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PECULIARITIES OF DEUTERON PRODUCTION IN ^{4}He-PROTON INTERACTIONS[1]

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Some features of fast deuteron production have been studied in ^{4}He nucleus-proton collisions at 8.6 GeV/c. An experiment has been carried out by means of a 1 meter hydrogen buble chamber at the JINR.

^{4}He$p \to ddp$ and ^{4}He$p \to dppn$ reactions have been compared with each other as well as with the results obtained by the Monte-Carlo procedure based on a double scattering model. The comparisons bear evidence that the great bulk of nonspectator deuterons is formed by a coalescence mechanism via a final state interaction. The coalescence is of a random nature and depends mainly on the proton and neutron relative momenta.

ОСОБЕННОСТИ ОБРАЗОВАНИЯ ДЕЙТРОНОВ ВО ВЗАИМОДЕЙСТВИЯХ ЯДЕР ^{4}He С ПРОТОНАМИ

В работе исследовались особенности выхода быстрых дейтронов во взаимодействиях ядер ^{4}Не с протонами при переданном импульсе 8,6 ГэВ/с. Эксперимент выполнен на 100-сантиметровой водородной пузырьковой камере ОИЯИ.

Сравнение характеристик реакций ^{4}НЕ$p \to ddp$ и ^{4}НЕР $\to dppn$ между собой, а также с результатами расчетов Монте-Карло в модели двухкратного рассеяния показало, что основная часть неспектаторных дейтронов образуется путем их слипания при взаимодействии в конечном состоянии. Процесс слипания носит стохастический характер и зависит главным образом от относительного импульса протона и нейтрона.

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I. INTRODUCTION

The abundant deuteron yield induced by high energy particles [1 – 5] from the nuclei has been in the centre of considerable interest for some time. Experiments carried out with proton beams impinging on a 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 the target mass number. The results could not be understood in the framework of the statistical model [5], have, however been satisfactorily described by the coalescence model [3, 5]. The coalescence model was also applied to nuclear collisions in order to explain the light fragment production.

We would like to note that all the quoted experiments were carried out with counter technique. Hence in measurements of the fragment production cross sections they were limited 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.

We had a unique opportunity to investigate on the JINR synchrophasotron the nuclear fragmentation processes caused by nuclei accelerated up to relativistic energies. The charged fragments with relatively hight momenta produced in nucleus-proton collisions, for example, in a hydrogen bubble chamber allow in most cases to reconstruct the full picture of reactions.

II. EXPERIMENTAL RESULTS AND DISCUSSION

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

If one considers nothing more than the pionless reactions, then only the following two channels supply deuterons:

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

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

Both reactions are constrained kinematically. Reaction (1) is notable for the usual presence of the spectator deuterons. This is easy to see from Fig. 1, where the slower deuteron momentum and angular distributions are displayed in a projectile rest frame. The other (fast) deuteron and the leading proton form a pair that is governed by the quasi two-particle kinematics in a natural way. 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 the two-dimensional momentum versus polar angle plot.

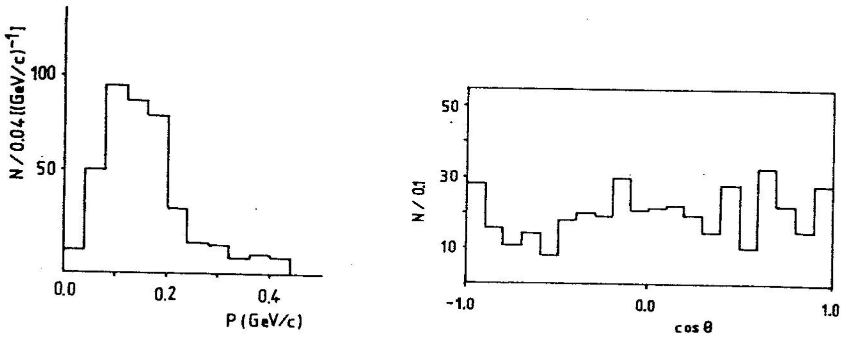


Fig. 1. Momentum (a) and angular (b) distributions of the slow deuteron from the p^4He → pdd reaction.

