Nuclear data measurement and propagation in Back-n experiments: methodologies and instrumentation

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Abstract

This article introduces the methodologies and instrumentation for data measurement and propagation at the Back-n white neutron facility of the China Spallation Neutron Source (CSNS). The Back-n facility employs backscattering techniques to generate a broad spectrum of white neutrons. Equipped with advanced detectors such as the Light Particle Detector Array (LPDA) and the Fission Ionization Chamber Detector (FIXM), the facility achieves high-precision data acquisition through a general-purpose electronics system. Data are managed and stored in a hierarchical system supported by the National High Energy Physics Science Data Center (NHEPDC), ensuring long-term preservation and efficient access. The data from Back-n experiments significantly contribute to nuclear physics, reactor design, astrophysics, and medical physics, enhancing the understanding of nuclear processes and supporting interdisciplinary research.

Full Text

Preamble

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This article introduces the methodologies and instrumentation for data measurement and propagation at the Back-n white neutron facility of the China Spallation Neutron Source (CSNS). The Back-n facility employs backscattering techniques to generate a broad spectrum of white neutrons. Equipped with advanced detectors such as the Light Particle Detector Array (LPDA) and the Fission Ionization Chamber Detector (FIXM), the facility achieves high-precision data acquisition through a general-purpose electronics system. Data are managed and stored in a hierarchical system supported by the National High Energy Physics Science Data Center (NHEPDC), ensuring long-term preservation and efficient access. The data from Back-n experiments significantly contribute to nuclear physics, reactor design, astrophysics, and medical physics, enhancing the understanding of nuclear processes and supporting interdisciplinary research.

Keywords: Nuclear physics, Data acquisition, Data storage and management, Data sharing, Neutron experiments, White neutron beam

Introduction

The Back-n White Neutron Facility at the China Spallation Neutron Source (CSNS) in Dongguan, China, is a state-of-the-art platform for advanced neutron research [**?**]. As the country's first pulsed neutron source, it employs backscattering techniques to generate a broad spectrum of white neutrons. These neutrons, produced by bombarding a tungsten target with high-energy protons, cover a wide energy range and are particularly useful for nuclear physics, data measurement, and engineering applications. Equipped with sophisticated detectors and instrumentation, the facility enables precise experiments that provide valuable insights into nuclear reactions.

These data provide a foundational resource for the development and refinement of nuclear models, which are essential for advancing our understanding of nuclear reactions and processes. By offering precise measurements, the data contribute to improved accuracy in nuclear reaction cross-sections, which are critical inputs for nuclear reactor design, radiation safety assessments, and the development of new nuclear materials. Moreover, the data have broad utility beyond the immediate research applications at Back-n. They can be leveraged by the wider scientific community to explore novel nuclear phenomena, thereby opening up opportunities for new collaborations and interdisciplinary studies. For instance, the data may aid in astrophysical research, where accurate neutron capture rates are crucial for modeling stellar nucleosynthesis. In addition to their scientific value, the data also have potential applications in medical physics, particularly in the design of radiation therapies and diagnostic tools. By facilitating a deeper understanding of neutron interactions with various isotopes, the data can help optimize these technologies for better patient outcomes. Overall, the nuclear data from Back-n serve as a versatile tool that not only supports current research initiatives but also paves the way for future innovations and collaborations across multiple fields.

As the first high-performance white neutron source in China, Back-n provides an unprecedented platform for broad neutron-induced nuclear data measurements [**?**]. Its neutron spectrum allows for precise measurements of neutron-induced reactions, essential for developing and validating nuclear models. These measurements refine nuclear reaction cross-sections, vital for reactor design, radiation shielding, and safety assessments. The facility also facilitates the study of neutron interactions with various isotopes, enhancing our understanding of nuclear processes and aiding in the development of new materials for nuclear energy. Additionally, its high-quality nuclear data benefits fields like astrophysics, where accurate neutron capture rates are crucial for modeling stellar nucleosynthesis. Overall, the Back-n facility is a key resource for advancing nuclear data research, supporting efforts to harness nuclear technology safely and efficiently across academic and industrial sectors.

