Progress in the measurement of the neutron-induced fission cross-section at CSNS Back-n

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Abstract. The China Spallation Neutron Source (CSNS) is a newly constructed large-scale facility located in Dongguan, which was completed and operational in 2018. It is generating neutrons by bombarding 1.6 GeV protons into a tungsten target for multidisciplinary research. A back-streaming neutron beamline (Back-n) at CSNS is built at the reverse direction opposite to the proton beam mainly for the nuclear data measurement. Back-n is characterized by its wide energy range (from 0.3 eV to 300 MeV), high flux (~107 n/cm2/s at 55 m) and good energy resolution (less than 1% below 1 MeV), standing as one of the state-of-the-art white neutron beams worldwide. Fission cross-sections of a series of nuclei, such as 235, 236, 238U, 232Th, 239Pu have been measured in wide energy ranges since 2018, and more isotopes (such as minor actinides) are planned to be measured in the near future. The CSNS Back-n facility and the progress in the fission cross-section measurements are reviewed in this paper. Then the prospects of the fission cross-section measurement at Back-n are discussed.

1 Introduction

Nuclear data encapsulates a wealth of information related to the fundamental properties and behavior of nuclei, serving as the foundation for numerous fields ranging from nuclear physics and engineering to medical applications and even beyond. It is highly involved in the development of modern society, influencing energy production, national security, healthcare improvements, etc.

Neutron-induced fission cross-section is one of the important nuclear data. It is essential for the design and operation of nuclear reactors, as it directly influences reactor performance, safety, and efficiency. Furthermore, accurate neutron-induced fission cross-sections are crucial in nuclear fuel cycle management, enabling scientists and engineers to predict fuel consumption rates, assess waste production, and develop strategies for sustainable nuclear energy.

Since most theoretical descriptions are descriptive rather than rigorously predictive, especially in terms of accuracy and across the entire energy range, most nuclear data must largely be measured directly [1]. These measurement data can then be used to calibrate empirical models, which in turn enhances the evaluation of nuclear data. The state-of-the-art facility for neutron-induced nuclear data measurement is supposed to be the time-of-flight (TOF) facility with the white neutron beam, such as the n_TOF [2] at CERN, GELINA [3] at JRC Geel, WNR [4] at LANSCE, and Back-n [5] at CSNS. This paper will briefly introduce the progress in the fission cross-section measurement on back-streaming neutron facility (Back-n) at China Spallation Neutron Source (CSNS).

2 CSNS Back-n facility

CSNS is a newly constructed facility completed in 2018 and has been operational since then. It generates neutrons by bombarding a massive tungsten target with 1.6 GeV protons. The current beam power of CSNS is approximately 170 kW, and it will be upgraded to 500 kW in CSNS-II project which will be completed by 2029. Different types of spectrometers have been constructed around the target station, and most of them are using moderated neutrons for material research based on the neutron scattering technique. Meanwhile, beam expanding applications are actively involved at CSNS, such as white neutron beam [5], muon source [6], associated proton beam experiment platform [7], and 1.6 GeV Single-particle proton beam [8].

Back-n beamline is built at the reverse direction with respect to the incident proton beam to exploit the backing-streaming neutrons. As shown in Figure 1, the incident proton beam is bent by 15 degrees by a bending magnet before hitting the tungsten target. The back-

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streaming neutrons pass by the bending magnet and continue to fly straight to reach end station 1 (ES#1) and end station 2 (ES#2), which are respectively ~55 m and ~76 m away from the spallation target. The bending magnet also serves as a sweeping magnet to clear the charged particle background in Back-n beam.

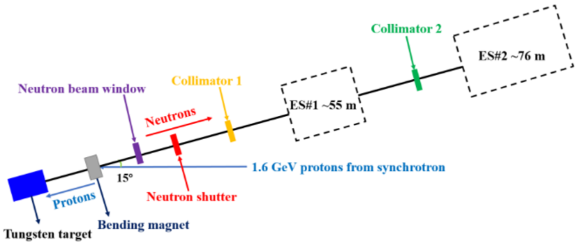

Figure 1. Layout of the Back-n beamline

There is one neutron shutter and two collimators (collimator 1 and 2) along the Back-n beamline. The aperture of each collimator is changeable, and combinations of different collimator apertures result in different beam profiles and fluxes at experimental end stations. The commonly used collimator configurations and the corresponding beam spots and fluxes are listed in Table 1 [9]. The sizes of the beam spots and the values of the neutron fluxes are simulated results normalized to a beam power of 100 kW.

