Measurement of the Differential Reaction Cross Section for Neutron-Induced Deuteron Production

Authors: Longxiang Liu, Sun Kang, Yi Han, Lu Fei, Wang Hongwei, Fan Gongtao, Cao Xiguang, Zhang Yue, Zhang Suyalatu, Wang Dexin, Li Xinxiang, Yang Yuxuan, Kuang Pan, Hu Xinrong, Hao Zirui, Jin Sheng, Chen Kaijie, Jiang Wei, Fan Ruirui, Li Qiang, Chen Yonghao, Tan Zhixin, Li Yang, Longxiang Liu, Sun Kang, Lu Fei

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Abstract

The angular differential cross sections for the 12C(n,d)x reaction at a neutron energy of 33.9 MeV were measured at the Back-n white neutron source terminal of the China Spallation Neutron Source (CSNS). Using the Light Charged Particle Detector Array (LPDA) ΔE-E telescope system, the angular differential cross sections were measured in the laboratory coordinate system from 24.5° to 155.5°. The experimental results are in good agreement with previous experimental results. Due to the lack of experimental data, this work provides an important reference for the evaluation and development of relevant databases.

Full Text

Preamble

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Measurement of Differential Reaction Cross Sections for Neutron-Induced d Production

Longxiang Liu[1], Kang Sun[2],[3],[4], Han Yi[2],[3], Fei Lu[1], Hongwei Wang[1], Gongtao Fan[1], Xiguang Cao[1], Yue Zhang[1], Suyalatu Zhang[5], Dexin Wang[5], Xinxiang Li[6],[4], Yuxuang Yang[7],[6], Pan Kuang[6],[4], Xinrong Hu[6],[4], Zirui Hao[6],[4], Kaijie

Chen[8],[6], Wei Jiang[2],[3], Ruirui Fan[2],[3],[9], Qiang Li[2],[3],[9], Yonghao Chen[2],[3], Zhixin Tan[2],[3], Yang Li[2],[3]

(1. Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China)

Abstract

The angular differential cross sections for neutron-induced deuteron production from carbon were measured at a neutron energy of 33.9 MeV using the Back-n white neutron source at the China Spallation Neutron Source (CSNS). By employing the ΔE-E telescopes of the Light-charged Particle Detector Array (LPDA) system, we measured the angular differential cross sections for the 12C(n,d)x reaction from 24.5° to 155.5° in the laboratory coordinate system. The experimental results are in good agreement with previous measurements. Due to the scarcity of experimental data, this work provides an important reference for the evaluation and development of relevant nuclear databases.

Keywords: 12C(n,d)x reaction; angular differential cross sections; CSNS Back-n white neutron source; Light-charged Particle Detector Array

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Introduction

Carbon is a fundamental and essential element constituting organic life on Earth. Light charged particles produced from reactions between neutrons of several tens of MeV and carbon nuclei provide important information about nuclear structure, and nuclear reaction models require such angular differential cross section data for validation, as exemplified by the 12C(n,lcp) reaction [1-2]. Among these (n,lcp) reactions, 12C(n,d)x is particularly important because human tissue contains substantial amounts of carbon, and dose calculations for fast neutron cancer therapy and cosmic-ray-induced neutrons in human tissue require extensive angular differential cross section data of this type [1,3-8].

Additionally, charged particle production reactions are significant for nuclear detection applications. For instance, when simulating the response of carbon-based neutron detectors such as plastic scintillators to fast neutrons, precise cross sections and differential cross sections for the 12C(n,d)x reaction are essential [9]. Majerle measured the reaction cross section for 12C(n,d_0)11B [10], while Pillon et al. measured cross sections for both 12C(n,d_0)11B and 12C(n,d_1)11B [11]. Both measurements utilized diamond detectors, demonstrating that D-product reactions contribute to the response of such detectors.

However, the reaction cross section for 12C(n,d)x is relatively small, creating numerous experimental challenges [12]. To date, several relevant measurements have been conducted, most in the tens-of-MeV neutron energy range [13]: McNaughton et al. at 56 MeV [9], Subramanian et al. from 27.4 to 60.7 MeV [14], Slypen et al. from 29.5 to 72.8 MeV [12,15], Nauchi et al. at 64.5 and 75.0 MeV [16], Bergenwall et al. at 95.6 MeV [2], and Tippawan et al. at 95.6 MeV [1] all targeted double-differential cross sections for the 12C(n,d)x reaction, while Young et al. at 60.0 MeV [17] focused primarily on measuring the differential cross section for 12C(n,d)11B. All these measurements below 100 MeV were performed using monoenergetic neutron sources such as 7Li(p,n). While previous results show consistent trends, some measurements exhibit substantial discrepancies. For example, the data from McNaughton et al. at 56.0 MeV [9] are larger than those from Slypen et al. at 55.3 MeV [12]. Brenner et al. performed theoretical calculations of double-differential cross sections using the Intranuclear Cascade (INCA) program [18], which show certain differences from experimental results [12]. Therefore, additional measurements are needed, particularly those employing white neutron sources that enable systematic studies. The CSNS Back-n white neutron source terminal provides neutrons over a broad energy range, making it suitable for measuring neutron-induced nuclear reaction data [19]. Cui Zengqi et al. have performed partial angular and energy measurements, but they used a relative cross section method [20].