However, this proof is not sufficient to make the quasielastic knock-out responsible for the fast deuteron production. On the contrary, the slope of the differential cross section $d\sigma/dt \sim e^{bt}$ of reaction (1), fitted in (0.0, 0.3) (GeV/c)^2, has turned out to be too small ($b = 7.0 \pm 0.7$ (GeV/c)$^{-2}$) in comparison with the slope of the elastic scattering ($b = 22.4 \pm 0.1$ (GeV/c)$^{-2}$)[1)] and to be close to the value, characteristic for the NN elastic scattering. These facts could prove the deuteron formation during the course of the reaction. As the reaction (2) is concerned it has been pointed out that the events with not too large deuteron momenta ($p_d < 0.7$ GeV/c) proceed via a double scattering of the leading proton on the ^{4}He 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 a final state interaction one may propose a number of simple diagrams to describe the deuteron production (Fig. 2). The charge exchange channel (623 events with the leading neutron) is excluded from the present analysis. Methodical cuts have been applied to reject the events in which, by mistake, the concurrent hypothesis was chosen, since the proton-deuteron ambiguity cannot be resolved unambiguously on the basis of ionization losses. As

[1)] This value has been obtained from the 1 m HBC data taken at 3.3 GeV/c deuteron momenta.

a consequence of the latter 212 events have been discarded. Thus, 1948 charge retention events entered the analysis of the $p^4He \rightarrow pdpn$ reaction.

The subscript "f" denotes the leading proton on the diagrams in Fig. 2. Diagram a) represents a double scattering suffered by the leading proton and a residual deuteron; b) corresponds to the final state interaction of one recoiled and spectator nucleons to give rise to a deuteron; c) is the analogue of the previous case but two recoiled nuclei are joined. The last diagram d) describes the $p^4He \rightarrow pdd$ reaction. Diagrams with the leading deuteron are not presented because no such event has been found.

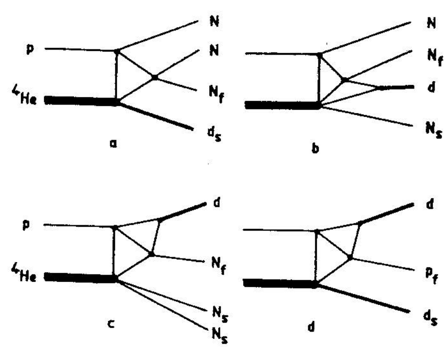


Fig. 2. Diagrams of pionless reactions with a deuteron produced in double scattering processes suffered by the leading proton.

The comparison of diagrams a), b), and c) in Fig. 2 leads to the following results: one would expect the fastest deuteron in case c) and the slowest in case a). For convenience the momenta of the secondary particles of the $p^4He \rightarrow pdpn$ reaction were put in descending order. Thus, 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 the leading deuteron for the reason mentioned above.

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

Now the other 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 diagram c) in Fig. 2 would result in spectator-like distribution for slow nucleons labelled 3 and 4.

The deuteron distributions would be similar to those of the fast deuteron from the "supplementary" $p^4He \rightarrow pdd$ reaction.

Table 1

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

Particle subscript \ Deuteron 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 ± 0.57	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
4	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

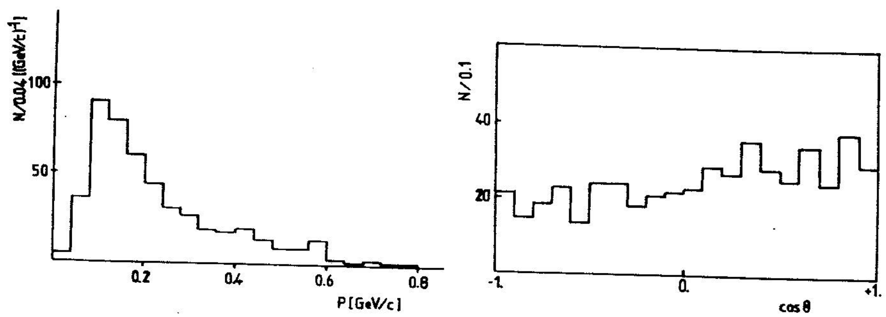
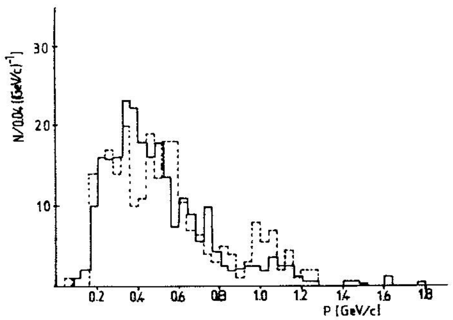


Fig. 3. Momentum (a) and angular (b) distributions of the slow nucleons from the $p^4He \rightarrow pdpn$ reaction containing a fast deuteron.

Fig. 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 that deuterons 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, too. The histograms are normalized to the same amount of events. It is easy to note that both results are in good agreement. Thus the hypothesis about the adequacy of diagram c) in Fig. 2 to the studied process may be considered to be proved.