The Back-n facility boasts a comprehensive and advanced detector system, including the Light Particle Detector Array (LPDA), the multi-layer Fission Ionization Chamber Detector (FIXM), and gamma-ray detectors such as C6D6. Recently, the facility has also incorporated the world' s leading Multi-purpose Time Projection Chamber (MTPC) and the Gamma Total Absorption Facility (GTAF) into its operations. These additions are expected to yield a wealth of high-precision nuclear data measurements [**?**].

Most of the detector systems rely on a high-precision waveform sampling electronics system, known as the general-purpose electronics system. The data collected by these systems are acquired through a Data Acquisition (DAQ) process and stored in the disk array system of the CSNS Computing Center' s cluster. Users utilize the ROOT software to convert this binary data into graphical formats, such as TTrees and one-dimensional or two-dimensional histograms. After performing necessary R-matrix fits, the data provide critical nuclear-related information, which is then published as measured nuclear data.

This paper will describe the typical data analysis process based on the Back-n facility, illustrating the methodologies and instrumentation used in data measurement and propagation in Back-n experiments.

II. Experimental Setup and Measuring Principle

In white neutron experiments, the measurement of flight time is of utmost importance. The experiment utilizes neutrons or secondary particles produced by neutrons interacting with the target as the timing reference, and obtains the reaction cross sections of neutrons of different energies. In Back-n, multiple experiments of different reaction types have been conducted [**?**]. In this paper, the total cross-section measurement experiment is taken as an example to illustrate the experimental principle and method.

The neutron-induced total cross-section refers to the probability of a nuclear reaction occurring when a neutron strikes the sample. The transmission measurement is the primary method for measuring the neutron-induced total cross-section, and the transmission rate T was obtained from the neutron counts, N and N_0, measured in the sample-in and sample-out configurations using Eq. 1.

$$T = \frac{N}{N_0} = e^{-n\cdot\sigma\cdot d}$$

where n denotes the number density of atoms, and d denotes the thickness of the sample. The neutron-induced total cross-section σ is calculated as Eq. 2.

$$\sigma = -\frac{1}{n \cdot d} \ln\left(\frac{N}{N_0}\right)$$

Neutrons possess rest mass, and the Time-of-Flight (TOF) method is commonly used to determine the energy of neutrons in nuclear physics experiments. It determines the neutron energy by recording the time when the neutron flies over a fixed distance. The relationship between neutron energy E and its flight time tof_n is shown in Eq. 3.

$$E = m_{nc}^2 \left(\sqrt{\left(\frac{L}{c \cdot tof_n}\right)^2 + 1} - 1\right)$$

where m_n denotes the mass of neutron, c denotes the speed of light, and L is the neutron flight length.

The neutron detector used is the FIXM (multi-layer fission chamber) [**?**]. It employs multiple layers of fissile materials as the target plates to detect the signals of fission fragments in the gas ionization chamber. The signals are amplified by the MSI-8 preamplifier from the Mesytec company and then sent to the general-purpose electronics for waveform acquisition.

III. General-Purpose Readout Electronics

For the Back-n facility, the neutron nuclear data is measured by the general-purpose readout electronics together with the neutron energy. In implementation, the neutron nuclear data can be deduced by acquiring the detector signal precisely, while the neutron energy can be obtained by measuring the time of flight (TOF) of the neutron. TOF is defined as the time difference between a start signal and a stop signal, where the start signal is designated as T_0 which represents the exact time when the proton beam bombards the tungsten target of CSNS. Therefore, there are two critical measurements for the readout electronics: TOF and waveform.

To measure the neutron TOF precisely, the T_0 signal, designated as the start time, must be distributed synchronously to each measurement point. [Figure 1: see original paper] shows the structure of T_0 signal fanning out for Back-n. There is a fanning out device on the ground which receives the FCT signal from the beam monitor system and then fans it out to the readout electronics placed in the two underground experiment halls through two long-distance coaxial cables with lengths of about 100m each. There are several electronics crates in both halls, and inside each crate there are installed several high-speed digitizers and a timing module named TCM (trigger and clock module). The T_0 signal is distributed to the TCM module installed in the master crate first and then fanned out to the TCM modules installed in the slave crates. The distribution path between the master and each slave crate is set to the same length, which eliminates the T_0 propagation skew.

