

In-beam gamma rays of CSNS Back-n characterized by black resonance filter

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Abstract

The back-streaming white-neutron beam line (Back-n) of the China Spallation Neutron Source is an essential neutron-research platform built for the study of nuclear data, neutron physics, and neutron applications. Many types of cross-sectional neutron-reaction measurements have been performed at Back-n since early 2018. These measurements have shown that a significant number of gamma rays can be transmitted to the experimental stations of Back-n along with the neutron beam. These gamma rays, commonly referred to as in-beam gamma rays, can induce a non-negligible experimental background in neutron-reaction measurements. Studying the characteristics of in-beam gamma rays is important for understanding the experimental background. However, measuring in-beam gamma rays is challenging because most gamma-ray detectors are sensitive to neutrons; thus, discriminating between neutron-induced signals and those from in-beam gamma rays is difficult. In this study, we propose the use of the black resonance filter method and a CeBr₃ scintillation detector to measure the characteristics of the in-beam gamma rays of Back-n. Four types of black resonance filters, ¹⁸¹Ta, ⁵⁹Co, natAg, and natCd, were used in this measurement. The time-of-flight (TOF) technique was used to select the detector signals remaining in the absorption region of the TOF spectra, which were mainly induced by in-beam gamma rays. The energy distribution and flux of the in-beam gamma rays of Back-n were determined by analyzing the deposited energy spectra of the CeBr₃ scintillation detector and using Monte Carlo simulations. Based on the results of this study, the background contributions from in-beam gamma rays in neutron-reaction measurements at Back-n can be reasonably evaluated, which is beneficial for enhancing both the experimental methodology and data analysis.

Full Text

Preamble

In-beam gamma rays of CSNS Back-n characterized by black resonance filter

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The back-streaming white-neutron beam line (Back-n) of the China Spallation Neutron Source is an essential neutron-research platform built for the study of nuclear data, neutron physics, and neutron applications. Many types of cross-sectional neutron-reaction measurements have been performed at Back-n since early 2018. These measurements have shown that a significant number of gamma rays can be transmitted to the experimental stations of Back-n along with the neutron beam. These gamma rays, commonly referred to as in-beam gamma rays, can induce a non-negligible experimental background in neutron-reaction measurements. Studying the characteristics of in-beam gamma rays is important for understanding the experimental background. However, measuring in-beam gamma rays is challenging because most gamma-ray detectors are sensitive to neutrons; thus, discriminating between neutron-induced signals and those from in-beam gamma rays is difficult. In this study, we propose the use of the black resonance filter method and a CeBr₃ scintillation detector to measure the characteristics of the in-beam gamma rays of Back-n. Four types of black resonance filters—¹⁸¹Ta, ⁵⁹Co, natAg, and natCd—were used in this measurement. The time-of-flight (TOF) technique was used to select the detector signals remaining in the absorption region of the TOF spectra, which were mainly induced by in-beam gamma rays. The energy distribution and flux of the in-beam gamma rays of Back-n were determined by analyzing the deposited energy spectra of the CeBr₃ scintillation detector and using Monte Carlo simulations. Based on the results of this study, the background contributions from in-beam gamma rays in neutron-reaction measurements at Back-n can be reasonably evaluated, which is beneficial for enhancing both the experimental methodology and data analysis.

Keywords: In-beam gamma rays, Back-n, CeBr₃ scintillator, Black filter resonance technique

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Introduction

The back-streaming white-neutron beamline of the China Spallation Neutron Source (CSNS) [1–6], known as Back-n, has served as a white-neutron facility for nuclear-data measurements and neutron-physics research since it became operational in early 2018 [7–12]. The layout of Back-n is shown in Fig. 1 [Figure 1: see original paper]. At CSNS, neutrons are generated by bombarding a proton

beam with an energy of 1.6 GeV and a pulse-repetition rate of 25 Hz onto a spallation target made of tungsten. Before the incident proton beam hits the spallation target, it is deflected by 15 degrees by a bending magnet specifically designed for this purpose. Consequently, the neutron beamline of Back-n was built in the 180-degree direction without any conflict with the proton-beam transfer line. Two experimental stations are located along the neutron beamline: the near station (ES#1) is approximately 56 m away from the spallation target, and the far station (ES#2) is approximately 20 m further than ES#1. At Back-n, different neutron-beam profiles can be obtained by changing the shape or size of the neutron collimators. Three collimators are located at 24 m, 50 m, and 70 m away from the spallation target. The first collimator is also used as a beam shutter.

