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# Fast deuteron production in proton-nucleus interactions

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**Abstract.** Deuteron formation in proton-nucleus reactions due to the coalescence mechanism with final-state interaction between nucleons is discussed in order to establish the kinematical region of the validity of this approach. The experimental data on fast deuteron production in proton-nucleus collisions at bombarding energies above 3 GeV are analyzed. It is shown that most experimental results were obtained for deuteron momenta below the critical limit of the coalescence model. It is discussed to which extent further experimental studies could help to identify contributions from the coalescence mechanism and to get better understanding of the fast deuteron-production process.

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## 1 Introduction

The production of fast deuterons in proton-nucleus collisions has, for a long time, attracted considerable attention [1, 2, 3, 4]. Of special interest are direct mechanisms for the production of fast fragments. The most intriguing process is the fragment production as a result of an interaction of the incident proton with a bound system of several nucleons or a multi-quark bag inside the target nucleus. In the single-particle approach, such a bound multi-nucleon state is described in terms of the high-momentum component of the nuclear-wave function. Therefore, the production of fast deuterons in proton-nucleus collisions is a good tool for studying the properties of nuclear matter at short distances.

The standard direct process for fast deuteron production is the reaction $p+N \to d+\pi$. The cross section for this reaction decreases rapidly with increasing proton energy. Contributions from this quasi-free process have been experimentally observed in proton-nucleus collisions at a projectile energy $T_p$ = 1.3 GeV [5]. At incident energies above 3 GeV [6], reactions with multiple pion production might contribute, but little is known about the corresponding reaction cross section. Another possibility for the direct production of fast deuterons is the formation of a six-quark state in the primary interaction.

Besides the direct deuteron-production processes mentioned above several competing mechanisms have been discussed: at low collision energies, the relative momentum of the impinging proton and a neutron inside the nucleus is small and the pick-up mechanism is considered to be responsible for the deuteron production. With increasing proton energies, the pick-up process is not expected to contribute considerably to the observed deuteron-production cross section because the relative proton-neutron momentum is much higher than the internal momentum of the nucleons in the deuteron.

At higher collision energies ($T_p \geq$ 1 GeV), several fast nucleons may be produced due to cascading of the incident proton and of secondary particles inside the target nucleus. When a created neutron-proton pair possesses a wave function that overlaps with the deuteron-wave function, these nucleons may fuse to a deuteron due to final-state interaction. This nondirect mechanism was first discussed by Butler and Pearson [1] who invented the simple coalescence model. The coalescence model has to be studied carefully in order to enable a reliable estimate of the secondary deuteron formation. Only if this formation rate is known, the deuteron-production rate in direct processes can be determined from the experimental data and information on multi-nucleon or multi-quark nuclear-bag effects can be deduced.

In this paper we discuss the general assumptions of the coalescence model and specify the kinematical region of its applicability. The experimental data on fast deuteron production in proton-nucleus collisions at energies above 3 GeV are reviewed and compared with calculations in the framework of the coalescence model.

This work has partially been motivated by realizing that measurements under forward angles using the 0° Facility [7, 8] at the proton synchrotron COSY-Jülich at incident energies $T_p \approx$ 1 GeV can help to obtain further information on the fast deuteron-formation process.

## 2 The coalescence model

The process of fast fragment production in hadron-nucleus collisions is frequently described in the framework of the co-

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alescence model [1, 2, 9, 10]. In this model it is assumed that a group of nucleons form a complex fragment if the relative momentum of each nucleon lies within a momentum sphere with radius $q_0$. The model describes the nondirect process of fragment production as a result of the interaction of the nucleons in the final state. It should be noted that the coalescence model has also been successfully used for the description of $\bar{d}$-production cross sections in $e^+e^-$ annihilations at $\sqrt{s}$ = 10 GeV [11].