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



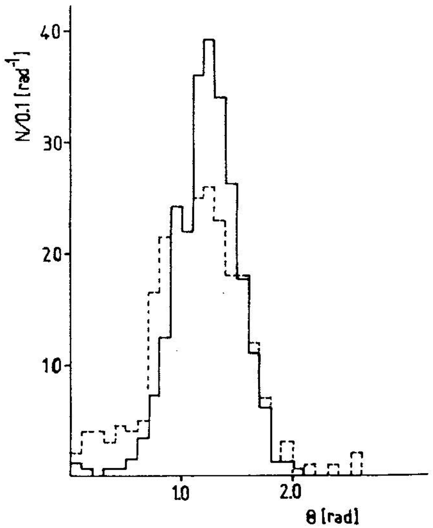


Fig. 4. Momentum (a) and angular (b) distributions of the fast deuterons from p^{3}He $\rightarrow$ pdd (full line) and the pHe $\rightarrow$ *pdpn* (dashed line) reactions.

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

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)	0.244 ± 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. The large values of asymmetries express the kinematics of the process in a transversal momentum space. The weaker the correlation between the deuteron and the leading proton is, the lower is the observed deuteron momentum. The same property can be found in Table 1, too.

Weak correlations are observed in relative azimuthal angles between the particles 2, 3 and 4 as it is shown in the lower half of Table 2. This fact does not contradict the mechanism represented by the diagrams in Fig 2 (a, b, c) where these particles either come from the different vertices or are spectators (diagram 2c). Thus, in the above, the characteristics of the fast deuterons have been compared from the "quasi two body" p^4He $\rightarrow$ *pdd* and p^4He $\rightarrow$ *pdpn* processes. The data have been found to be in good agreement.

Now we are going to the p^4He $\rightarrow$ *ppnd*, and the p^4He $\rightarrow$ *pdd* reactions in general, both having a spectator deuteron. The corresponding diagrams are represented in Fig. 2a) and d). Evident concurrence is expected between these reactions under the assumption that the deuteron formation proceeds via a final state interaction of the two recoiled nucleons which in turn come from the double scattering suffered by the leading proton.

The Monte Carlo generation of the double scattering process was performed to test this hypothesis. The Bassel-Wilkin wave function was used to obtain the Fermi momentum distributions of the nucleons in the ^{4}He nucleus. The energy conservation law was applied to determine the mass of the off-mass-shell nucleons. The deuteron in this case was supposed to be an on-mass-shell one. The slope of the elastic nucleon-nucleon differential cross section was entered into the generation process.

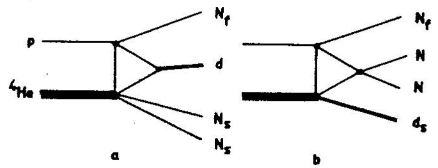


Fig. 5. Examples of diagrams describing deuteron production in simple scattering processes suffered by the leading proton.

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

The results of the previous comparison are presented in Fig. 6. The agreement between the generated and the experimental results confirms the proposed reaction mechanism. And so one may compare the generated sample separately with any of the studied reactions in order to understand the qualitative picture of the deuteron formation process.

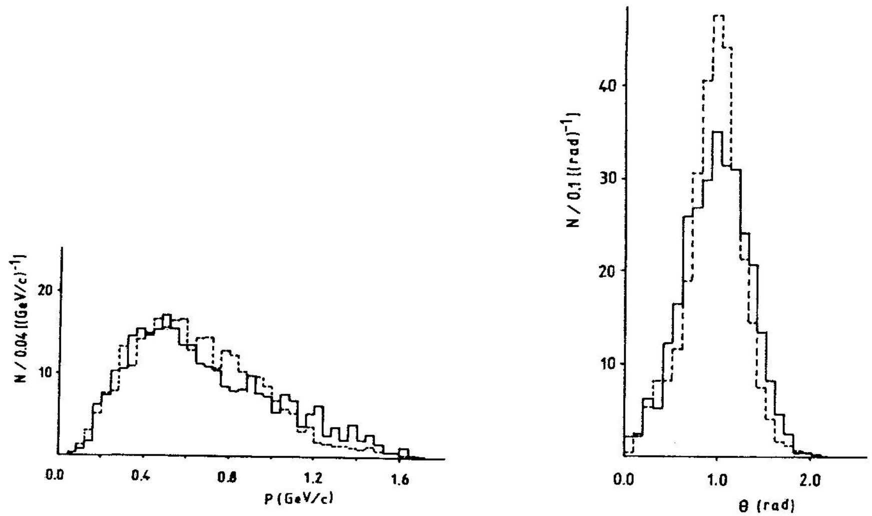


Fig. 6. Momentum (a) and angular (b) distributions: the full lines denote the distributions of the fast deuteron from the $p^4He \rightarrow pdd$ and those of the total momenta of the recoiled proton – neutron pairs from $p^4He \rightarrow pd_s pn$ joined together; d_s in the latter reaction denotes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

The modulus and the angular distributions of the fast deuteron momentum and those of the total momentum of the recoiled nucleon pair from the $p^4He \rightarrow pdd$ and the $p^4He \rightarrow pd_s pn$, respectively, are compared in Fig. 7. Both distributions are normalized to the same amount of events for visualization purposes.