Several types of nuclear data have been measured at Back-n in recent years, including the neutron total cross-section [13], radiative neutron capture cross-section [14–25], fission cross-section [26, 27], neutron-induced charged-particle emission cross-section [28, 29], and inelastic scattering cross-section. However, the experimental background induced by gamma rays was non-negligible in many Back-n measurements, particularly when the detectors were sensitive to both neutrons and gamma rays. Based on recent research [14, 15], gamma rays generated in the spallation target can be transmitted to the experimental station along with the neutron beam. These gamma rays are known as in-beam gamma rays. Back-n has two main types of in-beam gamma rays. One type is generated by the spallation process, called γ -flash. These are composed of prompt gamma rays produced by spallation reactions and arrive at the experimental station within 300 ns after the proton beam hits the spallation target. The other type of in-beam gamma ray usually arrives at the experimental station later than the γ -flash and is caused by neutron reactions in the spallation target, moderators, and structural materials. These gamma rays are called delayed in-beam gamma rays because they can last for more than 2 ms after the γ -flash. At Back-n, many types of nuclear-data measurements are influenced by in-beam gamma rays. Taking the neutron radiative capture cross-section measurement as an example, the background caused by in-beam gamma rays is the main component of the experimental background in the neutron-energy region above 200 eV [14–23]. Therefore, determining the characteristics of the delayed in-beam gamma rays, such as energy distribution and time structure, can improve nuclear-data measurements at Back-n. The energy distribution and time structure of the in-beam gamma rays were simulated in Ref. [14]. In addition, the time structure of in-beam gamma rays was evaluated using a lead (natPb) sample [14–25] to capture the cross-sections. However, the energy distribution and flux of in-beam gamma rays have not yet been measured for several reasons. First, in-beam gamma rays and those gamma rays produced by neutron-induced nuclear reactions are difficult to distinguish in beam-measurement experiments. Second, most gamma-ray detectors are also sensitive to neutrons, and separating the signals owing to gamma rays and neutrons is difficult. Third, detectors and electronic circuits can be damaged by the γ -flash and fast neutrons when

the detectors are located in the neutron beam.

In this study, we propose a method using a CeBr_3 scintillation detector and the black resonance filter method [30] to determine the energy distribution and flux of gamma rays in the Back-n neutron beam. The black resonance filter method assists with absorbing neutrons at certain energies, which are determined using the time-of-flight (TOF) technique. Thus, within these absorption-energy regions, the in-beam gamma rays can be measured using the CeBr_3 scintillation detector without being affected by neutrons. The energy distribution of the in-beam rays is verified, and the flux is calculated by analyzing the deposition energy spectrum of the CeBr_3 scintillation detector and comparing it with Monte Carlo simulation results.

Methods

The black resonance filter method is effective for absorbing neutrons at certain energies without significantly altering the source neutron beam. Filters are employed to achieve negligible transmission of neutrons at certain energies corresponding to a few strong resonances. Furthermore, the remaining events in the resonance region are not influenced by neutrons and represent in-beam gamma rays. In this study, the TOF method was used to determine the resonance energy of neutrons (E) via the following relation:

$$E_n = \frac{1}{2}m_n \left(\frac{L}{t_n} \right)^2$$

where m denotes the neutron mass, L is the flight path, and t is the neutron flight time. At Back-n, t is determined as $t = (t_{\text{det}} - t_{\gamma}) + L/c$, where t_{det} is the time at which the detector responds to neutrons or γ rays, t_{γ} is the time at which the γ -flash arrives at the detector, and c is the speed of light.

