sim 90^o$ which determines the direction of the final meson momentum in respect to the incident beam, all intermediate particles ($\pi-$meson, deuteron, nucleon) are near to on-mass-shell in a very wide energy range above the threshold [5]. For this reason the two-step mechanism corresponding to the Feynman graph in Fig.1,*b* seems to be the most realistic model of this reaction. It should be noted that for production of $\pi-$mesons and heavier mesons (ω, ϕ, η') as well as for target-nuclei with $A \geq 3$ the above mentioned velocity matching does not take the place.

Another interesting aspect of the $pD \to^3 H_\Lambda K^+$ reaction is connected with formation of the hypertritium nucleus $^3H_\Lambda$ in the final state. The $^3H_\Lambda$ nucleus is a loosely bound system with the binding energy $\varepsilon \sim 2.35 MeV$ which probably has a configuration of the $^3H_\Lambda \to d + \Lambda$ [6]. An investigation of the $pD \to^3 H_\Lambda K^+$ reaction can give a new independent information about the wave function of the $^3H_\Lambda$ nucleus.

In the framework of the two-step mechanism the amplitude $A^{twost}(pD \to ^3H_\Lambda K^+)$ of the $pD \to^3 H_\Lambda K^+$ reaction can be written in the full analogy with the amplitude of the $pD \to^3 He\eta$ reaction [4]. As a result, we get

$$A^{twost}(pD \to^3 H_\Lambda K^+) = C\frac{\sqrt{3}}{2m}A_1(pp \to d\pi^+)A_2(\pi^+ n \to K^+ d\Lambda)\mathcal{F}(P_0, E_0) \tag{1}$$

where A_1 and A_2 are the amplitudes of the processes $pp \to d\pi^+$ and $\pi^+ n \to K^+\Lambda$ respectively, m is the nucleon mass, $C = 3/2$ is the isotopic spin factor allowing for the summation over isotopic spin indices in the intermediate state; the nuclear formfactor in exp. (1) is defined as

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

Here $\Psi_d(\mathbf{q}_1)$ is the wave function of the deuteron and $\Psi_H(\mathbf{q}_2)$ is the wave function of the $^3H_\Lambda$ nucleus in the $^3H_\Lambda \to d + \Lambda$-channel in

momentum space; E_0 and $\mathbf{P}_0$ are the energy and momentum of the intermediate $\pi-$ meson at zero momenta of nucleons in the nuclear vertices $\mathbf{q}_1 = \mathbf{q}_2 = 0$:

$$E_0 = E_K + \frac{1}{3}E_Y - \frac{1}{2}E_D, \quad \mathbf{P}_0 = \frac{2}{3}\mathbf{P}_H + \frac{1}{2}\mathbf{P}_D, \tag{3}$$

where E_j is the energy of the jth particle in the c.m.s., $\mathbf{P}_D$ and $\mathbf{P}_H$ are the momenta in the initial deuteron and the $^3H_\Lambda$ nucleus in the c.m.s. respectively.

The amplitude (1) is connected to the differential cross section of the $pD \to^3 H_\Lambda K^+$ reaction by the following expression

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2}\frac{1}{s_{pd}}\frac{|\mathbf{P}_H|}{|\mathbf{P}_D|}\overline{|A(pD \to^3 H_\Lambda K^+)|^2}, \tag{4}$$

where s_{pd} is the invariant mass of the initial p+d state. The amplitudes $A_1(pp \to d\pi^+)$ and $A_2(\pi^+ n \to \Lambda K^+)$ are related to the corresponding differential cross sections by analogous relations. One should note that the amplitudes A_1 and A_2 are factored outside the integral sign at the point $\mathbf{q}_1 = \mathbf{q}_2 = 0$.

