Mechanism of High-Energy Neutron Beam Production via Deuteron Fragmentation

Authors: Wang, Rensheng, Ou, Li, Xiao, Zhigang, Wang, Rensheng, Ou, Li, Xiao, Zhigang

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Abstract

Within the framework of an improved quantum molecular dynamics model, we have studied the fragmentation process of high-energy deuterons on heavy target nuclei, particularly focusing on neutrons emitted at near-zero-degree angles. The simulations reproduce the experimentally measured neutron double-differential cross sections for the 102 MeV d+C reaction. Based on the agreement between model and experimental results, we demonstrate the feasibility of producing high-energy neutron beams via deuteron fragmentation on carbon targets. However, due to Fermi motion of nucleons inside the deuteron, the neutron energy, including that at laboratory 0°, possesses a substantial energy spread. According to model calculations, by measuring the accompanying protons emitted in the deuteron fragmentation process, the outgoing neutron energy can be constrained to within 5% (1σ). Furthermore, this work demonstrates the feasibility of generating monoenergetic high-energy neutron beams based on accompanying proton measurements.

Full Text

Preamble

Rensheng Wang,(^{1,2,∗}) **Li Ou,**(^{3,†}) and **Zhigang Xiao**(^{4,‡})

(^{1})School of Radiation Medicine and Protection, Medical College of Soochow University, Suzhou, 215123, China
(^{2})Collaborative Innovation Center of Radiological Medicine of Jiangsu Higher Education Institutions, Suzhou, 215123, China
(^{3})College of Physics and Technology, Guangxi Key Laboratory of Nuclear Physics and Technology, Guangxi Normal University, Guilin 541004, China
(^{4})Department of Physics, Tsinghua University, Beijing 100084, China

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The deuteron breakup on heavy target has been investigated in the framework of an improved quantum molecular dynamics model, focusing on the production of neutrons near zero degrees. The experimental differential cross sections of neutron production in 102 MeV d+C reactions are reproduced by simulations. Based on the consistency between model prediction and experiment, the feasibility of producing neutron beams through deuteron breakup on carbon targets has been demonstrated. Because of nucleon Fermi motion inside the deuteron, the energy spectrum of inclusive neutrons near 0° in the laboratory exhibits considerable energy broadening in the main peak, while the long tail on the low-energy side is suppressed. By measuring the accompanying proton from deuteron breakup in coincidence, the neutron energy can be tagged with an intrinsic uncertainty of about 5% (1σ). This enables the application of well-defined energy neutron beams in an event-by-event scheme.

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Introduction

High-quality monochromatic neutron beams have very important applications in many fields. For instance, neutron radiation hardness evaluation for electronic elements in aviation devices requires neutron beams with well-defined energy [1, 2]. The assessment of neutron dose received by patients in heavy ion therapy or by astronauts in aircraft relies on calibration using well-defined neutron beams [3]. In fundamental research, high-energy neutron beams are significant for calibrating high-energy neutron detectors, as well as for accumulating data on neutron-induced reaction cross sections [4]. Undoubtedly, high-quality and high-energy neutron beams have become necessary tools [5-8]. Since the neutron has no charge, while neutron beams below 20 MeV can be produced by nuclear reactions with fixed Q-values at given angles, monochromatic neutron beams above 20 MeV are usually produced in laboratories via proton-induced reactions on lithium targets [7, 9, 10]. Since nucleons are bound in target nuclei via nuclear force, the knocked-out neutron possesses a long energy tail that cannot be eliminated [7, 11], nor can it be tagged on an event-by-event basis.

The properties of the deuteron nucleus and its applications have been subjects of intense study since its discovery in 1932 [12]. Deuteron beams were first produced one year later [13], and the first photodisintegrations of deuteron were measured shortly thereafter [14]. Using photographic photometry, the deuteron spin was determined to be J = 1 [15]. The deuteron was found to possess an electric quadrupole moment [16], indicating the existence of an additional D-wave component. Such D-wave components could be generated by the tensor part of the one-pion exchange (OPE) potential [17] and led to profound understanding of the nature of nuclear force. Since the 1950s, enormous experiments on ed scattering have been performed to extract the form factors of the deuteron nucleus, including charge monopole, magnetic dipole, and charge quadrupole form factors. For a review, see [18].