In the framework of the coalescence model the invariant differential cross section for deuteron formation is proportional to the product of the neutron and proton cross sections:

$$E_d \frac{d^3\sigma}{dp_d^3} = \frac{\kappa}{\sigma_{\text{in}}} E_p \frac{d^3\sigma}{dp_p^3} E_n \frac{d^3\sigma}{dp_n^3} , \tag{1}$$

where the proton and neutron production cross sections are determined for nucleon momenta equal to one half of the deuteron momentum

$$p_p = p_n = p_d/2 . \tag{2}$$

In (1) $\sigma_{\text{in}}$ is the inelastic cross section for a proton-nucleus collision and the factor $\kappa$ is the coalescence coefficient.

If one neglects kinematical and dynamical correlations of the produced particles and represents the multi-particle distribution as a product of single-particle distribution functions of the nucleon final states, then the independent production of nucleons in the nucleus is suggested. This statistical approach has been used successfully for the description of low-momentum fragments. If one assumes that the invariant differential cross section for neutron production equals that for the protons, then

$$E_d \frac{d^3\sigma}{dp_d^3} = \frac{\kappa}{\sigma_{\text{in}}} (E_p \frac{d^3\sigma}{dp_p^3})^2 . \tag{3}$$

Thus, by measuring double-differential proton and deuteron spectra the coalescence factor $\kappa$ can be determined. The analysis by Schwarzschild and Zupancic [2] of the deuteron-production cross section shows that $\kappa$ is proportional to the volume of the sphere of the relative nucleon momenta:

$$\kappa \propto q_0^3 . \tag{4}$$

The analysis neglects the dependence of $\kappa$ on the target mass and on the fragment emission angle. It was shown [2] that $q_0$ equals about 150–200 MeV/c which is comparable with the average internal momentum of the nucleons in the deuteron. Although $\kappa$ is treated as a free parameter, it was assumed that it reflects the property of the deuteron-wave function and does not depend on the collision dynamics.

However, the concept of independent production is incorrect in the case of fast secondaries, since for the fast outgoing particles it is necessary to account for at least the correlations due to the reaction kinematics. In order to define a fast fragment it is convenient to use the Feynman variable $x$, that allows one to scale the data on particle production independently of the collision energy. It is defined as $x = p_l^*/p_{\text{max}}^*$, where $p_l^*$ is the longitudinal and $p_{\text{max}}^*$ the maximum momentum of the outgoing particle in the incident hadron-nucleon center-of-mass system. As a crude estimate in the case of forward-particle production we can define $x$ as the fraction of the incident momentum that is carried away by the secondaries. The $x$ region is divided into two parts: the first one with $x$ less than 0.2 is denoted as the nuclear-target fragmentation region, whereas the other one is called the incident-particle fragmentation region.

Fragmentation of the target nucleus may be roughly considered like the independent particle production due to cascading of the projectile and secondary hadrons in the nuclear medium. Because the coalescence-deuteron momentum equals twice the nucleon momenta, the limitation for the statistical approach for the description of the deuteron formation can be estimated by means of the momenta detected:

$$p_d^{\text{lim}} = 2 \times (0.2 p_{\text{in}}) = 40\% p_{\text{in}} , \tag{5}$$

where $p_{in}$ is the incident proton momentum. Thus one can define the "fast deuteron" as a particle with a momentum above the critical value given by (5). Equation (5) is useful to scale the data on deuteron production by means of various hadron beams at different collision energies.

Obviously, the most interesting experimental results are expected for deuterons with momenta above $p_d^{\text{lim}}$. In the region of high momenta of the produced particles ($x > 0.2$), the leading particle effects become appreciable, manifesting themselves through kinematical correlations due to energy and momentum conservation. For instance, when several particles are produced in the first collision of the incident hadron with a target nucleon, the energy and emission angle of every particle is kinematically related with the properties of the others. These kinematical relations are insignificant if the total multiplicity is large and if we analyze slow secondaries. Moreover, in the projectile fragmentation region a substantial role is played by dynamical correlations in the production mechanism. As shown by Remler [12] and Gyualassy et al. [13] for calculations with the coalescence model it is necessary to know the multiparticle density function of the final states of the nucleons emitted from the nucleus. In the deuteron case in (1) one has to use the neutron-proton density distribution instead of the product of the single particle distributions. The calculation of the multi-particle density matrix is a rather complex problem. It was suggested by Bertsch and Cugnon [9] to use the cascade model for these calculations.