Materials with strong resonances can be used as black-resonance filters. By placing these filters in the neutron-beam line, the neutrons are almost completely absorbed, allowing very few neutrons to reach the detector in the resonance-energy regions. Therefore, the residual signals of the detector in the absorption region are considered to be mainly induced by the in-beam gamma rays. The advantage of using materials with strong resonances is that they enable a thin filter, which can reduce the attenuation of gamma rays in the beam. However, to achieve reasonable statistical precision, relatively thick filters must be used in practice. To determine the best absorption regions, the Geant4 toolkit [31] was used to simulate the transmission rate of the filters used in Back-n.

In this simulation, the energy of the neutron beam was sampled according to the energy distribution of Back-n [8], and a virtual neutron detector was set up approximately 76 m away from the neutron source. The flight time required for the neutrons to pass through the filters and arrive at the detector was simulated.

Five filters were used at Back-n, including a silver (natAg) filter with a thickness of 0.4 mm, two cobalt (^{59}Co) filters with thicknesses of 0.4 mm and 1.0 mm, a 1.0 mm-thick tantalum (^{181}Ta) filter, and a 1.0 mm-thick natural cadmium (natCd) filter. The simulated neutron TOF spectra, with and without the filter, are shown in Fig. 2 [Figure 2: see original paper]. The dips absorbed by natAg (5.19 eV), ^{59}Co (132 eV and 5.016 keV), and ^{181}Ta (4.28 eV and 10.34 eV) can be clearly observed in the TOF spectrum of Fig. 2(a). Based on the neutron-transmission rate in Fig. 2(b), almost no neutrons were observed in the TOF regions near 85 μs , 480 μs , and 2.8 ms when the filters were online. Based on the time distribution of the in-beam gamma rays measured in Ref. [14], very few in-beam gamma rays exist in the TOF region above 2.0 ms. Therefore, the absorption region near 2.8 ms is unsuitable for measuring in-beam gamma rays at Back-n. The transmission rate in the 480 μs TOF region was lower than that in the 85 μs TOF region, indicating that the neutrons were more fully absorbed in the 480 μs TOF region. Finally, the TOF region around 480 μs was chosen to measure the in-beam gamma rays in this study.

Experimental Setup

The present measurement was performed at ES#2 of Back-n, with the CSNS operating in the two-bunch mode at a power of 140 kW. Fig. 3 [Figure 3: see original paper] shows the layout of the experimental setup. A CeBr_3 scintillation detector was used to measure the in-beam gamma rays located at the center of the neutron beamline, 76 m away from the spallation target. The CeBr_3 scintillator was selected as a γ -ray detector in this study for several reasons. First, the time response of the CeBr_3 scintillator to γ rays is less than a few tens of nanoseconds [32, 33], which is suitable for measurements using the TOF method. Second, the energy resolution of the CeBr_3 scintillator is better than that of commonly used gamma-ray scintillators such as $\text{NaI}(\text{Tl})$ and BGO. Third, the intrinsic activity of the CeBr_3 scintillator is considerably lower than that of a LaBr_3 scintillator with the same volume. Finally, most of the γ rays emitted by Ce and Br after neutron activation are less than 1.5 MeV, indicating that the in-beam gamma rays above 1.5 MeV are rarely affected by the activation γ rays.

The CeBr_3 scintillator used in this study had dimensions of $\Phi 38 \times 38$ mm and was manufactured by SCIONIX Holland B.V., as shown in Fig. 4 [Figure 4: see original paper]. A photomultiplier tube (PMT; R13089, Hamamatsu, Japan) was coupled to the CeBr_3 scintillator to receive the scintillation light. The CeBr_3 scintillation detector was placed perpendicular to the direction of the neutron beam, which reduces damage to the PMT owing to γ -flash and high-energy neutrons. The signals from the anode of the CeBr_3 detector were transmitted directly to a digitizer (DT5730B, CAEN SpA, Italy). In addition, the pickup signal (T0) from the pulsed proton beam was sent to the digitizer as the trigger for data acquisition.