The neutron fluxes under different conditions have also been measured. Figure 2 shows the measured fluxes [10-12] at different end stations with different beam configurations. The legend in Figure 2 indicates the corresponding end station, collimator configuration, and binning. For example, "ES#1: Ø12 + Ø15 (50 bpd)" refers to the neutron flux at ES#1 with 50 bins per decade (bpd), measured with neutron shutter of Ø12 mm and collimator 1 of Ø15 mm. It should be noted that the data of "ES#1: Ø50 + Ø50" stops at 30 MeV due to a technical reason. It is because this measurement was conducted with double-bunch beam mode at the very beginning of the CSNS commissioning, when the unfolding method was not fully developed yet. More details concerning the double-bunch mode is discussed in section 4. In fact, similar to other configurations, "ES#1: Ø50 + Ø50" can reach a maximum energy of a few hundred MeV.

Table 1. Different beam configurations and corresponding beam properties at CSNS Back-n (100 kW) [9]

Mode	Shutter (mm)	Coll#1 (mm)	Coll#2 (mm)	ES#1		ES#2	
				Beam spot (mm)	Flux (n/cm^2/s)	Beam spot (mm)	Flux (n/cm^2/s)
Low intensity	Ø3	Ø15	Ø40	Ø15	1.3×10^5	Ø20	4.6×10^4
Small spot	Ø12	Ø15	Ø40	Ø20	1.6×10^6	Ø30	6.1×10^5
Large profile	Ø50	Ø50	Ø58	Ø50	1.8×10^7	Ø60	6.9×10^6

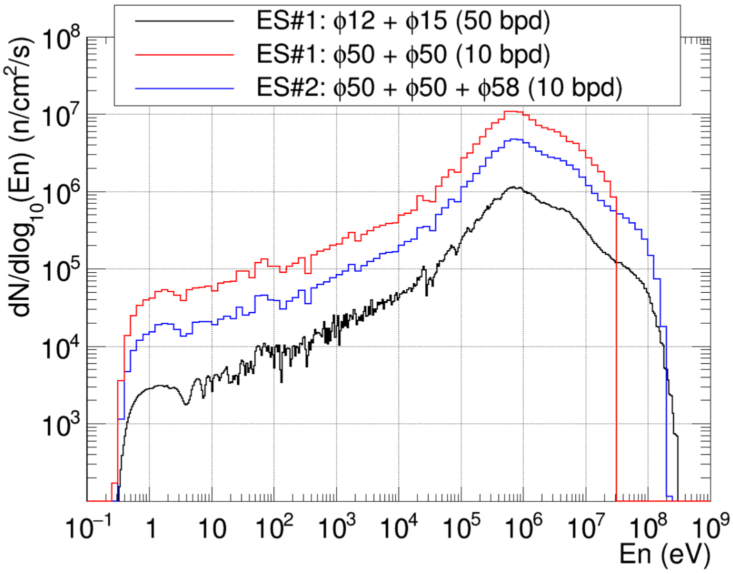

Figure 2. Measured neutron fluxes of CSNS Back-n with different beam configurations

3 Fission cross-section measurements at CSNS Back-n

Fission cross section measurements are one of the important nuclear data measurements at Back-n. Table 2 lists the fission cross-section measurements since 2018. Most of the measurements were conducted using a multi-cell fission chamber, which is referred to as fast ionization chamber for fission cross-section measurement (FIXM) [13]. Proton recoil telescopes (PRTs) [14] were used as well when the hydrogen scattering was employed as the reference for determining the fission cross section. Additionally, a Multi-purpose Time Projection Chamber (MTPC) [15] has been developed at Back-n, and it was first used in 2024 at Back-n to measure the fission cross-section of ^{235}U.

Table 2. Fission cross-section measurements campaigned at CSNS Back-n

Year	Nucleus	Detector	Ref.
2018	^{235,238}U	FIXM	[16-17]
2018	^{236}U	FIXM	[17-18]
2019	^{232}Th	FIXM	[19]
2019	^{239}Pu	FIXM	[20]
2020	^{232}Th	FIXM+PRT	[21]
2020	^{235,238}U	FIXM+PRT	[22]
2023	^{236}U	FIXM	
2024	^{235}U	MTPC	

