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PECULIARITIES OF DEUTERON PRODUCTION IN ^{4}He-PROTON INTERACTIONS*

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1. Introduction

The abundant deuteron yield induced by high energy particles /1-9/ from nuclei has received considerable attention. The experiments carried out with proton beams impinging on light and medium nuclear target (from Be to Pt)/1-3/ showed a weak dependence of the deuteron-to-proton ratio on the projectile momentum and its regular increase with target mass number. The results could not be explained by the statistical model /5/. But they were described satisfactorily by the coalescence model/3,5/. The coalescence model was also applied to nuclear collisions in order to explain the light fragment production/6-9/.

It should be noted that all the quoted experiments were performed with counter technique. So, in the measurements of the fragment production cross sections they are constrained to a given angle. Moreover, in such an arrangement it is impossible to identify the reaction and to study the correlation between the secondary particles.

Owing to nuclei accelerated up to relativistic energies at the Dubna synchrophasotron, the unique chance appeared to investigate nuclear fragmentation processes. The charged fragments with relatively high momenta produced in nucleus-proton collisions, for example, in a hydrogen bubble chamber, allow one to reconstruct the full picture of reactions in most cases.

2. Experimental Results and Discussion

The 1m hydrogen bubble chamber was exposed to a ^{4}He beam at a 8.6 GeV/c momentum. Different reactions were investigated. In particular, cross sections of deuteron production and deuteron momentum distributions/10/ were measured at a 8.6 GeV/c ^{4}He momentum. Later on all the experimental quantities are considered in the ^{4}He projectile rest frame. The deuterons are proved to be predominantly residual ones, i.e., they have spectator-like characteristics. They are distributed almost isotropically, and a typical maximum is seen near a value of 120 MeV/c in their momentum spectrum. On the other hand, a significant part of the produced deuterons is evidently of a non-spectator nature. To explain their origin is the main subject of the analysis carried out in this paper.

If one comes to nothing more than pionless reactions, deuterons are supplied only by the following two channels:

$$p^4He \longrightarrow ddp \quad (407 \text{ events}), \qquad (1)$$

$$p^4He \longrightarrow dppn \quad (2783 \text{ events}). \qquad (2)$$

Both reactions are constrained kinematically. The reaction (1) is notable for the usual presence of one spectator-deuteron.This is easy to see from fig. 1, where the slower deuteron momentum and angular distributions of the slower deuteron are displayed in the projectile rest frame. The other (fast) deuteron and the leading proton form a pair that is governed naturally by the quasi two-particle kinematics. For example, the points corresponding to the leading proton and the fast deuteron of the reaction (1) are located near the curve representing the pd elastic scattering kinematics on two-dimensional momentum versus polar angle plot. This proof is insufficient to make the quasi-elastic knock-out responsible for the fast deuteron production. On the contrary, the slope of the differential cross section $d\sigma/dt \sim e^{-b|t|}$ of the reaction (1), fitted over a range of (0.0, 0.3) $(GeV/c)^2$, turned out to be too small (b=7.0 ± 0.7 $(GeV/c)^{-2}$) in comparison with the slope of pd elastic scattering (b=22.4 ± 0.1 $(GeV/c)^{-2}$)* and to be close to the value, characteristic for NN elastic scattering. These facts speak in favour of the deuteron formation in the course of the reaction. As far as the reaction (2) is concerned, it is shown that the events with relatively small deuteron momenta ($p_d < 0.7$ GeV/c) proceed via the double scattering of the leading proton on the ^4He nucleus. In this case the residual deuteron is a spectator/11/. Taking this result as a starting-point and assuming that the deuteron is formed from a (p, n) pair by means of the final state interaction, one can propose a number of simple diagrams to describe the deuteron production (fig. 2). The charge exchange channel (623 events with leading neutron) is excluded from the present analysis. Methodical cuts were applied to reject the events, in which, by mistake, the concurrent hypothesis was chosen, as proton-deuteron ambiguity cannot be resolved uniquely on the basis of ionization losses. As a consequence of the latter fact, 212 events were discarded. So, 1948 charge reten-

*) This value was obtained from the 1m HBC data taken at a 3.3 GeV/c deuteron momentum.