The amplitude of the one-step mechanism corresponding to the Feynman graph in Fig.1, *a* can be written as

$$A^{onest}(pD \to^3 HK^+) = \sqrt{\frac{3}{m}}A_3(pN \to N\Lambda K^+)\Phi(Q), \tag{5}$$

where A_3 is the $pN \to N\Lambda K^+$ process amplitude which is factored outside the two-loop integration sign. The nuclear formfactor $\Phi(\mathbf{Q})$ is defined by

$$\Phi(Q) = \int d^3r\varphi_d(r)\varphi_d^+(r)\Psi_H^+(\frac{1}{2}\mathbf{r})\exp(\mathbf{iQr}), \tag{6}$$

where

$$\mathbf{Q} = \frac{1}{3}\mathbf{P}_H - \frac{1}{2}\mathbf{P}_D. \tag{7}$$

One should note that integral (6) has a meaning of the deuteron elastic formfactor $F_D(2Q)$ at the transferred momentum $\Delta = 2Q$ modified by the presence of the hypertritium wave function $\Psi_H(\frac{1}{2}r)$ in the integrand. It is obvious that the formfactor $\Phi(Q)$ decreases fast with growing Q.

The one-step amplitude has been numericaly calculated here using both $S-$ and $D-$components of the deuteron wave function for the RSC potential in parametrisation [7]. Using the experimental data on the total cross section $\sigma_{NN\to K^+}$ [8] we estimated here the squared amplitude $|A_3(pN \to N\Lambda K^+)|^2$ as $\sim 250 \div 450 GeV^{-2}$ in the initial proton energy range $1.6 - 3.0$ GeV. The numerical calculations for the two-step mechanism are performed in the s-wave approximation for the deuteron wave function [7]. (As was shown by our calculations, the contribution of the deuteron D-component to the cross section is about 10 %). For the wave function of the $^3H_\Lambda$ nucleus the d+p-model developed in Ref. [6] on the basis of separable $\Lambda N-$interaction is used. In this model the $^3H_\Lambda$ wave function only contains the S-component . In the S-wave approximation the factor (2) takes the form

$$\mathcal{F}_{000}(P_0, E_0) = \frac{1}{4\pi}\int_0^\infty j_0(P_0 r)\exp(iE_0 r)\varphi_d(r)\varphi_H(r) r\, dr. \qquad (8)$$

For the differential cross section of the reaction $pp \to d\pi^+$ the parametrisation of Ref. [9] is used here. For the $\pi^+ n \to \Lambda K^+$ differential cross section the parametrisation of the total cross section from Ref. [10] is used and isotropic behaviour of the cross section is assumed.

We have investigated here numericaly the behaviour of the formfactor $\mathcal{F}_{000}(P_0, E_0)$ as a function of incident proton kinetic energy T_p at different K^+-meson scattering angles $\theta_{c.m.}$. The momentum P_0 is

a rather fast decreasing function of T_p at $\theta_{c.m.} = 180^o$ ($P_0 = 0.5 - 0.1 GeV/c$ in the range $T_p = 1.1 - 3.0 GeV$). On the contrary, at the scattering angles $\theta_{c.m.} = 0^o$ and 90^o both the energy E_0 and momentum P_0 are increasing functions of T_p ($E_0, P_0 \sim 0.5 - 1.2 GeV$). This behaviour of P_0 results in a large value of the formfactor $|\mathcal{F}_{000}(P_0, E_0)|^2$ at $\theta_{c.m.} = 180^o$ in comparison to the ones at $\theta_{c.m.} = 0^o$ and 90^0. If one substitutes the wave function of the ^3He nucleus in the $d+p-$ channel [11] instead of the $^3H_\Lambda$ hypernucleus in exp. (8) then the squared formfactor $|\mathcal{F}_{000}(P_0, E_0)|^2$ corresponds to the one for the $pD \to^3 He\eta$ reaction and it turns out to decrease faster with growing incident energy T_p and its value at the threshold increases by a factor of 3—5.

The calculated differential cross sections of the $pD \to^3 H_\Lambda K^+$ reaction are presented in Fig.2 . One can see from this picture that for any scattering angle the differential cross section has a sharp maximum at the proton energy $T_p \sim 1.2 GeV$, which displays the corresponding sharp peak observed in the total cross section of the $\pi^+ N \to \Lambda + K^+$ reaction (see Ref. [10] and references therein). On the whole, the relations between differential cross sections at the angles $\theta_{c.m.} = 0^o, 90^o$ and 180^o follow from corresponding relations between formfactors $|\mathcal{F}_{000}(P_0, E_0)|^2$.

