Simulations of the measurement results of differential cross sections of n-p and n-d elastic scattering at CSNS Back-n WNS

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Abstract. Differential cross-section data for the *n-p* and *n-d* elastic scattering (^{1}H(*n, el*), ^{2}H(n, el)) are collected and analyzed from EXFOR library. For $E_n > 20$ MeV, the experimental results for both reactions are scarce with large uncertainties and discrepancies in general. For $E_n \leq 20$ MeV, the experimental results lack systematicness, most of which were measured around $E_n = 14$ MeV even though the differential cross sections of *n-p* scattering in 1 keV $\leq E_n \leq$ 20 MeV region are recommended as standard. Taking these facts into account, more accurate and systematic measurements are planned. The experiments will be conducted using ΔE-E detectors of the Light-charged Particle Detector Array (LPDA) system at China Spallation Neutron Source (CSNS) Back-n White Neutron Source (WNS), and simulations are carried out. Using polyethylene and deuterated polyethylene as samples, both *n-p* and *n-d* scattering reactions are simulated along with the neutron-induced ^{12}C background reactions, and the 2-D spectra and the counting rates of the ΔE-E detectors are obtained. According to the simulations, the applicable neutron energy range and positions of the detectors are recommended, and the beam time for the event and background measurements is suggested.

1 Introduction

n-p and *n-d* elastic scattering (^{1}H(*n, el*) and ^{2}H(*n, el*)) are two of the most fundamental processes in nuclear physics. The differential cross sections of them are crucial to the study of nuclear force in the few-body system [1–3]. The measurements of the differential cross sections are thus neccesary. Despite the fact that the cross section of *n-p* elastic scattering for neutron energy E_n from 1 keV to 20 MeV is one of the neutron cross section standards [4], there are only 28 measurements of *n-p* elastic scattering differential cross section (including relative angular distribution) in the energy region of 1 MeV < E_n < 80 MeV since 1965 [5], most of which were performed at neutron energy around 14 MeV, with D-T neutron sources. As for *n-d* scattering, there are only 24 measurements of the differential cross section for 1 MeV < E_n < 80 MeV since 1965, and 8 of them were perforemed at neutron energy around 14 MeV. In fact, the measurements of the differential cross sections of *n-p* and *n-d* for E_n > 20 MeV are scarce, with large uncertainties and discrepancies. Therefore, systematic experiments are needed and therefore schemed.

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The experiments for measuring the differential cross sections of *n-p* and *n-d* scattering reactions are planned at Chinese Spallation Neutron Source (CSNS) Back-n white neutron source (WNS). The detectors for the measurements are Δ*E-E* detectors array of the Light-charged Particle Detector Array (LPDA) system. Simulations of the measurements using Matlab are conducted. For both *n-p* and *n-d* elastic scattering, the samples prepared for the measurements are polyethylene and deuterated polyethylene of 100 μm and 32 μm in thickness, respectively, on which the simulations are based. The 2-D spectra of neutron energy (E_n) vs. the energy deposited in E detectors and the energy deposited in ΔE detectors vs. the energy deposited in E detectors are obtained along with the background, as well as counting rates of the Δ*E-E* detectors.

The goal of the simulations is to obtain the information about the experiments and to predict the experimental results. Moreover, the beam time can thus be estimated to acquire enough counts according to the count rate of the simulation.

2 Method

2.1 Experimental setup

The measurement will be performed at Endstation #1 (ES1) of CSNS Back-n white neutron source. The neutrons are generated by double-bunched proton beams (with 1.6 GeV energy and 25 Hz of pulse repetition rate) bombarding a tungsten target. Details of the neutron source could be found in Ref [6]. The time width of each proton bunch is approximately 41 ns, and the duration between the two proton bunches is 410 ns. The present beam power is 50 kW. The neutron flight path is 57.99m and the diameter of the neutron beam is about 20 mm, and the neutron flux is 8.75×10^5 n/cm^2/s (at 50 kW, ϕ20 mode). The experimental setup is shown in Fig. 1. There are 10 Δ*E-E* detectors, each consisting of a ΔE unit (a Si detector) and an E unit (a CsI detector), are placed inside the vacuum chamber, covering the detection angle from 10° to 55°. The Δ*E-E* detectors could a) provide particle identification; b) detect the energy of the charged particles and c) obtain the Time of Flight (TOF) of the neutrons using γ-flash signals of the CsI detectors to determine the T_0 moment. The surface of the sample is perpendicular to the neutron beam.