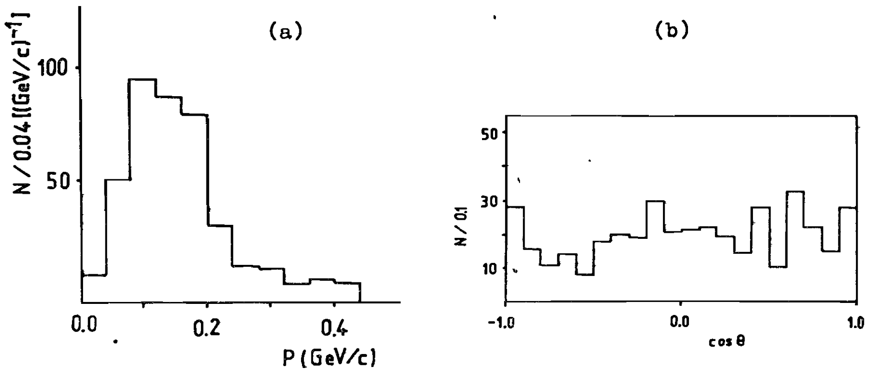

Fig. 1. Momentum (a) and angular (b) distributions of the slow deuteron from the $p^4He \rightarrow pdd$ reaction.

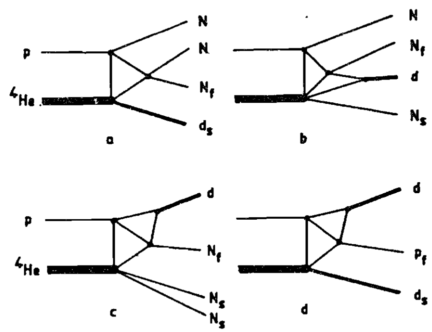

Fig. 2. Diagrams of pionless reactions with deuteron production in double scattering processes suffered by the leading proton.

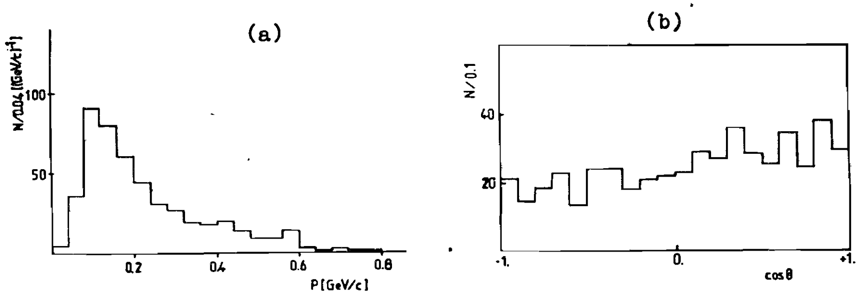

Fig. 3. Momentum (a) and angular (b) distributions of the slow nucleons from the $p^4He \rightarrow pdpn$ reaction containing a fast deuteron.

tion events were used in the analysis of the $p^4He \rightarrow pdpn$ reaction.

The leading proton on the diagrams in fig. 2 is denoted by "f". Diagram a) represents the double scattering undergone by the leading proton and a residual deuteron; diagram b) corresponds to the final state interaction between recoil and spectator nucleons to give rise to the deuteron; diagram c) is the analogue of the previous case but two recoil nucleonsstick together. The last diagram d) describes the $p^4He \rightarrow pdd$ reaction. Diagrams with the leading deuteron are not presented because no such events were found.

The comparison of the diagrams a), b) and c) in fig. 2 leads to the following results: the fastest deuteron is expected in the case c) and the slowest one in the case a). For convenience the momenta of secondary particles of the $p^4He \rightarrow pdpn$ reaction were put in the descending order. So, subscript 1 corresponds to the leading particle. The statistics was divided into three groups in accordance with the deuteron position on the momentum ladder. Table 1 does not contain any column with leading deuteron for the reason mentioned above.

Table 1. Average momenta and forward-backward asymmetries for secondary particles in the $p^4He \rightarrow pdpn$ reaction. The chamber analyzing power is taken as an error of the average momenta.

Deuteron subscript / Particle subscript	2	3	4
1	1.916 ± 0.015 1.00 ± 0.09	1.826 ± 0.015 1.000 ± 0.062	1.733 ± 0.015 1.00 ± 0.042
2	0.536 ± 0.015 0.717 ± 0.078	0.616 ± 0.015 0.828 ± 0.057	0.679 ± 0.015 0.895 ± 0.040
3	0.316 ± 0.015 0.281 ± 0.066	0.295 ± 0.015 0.268 ± 0.045	0.386 ± 0.015 0.327 ± 0.031
	0.165 ± 0.015 0.107 ± 0.064	0.162 ± 0.015 0.126 ± 0.044	0.163 ± 0.015 0.136 ± 0.030
Number of events	250	530	1168

All squares of table 1 comprise of two values: the upper and lower ones which are the average momentum in GeV/c and forward-backward asymmetry, respectively. To stress the deuteron quantities, the corresponding squares are marked. The characteristics of the slowest deuteron (subscript 4) coincide with those of the earlier published data at a deuteron momentum below 0.7 GeV/c [11] (diagram a) in fig. 2).

