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ON THE MECHANISM OF FAST HELIUM AND TRITIUM PRODUCTION BY 665 MEV PROTONS ON LIGHT NUCLEI

1. Introduction

Recently [1] the spectra of fast ^3He, ^3H and ^4He nuclei, produced when bombarding the ^6Li, ^9Be and ^{12}C targets with 665 MeV protons, have been measured at the $5.5°$ lab. angle. Among different possible production mechanisms of fast fragments (X) of some hundreds of MeV, direct nuclear reactions of type A(p,y X)B are of particular interest:

$$p + A \rightarrow y + X + B \ . \quad (1)$$

In these reactions the fast particles y and X are produced as a result of proton direct interaction with a nuclear cluster [c] in a two-particle process

$$p + [c] \rightarrow y + X \ , \quad (2)$$

while the final nucleus B arises via the virtual decay of the target nucleus $A \rightarrow B + [c]$.

In [2] the high energy parts of the spectra of fast ^3He and ^4He fragments have been interpreted as a result of the quasielastic A(p,NX)B knock-out when process (2) is of the character of elastic scattering or charge-exchange scattering. There it has been also shown, that an essential contribution to the fast fragment spectra may arise from direct nuclear reactions on clusters with the pion production - $A(p,\pi X)B$. For the production of ^3He, ^3H and ^4He nuclei processes (2) are of the following form:

$$p + [2N] \rightarrow \pi + {}^3He\,({}^3H) \quad (3)$$

$$p + [3N] \rightarrow \pi + {}^4He \ . \quad (4)$$

The aim of the present work is to identify the mechanism of fast fragment production from the interaction of intermediate energy protons with light nuclei under our experimental conditions /1/. The following problems will be discussed:
(i) compatibility of the experimental data /1/ with the assumptions about dominating contributions from quasielastic scattering and pion production channels on clusters, producing fast fragments;
(ii) mechanism of the momentum transfer of the order of 10 fm^{-1} to three-nucleon clusters in quasielastic scattering processes.

2. Method of Cross Section Calculation for Fast Fragment Production

The differential cross section for production of fragments X in processes of type (1) can be estimated by means of the following formula:

$$\frac{d\sigma}{d\Omega_x}(p,yX) = \gamma_{yx} M_c^{-2} \sum_i N_{eff}(c_i) M_{c_i}^2 \frac{d\sigma}{d\Omega_x}(p+c \to y_0 + X), \qquad (5)$$

where

$$\frac{d\sigma}{d\Omega_x}(p,yX) = \int_{P_1}^{P_2} \frac{d^2\sigma}{d\Omega_x dP_x} dP_x \quad \text{and} \quad P_1 \div P_2$$

is the momentum interval within which the fragments X in the reaction (p,yX) are produced; $N_{eff}(c_i)$ is the total effective number of clusters $[c_i]$ in the target nucleus; M_{c_i} is the matrix element of the reaction $p+[c_i] \to$

$\to y_i + X$; M_c and $\frac{d\sigma}{d\Omega_x}(p+c \to y_0 + X)$ are the

matrix element and the differential cross section of the reaction $p+c \to y_0 + X$ on a free nucleus c, respectively. Formula (5) is different from that obtained in plane wave impulse approximation in two cases (see, e.g., /3/):
(i) Summation over all types of clusters $[c_i]$ with the different isospin T and projection T_z in two-particle reactions of type (2) producing particles y and X is carried out.
(ii) Distortion of incident proton waves in the target nucleus and outgoing waves of fragments in the final nucleus is taken into account using the distortion factor γ_{yX} . As is known, a similar factorization of the cross section does not exist in distorted wave impulse approximation, because distortion factors are dependent on the spatial and momentum distributions of clusters $[c_i]$ and therefore differ in various partial transitions. On the other hand, total effective numbers are obtained only by summation over all partial transitions. In the context with this, the factor γ_{yX} introduced in (5) has the meaning of an effective distortion factor and must be calculated for the effective cluster distribution $\rho_{c_i}(r)$ in the target nucleus. For calculation of γ_{yX} the direct trajectory approximation has been used similarly to /4,5/. The results of /5/, where the differential cross sections for deuteron production from $(p,\pi d)$ – reactions have been calculated, may give an idea about the accuracy of such an approximation: The values of cross sections agree with the experimental ones within the 20% accuracy. An additional uncertainty arises in the calculations of γ_{yX} for interaction processes on clusters (and not on nucleons as in the case $(p,\pi d)$– reactions) which is connected with the fact, that we have to choose a certain function of cluster density distribution. The general ideas and results of concrete model calculations (see, e.g., /6,7/) point out, that clustering of nucleons occurs mainly on the nuclear surface. Therefore, the density distributions of clusters must be of a more peripheral character than density distributions $\rho(r)$ of nucleons. Thus, for example, the shell model gives /3/ a density distribution $dN(\alpha)/dr$ for alpha particle clusters in ^{16}O, which is nearer to the function $r^2\sqrt{\rho(r)}$ than to $r^2\rho(r)$ /5/.