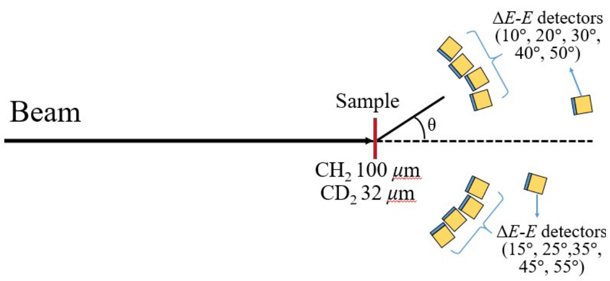


Figure 1. Diagram of the experimental setup (birds-eye view).

The distance between the center of the sample and the center of the surface of the ΔE detector at 10° is 410 mm, while that of the Δ*E-E* detector at 15° is 290 mm so that these two detectors are not affected by the neutron beam halo. The distance is 240 mm for detectors at 20°, 25°, 40°, 45°, and 248.5 mm for those at 30°, 35°, 50° and 55°.

The sample for *n-p* scattering measurement is polyethylene (CH_2). The measurement of the differential cross section of *n-p* scattering were already finished in May 13th, 2019, with 135 hours of beam time for foreground and 65 hours for background (C sample, 50 μm in thickness, 99.99% in purity) and empty target measurement. The CH_2 sample used in the experiment is 100 μm in thickness to obtain good enough statistics and to minimize self-absorption. The samples and the sample holder for the *n-p* scattering measurement experiment are shown in Fig. 2.

The *n-d* scattering measurement has not been performed yet. However, The sample for *n-d* scattering measurement is deuterated polyethylene (CD_2) and it was already prepared 32 μm in thickness.

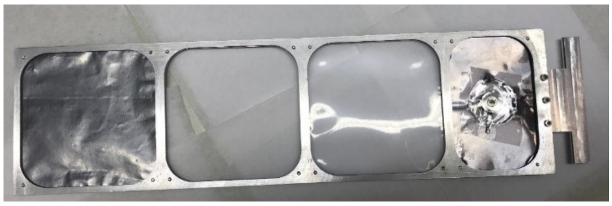


Figure 2. Samples and the sample holder. From left to right: C sample (for background measurement), empty target, CH_2 sample and α sources.

2.2 Simulation

The simulation is based on Monte Carlo method, a step-by-step tracking of charged particles. The process for the simulation is illustrated in Fig. 3. The data of cross sections and differential cross sections are taken from ENDF/B-VIII.0 [7] and FENDL-3.1c [8] data libraries.

3 Results

3.1 n-p scattering

The preliminary results of the measurement and those of the simulation are compared in Fig. 4. The experimental results are from the data files of about 24 hours of measuring on May 3rd, 2019. The results of the experimental 2-D spectra of E_n vs. amplitude of Si detector at $\theta = 10°$, E_n vs. amplitude of CsI detector at $\theta = 10°$ and ΔE vs. E at $\theta = 10°$ in Figs. 4(a), 4(c) and 4(e), respectively. The same kind of 2-D spectra obtained by simulation are also given in Figs. 4(b), 4(d) and 4(f), respectively. In addition, the total counts of *n-p* scattering events for 135 hours of beam time for detectors at each angle calculated by simulation are presented in Fig. 5.