T_0 jitter is the primary factor degrading the precision of the TOF measurement. The fan-out device on the ground uses an oversaturated circuit to amplify the FCT T_0 signal to obtain a new T_0 signal with a very fast leading edge, which is better for increasing timing accuracy. Additionally, long-distance cables can worsen the jitter of transmitted signals because of limited bandwidth. The longer the distance, the greater the deterioration. To reduce the influence of long-distance transmission, the fanning out device uses a long-distance driver to pre-emphasize the high-frequency part of the T_0 signal to improve signal quality after transmission over 100m, ensuring the received T_0 signal has a good enough leading edge to guarantee timing accuracy. Finally, an FPGA (field programmable gate array) based time digital converter [**?**] is used to measure the TOF, which can achieve good performance of 280ps (RMS) as shown in [Figure 3: see original paper].

To measure the waveform of detector signals precisely, Back-n proposes an innovative full hardware digital trigger method based on high-speed waveform digitizing. [Figure 4: see original paper] shows the principle of the digital trigger [**?**]. On the top side, the signal from the neutron detector is fed into the signal conditioning module to generate proper signals compatible with the ultra high-speed digitizer [**?**] [**?**]. With the help of the folding structure of the analog-to-digital converter, full digitized waveforms of detector signals are obtained with very good magnitude and time resolution. The sampling rate can reach up to 1 GSa/s, while the resolution can be 12 bit. The L1 hardware digital algorithm is executed on FPGA. On each digitizer’ s local FPGA, the digitizing data stream is divided into two parallel branches: one is fed into a trigger match FIFO waiting for the global trigger, and another is fed into the sub-trigger processing module simultaneously. In the L1 hardware trigger structure, there is one master global trigger module, which receives all sub-trigger packets from all local trigger modules on each digitizer to generate the global trigger signal based on a specific algorithm to indicate when a valid good event occurs. This global trigger signal is fanned out to each trigger match FIFO (First In First Out) so that the digitizer can read out the correct data corresponding to this good event. After being built, the good event data is finally transmitted to the

DAQ server through Ethernet.

The general-purpose readout electronics hardware comprises three kinds of modular components: the FDM, TCM, and Signal Conditioning Modules (SCMs). These modules can be flexibly configured according to experimental requirements and integrated into a PXIe chassis, as shown in [Figure 5: see original paper].

IV. Data Acquisition and Records

A. Overview

Several detector systems, each designed for specific functions, have been established at the Back-n facility. Typically, only one detector system is in operation at a time. Additionally, the experimental halls ES1 and ES2 at Back-n are not typically used simultaneously. Therefore, the Data Acquisition (DAQ) system is designed to support a single active detector system at a time. All detector systems are built on the same electronics platform.

The overview of the electronics and DAQ system is shown in [Figure 6: see original paper]. The controller located in the NI PXIe crate is a computer with x86 architecture running Linux OS. It reads data from several FDMs (Field Digitizer Modules) and a TCM (Trigger and Clock Module) through the PXIe backplane. Data are transferred to the DAQ server through Gigabit Ethernet.

The pulsed neutron source beam strikes the target at a frequency of 25 Hz, generating neutron bunches that are input to the detector at the same frequency, producing corresponding T_0 signals. The T_0 signal is fed into the electronics module, which uses this signal to tag the data with a T_0 ID label (an 8-bit integer). Multiple readout processes run on the PXIe controller. Each process reads data from a single electronic module and establishes a TCP/IP connection with the DAQ data flow, transferring data fragments to DAQ servers.

B. Online Processing

The waveform data produced by each neutron bunch are assembled as T_0 fragments in the DAQ software. T_0 fragments are quickly analyzed online for quality monitoring purposes.

The online processing software is designed with a modular architecture, allowing data processing algorithms to be dynamically loaded. This flexibility enables different detectors to customize their data processing pipelines according to their specific requirements. The fundamental unit of online data processing is the T_0 fragment, which contains all signal data corresponding to a single neutron bunch. The processing framework retrieves T_0 data packets from the assembly queue and processes them in a data-driven manner, ensuring efficient and timely analysis. It supports the publication and real-time display of ROOT-format histograms, historical trends, and waveform data. Additionally, some common online data processing algorithms, including waveform peak finding, time-of-flight spectra analysis, charge spectra analysis, and waveform sampling, are provided as universal functions for all Back-n experiments.