Table 1 presents the results of our calculation of γ_{yX} with density distribution functions $\rho(r)$ and $\sqrt{\rho(r)}$ of

Table 1
Values of the distortion factors γ , calculated for quasielastic knock-out and pion production processes on clusters in ^{12}C.

Process	$\gamma(\rho(r))$	$\gamma(\sqrt{\rho(r)})$	$\bar{\gamma}=\frac{1}{2}(\gamma(\rho)+\gamma(\sqrt{\rho}))$
(p,Nd)	0,22	0,37	0,30 ± 0,08
$(p,\pi\,^3He)$	0,17	0,31	0,24 ± 0,07
$(p,\pi\,^3H)$	0,14	0,29	0,22 ± 0,08
$(p,N\,^3He)$	0,20	0,34	0,27 ± 0,07
$(p,N\,^3H)$	0,17	0,32	0,25 ± 0,08
$(p,\pi\,^4He)$	0,11	0,25	0,18 ± 0,07
$(p,N\,^4He)$	0,15	0,29	0,22 ± 0,07

clusters. The more peripheral the density distribution, the larger γ_{yX} and, consequently, the larger the calculated value of cross section. For the cross section estimations the arithmetical mean $\bar{\gamma}$ of the values $\gamma(\rho(r))$ and $\gamma(\sqrt{\rho(r)})$ has been used. On this basis, it is supposed, that the value γ_{yX} used by us does not overestimate the calculated cross sections.

3. Production of ^3He and ^3H Nuclei with the Momentum near 1500 MeV/c

From shell model calculations it is known, that the effective number of two-proton clusters in ^{12}C is three times smaller, than that of deuteron clusters, the value of which is 10.5 (see, for instance [3]). On the other hand, in an isoscalar nucleus clustering of nucleon pairs, where only the isospin component T_z is different, is equally probable. Hence, for ^{12}C

$$N_{eff}([np]_{T=1}) = N_{eff}([nn]_{T=1}) = N_{eff}([pp]_{T=1}) =$$

$$= \frac{1}{3} N_{eff}([np]_{T=0}).$$

Analogous information about effective numbers in the case of ^6Li and ^9Be is absent. Therefore, the estimations of cross sections were carried out only for the ^{12}C target nucleus, although for lighter nuclei the discussed direct reactions may appear more distinctly.

The matrix elements of reactions (3) can be expressed through three independent amplitudes $a_{T,T(2N)}$ of transitions with the definite total isospin T(1/2 or 3/2) of the system incident proton-nucleon pair and the isospin $T(2N)$ (0 or 1) of the nucleon pair (see Table 2). In analogy to the elastic backward-scattering process of protons at high energy on $[np]$ -pairs in singlet and triplet states [8,9] it is supposed, that

$$(a_{11})^2 = (a_{10})^2.$$

Moreover, we assume, that the process

Table 2
Matrix elements of two-particle reactions with pion production on [2N]- clusters.

$M_1(p + [np]_{T=0} \longrightarrow \pi^+ + {}^3H)$	$= \sqrt{2/3}\,\alpha_{10}$
$M_2(p + [np]_{T=1} \longrightarrow \pi^+ + {}^3H)$	$= \sqrt{2/3}\,(\alpha_{31} - \alpha_{11})$
$M_3(p + [nn]_{T=1} \longrightarrow \pi^o + {}^3H)$	$= \sqrt{2/3}\,(\alpha_{31} - \alpha_{11})$
$M_4(p + [np]_{T=0} \longrightarrow \pi^o + {}^3He)$	$= 1/\sqrt{3}\,\alpha_{10}$
$M_5(p + [np]_{T=1} \longrightarrow \pi^o + {}^3He)$	$= 1/3\,(2\alpha_{31} + \alpha_{11})$
$M_6(p + [nn]_{T=1} \longrightarrow \pi^- + {}^3He)$	$= 1/3\,(\alpha_{31} + 2\alpha_{11})$
$M_7(p + [pp]_{T=1} \longrightarrow \pi^+ + {}^3He)$	$= \alpha_{31}$

$$p + [nn]_{T=1} \to \pi^- + {}^3He \quad (6)$$

in comparison with the other channels of Table 2 is greatly suppressed. This assumption comes out naturally due to the following reasons:

(i) At energies of about 600 - 700 MeV the π^- production is essentially lower than the π^+ production in proton-nucleon collisions as well as in pion production processes with protons on light nuclei. In fact, at 660 MeV the cross section of the π^- production in pn collisions is some times smaller than the cross sections of π^+ and π^o production in pn and pp collisions /10/. At 740 MeV the ratios $\sigma(\pi^-)/\sigma(\pi^+)$ amount 0.23 for ^9Be and 0.19 for ^{12}C /11/.

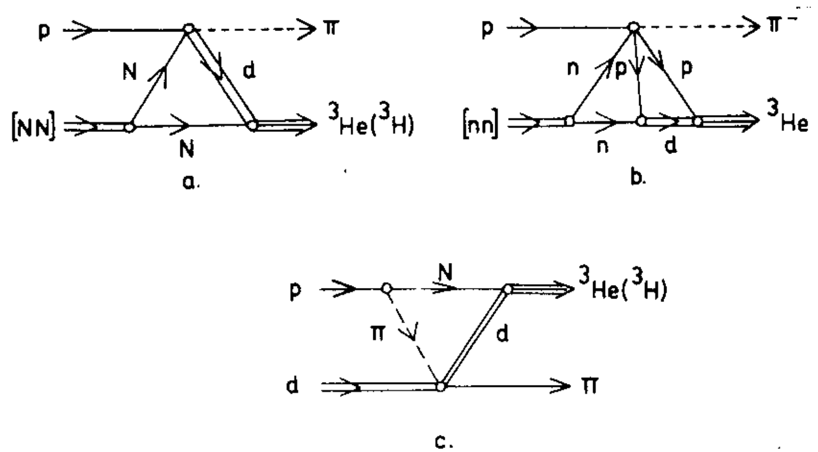

Fig. 1. Diagrams describing processes (3).

(ii) The cross section of reaction (6) may be suppressed also because of the peculiarity of the reaction mechanism. In some refs. (see for instance /12,13,14/) the experimental data of the cross sections of the reactions

$$p + d \to \pi^o + {}^3He \quad (7)$$

and

$$p + d \to \pi^+ + {}^3H \tag{8}$$

have been described with a mechanism, corresponding to the diagram of fig. 1a. Obviously, all processes listed in Table 2 except (6) can have contributions from such a diagram, while for process (6) an analogous mechanism can be expressed only by diagrams with a larger number of vertices (fig. 1b).

For the ratio of differential cross sections for ^3H and ^3He production in momentum region according to process (3) we obtain the expression

$$\frac{\frac{d\sigma}{d\Omega}(p,\pi\,{}^3H)}{\frac{d\sigma}{d\Omega}(p,\pi\,{}^3He)} = \frac{\gamma_{\pi\,{}^3H}}{\gamma_{\pi\,{}^3He}} \times$$

$$\times \frac{\{M_1^2 + \frac{1}{3}M_2^2 + \frac{1}{3}M_3^2\}M_4^2\,\frac{d\sigma}{d\Omega}(p+d\to\pi^+ + {}^3H)}{\{M_4^2 + \frac{1}{3}M_5^2 + \frac{1}{3}M_6^2 + \frac{1}{3}M_7^2\}M_1^2\,\frac{d\sigma}{d\Omega}(p+d\to\pi^0 + {}^3He)}. \tag{9}$$

The above-mentioned arguments allow us to neglect the matrix element of reaction channel (6), hence $M_6 = -\frac{1}{3}(a_{31} + 2a_{11}) = 0$ and $a_{31} = -2a_{11}$. Then from (9) it follows

$$\frac{\frac{d\sigma}{d\Omega}(p,\pi\,{}^3H)}{\frac{d\sigma}{d\Omega}(p,\pi\,{}^3He)} = \frac{\gamma_{\pi\,{}^3H}}{\gamma_{\pi\,{}^3He}} = 0.92\,. \tag{9$'$}$$

The experimental value /1/ of this ratio for the momentum interval 1400 - 1700 MeV/c amounts 0.85 ± 0.05.