Deuteron-induced reactions also exhibit intriguing features. Coulomb polarization of deuteron-induced transmutation was discovered in 1935 [19, 20], and such polarization has been reported to increase fusion reaction rates very recently [21]. Measurements of deuteron breakup date back to the 1970s [22]. Moreover, the isovector reorientation effect has been predicted in deuteron-induced scattering on heavy targets, providing a novel probe of nuclear symmetry energy that remains a topic of hot discussion [23, 24].

Can deuteron be used to generate high-quality neutron beams? The answer appears to be yes. It has been mentioned that deuteron-induced reactions can be used to produce neutron beams and that the neutron energy can be tagged in the specific p(d, np)p channel [18], and some early measurements of the n-p angular and energy correlation in deuteron breakup have been reported [25]. Recently, Jin et al. reported that deuteron-induced spallation reactions could serve as a powerful method to generate neutron beams [26]. These results arise from the fact that the deuteron is a loosely bound nucleus with binding energy EB = 2.2 MeV and is easily dissociated in reactions with targets. Our motivation in this paper is to study the breakup process of deuteron in peripheral reactions, focusing on the advantageous possibility of precisely determining neutron beam energy. Since monochromatic deuteron beams are easily obtained from modern accelerators, if the idea of producing neutron beams with deuterons proves feasible, the neutron would be expected to retain half the momentum of the incident deuteron and could be used as a (quasi)monochromatic neutron beam. The paper is organized as follows: Section 2 briefly presents the improved quantum molecular dynamics (ImQMD) model, Section 3 discusses the distribution properties of the generated neutron beam, and Section 4 provides the conclusion.

Model Description

The ImQMD model is an extended version of QMD [27]. Detailed descriptions of the ImQMD model and its ImQMD05 version and their applications can be found in Refs. [23, 28–32], where deuteron- and nucleon-induced reactions are particularly simulated. Within the ImQMD05 model, the nucleon is represented by a Gaussian wave packet

$$\phi_i(\mathbf{r}) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left[-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{4\sigma_r^2} + \frac{i}{\hbar}\mathbf{r}\cdot\mathbf{p}_i\right]$$

where $\mathbf{r}_i$ and $\mathbf{p}_i$ are the centers of the wave packet of the ith nucleon in coordinate and momentum space, respectively.

According to results from our previous studies, a traditional value of $\sigma_r^2 = 2.0$ fm^2 is appropriate for intermediate-energy nucleon-induced reactions. Nucleons in a system move under the mean field with the nuclear potential energy density functional, which reads

$$V_{\text{loc}} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + g_{\text{sur}}(\nabla\rho)^2 + g_{\text{sur,iso}}[\nabla(\rho_n-\rho_p)]^2 + g_\tau\rho\tau + C_s\frac{\rho\delta^2}{2}$$

where ρ, ρ_n, ρ_p are the nucleon, neutron, and proton densities, $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry degree, and τ is the kinetic energy density.

The parameters in the equation, except C_s and γ which describe symmetry potential energy, are fully determined by Skyrme interactions. The Skyrme parameter set MSL0 [33], one of the Skyrme parameter sets that satisfies the current understanding of nuclear matter physics over a wide range of applications [34], is used in the calculations. The parameters are listed in Table I.

While the initialization of heavy target nuclei is done as usual in traditional QMD, the deuteron is initialized semiclassically using a simplified scheme as in [23]. At the end of the ImQMD calculations, clusters are recognized by a minimum spanning tree (MST) algorithm [27, 35] widely used in QMD calculations. In this work, nucleons with relative momenta smaller than 250 MeV/c and relative distances smaller than 3.0 fm are coalesced into the same cluster. Information on clusters with excitation energy is input into the statistical decay model GEMINI [36, 37] to perform statistical decay calculations.

TABLE I. Parameter set used in the ImQMD calculations. The parameters include α (MeV), β (MeV), γ, g_{sur} (MeV $\cdot$ fm^2), $g_{\text{sur,iso}}$ (MeV $\cdot$ fm^2), g_τ (MeV $\cdot$ fm^5), C_s (MeV), and ρ_0 (fm^{-3}).

Results and Discussions

We first calculate the phase space distribution of free neutrons in d+C reactions at 102 MeV where experimental data are available [38]. We choose stable carbon instead of heavy metal as the target simply to suppress contributions from target neutrons. Fig. 1 presents the doubly differential cross section $d\sigma/d\Omega dE_n$ as a function of kinetic energy E_n and polar angle θ in the laboratory for neutrons produced in the reactions.