The differential cross section of the $pD \to^3 H_\Lambda K^+$ reaction predicted by the two-step model differs from that for the $pD \to 3He\eta$ reaction in two respects [4]. First, the maximum value of the K^+-meson production cross section $\sim 1nb/sr$ is about 50 times smaller than that for the $\eta-$meson production. Secondly, the $pD \to 3H_\Lambda K^+$ reaction cross section is a smoother decreasing function of incident proton

energy in comparison with the cross section of the $pD \to ^3He\eta$ reaction. As follows from the behaviour of the formfactor $|\mathcal{F}_{000}(P_0, E_0)|^2$ both these peculiarities are in part connected to the form of the wave function of the $^3H_\Lambda$ nucleus.

The results of calculation in the framework of the one-step mechanism are presented in Fig.3 . One can see that the contribution of this mechanism is two - three orders of magnitude smaller than that following from the two-step model.

In conclusion, we note that the two-step mechanism of the $pD \to 3H_\Lambda K^+$ reaction is used owing to the velocity matching. In the case of η–meson production this mechanism explains qualitatively the energy dependence of the cross section above the threshold [4]. However, just at the threshold this model is in strong contradiction with the experimental data on the $pD \to ^3He\eta$ reaction [4]. One of a reason for it is probably a strong attractive interaction in the final $\eta -^3He$ state caused by an excitation of the nucleon $N^*(1535)$ resonance [4, 12]. At present there are no experimental data pointing to the presence of strong coupling of the K^+–meson to any nucleon resonance in the resonance mass region of $1.2 - 2.0\ GeV$. Therefore one can suppose that final state interaction in the $pD \to ^3H_\Lambda K^+$ reaction will not be of great importance in contrast to the η–production.

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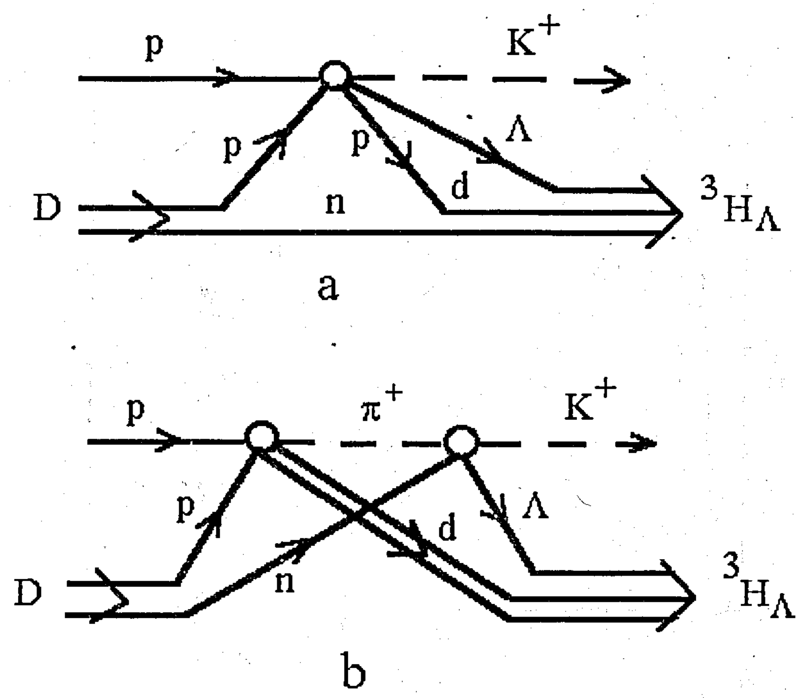

Fig.1 The one- step (a) and two-step (b) mechanisms of the $pD \to ^3H_\Lambda K^+$ reaction.