Finally, for the ^3He and ^3H cross sections in the kinematical region of process (3) with the pion production on two-nucleon clusters the following absolute values are obtained:

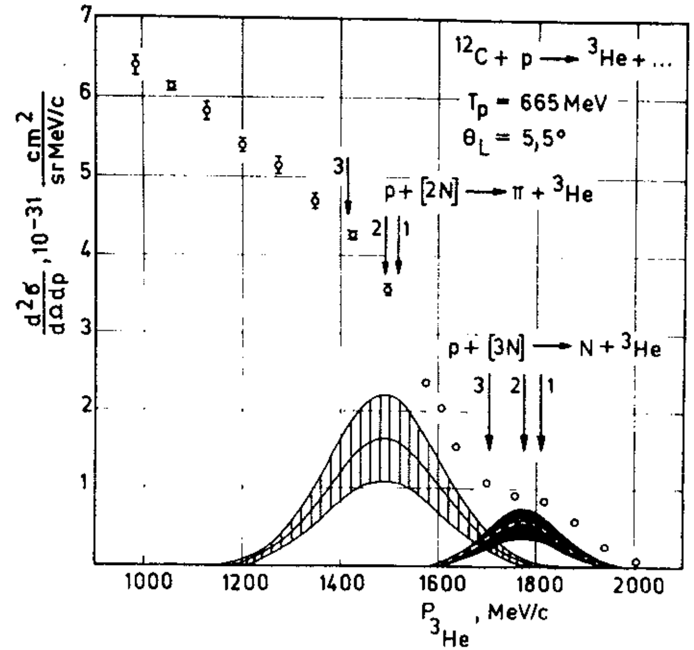

Fig. 2. Comparison of experimental data /1/ with the calculated cross section of the processes $p + [2N] \to \pi + {}^3He$ (the solid line) and $p + [3N] \to N + {}^3He$ (the dashed line). The standard deviation areas include the errors of experimental cross section (7) and elastic $p\,{}^3He$ -scattering as well as the uncertainty of the distortion factors γ. Arrows indicate the momentum values of ^3He nuclei, where: 1 - from two-particle processes on free deuterons and ^3He, 2 - the binding energy of ^3He in the ^{12}C nucleus and 3 - break-up of the final nucleus taken into account.

$$\frac{d\sigma}{d\Omega}(p,\pi\,{}^3H) = (47 \pm 18)\,\frac{\mu b}{sr}, \tag{10}$$

$$\frac{d\sigma}{d\Omega}(p,\pi\,{}^3He) = (48 \pm 15)\,\frac{\mu b}{sr}. \tag{11}$$

(Some difference of the ratio of these cross sections to the one introduced in (9′) is connected with the fact, that for calculation of absolute values (10) and (11) experimental data of cross sections (7) and (8) were used, while in (9′) use was made only of the isospin relation of processes (7) and (8)). Figures 2 and 3 show, together with experimental ^{3}He and ^{3}H spectra Gaussian curves, normalized to the values of cross sections (10) and (11). The value $\Delta P = 280$ MeV/c FWHM used is obtained from the quasielastic scattering data of protons on