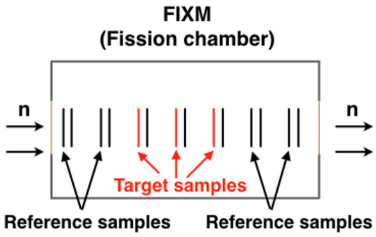

Figure 3. Scheme of the FIXM detector at Back-n

FIXM is a classical fission chamber, in which the target samples and reference samples (^{235}U and ^{238}U) are mounted in parallel as shown in Figure 3. The samples and electrodes are usually very thin, so the irradiation neutron fluxes for both the target and reference samples are almost same. The flux attenuation due to the absorption of the samples and electrodes can be simulated as well. By measuring the fission rates as a function of neutron energy of both target and reference samples and then applying some necessary corrections, such as the correction of efficiency and flux attenuation, the fission cross-section of the target sample can be obtained. The FIXM has measured the fission cross-section ratios of ^{238}U to ^{235}U for neutron energies ranging from 0.5 to 200 MeV [16-17], the fission cross-section of ^{236}U from 0.4 to 200 MeV [17-18], the fission cross-section of ^{232}Th from 1 to 200 MeV [19], and the fission cross-section of ^{239}Pu from 4 keV to 100 MeV [20].

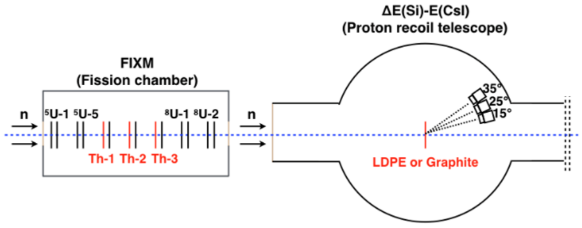

Figure 4. Experiment setup of using both FIXM and PRTs

Apart from using ^{235}U or ^{238}U as the references, hydrogen scattering (n-p scattering) can be also used as a reference for measuring the fission cross-section, since n-p scattering cross-section is considered to be the most accurate neutron data standard. In this case, PRTs are used for measuring the scattering protons to extract the neutron flux. A dedicated measurement using both FIXM and PRTs was conducted in 2020 to measure the fission cross-section of ^{232}Th [21]. As illustrated in Figure 4, ^{235}U, ^{238}U and ^{232}Th samples were mounted in the FIXM. PRTs were set up downstream of the FIXM. The fission cross-section of ^{232}Th was measured relative to both ^{235}U (n, f) and n-p scattering, within the neutron energy ranges of 1-300 MeV and 10-70 MeV, respectively. Meanwhile, the fission cross-section of ^{235}U and ^{238}U were obtained relative to n-p scattering in the neutron energy range of 10-70 MeV [22].

4 Prospects

CSNS-II upgrading project was initiated in 2024, with the aim of upgrading the beam power to 500 kW and constructing 11 new instruments and end stations by 2029. The neutron flux of Back-n will be accordingly increased by several times. New type of fission detectors with a high counting rate capability is planned to be developed to accommodate the increasing flux. Parallel plate avalanche counter (PPAC) is a good candidate thanks to its excellent performance, including fast signal response, position sensitivity, and high counting rate. Furthermore, with the increased neutron flux and new fast detector, more kinds of samples with small cross-sections and/or small quantities can be potentially measured. For example, some minor actinides are highly radioactive due to their short half-life. Thus, their sample quantities have to be very limited to control the radioactivity level. It would be essential to explore the possibility to measure those kinds of samples with intense neutron flux.

CSNS accelerator is usually operated in double-bunch mode. It means there are two identical proton bunches with a well-defined 410 ns interval in each proton pulse, introducing an uncertainty of 410 ns for TOF determination. It is negligible for most of other CSNS spectrometers who only use moderated neutrons. However, this is not the case for Back-n, where neutron energies can reach much higher energies. Therefore, the double-bunch effect must be taken into account. We are currently using either single-bunch mode or the double-bunch unfolding method [23] to address this issue.

However, on one hand, the availability of single-bunch mode is very limited at CSNS because it reduces the neutron flux by half; on the other hand, double-bunch unfolding method can correct the TOF in a good manner but it inevitably introduces systematic errors. Given this situation, CSNS accelerator department proposed a fast bunch merging solution [24], which means merge two bunches into one without losing beam intensity. Some progress in theoretical calculations and experiments has been made.

5 Summary

Back-n beamline at CSNS is a state-of-the-art white neutron facility, characterized by its wide energy range from 0.3 eV to 300 MeV, high neutron flux of ~10^7 n/cm^2/s, and excellent energy resolution of less than 1% for neutrons below 1 MeV. Due to these features, Back-n is suitable for nuclear data measurement, fundamental nuclear physics research, irradiation effect studies, neutron imaging, and other applications. A series of relevant experiments have been conducted since 2018.

Fission cross-sections of ^{235,236,238}U, ^{239}Pu, ^{232}Th have been measured in wide energy ranges at Back-n, utilizing various types of detectors such as FIXM, PRT and MTPC. More types of fission detectors will be developed, and more kinds of samples will be measured to align with the upgrading of CSNS.

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