One more assumption which is largely unjustified is the use of the coalescence parameter $\kappa$ instead of the deuteron wave function. Although the coefficient $\kappa$ may be expressed through the average momentum of the nucleons in the deuteron, this simple approach does not account for the high-momentum component of the deuteron itself. As shown by the analysis of Lobov and Sibirtsev [14] and Gugelot and Paul [6] the secondary neutron-proton pairs produced with high total momenta basically have large relative momenta $q > q_0$. Only when one takes into consideration a realistic deuteron-wave function which contains momenta above 200 MeV/c, these neutron-proton pairs can fuse to form the deuteron. The differential cross section for the deuteron formation may be expressed as

$$E_d \frac{d^3\sigma}{dp_d^3} = \sigma_{in} \int \phi_d(q) G_{np}(q, p_d) \mathrm{d}^3 q , \tag{6}$$

where $\phi_d$ is the squared deuteron-wave function in momentum space and $G_{np}$ the two-particle density matrix of the neutron-proton states with total momentum $p_d$ and relative momentum $2q$. We use the deuteron-wave function in the form of the phenomenological approximation suggested by Alberi et al. [15].

**Table 1.** The kinematical ranges of the reported data on deuteron production in proton-induced reactions

| Ref. | Incident momentum [GeV/c] | $p_d^{\rm lim}$ [GeV/c] | Deuteron momenta [GeV/c] |
|---|---|---|---|
| [17] | 10.1 | 4 | 0.2–7.5 |
| [18] | 3 | 1.2 | 0.6–1.0 |
| [18] | 7.5 | 3 | 0.6–1.0 |
| [19] | 10.1 | 4 | 0.8–1.8 |
| [20] | 71 | 28 | 2.9–9.4 |
| [21] | 300 | 120 | 30–60 |

The density matrix was calculated by the three-dimensional cascade model described in details in [16]. A Monte-Carlo method was used in order to calculate primary and secondary collisions of the incident and cascade particles in the nuclear medium.

## 3 Data analysis

Although the possibility for production of fast fragments in the breakup of a multi-nucleon or multi-quark nuclear bag was pointed out long time ago, the number of experimental studies on the fast deuteron production has been rather limited. Moreover, there is an appreciable uncertainty in the analysis and theoretical interpretation of the available experimental data.

In Table 1 we collect the experimental data measured in proton-nucleus collisions. For every proton energy we also list the deuteron momentum (5) above which the reliability of the statistical approach to the particle-production dynamics becomes questionable. Among the available experimental results the most interesting ones were measured with 10 GeV/c incident protons and deuteron momenta $p_d$ higher than $p_d^{\rm lim}$ from (5) [17].

Figure 1 shows the experimental energy spectra of deuterons produced at angles of 59° and 119° in the interaction of 3 GeV/c protons with copper nuclei [18]. The solid lines show the results of our calculations using (6). Figure 2 gives the same comparison for the deuteron-production cross section at emission angles of 40° and 119° in collisions of 7.5 GeV/c protons with a lead target [18]. The results of the calculations provide a reasonably good description of the experimental data.

The analysis of the experimental results on deuteron production at high incident proton energies showed [19, 20, 21] that the coalescence model reproduces the data quite well. However, as is shown in Table 1 the deuteron data are below the critical region of the coalescence model.

Figure 3 shows the invariant differential cross section for deuteron production at an angle of $3.5^\circ$ in collisions of 10 GeV/c protons with Be, Al, Cu and Ta nuclei [17]. Because the deuterons are produced at forward angles it is possible to use the small-angle Glauber approach and to calculate the neutron-proton density matrix analytically. The lines in Fig.3 show our coalescence-model results calculated in analogy with [17]. The model quite reasonably reproduces the experimental data for the production of deuterons with momenta below 4 GeV/c.