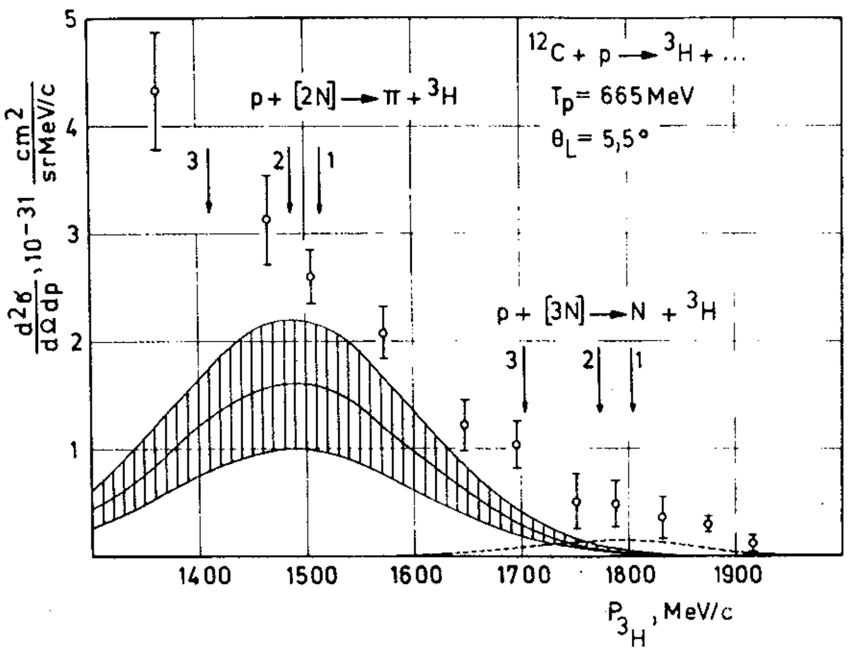

Fig. 3. Comparison of experimental data [1] with the calculated cross sections of the processes $p + [2N] \to \pi + {}^3H$ (the solid line) and $p + [3N] \to N + {}^3H$ (the dashed line). The standard deviation area in the case of the pion production process includes the error of experimental cross section (8) as well as the uncertainty of the distortion factor γ. Arrows indicate the momentum values of ^{3}H nuclei, where 1 - from two-particle processes on free deuterons and ^{3}H , 2 - the binding energy of ^{3}H in the ^{12}C nucleus and 3 - the break-up of the final nucleus taken into account.

two-particle clusters [5] taking into account the kinematics of the reactions. In the standard deviation area (the dashed region) only the errors of γ and cross sections (7), (8) are included, however, not the uncertainty of the theoretical value $N_{eff}[np]_{T=0}$). This uncertainty of effective numbers is also excluded in the further estimations below. Comparing the calculated curves with the experimental spectra it is seen, that reactions of type (3) essentially contribute to the cross sections of ^{3}He and ^{3}H production at the momentum of about 1500 MeV/c.

Recently Kopeliovich and Potashnikova [15] have shown, that the experimental data of differential cross sections (7) and (8) with pions in c.m.s. backward direction can be also described by the one-pion exchange mechanism (fig. 1c). It is possible to show, that in this case $a_{11} = -2a_{31}$ and the ratio of cross sections (9) equal to 1.84, which is distinctly in disagreement with the experimental value. Using the one-pion exchange model for ^{3}He and ^{3}H production in the kinematical region discussed here the absolute cross sections

$$\frac{d\sigma}{d\Omega}(p,\pi\,{}^3He) = (12 \pm 4)\ \frac{\mu b}{sr} \text{ and } \frac{d\sigma}{d\Omega}(p,\pi\,{}^3H) = (24 \pm 9)\ \frac{\mu b}{sr}$$

are estimated, which are essentially smaller than the experimental ones. Apparently, this is connected with the fact, that at 670 MeV proton energy diagram of fig. 1c is not dominating, and considerable contributions from other diagrams, i.e., similar to fig. 1c with two-nucleon pairs different from deuterons in the intermediate state, are possibly present.

It is useful to draw attention to the fact, that the calculated values can explain an essential part of the experimental cross sections, if besides quasideuterons all other two-nucleon clusters are taken into account. In fact, restricting oneself only to clusters of type $[np]_{T=0}$, the values of cross sections $\frac{d\sigma}{d\Omega}(p,\pi\,{}^3He)$ smaller by six times and $\frac{d\sigma}{d\Omega}(p,\pi\,{}^3H)$ smaller by three times in comparison with (10) and (11) are obtained.

4. The Quasielastic Knock-Out of ^3He and ^3H Nuclei

As two-particle processes (2) for the quasielastic part of ^3He and ^3H spectra ($P \simeq 1800$ MeV/c) the following reactions are possible:

$$p + [^3He]_{T=1/2} \to p + {}^3He, \qquad (12)$$

$$p + [^3H]_{T=1/2} \to n + {}^3He, \qquad (13)$$

$$p + [^3H]_{T=1/2} \to p + {}^3H, \qquad (14)$$

$$p + [3N]_{T=3/2} \to N + {}^3He({}^3H). \qquad (15)$$

In the final state the nucleon is backward scattered at an angle of about 180°, at which the momentum transferred to ^3He or ^3H is about 9 fm^{-1}. Under these conditions according to /16,17/ the cross sections of elastic proton-nucleus scattering are determined preferably by the probability, that the nucleons simultaneously are close together. For three-nucleon clusters with the isospin state $T = 3/2$ this probability should be essentially smaller, than for $[^3He]_{T=1/2}$ and $[^3H]_{T=1/2}$. In fact, while in $[^3He]_{T=1/2}$- and $[^3H]_{T=1/2}$- clusters all three nucleons are in the S -state of relative motion, in the $[3N]_{T=3/2}$ -system one nucleon is in the P -state and, consequently, the probability of finding it closely by the other two nucleons is reduced. Moreover, while in $[3N]_{T=3/2}$ all nucleon pairs are in the isospin state $T(2N)=1$, in $[^3He]_{T=1/2}$ - and $[^3H]_{T=1/2}$ - cluster states with the isospin $T(2N)=0$ are present.