The entire online data flow runs on a single server. Data are processed in a pipeline from readout to storage. Fast analysis of T_0 fragments is performed in multiple threads.

C. Run Control and Monitoring

The user interface of the DAQ software is web-based and consists of two main components: the run control module and the online computation results display module.

As shown in [Figure 9: see original paper], the run control module provides essential functionalities, including start/stop control, modification of operational parameters, real-time display of various count rates, and error message notifications. As shown in [Figure 10: see original paper], the online computation results display module retrieves and visualizes online computation results (in ROOT format) from the information sharing service. It leverages the JSROOT library [**?**] to enable dynamic rendering of ROOT graphics directly within the web interface.

D. DAQ Performance

The performance test involved two electronic chassis, each equipped with a controller connected via Gigabit Ethernet, while the data acquisition (DAQ) server featured a 10-Gigabit uplink. To evaluate the transmission performance of the DAQ system and associated electronics, a signal generator was used to simulate detector signals and feed them into the electronic components. The test setup maintained a fixed 8,000 sampling points per channel across a total of 16 channels. During the experiment, the frequency of the signal generator was varied to change the data rate while keeping the number of sampling points constant. The expected data rate was calculated as the product of the number of sampling points and the anticipated signal rate.

The results, illustrated in [Figure 8: see original paper], indicate that the system’ s data acquisition rate increases linearly with the signal rate, reaching a maximum around 10 kHz. The DAQ performance is approximately 1.2 Gbps.

The information sharing service operates as an independent process, storing online computation results in memory. Based on the summarized requirements of Back-n experiments, the online computation results can be categorized into three types: histograms, historical curves, and sampled waveforms. To facilitate efficient data access and sharing, the information sharing module provides an interface with the following functionalities:

1. Serialize ROOT-type computation results (histograms, historical curves, two-dimensional scatter plots) and store them in the information service.

2. Retrieve result data from the information service, deserialize it, and reconstruct it into the corresponding ROOT type.

V. Recommended Repositories to Store and Find Data

A. National High Energy Physics Science Data Center

The storage, computing, and sharing of white neutron beam data are supported by the National High Energy Physics Science Data Center (NHEPDC), one of China’ s 20 national scientific data centers. Comprising the Beijing Data Center and Guangdong-Hong Kong-Macao Greater Bay Area Branch, NHEPDC focuses on the integration and sharing of data resources, software tools, and data analysis techniques in fields of high-energy physics, neutron science, photon science, astrophysics, and interdisciplinary research. Currently, NHEPDC manages a total data volume of 37.55 PB and serves more than 4000 users from hundreds of institutions worldwide, with annual data access volumes reaching several hundred PB. Furthermore, through long-term cooperation with the European Organization for Nuclear Research (CERN), NHEPDC has established itself as a core node within the international high-energy physics data grid.

B. Storage System

For the storage of white neutron beam data, NHEPDC provides long-term preservation, offers file system access interfaces for offline data analysis tasks, and facilitates cross-domain data sharing services for remote users. The data is stored within a three-tier hierarchical storage system, comprising experimental station disk storage, central disk storage, and central tape storage. The data from Back-n experiments are first saved to the experimental station storage, and then the data transmission system moves the data to central disk and tape storage. The central disk and tape storage facilities are provided by NHEPDC, Guangdong-Hong Kong-Macao Greater Bay Area Branch. The central disk storage primarily employs the Lustre distributed file system, enabling linear scalability for read/write throughput. Raw data is retained for 1-2 years according to the data policy, allowing users to conduct large-scale data analysis and remote access during this period. Meanwhile, the data is archived in tape libraries for long-term preservation. The hierarchical storage management system, EOSCTA [**?**], enables transparent data transfer and access across multiple media, including disk and tape. Data is archived daily and transferred from the central disk storage to the EOS distributed file system. The CTA management software then archives the data to tape storage. When a user initiates an access request through the data management system, the backend uses metadata to locate the physical storage position of the data. If the data resides on the central disk storage, it can be directly accessed. If the data is stored on the central tape storage, the CTA management software will initiate a process to restore the data to the EOS system and transfer it to the corresponding location within the central disk storage for user access and manipulation.