**Fig. 1.** Energy spectra of deuterons produced at 59° (◯) and 119° (+) in proton-copper collisions at 3 GeV/c. Experimental points are from [18], the solid lines show our calculations with the coalescence model. The arrow indicates the statistical limitation

**Fig. 2.** Energy spectra of deuterons produced at 40° (◯) and 119° (+) in proton-lead collisions at 7.5 GeV/c [18]

Note that this momentum coincides with the limitation (5) for the statistical approach. At deuteron momenta above 6 GeV/c the experimental data diverge from the model calculations. The underestimation of the Be results in the whole momentum range might be due to the limitation of the Glauber approach for light nuclei.

Summarizing, only a limited set of experimental results on deuteron production in proton-nucleus collisions is available. Most of the data were obtained at momenta where the statistical approach for the description of particle-production dynamics is expected to provide a reasonable explanation and, in fact, the coalescence model reproduces the slow deuteron spectra from nuclei. At least there is no evident signature for the contribution from other mechanisms which may be responsible for the deuteron production.

The experimental data from [17] on the production of deuterons with momenta above limitation (5) are described reasonably well by our calculations, whereas the statistical approach cannot be used for the analysis of the high-momentum deuterons. Probably, the remaining discrepancy is caused by

**Fig. 3.** Momentum spectra of deuterons produced at $3.5°$ in proton-nucleus collisions at 10.1 GeV/c [17]

**Fig. 4.** Neutron-proton state-density function versus the internal momentum $q$ calculated for proton-carbon collisions at 1 GeV (solid line) and the deuteron-wave function from [15] (dashed)

an uncertainty of the parametrization of the deuteron-wave function from [15].

## 4 Proposed deuteron studies

In principle, the direct process of the break-up of a multi-nucleon or multi-quark nuclear bag can contribute significantly to forward particle production because of the reaction kinematics. The nondirect mechanism of the deuteron formation due to the neutron-proton final-state interaction should lead to a more isotropic angular distribution of the deuterons. For this reason the study of fast deuteron production at small angles is advantageous for the investigation of nontrivial effects.

The 0° Facility at COSY-Jülich is especially designed for studies of physical processes at small angles and low cross sections. One of the goals is to measure fast forward deuterons ($x > 0.3$) in coincidence with $K^+$ mesons produced in proton-nucleus collisions at bombarding energies around 1 GeV [7, 22].

In order to estimate the "background" from deuteron production due to the coalescence mechanism we made calculations where the neutron-proton density matrix was obtained using the cascade model [16]. The neutron-proton density matrix integrated over the total momentum of the nucleon pair is shown in Fig.4 (solid line) as a function of the internal momentum of the two-nucleon system. The statistical approach (3) to the deuteron formation accounts only for neutron-proton pairs with momenta $q$ below 0.2 GeV/c, that is about 60 percent of the nucleon pairs produced in proton-carbon collisions at 1 GeV. By the dashed line in Fig.4 we show the deuteron-wave function from [15]. Since the deuteron contains a high-momentum component of about 5% ($q > 0.2$ GeV/c), the overlapping of the tail of the deuteron-wave function with the neutron-proton density function may contribute roughly a fraction of $0.05 \times 0.4$ to the total deuteron yield. For this reason the high-momentum component of the deuteron-wave function is important to account for the fast deuteron formation.

Figure 5 shows the calculated (6) deuteron-momentum spectra produced in collisions of protons with carbon nuclei at 1.0 GeV. The spectra are integrated over all deuteron-emission angles. The coalescence model (solid line) which accounts for the neutron-proton density matrix and the deuteron-wave function from [15] predicts that about 10 percent of the deuterons with momenta above the limitation (5) are produced due to the final-state interaction. The dashed line in Fig.5 shows the results calculated in the statistical approach (3). It is clear that the measurement of deuterons with momenta above $\sim 0.7$ GeV can serve as a test of the coalescence mechanism at beam energies around 1 GeV which are accessible at COSY.