Now another extreme case of the $p^4He \rightarrow pdpn$ reaction will be studied, namely that with a fast deuteron. Here the deuteron follows immediately the leading proton on the momentum ladder (subscript 2). In this case the expected predominance of the diagram c) in fig. 2 would result in a spectator-like distribution for slow nucleons labelled 3 and 4. The deuteron distributions should be similar to those of the fast deuteron from the "supplementary" $p^4He \rightarrow pdd$ reaction.

Figure 3 displays the momentum and solid angle distributions of the two slow nucleons from the $p^4He \rightarrow pdpn$ reaction (deuteron subscript 2). One can see that the momentum distribution is a typical spectator-like one and the nucleons are distributed almost isotropically. The deuteron momentum and polar angle distributions for the above class of events are presented in fig. 4 a) and b), respectively. The distributions of the fast deuteron from the $p^4He \rightarrow pdd$ reaction are displayed as well. The histograms are normalized to the same amount of events. It is easy to note that both events are in good agreement. Thus, the hypothesis of adequacy between the diagram c) in fig. 2 and the studied process can be considered to be proved.

The diagram b) in fig. 2 and the third column of table 1 correspond to an interim case when the recoil and spectator nucleons coalesce to form a deuteron by means of the final state interaction. The ^4He full break-up reaction is the supplemental channel in this case. However, the kinematics of the full break-up cannot be reproduced completely. For that very reason we compare only the $p^4He \rightarrow pdd$ and $p^4He \rightarrow pdpn$ reactions with one fast deuteron. Of course, the scheme under study is idealized to some extent. There exist areas where the diagrams overlap. Other diagrams, e.g., diagrams with single scattering suffered by the leading particle (fig. 5), can contribute.

Azimuthal correlation results, however, show evidence for a small probability of these processes in the $p^4He \rightarrow pdpn$ reaction. Table 2 lists the asymmetries around 90° in the relative azimuthal angle distribution of secondary particles which are paired after putting their momenta in the descending order. The combinations containing a deuteron are marked again.

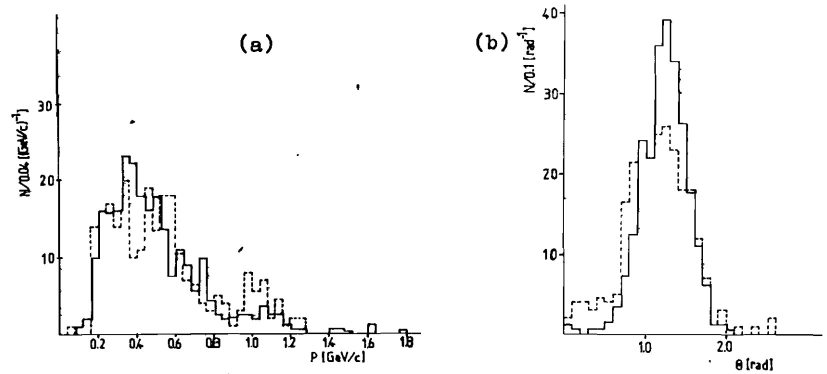

Fig. 4. Momentum (a) and angular (b) distributions of the fast deuterons from the $p^4He \rightarrow pdd$ (full line) and $p^4He \rightarrow pdpn$ (dashed line) reactions.

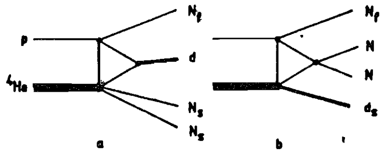

Fig. 5. Examples of the diagrams describing deuteron production in simple scattering processes suffered by the leading proton.