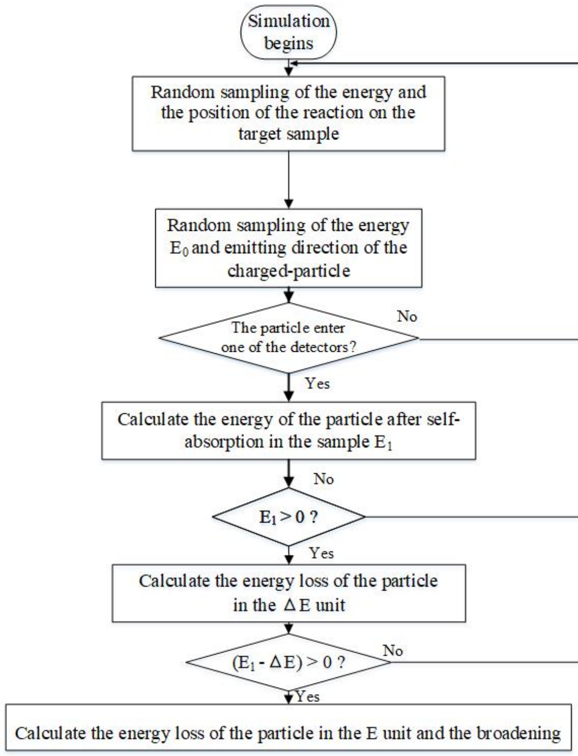


Figure 3. The flowchart of the simulation process.

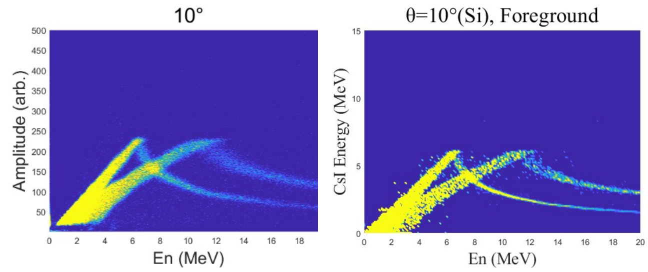
According to the results of the simulation, the background from the ^{12}C is relatively weak. Only the deuterons from the ^{12}C$(n,\ d)^{11}$B reactions is relatively obvious in Fig. 4(f).

According to the 2-D distribution of the ΔE-E detector, the events, i.e. the recoiled protons can be identified up to E_n = 80 MeV. The detection of protons produced below E_n = 10 MeV are only feasible for the detectors at small angles ($\theta < 30°$) according to Fig. 5. Meanwhile, the counts are adequate for *n-p* scattering (hundreds or more) for 1 MeV $< E_n <$ 80 MeV. Thus, the applicable E_n range for the measurement is 10 - 80 MeV.

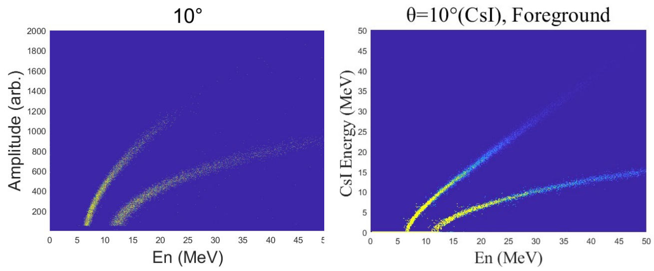
From the comparison above, it is evident that the simulations agree with the experiments well, except for the slight curved trend in Fig. 4(c) as E_n increases , which is caused by the non-linear energy response of the CsI detectors. The experimental data is currently under processing.