C. Data Management System

For the management and services related to the access and sharing of white neutron beam data, NHEPDC provides full-lifecycle data management services, encompassing data transmission, storage, analysis, and sharing, to ensure the efficient organization and management of scientific data as shown in [Figure 11: see original paper]. White neutron beam data involves numerous metadata, primarily categorized into scientific metadata and management metadata. Scientific metadata includes various parameters related to high-energy physics in white neutron beam experiments, such as beam power. Management metadata consists of information generated during the processes of data transmission, storage, analysis, and sharing, such as data storage paths and file permissions. The data management is implemented by the DOMAS framework [**?**], which primarily provides metadata catalog service, metadata acquisition and processing system, data transmission system, and data service system.

1. Metadata Catalog Service The metadata catalog service leverages MongoDB as its database, offering robust capabilities for storing complex metadata and providing APIs for efficient access. This service facilitates the seamless utilization of relevant metadata by related systems such as the proposal system, experiment system, and sample system. Additionally, it includes a visualization tool that automatically generates metadata access interfaces based on metadata model designs, enhancing accessibility and usability.

2. Metadata Acquisition and Processing System The metadata acquisition and processing system supports the acquisition of administrative metadata and scientific metadata from various subsystems involved in the entire lifecycle of experimental processes, including experimental application, experiment conduction, DAQ, data storage, data transfer, data analysis, data sharing, and data publication. This multi-source architecture system utilizes diverse acquisition plugins to extract metadata from different interfaces. In addition, the extracted metadata is associated, integrated, and then stored in the metadata database using the APIs provided by the metadata catalog.

3. Data Transmission System The data transmission system automates the near-real-time, efficient, and reliable migration of data produced from Back-n experiments across different storage systems by leveraging the APIs of various storage systems as described in Section V.B. It integrates multiple protocols including rsync, scp, xrdcp, and eoscp to ensure flexibility and compatibility. To maintain integrity and accuracy of data files, the system employs checksum validation. In the event of transmission failures, automatic retransmission is initiated. Furthermore, the system offers comprehensive transfer logs and monitoring capabilities, enabling effective tracking and management of the entire transfer process.

4. Data Service System The data service system provides a web-based interface designed to enhance user experience by enabling seamless access, visualization, downloading, analysis, and sharing of data. It supports the viewing of organized data files along with their associated metadata, providing users a detailed overview of data structures and contextual information. To safeguard data privacy while promoting collaboration, the system implements dataset-level access control. Principal Investigators (PIs) can securely authorize other researchers to access specific datasets via email, ensuring streamlined and secure sharing processes. Additionally, the system supports online previews of data files in HDF5 and Nexus formats, allowing users to examine file contents efficiently without requiring downloads or specialized software. For data analysis, the system leverages high-performance computing (HPC) resources from NHEPDC, Guangdong-Hong Kong-Macao Greater Bay Area Branch. These HPC systems provide over 4500 TFLOPS of double-precision floating-point performance and are equipped with specialized neutron simulation and analysis tools, such as FLUKA and MCSTAS. To further enhance flexibility and resource utilization, virtualization technologies are being implemented. This allows users to create customized virtual machines tailored to complex computational requirements, significantly improving the efficiency and adaptability of data analysis workflows.