The energy response of the CeBr_3 scintillation detector to gamma rays was

calibrated using four radioactive sources: ^{22}Na , ^{60}Co , ^{133}Ba , and ^{137}Cs . The relationship between the deposited energy of the gamma rays and charge integral value of the digitized signal was calibrated at energies of 0.276 MeV, 0.302 MeV, 0.356 MeV, 0.511 MeV, 0.662 MeV, 1.173 MeV, 1.275 MeV, and 1.332 MeV. Based on the calibration results shown in Fig. 5 Figure 5: see original paper, the charge integral value of the digitized signal exhibited good linearity with respect to the energy of the gamma rays. In addition, the energy resolution of the CeBr_3 scintillation detector was determined using the same measurements. As shown in Fig. 5(b), the energy resolution of the detector was 4.0% at 662 keV.

In the present measurement, ^{181}Ta and ^{59}Co filters, both 1.0 mm thick, were placed at a distance of approximately 26 m from the spallation target. A 0.4 mm-thick ^{59}Co filter and 0.4 mm-thick natAg filter were installed in the beam window chamber of Back-n. Additionally, a 1 mm-thick cadmium (natCd) filter was installed in the beam window chamber to absorb neutrons with energies below 0.3 eV and avoid overlap between consecutive neutron-beam pulses. The filter characteristics are shown in Tab. 1 .

The aperture of the collimator was changed during this measurement to study the flux of the in-beam gamma rays with different collimator assignments. Three types of collimator assignments were measured in this study: 3–15–40 mm, 12–15–40 mm, and 50–15–40 mm, where 3 mm, 12 mm, and 50 mm correspond to the apertures of the neutron-beam shutter. The values 15 mm and 40 mm correspond to the apertures of collimators 1 and 2, respectively, which did not change in this measurement. To normalize the measurement results between the different collimator assignments, the intensity of the proton beam was recorded using the accelerator operating system of CSNS.

Data Analysis

A. TOF spectrum

Signals from the CeBr_3 scintillation detector were digitized and recorded using a digitizer for offline analysis. Owing to its 14-bit resolution and 500 MS/s sampling rate, the digitized waveforms retained most of the characteristics of the original signals, such as amplitude, charge, and time. A typical waveform of the CeBr_3 scintillation detector is shown in Fig. 6 [Figure 6: see original paper] (black solid line). The rise time of this waveform is 17 ns and the full width is 120 ns. The ADC channel of the ordinate in Fig. 6 represents the amplitude, with one channel representing approximately 0.122 mV. In this study, the charge integral value of the waveform was used to represent the deposited energy of the gamma rays in the CeBr_3 scintillator, which was calibrated using gamma-ray sources, as mentioned above. In the present waveform processing, the fast filter (FF) and constant fraction discriminator (CFD) methods were used to handle the pile-up signals and obtain good timing accuracy. The waveforms after FF and CFD are indicated by the red dashed and blue dotted lines in

Fig. 6, respectively. The zero-crossing point of the CFD waveform was used as the signal time in the data-analysis routine. After waveform processing, the response time (T_{det}) was determined, and the TOF of the CeBr_3 detector was calculated using Eq. (2). The experimental TOF spectra with the 3–15–40 mm collimator assignment are shown in Fig. 7 [Figure 7: see original paper], in which the black solid line represents the measurement without the resonance filters, and the red dashed line represents those performed with the filters. The TOF spectra were normalized by the proton-beam intensity. Based on Fig. 7, two narrow peaks were observed at the beginning of the TOF spectra, which were induced by the γ -flash. The double-peak structure of γ -flash indicates that the accelerator of CSNS operated in the double-bunch mode. The maximum TOF range was 40.0 ms owing to the 25 Hz repetition rate of the pulsed proton beam. The dips absorbed by the ^{59}Co , ^{181}Ta , and natAg filters are shown in Fig. 7. The resonance peak of the $^{81}\text{Br}(n,\gamma)^{82}\text{Br}$ reaction at 135 eV was invisible when the filters were in place, indicating that the neutrons in this TOF region were completely absorbed by the filters.