In this work, we completed measurements of the differential cross sections for the 12C(n,d)x reaction at a neutron energy of 33.9 MeV. A graphite target served as the sample for the 12C(n,d)x reaction. The Light-charged Particle Detector Array (LPDA) ΔE-E telescope system was employed in the experiment, with each detector set comprising a low-pressure multi-wire proportional chamber (LPMWPC) as ΔE, a silicon detector (ΔE or E), and a CsI detector (E). The telescopes were positioned at forward angles from 24.5° to 91° and backward angles from 89° to 155.5° relative to the neutron beam direction [20-25].

1. Experimental Setup

1.1 Neutron Source

The China Spallation Neutron Source produces spallation neutrons by bombarding a tungsten target with a 1.6 GeV, 100 kW proton beam at 25 Hz in a rapid cycling synchrotron. This measurement was conducted at the Back-n white neutron beamline Endstation 1 [24]. The Back-n white neutron beamline provides a neutron source with a broad energy range from 0.5 eV to 100 MeV. Charged particles emitted from the tungsten target are removed by a sweeping magnet to prevent interference with measurements. The proton beam operates in double-bunch mode with a pulse width of 43 ns and an inter-pulse spacing of 410 ns [26]. The neutron flight path from the spallation target to the sample is 57.99 m. The neutron beam spot diameter is 20 mm, with a flux rate of 1.6×10^6 n/cm^2/s [27].

1.2 Sample

[Figure 1: see original paper] shows a photograph of the samples and sample holder used in the experiment. Three sample positions were utilized for measurements: a natural graphite foil with a thickness of 2.219 mg/cm^2 for measuring the 12C(n,d)x reaction (carbon sample), an empty target holder identical to the carbon sample holder for measuring neutron beam background, and an α source for detector signal testing. Two back-to-back ^{241}Am α sources with an activity of 33 kBq were used. All samples were mounted on a custom aluminum holder with four sample positions. The carbon sample and empty target occupied two 40 mm diameter holes, a rectangular sample position held the α source, and one position remained unused.

1.3 Detectors

The LPDA detector system was used to measure the 12C(n,D)x reaction cross sections. Figure 2: see original paper shows a photograph of the LPDA detectors installed in the vacuum target chamber, while Figure 2: see original paper illustrates the detailed detector layout. Sixteen sets of LPDA ΔE-E telescope systems were placed in the vacuum target chamber. Each telescope comprised a low-pressure multi-wire proportional chamber (LPMWPC) as the ΔE detector, a 300 m thick silicon (Si-PIN) detector serving as either E or ΔE, and a 30 mm thick CsI scintillator as the E detector. The LPMWPC features a 2 m thick PET window and operates at 20000 Pa with a bias voltage of 690 V. Signals from the LPMWPC are first processed by a charge-sensitive preamplifier. Si-PIN signals are amplified and preprocessed by an amplifier. CsI detector signals are amplified by silicon photomultipliers (SiPM) and then processed by a main amplifier [28].

The telescope detectors were positioned at angles from 24.5° to 155.5° relative to the neutron beam direction. Eight telescopes at angles = 24.5°, 34.0°, ···, 91° (labeled L1, L2, ···, L8) were placed on the left side of the neutron beamline. Another eight telescopes were positioned on the right side at angles = 89°, 98.5°, ···, 155.5° (labeled R1, R2, ···, R8). During this measurement, three telescope systems (R1, R4, and R8) did not function properly. lists the distance from each telescope's center to the sample center. The telescopes were calibrated using the ^{241}Am source mounted on the sample holder. Based on the detector solid angle and source activity, the number of α particles entering each detector was determined. The ratio of detected to incident particles yielded the detection efficiency. also presents the spatial solid angles and average detection angles for each telescope calculated using Geant4 simulations [29], which accounted for errors introduced by beam spot size. Throughout the experiment, the sample plane was oriented at 30° relative to the neutron beam direction.

1.4 Experimental Procedure

The total beam time for the measurement was 202.3 hours, comprising 191.9 hours with the graphite target and 10.4 hours with the empty target. Since this experiment focused primarily on n-d reaction measurements, the empty target measurement served as a background measurement, resulting in significantly longer measurement time for the graphite sample. The ^{241}Am source was used primarily to monitor detector and data acquisition system performance before, during, and after the experiment, with five measurements totaling 3.6 hours. Additionally, a 20-hour background measurement was performed without beam.

1.5 Data Acquisition System

The Back-n data acquisition system recorded waveform binary files from the telescope detectors [30]. Three signal types were processed: LPMWPC signals, Si detector signals (preamplifier only), and CsI detector signals (amplified by SiPM and then by the main amplifier).