3.2 n-d scattering

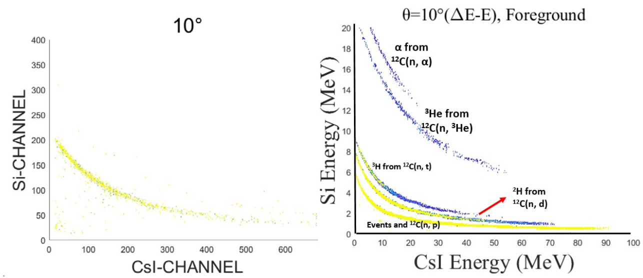
The experiment for *n-d* scattering has not yet been conducted. Therefore, the results shown below are only from simulations. The estimated beam time for the simulation is 300 hours. The ratio of time for foreground and background measurement is 3:1 (225 hours for foreground, 75 hours for background and the empty target). The beam power is likely to be upgraded to 80 kW this year, which is used in the simulation for *n-d* scattering rather than 50 kW. The results are presented in Fig. 6 as a comparison between event and foreground (event plus background). The simulation results for pure *n-d* scattering event are presented as 2-D spectra of E_n vs. amplitude of Si detector at $\theta = 10°$, E_n vs. amplitude of CsI detector at $\theta = 10°$ and ΔE vs. E at $\theta = 10°$ in Figs. 6(a), 6(c) and 6(e), respectively. As a comparison, the simulation results for foreground measurement are shown in the same format as event in Figs. 6(b), 6(d) and 6(f). Meanwhile, the total counts of *n-d* scattering events for detectors at each angle are presented in Fig 7.



(a) 2-D spectrum of E_n vs. amplitude of the Si detector (experiment).
(b) 2-D spectrum of E_n vs. amplitude of the Si detector (simulation).



(c) 2-D spectrum of E_n vs. amplititude of the CsI detector (experiment).
(d) 2-D spectrum of E_n vs. amplitude of the CsI detector (simulation).



(e) 2-D spectrum of ΔE vs. E (experiment).
(f) 2-D spectrum of ΔE vs. E (simulation).

Figure 4. Results of simulation and experiment for *n-p* scattering measurement at $\theta = 10°$.

Figs. 6(b), 6(d) and 6(f) indicate the interference of *n-p* scattering from the 10% of CH_2 in the CD_2 sample and that of the ^{2}H$(n,\ 2n)^2$H reaction. Using the ΔE-E detectors, the protons and the deuterons could be distinguished from each other until about 60 MeV. Based on the simulation, the lower limits of E_n of the *n-d* scattering measurement are 11 MeV for detectors at $\theta \leq 35°$, 13 MeV for that at $\theta = 45°$ MeV, and 20 MeV for the detectors at 50° and 55°. Moreover, the upper limit of E_n is 60 MeV to ensure adequate counts.

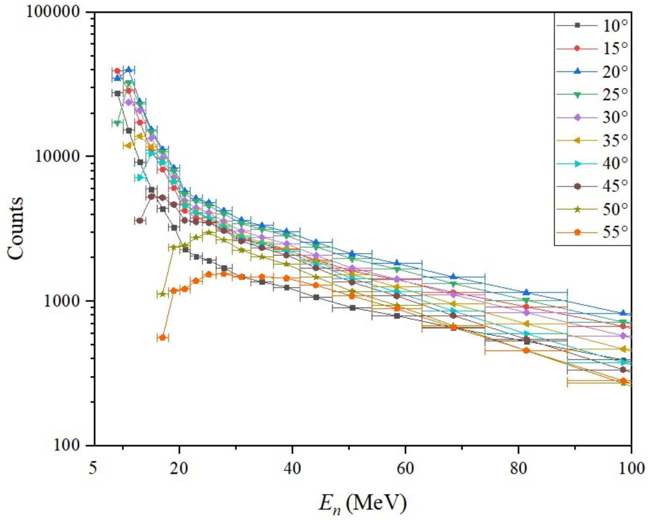
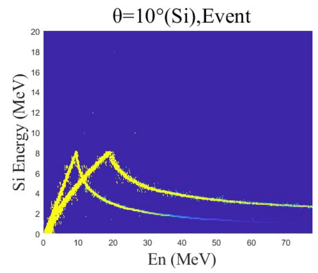
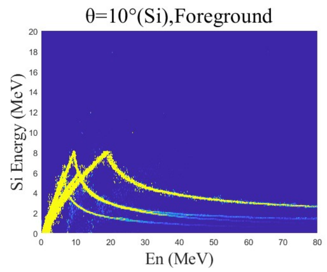


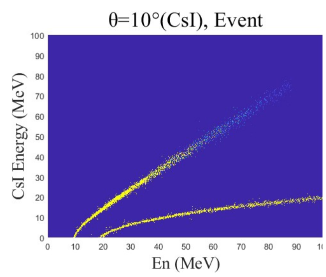
Figure 5. The total counts from simulation of detectors at each angle for *n-p* scattering measurement (for 135 *h*).