B. Deposited energy spectrum

The signals in the absorption TOF region between 425 μs and 505 μs (Area 1) were selected to obtain the deposited energy spectra of the CeBr_3 detector. As shown in Fig. 8 [Figure 8: see original paper], the deposited energy spectrum without the filters (black solid line) was considerably higher than that with the filters (red dashed line) in the energy regions between 1.8 MeV and 7.0 MeV and below 0.511 MeV, which was primarily due to the cascade gamma rays produced by the $^{81}\text{Br}(n,\gamma)^{82}\text{Br}$ reaction around 132 eV.

Ideally, the energy spectrum deposited in the absorption TOF region is mainly attributed to the in-beam gamma rays. However, even in the absorption TOF region, a significant number of gamma rays were from the activation of the environmental materials and the CeBr_3 detector itself. In this study, signals in the TOF region at approximately 28.0 ms (Area 2 in Fig. 7, corresponding to neutron energies less than 0.3 eV) were analyzed to evaluate the contribution of the activation gamma rays. In Area 2, all primary neutrons were absorbed by a natCd filter, and the residual signals were attributed to the activation of gamma rays. Fig. 9 [Figure 9: see original paper] shows the normalized deposited energy spectra of Area 1 (black solid line) and Area 2 (red dashed line), indicating that the activation gamma rays mainly affected the energy region below 2.3 MeV. By subtracting the deposited energy spectrum of the activation gamma rays from that of Area 1, the deposited energy spectrum, which was induced only by the in-beam gamma rays, was obtained, as indicated by the blue dotted line in Fig. 9.

Results and Discussion

A. Energy distribution

Using the response function of the CeBr_3 detector for monoenergetic γ rays, the energy distribution of the incident γ rays can be obtained by unfolding the deposited energy spectra using an iterative algorithm. However, the experimental threshold and fluctuation of the deposited energy spectra owing to low statistics make accurately obtaining a real energy distribution over a wide energy range difficult. In this study, a Monte Carlo simulation was utilized to verify the energy distribution of the in-beam gamma rays of Back-n. As mentioned in Ref. [14], the entire spallation target was modeled using the Geant4 toolkit, as well as the moderators and reflectors around the target. The time distribution of the in-beam gamma rays was simulated and was in good agreement with the experimental results. The energy spectra of the γ -flash and delayed in-beam gamma rays were obtained using the same simulation. In addition, based on the simulation results, the energy distributions of the delayed in-beam gamma rays were similar for different TOF ranges [14]. Therefore, we propose simulating the response of the CeBr_3 detector to gamma rays with the energy spectrum given by Ref. [14] and comparing the simulated deposited energy spectrum with the experimental one obtained in this study. The entire experimental setup was modeled using the Geant4 toolkit, including the CeBr_3 detector, neutron beam line, BaF_2 detector array [21] installed at the experimental station, beam dump, and walls, as shown in Fig. 10 [Figure 10: see original paper]. In addition, resonance filters and neutron-beam windows were included in this simulation.

A circular surface gamma-ray source was constructed using the Geant4 code with a diameter of 20.0 mm, approximately 76 m away from the CeBr_3 detector. The energy of the gamma rays was sampled according to the energy spectrum, as shown in Fig. 11 [Figure 11: see original paper]. The peaks at 6–10 MeV are associated with gamma rays from the neutron capture reactions of spallation targets (W, Ta, Fe), and the peak at 2.23 MeV corresponds to gamma rays from the hydrogen capture reactions. Parallel gamma rays passed through the resonance filters in the vacuum beam line. The interactions of gamma rays in the CeBr_3 detector were simulated, and the deposited energy was recorded. The energy-resolution function shown in Fig. 5 was used to broaden the simulation spectrum, and a threshold of 150 keV was used in the simulation. Fig. 12 [Figure 12: see original paper] shows the simulated deposited energy spectrum, indicated by the red dashed line, and the black solid line represents the experimental result corresponding to the blue dotted line in Fig. 9. According to Fig. 12, the simulated deposited energy spectrum is consistent with the experimental spectrum above 0.4 MeV, indicating that the energy distribution used in this simulation can reasonably reflect the real energy spectra of the in-beam gamma rays at Back-n.