5. Workflow of Data-Driven Processing A brief overview of the fundamental process for managing data generated by experiments within a data management system is as follows:

1. Upon generation of data files by the experimental terminal, a Kafka message containing metadata such as proposal ID, sample ID, experimental details, and file information is sent.
2. The data-driven processing system consumes the Kafka message based on its offset from step 1, leveraging the metadata catalog service' s API to extract metadata from various systems. The management metadata and scientific metadata are then reorganized, assigning data file ownership to the proposal' s PI (Principal Investigator). Subsequently, the metadata is aligned by proposal ID and written into the metadata database. Additionally, a file transfer task for moving files from experimental station storage to central disk storage is logged in the transfer task database.
    - Proposal metadata, including proposal name, abstract, PI name, and email, is retrieved from the user system using the proposal ID.
    - Sample metadata, such as sample name and quality, is extracted from the sample management system using the sample ID.
    - Other systems provide additional metadata.
3. The data transfer system polls the transfer task database and initiates the transfer upon detecting a new task. After successful transfer, it sends a Kafka message containing transfer metadata.
4. The data-driven processing system consumes this Kafka message based on its offset from step 3 and uses the metadata catalog service' s API

to write the transfer metadata into the metadata database, updating the directory location of the data files. A new transfer task for moving files from central disk storage to central tape storage is then logged in the transfer task database.

5. The data-driven processing system processes subsequent Kafka messages from step 4 similarly, as outlined in step 4, continuing the workflow for later stages.

With the support of NHEPDC, storage and computing systems for white neutron beam data have been officially deployed and are operating efficiently. The data management system is currently in trial operation. Moving forward, we aim to expand the utilization of data by developing an experimental nuclear reaction database.

VI. Verification and Dissemination of Nuclear Data

In order to screen out data related to neutron reactions from raw experimental data, detailed data processing and analysis are necessary.

A. Experimental Data Processing and Analysis

1. Data Preprocessing **Data format conversion:** Convert binary files to ROOT format files based on the DAQ system' s storage format. The Back-n collaboration has provided the reference code for this work. The ROOT file stores all the signal information of each event (one proton targeting is an event), including RunNumber, EventNumber, ChannelID, MovieLength, T, ADCValue.

Abnormal Data Filtering: Judge whether there is abnormal data through statistical methods or domain knowledge, and handle them appropriately.

Data normalization: Data normalization or standardization is performed through the proton beam intensity to eliminate the effects of different scales and magnitudes.

2. Signal Processing The proton beam hitting the target triggers the T_0 signal, after which the system opens a signal acquisition window of about 10 ms. All signals of events within this time window are extracted in chronological order from the ROOT file. A complete waveform diagram of an event can be obtained, as shown in [Figure 12: see original paper].

The signals are smoothed by the ROOT program to effectively reduce the effect of noise. Then, peak search and baseline calculation are performed on the signals, and the amplitude and corresponding fission time information of each signal can be extracted.

B. Determination of Neutron Energy by TOF Method

1. Neutron Flight Time Determination Neutron production by a 1.6 GeV proton beam hitting the tungsten target is accompanied by the generation of high-intensity γ-rays, called γ-flash. γ-flash signals and fission signals detected by the FIXM are shown in Figure 12: see original paper. After traveling at the speed of light for a distance, γ-flash will reach the detector earlier than neutrons with rest mass. The moment of neutron production is difficult to determine, so the time difference between the detected γ-flash and the neutron signal can be used to determine the neutron' s time-of-flight. The time-of-flight can be calculated by Eq. 4.

$$tof_n = T_n - T_{n0} = T_n - (T_\gamma - tof_\gamma)$$

where T_n is the neutron arrival time detected by the detector, T_{n0} is the generation time of neutron, T_γ is the time when γ-flash is detected, and tof_γ is the flight time of γ-flash from the target to the detector.

2. Neutron Flight Distance Calibration The cathode of the FIXM consists of target cells coated with fissionable nuclides (^{235}U, ^{238}U), and the energies and neutron flight times corresponding to the ^{235}U resonance peaks can be used to calibrate the neutron flight distance. [Figure 13: see original paper] shows the fission time distribution of the signals obtained from the ^{235}U fission cell, and the three low-energy resonance peaks (8.77 eV, 12.38 eV, 19.28 eV) are clearly visible. The resonance peaks were fitted using a Gaussian function to obtain the fission time. According to the relationship between the energy of the resonance peaks and the corresponding fission time in the TOF method, the neutron flight distance can be obtained by fitting based on Eq. 5.

$$T_{cf} - T_\gamma = \sqrt{\frac{m_{nc}^2}{2E_n} + 1} \cdot \frac{L}{c}$$

where T_{cf} is the fission time corresponding to the resonance peak, and E_n is the energy.