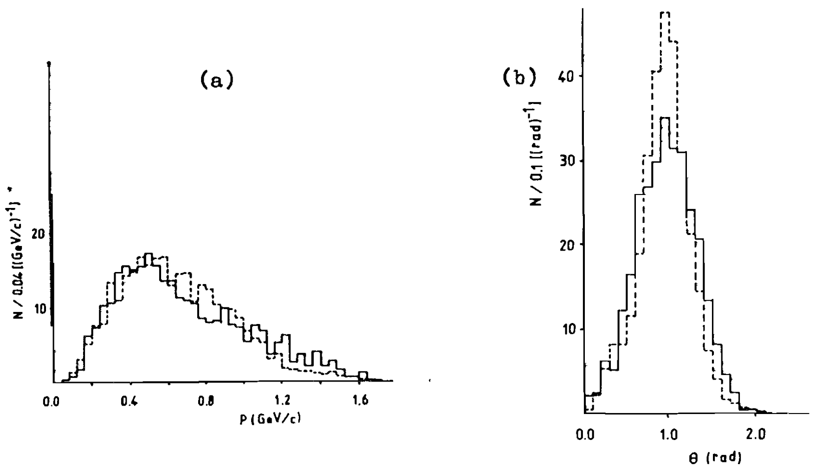

Fig. 6. Momentum (a) and angular (b) distributions: the full lines denote the distributions of the fast deuteron from $p^4He \rightarrow pdd$ and those of the total momenta of the recoil proton-neutron pairs from $p^4He \rightarrow pd_s pn$ joined together; in the latter reaction d_s denotes spectator deuteron. The dashed lines represent the distributions of the total momentum of the two recoil nucleons from the Monte-Carlo sample.

Table 2. Asymmetries in the relative azimuthal angles of the pairs of secondary particles

Pairs of particles \ Deuteron subscript	2	3	4
(1,2)	0.911 ± 0.086	0.918 ± 0.059	0.883 ± 0.039
(1,3)	0.426 ± 0.069	0.384 ± 0.047	0.453 ± 0.032
(1,4)	0.224 ± 0.065	0.147 ± 0.044	0.048 ± 0.029
(2,3)	0.071 ± 0.064	0.063 ± 0.044	0.029 ± 0.029
(2,4)	0.006 ± 0.064	0.052 ± 0.044	0.094 ± 0.030
(3,4)	0.030 ± 0.064	-0.025 ± 0.044	0.088 ± 0.030

The azimuthal asymmetries of pairs involving the leading particle (subscript 1) are presented in the upper half of the table. Large values of the asymmetries reflect the kinematics of the processes in transversal momentum space. The weaker correlation between the deuteron and leading proton, the lower deuteron momentum is observed. The same property can be also found in table 1.

As seen from the lower part of table 2, weak correlations are observed in the relative azimuthal angles between the particles 2,3 and 4. This fact does not contradict the mechanism presented by the diagrams in fig. 2 (a,b,c) where these particles come from different vertices or they are spectators (diagram 2c). The characteristics of the fast deuterons from the "quasi-two-body" $p^4He \rightarrow pdd$ and $p^4He \rightarrow pdpn$ processes are compared above. The data are in good agreement.

Now we are going to examine the $p^4He \rightarrow pd_s pn$ and $p^4He \rightarrow pdd$ reactions in common, both having a spectator deuteron. The corresponding diagrams are presented in fig. 2 a) and d). Evident concurrency is expected between these reactions under the assumption that the deuteron formation proceeds via the final state interaction of the two recoil nucleons which in turn come from the double scattering suffered by the leading proton.

To test this hypothesis, the double scattering process was generated using the Monte-Carlo method. The Bassel-Wilkin wave function was used to obtain the Fermi momentum distributions of nucleons in the ^4He nucleus. The energy conservation law was applied to determine the mass of off-mass-shell nucleons. In this case the deuteron was supposed to be on-mass-shell. The slope of the elastic nucleon-nucleon differential cross section was used in the generation process.

The modulus and angular distributions of the total momentum of the two recoil nucleons from the generated sample (3000 events) are compared with the experimental ones. They are presented by the same distributions of the recoil proton-neutron pair and by the corresponding distributions of the fast deuteron, taken as a whole, from the $p^4He \to pd_s pn$ and $p^4He \to pdd$ reactions, respectively.

The results of the previous comparison are given in fig. 6. The agreement between the generated and experimental results confirms the proposed reaction mechanism. So, the generated sample can be compared separately with any of the reactions under study in order to understand a qualitative picture of the deuteron formation process.

The modulus and angular distributions of the fast deuteron momentum from the $p^4He \to pdd$ reaction and the total momentum of the recoil nucleon pair from $p^4He \to pd_s pn$ are compared in fig. 7. Both distributions are normalized to the same amount of events for visualization.