B. Flux calculation

Using the energy distribution of the in-beam gamma rays and the detection efficiency of the CeBr₃ detector, the flux (Φ_γ) was obtained via the following relation:

$$\Phi_\gamma = \frac{N \cdot f}{S \cdot \epsilon}$$

where N is the count rate of the measured deposited energy spectrum in the energy region between 0.4 MeV and 10 MeV in Fig. 12, with the units being events per second. S is the effective area of the CeBr₃ detector covered by the in-beam gamma rays, with units of square centimeters. ϵ is the detection efficiency of the CeBr₃ detector and f is the correction factor, with no units.

The correction factor f in Eq. (3) can be expressed as follows:

$$f = f_{att} \cdot f_{tof} \cdot f_{dt}$$

where f_{att} is the correction factor for the attenuation of gamma rays passing through the black resonance filters. f_{tof} represents the ratio of the total flux of in-beam gamma rays to the flux of gamma rays within a specific absorption region of the TOF spectrum. f_{dt} is the dead-time correction factor, which is due to the pile-up of signals when the counting rate is high.

The attenuation factor f_{att} was calculated using the Geant4 toolkit. The simulation procedure was similar to that used to calculate the detection efficiency. f_{att} was determined by simulating the ratio between the detector responses to the in-beam gamma rays with and without the resonance filters in the flight path. Considering the resolution function and detection threshold, the attenuation factor f_{att} was equal to 1.55 in this study. The uncertainty of f_{att} was assigned a conservative value of 2.0%.

f_{tof} was used in this study because only the absorption region in the TOF spectrum was used to measure the in-beam gamma rays, whereas the in-beam gamma rays lasted for more than 2 ms after the proton beam was injected into the spallation target. According to the time distribution given in Ref. [14], the total number of in-beam gamma rays was 1.0 after normalization, whereas the integral count of gamma rays with a TOF between 425 μ s and 505 μ s was 6.76×10^{-4} . f_{tof} was equal to 1.48×10^3 in this calculation. In Ref. [14], the time distribution of in-beam gamma rays was simulated and verified using experimental data. Therefore, the uncertainty of f_{tof} was estimated to be less than 10.0%.

The dead-time correction factor f_{dt} was determined as follows:

$$f_{dt} = \frac{1}{1 - \tau \sum_i N_i}$$

where τ is the time interval used in the waveform analysis, in which all signals that occurred were treated as one signal pulse and N_i is the counting rate associated with a bin in the TOF spectrum. In this study, τ was set to 60 ns to process the waveforms after the fast-filter procedure. Fig. 13 [Figure 13: see original paper] shows the f_{dt} obtained from the measurement with a 3–15–40 mm collimator assignment, where the presence of filters is indicated by the black solid line, and their absence by the red dashed line. Based on Fig. 13, the dead-time correction factor f_{dt} around the absorption region (Area 1) was 1.0 ± 0.001 ; thus, very few pile-up signals were observed under this experimental condition.

In the present measurement, the count rate N was 0.73 ± 0.03 per second. The uncertainty was mainly due to the poor statistics of gamma rays with deposited energies above 7 MeV and the uncertainty of the threshold. The effective area S was 1.57 cm^2 , which was equal to half the area of the beam spot, as recommended by Ref. [9]. According to the measurement results of the beam spot at Back-n [34], the measured diameter of the beam spot in ES#2 is 5% larger than the simulated diameter. Therefore, the uncertainty of S was assigned a value of 7.07% in this study. In this study, ϵ was determined via Monte Carlo simulations because no gamma-ray source had the same energy distribution as the in-beam gamma rays for the detection-efficiency calibration. The gamma-ray generator and detector geometry were the same as those mentioned in Section 5.1 in the Geant4 code. In addition, a resolution function was considered and a threshold of 0.4 MeV was used in this simulation. In this study, the detection efficiency was calculated to be 0.29. Determining the uncertainty of ϵ was difficult because it was the total simulation result. The statistical uncertainty was less than 0.1% due to the measurement statistics, uncertainty of the effective area, uncertainty of the dead-time correction, and uncertainty of $\Phi_{\gamma,3-15-40}$. The uncertainties of the flux in Tab. 3 were 16.58% for $\Phi_{\gamma,3-15-40}$, 18.06% for $\Phi_{\gamma,12-15-40}$, and 18.74% for $\Phi_{\gamma,50-15-40}$.