The differential cross section is calculated by

$$\frac{d\sigma}{d\Omega dE} = \int_{b_{\min}}^{b_{\max}} 2\pi b\, f(E,\Omega,b)\, db = \sum_{i=b_{\min}}^{b_{\max}} 2\pi b_i \Delta b\, f(E,\Omega,b_i)$$

where $b_{\min} = 0.5$ fm, $b_{\max} = 8$ fm, and $\Delta b = 0.5$ fm are taken in our calculations. The probability distribution is written as $f(E,\Omega,b_i) = y(E,\Omega,b_i)/N$, where y is the yield of neutrons in each cell and N is the total number of simulated events under a given reaction condition. The scatter plot shows two components standing out statistically. One distributes nearly homogeneously over a wide angular range with $E_n < 20$ MeV, originating from the target region; the other sits in the projectile region, maintaining approximately the beam energy per nucleon at very forward angles with $\theta_{\rm lab} < 10^\circ$. Apart from these two components, neutrons from target fragmentation are distributed widely on the plot. The intensity in the target rapidity region is not high because (i) we chose a light target containing fewer neutrons and (ii) the binding energy of the deuteron is much less than the separation energy of neutrons in carbon nuclei.

The energy spectra at specific laboratory angles can be obtained from Fig. 1 by slicing the two-dimensional histogram. Figure 2 presents neutron energy spectra with logarithmic scale on the ordinate at various angles in comparison to experimental data [38]. Our calculation reproduces the main peak near beam energy per nucleon well, particularly at small angles with $\theta_{\rm lab} \leq 5^\circ$. The height of the main peak decreases rapidly with $\theta_{\rm lab}$ in accordance with the data, indicating that neutrons are peaked at forward angles. On the other hand, due to clustering inefficiency of the transport model—i.e., the model counts fewer (more) clusters (nucleons) than experiment—the yield of neutrons at very low energy, originating mainly from target fragmentation, is overestimated by approximately 30%. Additionally, a very small peak near 100 MeV, corresponding to direct knock-out neutrons from the target, is not reproduced in our calculation.

FIG. 1. (Color online) The doubly differential cross section $d\sigma/d\Omega dE_n$ as a function of kinetic energy and emission angle relative to the beam direction.

If one counts only the main peak of the spectrum at 0° and 5°, a full width at half maximum (FWHM) of approximately 20 MeV can be derived. This readily indicates that direct deuteron breakup can serve as a neutron beam source with 20 MeV energy broadening.

Figure 3 further presents neutron energy spectra in the angular range $\theta_n < 2^\circ$ produced in d+C reactions with incident deuteron energies of 102, 200, and 400 MeV, respectively. The ImQMD simulation results with a GEMINI afterburner are represented by histograms in the upper panel. The standard deviation σ_{E_n} of the neutron beam normalized to the average neutron energy $\langle E_n \rangle$ is plotted in panel (b). At $E_{\rm beam} = 200$ MeV, σ_{E_n}—reflecting the monochromaticity of the secondary neutron beam—is about 33 MeV, which is larger than neutron spectra produced in p+Li reactions [7, 11]. The long tail on the low-energy side is much suppressed in d+C compared to that in the p+Li neutron production channel.

Although the binding energy of the deuteron is only 2.2 MeV, the proton and neutron in the deuteron have Fermi motion with an average momentum of 75 MeV/c, which causes broadening of the neutron energy in the main peak. In deuteron breakup or stripping reactions, the total energy of the projectile remains approximately constant, so anti-correlation is expected between the energies of the proton and neutron from deuteron breakup. Figure 4(a) presents a scatter plot of proton energy versus neutron energy in d+C reactions at various beam energies ranging from 60 to 400 MeV. A sharp band appears at each energy point, confirming the anti-correlation between proton and neutron energies. The total energy of the proton and neutron, $E_n + E_p$, is displayed in panel (b), where neutrons are counted within $\theta_{\text{lab}} < 2^\circ$. The total energy is constant with an intrinsic FWHM of about 5 MeV despite a tiny tail appearing on the low-energy side. This feature has been observed in d+12C at 270 MeV where correlated protons and neutrons were measured at 0° [40]. According to that experiment, the FWHM of the $E_n + E_p$ spectrum at 0° is about 2.5 MeV. Moreover, the intrinsic broadening of the total energy shows insignificant dependence on beam energy, implying that it originates from Fermi motion of nucleons rather than kinetic effects. This suggests that if one can measure the accompanying proton at forward angles, the neutron energy can be tagged with greatly improved accuracy compared to the raw main peak in Fig. 3.