3. Double-Bunch Unfolding In order to increase neutron intensity, the experiment uses double-bunch mode, with a time interval of approximately 410 ns between the two bunches. However, this mode leads to superposition of the TOF spectrum, introducing bias to the counting of high-energy neutrons. At neutron energies up to 10 keV, the time resolution impact caused by the double-bunch is about 1%. As the neutron energy rises, the time resolution gradually worsens. To address this problem, the Back-n collaboration has developed a Demo Unfolding code, which is based on the Bayesian iterative method [**?**]. The TOF spectrum corresponding to the single-bunch mode can be obtained by linking the measured values with the true values through the response matrix and using

Bayes' theorem and iterative algorithms to estimate the true values. The error of the unfolding is determined by factors of neutron energy and statistics, so there will be differences in experiments.

Among these, the measurement of neutron energy spectrum is the most important. The neutron energy spectra of Back-n were measured several times, and the neutron energy spectra under different end stations and collimation aperture diameters were obtained. The related errors were also analyzed. These neutron energy spectrum data can serve as references for most nuclear data measurement experiments [?][?][?]. Reference [?] presents the neutron spectrum errors brought by unfolding.

[Figure 14: see original paper] demonstrates the changes in the TOF spectrum and energy spectrum before and after the unfolding process, and the double peaks in the high-energy region are restored to single peaks after unfolding.

The sources of experimental background for different nuclear reaction measurements are different and need to be analyzed according to specific experimental conditions and reaction types. For the measurement of neutron-induced total cross-sections using FIXM, the experimental background can be deducted by setting a threshold. After deducting the background, the neutron counts obtained for sample-in and sample-out are ratioed to obtain the neutron transmission. The neutron-induced total cross-sections are obtained according to Eq. 2. Further analysis needs to consider data corrections, e.g., dead time correction, multiple scattering correction. Uncertainty analysis is needed, such as the error of counting statistics, the error of neutron energy scale, etc. Finally, based on the analysis results, a detailed explanation and discussion is carried out in relation to the experimental objectives. [Figure 15: see original paper] shows the results of neutron-induced cross-section measurements of ^{209}Bi from 0.3 eV to 20 MeV on Back-n at CSNS [?].

The statistical uncertainties associated with the neutron counts are a primary source of error. These uncertainties are particularly significant in regions with low neutron flux, such as the resonance region (1 eV to 1 keV). The use of thicker samples (e.g., 20 mm) helps reduce these uncertainties by increasing the number of detected events, thereby improving the statistical quality of the data. At 98% of these energy bins, uncertainties were less than 10%, with 80% of them being below 5%. Furthermore, 12% of the energy bins had uncertainties of less than 2%. It can be seen that the measured data are in good agreement with the evaluation data and other experimental data. It is worth noting that total cross-section measurement is one of the experiments with relatively small errors in nuclear data measurement. In some other measurements, such as capture cross-section measurement and neutron-induced charged particle emission cross-section measurement, the interference from background and substrate is also an important source of error. These experiments often use standard cross-section targets or empty target experimental results as references for measurement to subtract the background.

This is only a simplified overview of the analysis process. Measurements of different nuclear reactions are unique and therefore the data processing steps will vary.

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Code Availability

In accordance with the principles of open-source sharing, all custom code utilized in the generation and processing of datasets at the Back-n facility is made publicly accessible. This ensures transparency and facilitates the reproducibility of our research findings. The code can be accessed without any restrictions, and comprehensive documentation is provided to assist users. This documentation includes details on the software versions employed, as well as specific variables and parameters used in the dataset generation, testing, and processing phases. Researchers and interested parties can access the code and additional resources at the following URL: https://code.ihep.ac.cn/beag_{csns}/.

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Author Contributions Statement

Minhao Gu was responsible for writing the section on DAQ. Ping Cao contributed by writing the section on electronics. Yakang Li and Peng Hu handled the writing related to data storage and management. Jieming Xue, Jie Ren, and Yonghao Chen were in charge of the sections on data processing and dissemination. Ruirui Fan, as the beamline leader, oversaw the integration and organization of the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

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

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