Using Eq. (3), the flux of the in-beam gamma rays measured by the CeBr_3 detector with a 3–15–40 mm collimator assignment was $3.68 \times 10^3 \text{ cm}^{-2} \cdot \text{s}^{-1}$. The values of the parameters in Eq. (3), Eq. (4), and their uncertainties are listed in Tab. 2.

Three types of collimator assignments were used in the measurements: 3–15–40 mm, 12–15–40 mm, and 50–15–40 mm. Fig. 14 [Figure 14: see original paper] shows the TOF spectrum with different collimator assignments and with the resonance filters online. As the aperture of the first collimator increased, the response of the CeBr_3 detector became significantly delayed. This was because the flux of the γ -flash became considerably stronger, such that the CeBr_3 detector was blinded and the recovery time was typically greater than 20 μs . Notably, the threshold used in the measurements for Fig. 14 was approximately 2.0 MeV. This occurred because when the aperture of the first collimator was larger than 3 mm, the data size with a low threshold was considerably larger than the data-transmission limit, which was 5.12 MB/s for the DT5730B. Considering that

the flux of the in-beam gamma rays with the 3–15–40 mm collimator assignment ($\Phi_{\gamma,3-15-40}$) was measured previously, the flux of the other collimator assignments could be determined via:

$$\Phi_{\gamma} = \frac{N}{N_{3-15-40}} \cdot \frac{S_{3-15-40}}{S} \cdot \Phi_{\gamma,3-15-40}$$

where N is the count rate of the TOF spectra in the region between 425 μ s and 505 μ s and S is the effective area, as shown in Eq. (3). For collimator assignments of 12–15–40 mm and 50–15–40 mm, the S values were 3.53 cm² according to Ref. [9]. The flux of the in-beam gamma rays, calculated using Eq. (6), are listed in Tab. 3. The uncertainties were mainly due to the measurement statistics, uncertainty of the effective area, uncertainty of the dead-time correction, and uncertainty of $\Phi_{\gamma,3-15-40}$.

Based on the energy distribution shown in Fig. 11 and the total flux of the in-beam gamma rays, the flux of the delayed in-beam gamma rays at ES#2 of Back-n was determined in different energy regions. The determined fluxes are listed in Tab. 4.

C. Background evaluation for (n, γ) reaction measurement

By utilizing the energy distribution and flux of the in-beam gamma rays determined in this study, the experimental background induced by the in-beam gamma rays can be evaluated for neutron-reaction measurements at Back-n, which is helpful for experimental optimization and data analysis. Taking the radiative neutron capture cross-section measurement using the C₆D₆ detectors at Back-n as an example, the gamma rays detected by the C₆D₆ detectors may originate from (n, γ) reactions or from the interactions of the in-beam gamma rays with the experimental sample. The C₆D₆ detector cannot distinguish between the in-beam gamma rays scattered off the sample and those produced by the neutron-capture reaction. Therefore, the experimental background increased with an increase in the number of scattered in-beam gamma rays.

To study the effect and background before an actual measurement, we propose simulating the response of the C₆D₆ detectors to in-beam gamma rays, as well as gamma rays from the (n, γ) reaction. A geometrical model of the C₆D₆ detectors was built with the Geant4 toolkit, similar to the model used in Ref. [10]. Two samples, ¹⁹⁷Au and ²⁰⁹Bi, were selected for the simulation in this study, with diameters of 30.0 mm and 1.0 mm respectively. The scattered cross-sections of ¹⁹⁷Au and ²⁰⁹Bi for the gamma rays were similar, whereas the neutron capture cross-section of ¹⁹⁷Au was significantly larger than that of ²⁰⁹Bi. In this simulation, neutrons and gamma rays were generated approximately 76 m away from the ¹⁹⁷Au and ²⁰⁹Bi samples, which was the same as the distance between the experimental sample and spallation target of CSNS. The energy distribution and flux of the neutron beam of Back-n used in the simulation were obtained from Ref. [8], and the time distribution of the in-beam gamma rays