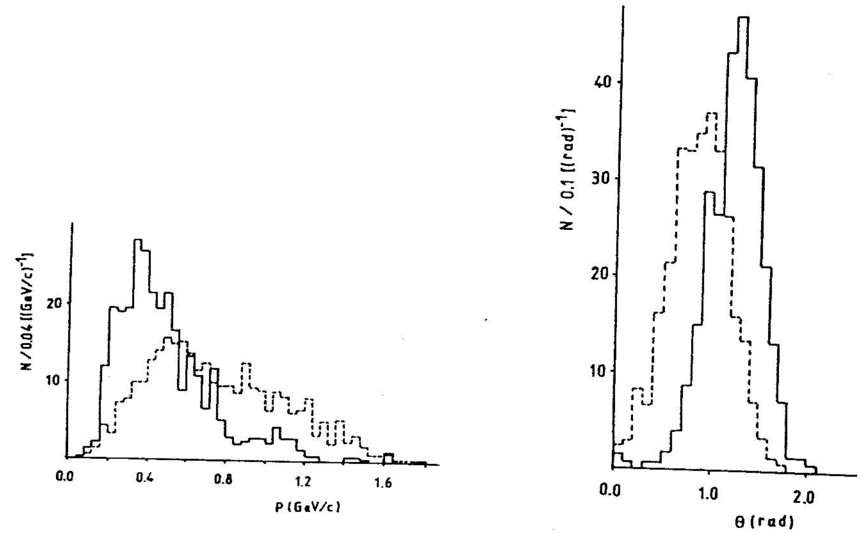


Fig. 7. Momentum (a) and angular (b) distributions: the full lines refer to the fast deuteron from $p^4He \rightarrow pdd$ and the dashed lines are for the total quantities of the slow proton – neutron pair from the $p^4He \rightarrow pd_s pn$, where in the fast case only the events containing spectator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

The figure indicates that deuterons are formed from those nucleon pairs which have not too large total momenta and comparatively large polar angles. Such correlation is again an evidence in favour of the proposed mechanism for a fast deuteron formation from recoiled nucleons, because it corresponds to the kinematics of quasielastic scattering.

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

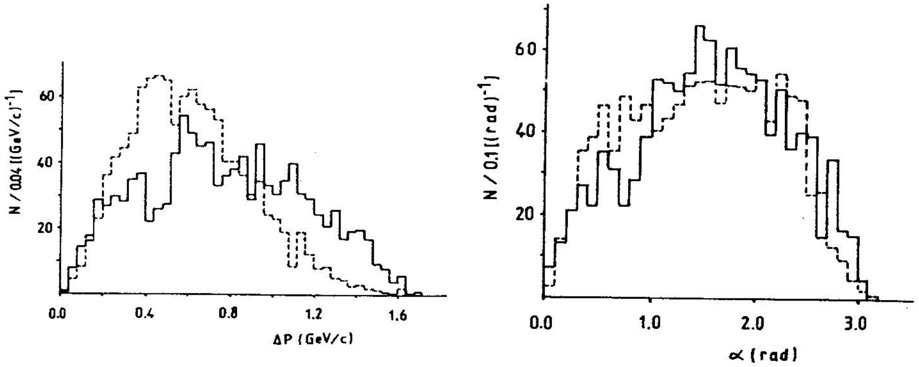


Fig. 8. Relative momentum (a) and relative angle (b) distributions (full lines); d_s denotes a spectator deuteron. The dashed lines correspond to the recoiled nucleons from the Monte Carlo generated sample.

CONCLUSION

Special features of the fast deuteron formation in the p^4He $\rightarrow$ *pdd* and the p^4He $\rightarrow$ *pdpn* reactions have been studied. Concretely, the momentum and angular distributions of the fast deuterons have been compared with each other and then both compared with the results of a Monte Carlo sample generated in the framework of a simple multiple scattering model. From all these facts we can draw the conclusion that the bulk of the nonspectator deuterons is formed by nucleon coalescence via a final state interaction. This coalescence process is of a random nature and is determined mainly by the proton and the neutron relative momenta.

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