A further question remains: can one maintain high efficiency in delivering a neutron beam with well-determined energy using proton tagging? Figures 5(a) and 5(b) present the proton tagging efficiency R_{tag} and the monochromaticity of the neutron beam using coincident protons with different angular cuts as a tag, respectively.

FIG. 2. (Color online) Comparison of neutron spectra at various angles between experimental results [38] and ImQMD calculations.

Here R_{tag} is derived from the ratio of the number of p-n coincidences to the total number of neutrons. When a neutron is found with $\theta_{\text{lab}} < 2^\circ$, the coincident proton is searched for with an angular cut in the laboratory as indicated in the figure. It reads $R_{\text{tag}} = N_{pn}/N_n$. The efficiency increases rapidly at low beam energy and gradually saturates at 90% for beam energies above 200 MeV/u. Comparing results at different θ_p cuts implies that the coincident proton remains at forward angles, in accordance with experimental observations [25]. The monochromaticity in panel (b) is defined as the standard deviation $\sigma_{E_{np}}$ of the total energy $E_n + E_p$ normalized to the mean neutron energy, $\sigma_{E_{np}}/\langle E_n \rangle$. Clearly, the monochromaticity improves with beam energy and is better than 3% in neutron beam production above 200 MeV.

Finally, Fig. 6 compares the cross sections for neutron production in two different channels: the deuteron-induced production d+12C studied in this work and the conventional channel p+7Li [11, 42–44]. The angular emittance of the neutron beam is $\theta_n < 2^\circ$ with respect to the primary beam in the laboratory system. The cross section for neutron production in d+12C is higher by a factor of 100, with only slight energy dependence. This result has important implications: to obtain the same neutron beam intensity, the primary deuteron beam intensity in the (d,np) channel can be lower than the proton beam intensity in the (p,n) channel by two orders of magnitude. As an advantage, the background is significantly reduced. The data point at $E_n = 51$ MeV sits on top of the simulation [38], indicating our calculation is reliable. This suggests that deuteron breakup provides a novel method to generate high-energy neutron beams with well-determined energy and high efficiency. It is worth mentioning that the cross section of secondary neutrons from deuteron breakup increases with the atomic number of the target [40], but likely at the price of producing more neutrons originating from the target, which degrades monochromaticity. It should be noted that in our transport model calculations, the mechanisms of stripping and breakup are not distinguished, since no coupled channels are considered [41].

FIG. 3. (Color online) The energy spectra (a) of neutrons in d+C at $E_d = 102$, 200, and 400 MeV deuteron beam energy within $\theta_{\mathrm{lab}} < 2°$. The relative standard deviation σ_{E_n}/E_n as a function of neutron energy is plotted in panel (b).

FIG. 4. (Color online) The correlation of high-energy neutron and proton at forward angles (a), and the total energy distribution of the neutron and accompanying proton (b).

Summary

To summarize, we calculated neutron spectra produced in d+C reactions at various incident energies and compared them with available experimental data. Neutrons originating from deuteron breakup retain kinetic memory of the projectile with some energy broadening arising from Fermi motion of nucleons in the projectile. The accompanying proton from deuteron breakup exhibits sharp anti-correlation with the neutron, and the total energy of the neutron and proton remains constant with less than 5 MeV intrinsic energy variation. Thus, with approximately 90% efficiency, the neutron energy can be tagged by the accompanying proton on an event-by-event basis with enhanced precision. The cross section for neutron beam production is much higher in the (d,np) channel than in the (p,n) channel.

FIG. 5. (Color online) The efficiency of proton tagging and the monochromaticity of the total energy of neutron and proton. Neutrons within θ_n are counted, while coincident protons are searched for with different angular cuts on θ_p in the laboratory.

FIG. 6. (Color online) The cross section of neutron production for two channels: d+12C and p+7Li.

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(^{∗}) wrs16@mail.suda.edu.cn
(^{†}) liou@gxnu.edu.cn

(^{‡}) xiaozg@tsinghua.edu.cn

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