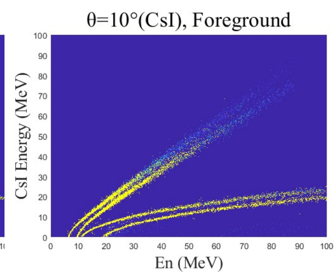
(a) 2-D spectrum of E_n vs. amplitude of the Si detector (event).



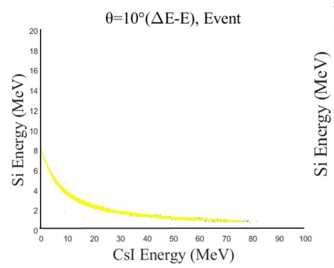
(b) 2-D spectrum of E_n vs. amplitude of the Si detector (foreground).



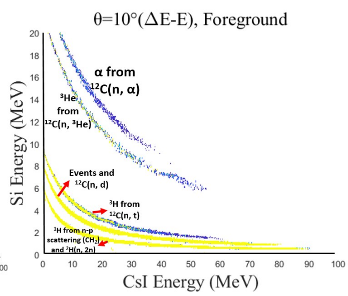
(c) 2-D spectrum of E_n vs. amplitude of the CsI detector (event).



(d) 2-D spectrum of E_n vs. amplitude of the CsI detector (foreground).



(e) 2-D spectrum of ΔE vs. E (event).



(f) 2-D spectrum of ΔE vs. E (foreground).

Figure 6. Results of simulation for *n-d* scattering measurement at $\theta = 10°$.

4 Conclustions & Discussions

In this work, the results of the measurements for the differential cross sections of *n-p* and *n-d* elastic scattering using white neutrons at CSNS Back-n WNS are simulated along with the background reactions from ^{12}C in the samples. The 2-D spectra of the ΔE-E detectors for both *n-p* and *n-d* scattering reactions are obtained. The results of simulations for *n-p* scattering are compared with those of the experiments and they show good agreement. The counting rates of the ΔE-E detectors are obtained. According to the simulations, the applicable neutron energy range are: 10 - 80 MeV for *n-p* scattering measurement and 20 - 60 MeV for *n-d* scattering measurement. Finally, the beam durations for the event and background measurements are suggested.

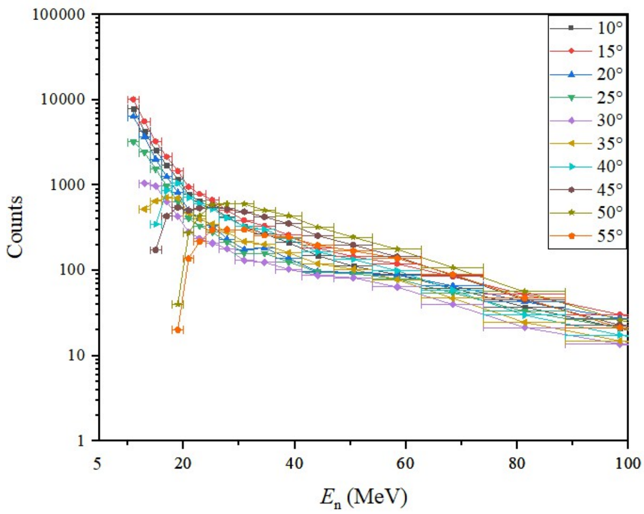


Figure 7. The total counts from simulation of detectors at each angle for *n-d* scattering measurement (for 225 *h*).

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