The effective number of the $T(2N)=0$ pairs are larger by a factor 3, as mentioned above. From these conceptions it is acceptable to neglect process (15) in comparison with (12) and (14).

For estimation of the effect of process (13) in quasielastic ^3He knock-out experimental data of the ratio ξ of cross sections for ^3He and ^3H production are used. Obviously, for isoscalar nuclei, where $N_{eff}(^3He) = N_{eff}(^3H)$, the following relation can be obtained:

$$\frac{d\sigma}{d\Omega}(p^3H \to n^3He) = \frac{1}{\xi}\cdot\frac{d\sigma}{d\Omega}(p^3H \to p^3H) - \frac{d\sigma}{d\Omega}(p^3He \to p^3He), \qquad (16)$$

where
$$\xi = \int_{P_1}^{P_2} \frac{d^2\sigma(^3H)}{d\Omega\, dP}\, dP \Big/ \int_{P_1}^{P_2} \frac{d^2\sigma(^3He)}{d\Omega\, dP}\, dP.$$

With the renormalization of the cross sections by a factor of 1.3* we used the following values: For the cross section of elastic p^3H - scattering, the value 0.19 μb/sr, calculated in /15/, and for proton backward-scattering ($\theta_{cm} = 169°$) on ^3He the experimental cross section (0.76 ± 0.18) μb/sr /17/.
With $\xi = 0.5 \pm 0.1$ ($P_1 = 1800$ MeV/c, $P_2 = 2000$ MeV/c) from /1/

$$\frac{d\sigma}{d\Omega}(p^3H \to n^3He) = -(0.38 \pm 0.20)\,\mu b/sr$$

is obtained, from where it is allowed to neglect also reaction channel (13) in comparison with (12) and (14). Following /3/, we assume now $N_{eff}(^3He) = N_{eff}(^3H) = 11.8$ for the effective number of three-nucleon clusters in ^{12}C. Then the cross sections

$$\frac{d\sigma}{d\Omega}(p, N^3He) = (10 \pm 4)\,\mu b/sr \qquad (17)$$

and

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* The experimental cross sections from /2,13,17,22/ used in this work have been reduced by a factor of 1.3. This is connected with the fact, that at present a more accurate value of the cross section for the $pp \to d\pi^+$ process is available, which has been used in the earlier investigations to normalize the experimental data of the cross sections.

$$\frac{d\sigma}{d\Omega}(p,N\,^3H) = (2.4 \pm 0.8)\ \mu b/sr \tag{18}$$

are obtained, where the error in (18) contains only the error of the calculated distortion factor $\gamma_{N\,^3H}$, and in (17) beyond in the error of the $p\,^3He$ cross section measurement [17]. The areas of Gaussian curves in figs. 2 and 3 in the region of the quasielastic scattering peak are normalized to the cross sections (17) and (18), where the value ΔP = 200 MeV/c FWHM has been extrapolated from ^6Li and ^9Be data [1].

As is seen, the calculated value of cross section for ^3He production is in reasonable agreement with the experimental one. In the case of ^3H the experimental points are clearly higher than the calculated curve, what is probably connected with an underevaluation of the elastic $p\,^3H$ scattering cross section. For more exact evaluation of this cross section it is possibly necessary to consider the diagrams of type fig. 4d with two nucleons different from the deuteron in the intermediate state.

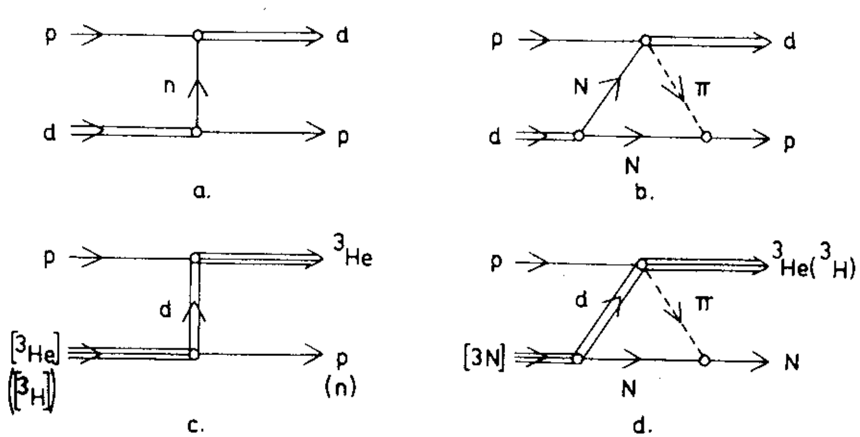

Fig. 4. Diagrams describing elastic pd, $p\,^3He$ and $p\,^3H$ scattering [15,18,19,21].