2. Data Analysis

Signal waveforms were processed to select and accumulate events with and without background. Background events from the empty target were negligible and could be ignored. Events with background were considered net events. The convolution effect from the double proton bunches was deconvolved using an iterative Bayesian method [31], yielding the final 12C(n,d)x reaction cross sections.

2.1 Signal Processing

All digital waveforms from the detectors were analyzed using a multi-digital signal processing (DSP) network based on ROOT software. Event amplitudes and times were extracted using a simple smoothing and band-pass filtering algorithm that converted signal waveforms into Gaussian shapes for amplitude information [32-33]. Time information was obtained through a constant-fraction discrimination algorithm applied to the signal waveforms. [Figure 3: see original paper] shows the analog filter circuit diagram used to derive the digital filtering algorithm.

Neutron energy for each event was determined using the time-of-flight (TOF) method. Gamma flashes produced during the spallation process were used as timing references, with their peak positions defining the gamma flight time Tγ. Figure 4: see original paper and (b) show the TOF distributions of gamma flash counts for the Si-PIN and CsI detectors at = 24.5°. The TOF distributions of gamma flash events detected by the Si-PIN detector can be fitted with a double Gaussian distribution having a standard deviation of 39 ns, primarily due to the proton pulse width. The Si-PIN detector event resolution is better than 10 ns, and the data acquisition system time resolution is better than 1 ns.

Signals from the CsI and Si-PIN detectors within the same telescope system were considered to originate from the same event if their arrival time difference was within 700 ns. The CsI detector start time was calibrated using the time difference between coincident Si-PIN and CsI detector signals.

The neutron time-of-flight was calculated using the following formula:

$$= \quad - (\gamma -$$

where Td is the arrival time of the d event, L is the neutron flight distance (57.99 m), and c is the speed of light. Neutron energy was derived from its TOF, with relativistic effects properly considered.

2.3 d Identification via ΔE-E Spectra

Thirteen telescope systems provided ΔE-E spectra for identifying d events from both carbon samples and the empty target. [Figure 5: see original paper] shows the two-dimensional ΔE-E signal amplitude distribution for the carbon sample at = 24.5°. The corresponding two-dimensional spectrum from the empty target is nearly empty, demonstrating that the aluminum sample holder under neutron beam irradiation and the neutron beam itself produce no charged particle background.

2.4 Counting per TOF Channel

In this work, the neutron TOF spectrum was binned with a channel width of 10 ns. The neutron energy spectrum used logarithmic binning, with 300 channels covering 1 MeV to 1000 MeV. After background subtraction, net event counts were obtained for each TOF channel and detector angle. The number of protons hitting the tungsten target was recorded during both background and sample measurements to normalize the background subtraction.

2.5 Double-Bunch Deconvolution

Neutrons were produced by double proton bunches separated by 410 ns, creating two possible neutron energies whose difference increases with neutron energy. An iterative Bayesian algorithm was employed to deconvolve this effect [31]. The iteration formula is:

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where S represents counts per channel in single-bunch mode, D represents measured counts per channel in double-bunch mode, Δ is the number of channels corresponding to the 410 ns interval (Δ = 410 ns/w, where w is the channel width in ns), and the superscript (k) denotes the k-th iteration.

The deconvolution software used in this work was developed by the CSNS Back-n staff [31] and is based on the iterative Bayesian method, which has been tested with experimental data.

2.6 Differential Cross Section of 12C(n,d)x

The angular differential cross section σ , can be calculated using the following formula:

$$- \quad , = - \quad , \quad - \qquad - \quad ,$$

where N is the total count of net d events, ϕ is the neutron fluence (measured primarily using a fission ionization chamber based on the ^{238}U(n,f) reaction [26]), is the detector efficiency, Ω is the solid angle of the Si-PIN detector, and N is the number of ^{12}C nuclei in the sample. The subscripts E-bin and denote neutron energy bin and detection angle, respectively. lists the sources and magnitudes of uncertainties in this work.

3. Results and Discussion

[Figure 6: see original paper] presents the differential cross sections for 12C(n,d)x measured in this experiment at a neutron energy of 33.9 MeV at laboratory angles = 24.5°, 34.0°, 43.5°, 53.0°, 62.5°, 72.0°, 81.5°, 91.0° and = 98.5°, 108.0°, 127.0°, 136.5°, 146.0°. The results are compared with previous measurements by Cui Zengqi et al. from Peking University, showing good agreement within experimental uncertainties. Cui et al. used a relative cross section method normalized to proton reaction cross sections, whereas this work employs an absolute cross section measurement method. Due to limited statistics, energy information for d particles was lost during the deconvolution of the double-bunch time distribution, making Q-value calculation difficult.

In this work, we measured the differential cross sections for the 12C(n,d)x reaction at 13 angles and a neutron energy of 33.9 MeV at the CSNS Back-n white neutron source. The results are generally consistent with previous measurements in both trend and magnitude, while providing differential cross section data over a wider angular range. Data analysis for additional energy points is ongoing.

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Note: Figure translations are in progress. See original paper for figures.