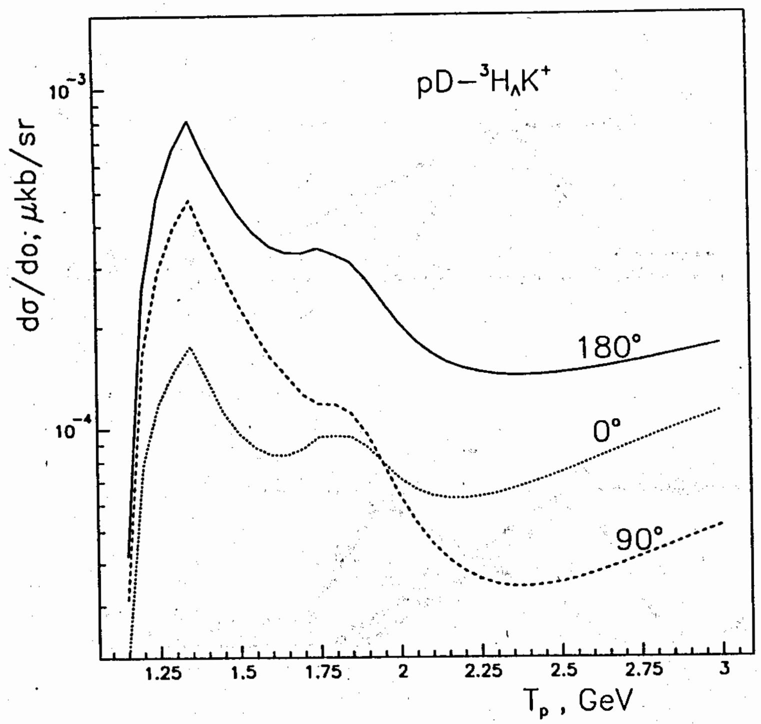

Fig.2. The differential cross section of the $pD \rightarrow^3 H_\Lambda K^+$ reaction calculated for the two-step mechanism as a function of incident proton kinetic energy at different angles of K^+-meson $\theta_{c.m.} = 0^o,\ 90^o,\ 180^o$

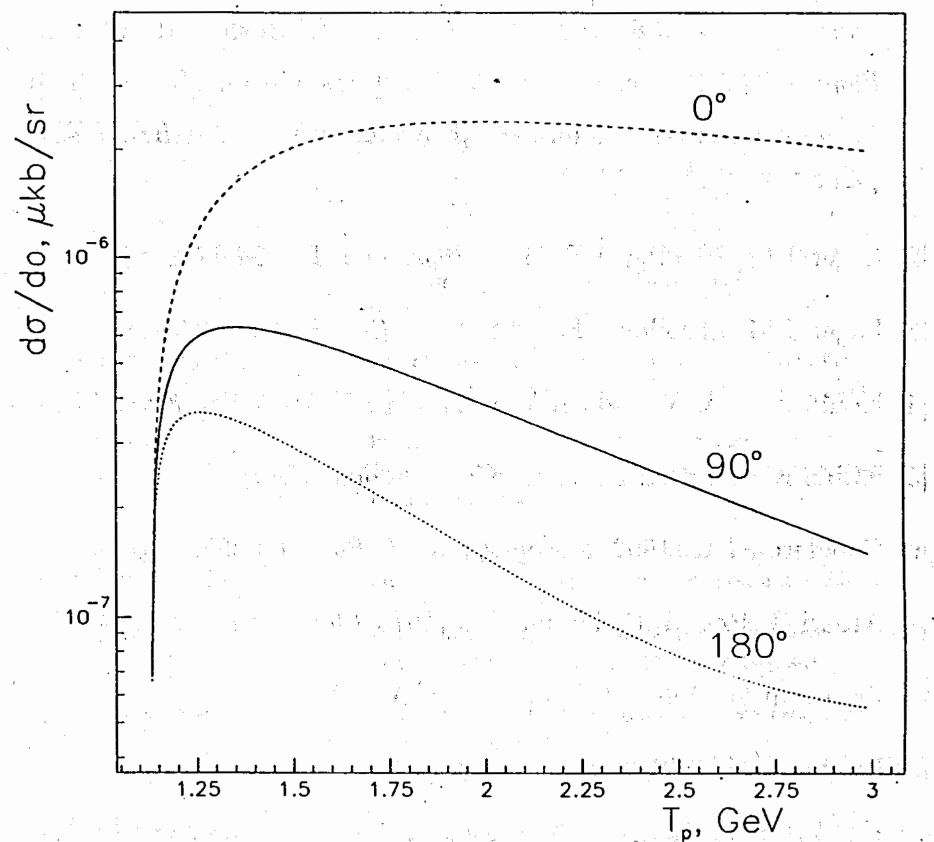

Fig.3. The same as in Fig.3 but for the one-step mechanism

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