5. Elastic $p\,^3He$ and $p\,^3H$ Backward-Scattering

The mechanism of elastic backward-scattering of protons with energies of some hundreds of MeV on light nuclei is of considerable interest. Recently in some refs. (see, e.g., [18,19,20]) it has been shown, that the elastic backward-scattering of protons on the lightest nucleus, the deuteron, essentially is described by means of two diagrams: At energies of about 100 - 300 MeV the pole diagram of the neutron pick-up process (fig. 4a), at energies of about 400 - 800 MeV the triangle graph with a pion in the intermediate state (fig. 4b) is dominant.

In [21] the elastic backward-scattering of protons on ^3He in pole graph approximation (deuteron pick-up, fig. 4c) has been calculated. It has been shown, that such a mechanism, in principle, can explain the experimental data of elastic $p\,^3He$ scattering at 665 MeV, but it is not applicable to account for the $p\,^3H$ scattering. Denoting the amplitudes of isoscalar and isovector exchange in the t -channel by A_s and A_v, the following relations are valid [21]:

$$A_1(p + {}^3He \to p + {}^3He) = A_s + A_v, \tag{19}$$

$$A_2(p + {}^3H \to n + {}^3He) = A_s - A_v, \tag{20}$$

$$A_3(p + {}^3H \to p + {}^3H) = 2A_v, \tag{21}$$

at which the pole graph gives only a contribution to the amplitude A_s. If in the energy range discussed the pole mechanism is dominating, then the cross section of $p\,^3H$ backward-scattering in comparison with $p\,^3He$ scattering should be greatly suppressed. Consequently, for isoscalar target nuclei also a suppression of the cross section of quasielastic ^3H knock-out is expected [15,21]. The significant production of ^3H in quasielastic knock-out processes experimentally observed [1] qualitatively confirms the conclusions in [15], where it has been shown, that the isovector amplitude

A_v is entirely comparable with A_s. The isovector amplitude A_v in /15/ was calculated by means of the one-pion exchange triangle graph (fig. 4d), which is analogous to the diagram of fig. 4b for the pd -scattering. The large values of $pN \to d\pi$ and $pd \to {}^3He({}^3H)\pi$ vertices at energies of about 400 - 800 MeV are finally involved by the excitation of the (3/2, 3/2) baryonic resonance. Therefore, the available experimental data and theoretical results must be considered as an indication, that in the processes of elastic backward-scattering of protons with energies of some hundreds of MeV on the lightest nuclei nucleon excitations are essential.

6. Production of Fast ^4He Nuclei

Taking into account the isospin relation of cross sections

$$\frac{\sigma(p + [{}^3He] \to \pi^+ + {}^4He)}{\sigma(p + [{}^3H] \to \pi^\circ + {}^4He)} = 2$$

for the one-pion production processes on three-nucleon clusters in ^{12}C the following cross section

$$\frac{d\sigma}{d\Omega}(p, \pi\, {}^4He) = \gamma_{\pi\, {}^4He} \cdot \frac{3}{2} N_{eff}({}^3He) \frac{d\sigma}{d\Omega}(p + {}^3He \to \pi^+ + {}^4He) =$$

$$= (8.0 \pm 4.5)\ \mu b/sr \qquad (22)$$

is obtained with:

$$\frac{d\sigma}{d\Omega}(p + {}^3He \to \pi^+ + {}^4He) = (2.5 \pm 1.0)\ \mu b/sr$$

taken from /22/. The corresponding Gaussian curve normalized to (22) is shown in fig. 5 (the solid line). The FWHM value ($\Delta P = 300$ MeV/c) used has been converted from momentum distribution of ^3He nuclei (including the kinematics of the reactions) quasielastically knocked out from ^{12}C. For the quasielastic ^4He knock-out the most probable reaction channel of type (2) is