The figure shows that deuterons are formed from those nucleon pairs which have not too large total momenta and relatively large polar angles. Such a correlation shows an evidence in favour of the proposed mechanism for fast deuteron formation from recoil nucleons because it corresponds to the kinematics of quasi-elastic scattering.

The difference of two momentum vectors is referred to as a relative momentum for the rest. The relative momentum and relative angular distributions of the recoil proton and neutron and the same distributions for the recoil nucleons are demonstrated in fig. 8 from the $p^4He \to pd_s pn$ reaction and from the Monte-Carlo generated sample, respectively. The different characters of the relative momentum distributions show evidence in favour of coalescence. As a consequence, the nucleon pairs with small relative momenta leave for the concurrent $p^4He \to pdd$ reaction. Since the relative angular distributions are identical, there is no clear sign for the presence of some angular correlations caused by nucleon coalescence. This last result argues in favour of a random nature of the nucleon coalescence mechanism, and the temperature seems to be the principal parameter determining it.

Conclusion

The distinguishing features of fast deuteron formation in the $p^4He \to pdd$ and $p^4He \to pdpn$ reactions have been studied. Concretely, the momentum and angular distributions of fast deuterons are compared with each other and both of them are confronted with the results

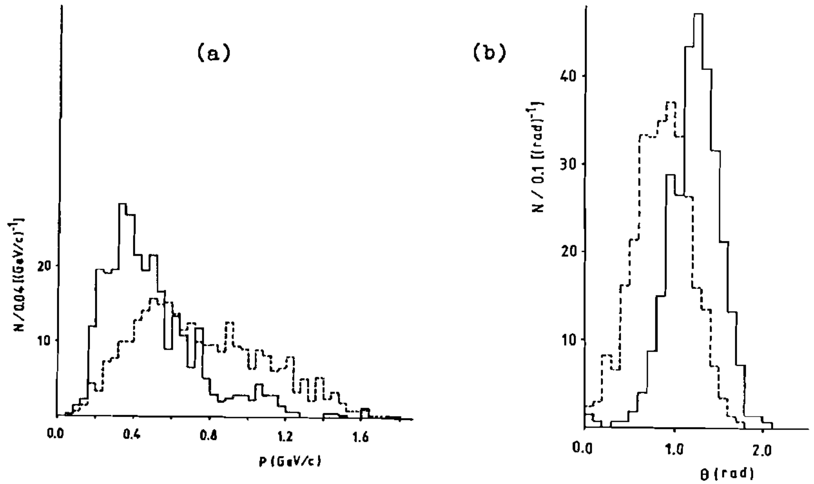

Fig. 7. Momentum (a) and angular (b) distributions: the full lines refer to the fast deuteron from $p^4He \to pdd$ and the dashed lines are for the total quantities of the slow proton-neutron pair from $p^4He \to pd_s pn$, where in the last case only the events containing spectator deuterons are considered.

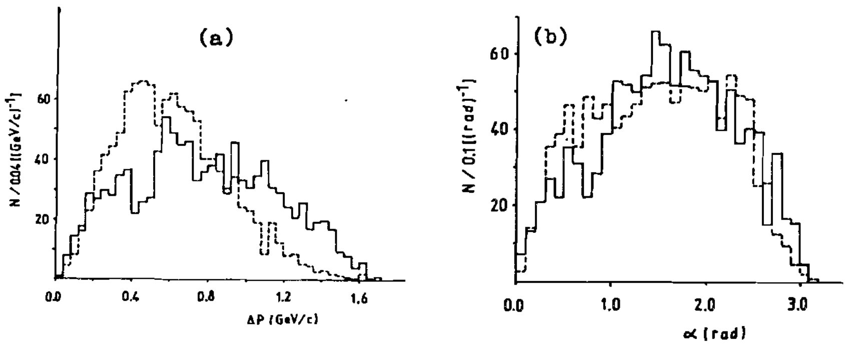

Fig. 8. Relative momentum (a) and relative angle (b) distributions of the slow proton and neutron from the $p^4He \to pd_s pn$ reaction (full lines); d_s means a spectator deuteron. The dashed lines correspond to the recoil nucleons from the Monte-Carlo generated sample.

of the Monte-Carlo sample generated in the framework of a simple multiple scattering model. All these facts lead to the conclusion that the bulk of nonspectator deuterons is formed by nucleon coalescence via final state interaction. This coalescence process is of a random nature, and it is determined mainly by the proton and neutron relative momenta.

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