**Fig. 5.** Deuteron-momentum spectrum produced in proton-carbon collisions at 1 GeV. The dashed line shows the result of the calculation in the statistical approach; the solid line the deuteron spectrum from the coalescence mechanism. Deuterons produced in the quasi-free mechanism (dotted line) are peaked around 1.7 GeV/c

The measurement of fast deuterons from quasi-free reactions is a very attractive goal since it has been under discussion if deuterons do exist in nuclei at central densities $\rho = \rho_0$ [23, 24]. Furthermore, details of the deuteron-formation process in the nuclear medium can be obtained. As mentioned above, the measurement of such quasi-free deuterons in coincidence with $K^+$ mesons is planned at the 0° Facility. Since the cross section for the production of $K^+$-deuteron pairs is extremely small [22] it is planned, however, to begin the ex-

**Fig. 6.** Same like Fig.5 for coalescence and quasi-free deuterons with emission angles $\theta_d < 10°$

perimental program with the measurement of uncorrelated deuterons.

The dotted line in Fig.5 shows the spectra of deuterons produced in the quasi-free reaction $p + N \rightarrow d + \pi$. In our calculations we used the parametrization by VerWest and Arndt [25] and account for Fermi motion. At a bombarding-proton energy of 1 GeV the reaction cross section on free nucleons equals about 0.3 mb. Thus the yield of direct deuterons from nuclei is also small. It is seen from the figure that, if the deuterons from the quasi-free mechanism exist, it will be difficult to disentangle them from the background of coalescence deuterons without any angular information. However, in the following we show that measurements under forward angles are more sensitive.

The angular spectrum of the coalescence deuterons is quite close to an isotropical distribution. Our calculations show that the anisotropy of the deuteron spectrum, which can be defined as the ratio of the number of deuteron produced at forward angles with $0° < \theta < 90°$ to the number of backward deuterons, equals about 1.2. On the other hand, deuterons produced in the quasi-free reaction are located in the region $\theta < 25°$. In Fig.6 we show the momentum spectra for quasi-free and background deuterons emitted under forward angles $\theta < 10°$. The quasi-free deuterons are now clearly separated from the background and can be identified due to the clear peak structure in the spectrum.

It is important to emphasize two basic reasons which demonstrate the advantages of studing the fast deuteron production at moderate energies and at small angles. First, the contribution from direct processes $p + N \rightarrow d + \pi$ to fast deuteron production is negligible at high collision energies, because of the small reaction cross section [5]. We can assume that direct deuteron production in this regime is mainly accompanied by multiple pion emission. However, little is known about the cross section of the reaction with multiple pion production.

Second, as we showed, the deuteron production due to final-state interaction is characterized by an isotropic angular distribution. Due to the two-body reaction kinematics, direct deuteron production is forward peaked. Small angles are expected to be enriched by the direct fast deuteron production mechanisms.

## 5 Conclusions

We analyzed deuteron production by the coalescence mechanism due to final-state interaction between the nucleons. In the framework of the coalescence model the deuterons are formed when the outgoing neutron-proton pairs possess a wave function which overlaps with the deuteron-wave function. The neutron-proton density-distribution matrix was calculated by means of the cascade model. So far, only experimental data are available for incident proton energies above 3 GeV and, which is more important, most of the data are limited to deuteron momenta below 40% of the projectile momentum. We get a good description of the experimental data obtained in the target-nucleus fragmentation region, where the independent-particle production dynamics should be valid. The crucial test of the coalescence mechanism is to analyze data of fast deuterons ($p_d > 40\% p_{in}$) because here the particle-production dynamics and the realistic deuteron-wave function contribute significantly. For this reason, we propose experimental studies at the 0° Facility at COSY-Jülich where proton beams with energies below 2.5 GeV will be available. We analyzed the contribution from the coalescence mechanism to the deuteron production in proton-nucleus collisions at bombarding energies of 1 GeV. It is shown that the observation of deuterons with momenta higher than 0.7 GeV/c under forward angles will allow to probe the coalescence approach.

It is important to note, that fast deuterons may be produced via the direct mechanism, particularly in quasi-free reactions $p + N \rightarrow d + \pi$ or the break-up of multi-quark nuclear bags or the formation of a six-quark state. We calculated the fast deuteron production in quasi-free reactions for a projectile energy of 1 GeV. It is shown that measurements at the 0° Facility at COSY-Jülich under forward angles are most sensitive to this process and allow to disentangle the quasi-free deuterons from the coalescence ones.

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