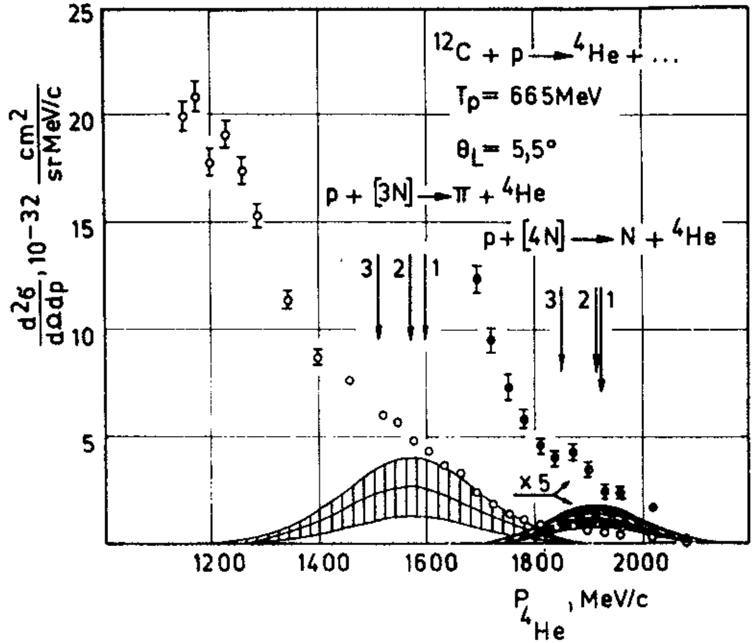

Fig. 5. Comparison of experimental data /1/ with calculated cross sections of the processes $p + [3N] \to \pi + {}^4He$ (the solid line) and $p + [4N] \to N + {}^4He$ (the dashed line). The standard deviation areas include the errors of cross sections (4) and elastic p^4He scattering as well as the uncertainty of the distortion factors γ. Arrows indicate the momentum values of ^4He nuclei, where 1 - from two-particle processes on free ^3He and ^4He nuclei, 2 - the binding energy of ^4He in the ^{12}C nucleus and 3 - the break-up of the final nucleus taken into account.

$p + [{}^4He] \to p + {}^4He$, and therefore

$$\frac{d\sigma}{d\Omega}(p, p\, {}^4He) = \gamma_{p\, {}^4He}\, N_{eff}({}^4He) \frac{d\sigma}{d\Omega}(p + {}^4He \to p + {}^4He) =$$

$$= (0.56 \pm 0.25)\ \mu b/sr. \qquad (23)$$

In this evaluation $N_{eff}(^4He) = 7.3$ from [3] and

$$\frac{d\sigma}{d\Omega}(p + {}^4He \to p + {}^4He) = (0.35 \pm 0.10)\,\mu b/sr$$

from experiment [17] have been used. The Gaussian curve with $\Delta P = 175$ MeV/c FWHM normalized to the value (23) is drawn in fig. 5 (the dashed line) at the momentum of ^4He nuclei from quasielastic scattering. Considering the standard deviation area, it is seen, that the calculated cross sections (22) and (23) are not contradicting the experimental data.

It should be remarked that the Gaussian curves, used in this work, describing the contribution of mechanisms discussed here, were taken only because of simplicity. The utilization of more complicated forms of dependences (for instance, calculated in the pole graph approximation of the dispersion theory of direct nuclear reactions) would not change the qualitative conclusions of this work.

7. Conclusions

(i) The production of ^3He and ^4He nuclei at a small lab. angle with energies higher than 350 MeV from the interaction of 665 MeV protons with light nuclei in a substantial part can be explained by two types of direct nuclear reactions:

a) quasielastic scattering of protons on clusters - $(p, N\,^3He)$, $(p, N\,^4He)$

b) reactions with pion production on clusters - $(p, \pi\,^3He)$, $(p, \pi\,^4He)$.

Obviously, fast ^3H production under the same kinematical conditions is also connected with the reaction channels mentioned above - (p, N^3H) and $(p, \pi\,^3H)$, although in the case of quasielastic scattering a direct comparison of calculation with experiment is more difficult because the experimental data of the elastic $p\,^3H$ backward-scattering are not yet available.

(ii) Qualitative agreement of evaluation with experiment is obtained under the following assumptions:

a) Effective numbers of clusters are equal to the values obtained from shell model calculations.

b) Wave distortion of incident protons and produced fast fragments is taken into account in direct trajectory approximation, where for the effective spatial distribution of clusters a function intermediate between the density distribution $\rho(r)$ of nucleons and $\sqrt{\rho(r)}$ is used.

c) In reactions on two-nucleon clusters besides quasideuterons also two-nucleon clusters with isospin $T(2N) = 1$ are considered.

(iii) The experimental and theoretical results available now indicate the substantial role of the excitation of the (3/2, 3/2) baryonic resonance in elastic proton scattering processes at energies of about 400 - 800 MeV on lightest d, ^3He, ^3H nuclei.

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