was obtained from Ref. [14]. Because the collimator assignment used in the radiative neutron capture cross-section measurement was typically 12–50–40 mm, the fluxes of the neutron beam and in-beam gamma rays were given as $7.81 \times 10^5 \text{ cm}^{-2} \cdot \text{s}^{-1}$ [9] and $3.16 \times 10^4 \text{ cm}^{-2} \cdot \text{s}^{-1}$, respectively. The TOF spectra of the responses of the C_6D_6 detectors to scattered in-beam gamma rays (black solid line) and gamma rays from the (n, γ) reaction (red dashed line) are shown in Fig. 15 [Figure 15: see original paper]. Fig. 15(a) shows the simulated result of the ^{197}Au sample, while Fig. 15(b) shows that of the ^{209}Bi sample. The time structure of the proton-beam pulse and time resolution of the neutron beam of Back-n were not involved in the TOF spectra. According to the TOF spectra, the γ -flash scattered off the sample at approximately 230 ns, causing a significant response in the C_6D_6 detector. Subsequently, the detector's response to the in-beam gamma rays persisted for approximately 4.5 ms. Only (n, γ) reactions induced by neutrons with energies between 0.3 eV and 20.0 MeV were recorded in the simulation. Therefore, the TOF for the reaction gamma rays was primarily within the range of approximately 1 μs to 10 ms. The signal-to-background ratio of Fig. 15(a) was better than that of Fig. 15(b) because the cross-section of $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ was approximately ten to a hundred times larger than that of the $^{209}\text{Bi}(n, \gamma)^{210}\text{Bi}$ reaction. The poor signal-to-background ratio shown in Fig. 15(b) indicates that determining the cross-section of the $^{209}\text{Bi}(n, \gamma)^{210}\text{Bi}$ reaction when using the C_6D_6 detector at Back-n requires the precise removal of this background. This simulation provided a preliminary evaluation of the background induced by in-beam gamma rays in neutron capture cross-sectional measurements. However, the pulse-height weighting technique, neutron-scattering background, and activation background were not considered in this simulation. To determine the in-beam gamma background accurately, dedicated measurements of the Pb and C samples should be performed in the neutron capture cross-section measurement at Back-n [14–25].

Conclusion

In-beam gamma rays are common in almost all spallation neutron facilities and may affect the detectors on the beam line and increase the experimental background. In this study, the energy distribution of the in-beam gamma rays of Back-n was verified using the black resonance filter method and analyzed using Monte Carlo simulations. In addition, the flux of the in-beam gamma rays was determined. With the characteristics of in-beam gamma rays, the feasibility of neutron-reaction measurements at Back-n could be reasonably evaluated before an actual experiment.

According to the results of this measurement, the energy of the in-beam gamma rays ranged from keV to approximately 10 MeV, with approximately 75% above 0.4 MeV. Most high-energy in-beam gamma rays after the γ -flash are produced by neutron-capture reactions in the spallation target. Three collimator assignments were used in this study, and the fluxes of the in-beam gamma rays with different collimator apertures were more than 10 times lower than the neutron

fluxes with the same collimator assignment, according to Ref. [8]. Considering that more than 90% of the in-beam gamma rays are γ -flash rays, the flux of the delayed in-beam gamma rays, which may affect the (n,γ) cross-section measurement, were more than 100 times lower than that of the neutron beam. However, for an isotope with a small (n,γ) reaction cross-section and high gamma scattering cross-section, the background induced by the in-beam gamma rays was still too high to perform an accurate measurement with a C_6D_6 detector system. Therefore, we recommend using the 4π BaF₂ array detection system to measure the (n,γ) reaction with a small cross-section at Back-n. By measuring the multiplicity and total energy of the (n,γ) reaction, the background due to scattered in-beam gamma rays can be effectively suppressed, and the accuracy of the measurement can be significantly improved.

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