

Postprint: Advances in China's Nuclear Data Experimental Research

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Abstract

Nuclear data, particularly neutron nuclear data, forms the foundation of national defense construction, nuclear energy development, and nuclear technology applications, while also playing a significant role in fundamental nuclear physics research. The quality of nuclear data directly impacts the effectiveness, safety, reliability, and economic viability of related facilities and products. Experimental data serves as the basis for developing relevant theoretical models and nuclear databases; consequently, experimental nuclear data research holds an extremely important position in nuclear data studies. China's experimental nuclear data research commenced in the mid-20th century, and through decades of development, has yielded substantial achievements. This paper will briefly introduce the progress made in China's experimental nuclear data research and attempt to prospect future developments.

Full Text

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Progress in Nuclear Data Experimental Research in China

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Abstract

Nuclear data, especially neutron-induced nuclear data, forms the foundation of national defense, nuclear energy development, and nuclear technology applications, while also playing a critical role in fundamental nuclear physics research. The quality of nuclear data directly impacts the effectiveness, safety, reliability, and economy of related devices and products. Experimental data serves as the

foundation for developing theoretical models and nuclear data libraries, making experimental research paramount in nuclear data studies. China's experimental nuclear data research began in the mid-1950s and has achieved fruitful results after decades of development. This article provides a brief overview of progress in experimental nuclear data research in China and outlines potential future advancements.

Keywords: Nuclear data, Experimental data, Neutron source

Nuclear data is a general term describing nuclear reaction data for incident particles of specific energies interacting with atomic nuclei, as well as nuclear structure and radioactive decay data describing fundamental properties of individual nuclides. Nuclear reaction data primarily includes reaction cross-sections, angular distributions and energy spectra of secondary particles, double-differential cross-sections, gamma production cross-sections, and fission product yields. Nuclear structure and decay data mainly includes atomic nuclear masses, half-lives, decay branching ratios, and level schemes. Neutron-induced nuclear reaction data holds the most important applications in nuclear energy development (including fission and fusion energy) and nuclear technology applications. The nuclear data generation process involves three key steps: First, critical nuclear reaction and structure experimental data are obtained through nuclear physics experimental methods. While experimental data is fundamental, it is often discrete and incomplete, making it impossible to construct a complete, systematic nuclear database from experimental data alone. Second, theoretical models of nuclear reactions and structures are used with existing experimental data to determine and optimize model parameters, enabling the calculation of comprehensive nuclear databases. Third, macroscopic validation experiments using nuclear data are performed in conjunction with particle transport calculations to ensure database quality. This workflow demonstrates that experimental nuclear data research is the most important and fundamental aspect of nuclear data work. Recognizing this importance, all nuclear powers have invested substantial human and material resources in experimental work. International nuclear data experimental efforts began in the 1940s, providing strong support for nuclear weapon design, development, and testing. Subsequently, to meet the needs of national defense, nuclear energy development, and nuclear technology applications, countries have continued nuclear data experimental work, making important contributions to several major international nuclear databases. China's nuclear data experimental work began in the 1950s, making important contributions to national defense, nuclear energy development, and nuclear technology applications across different periods. After decades of development, China has established an experimental research system with considerable scale, high capability, and distinctive features, providing crucial support for the development of China's independent nuclear database, the Chinese Evaluated Nuclear Data Library (CENDL), which has established China as a major nuclear data power internationally.

This article introduces progress in nuclear data measurement in China and pro-

vides future perspectives. The supporting conditions for nuclear data measurement work include neutron sources, detectors, measurement methods, and sample preparation. Therefore, this article first introduces neutron sources and detector systems for nuclear data measurement, then discusses progress in nuclear data measurement, and finally provides an outlook and future directions.

Neutron Sources for Nuclear Data Measurement

Currently, China's neutron sources for nuclear data measurement mainly include: (1) Reactor neutron sources, such as the China Advanced Research Reactor and Mianyang Research Reactor, which primarily provide thermal neutron beams; (2) Electrostatic accelerator neutron sources, including the HI-13 Tandem Accelerator, 600 kV Cockcroft-Walton accelerator, and 5SDH-2 tandem accelerator at the China Institute of Atomic Energy, the 4.5 MV Van de Graaff accelerator at Peking University, the 2 \times 3 MV tandem accelerator at Sichuan University, and Cockcroft-Walton accelerators at the Institute of Nuclear Physics and Chemistry (China Academy of Engineering Physics), Lanzhou University, and Institute of Nuclear Energy Safety Technology (Chinese Academy of Sciences), which provide monoenergetic and quasi-monoenergetic neutrons from tens of keV to 40 MeV; (3) Electron accelerator neutron sources, such as the TMSR-PNS at the Shanghai Institute of Applied Physics (Chinese Academy of Sciences), which provides white neutrons from thermal energies to the keV region; and (4) The CSNS Back-n white neutron source at the China Spallation Neutron Source, which provides white neutrons from thermal energies to 300 MeV. These neutron sources constitute China's primary facilities for nuclear data measurement, with their main parameters listed in Table 1 .

Status of Nuclear Data Experimental Facilities

Based on these neutron sources, a series of nuclear data experimental facilities have been established, including the following major systems.

2.1 Multi-Detector Fast Neutron Time-of-Flight Spectrometer on the HI-13 Tandem Accelerator

This spectrometer [10] is primarily used for measuring differential cross-sections of neutron elastic and inelastic scattering, as well as secondary neutron double-differential cross-sections. As shown in Figure 1 [Figure 1: see original paper], the spectrometer consists of three main neutron detectors, a monitor, and an angular spectrometer covering angles from 30° to 160°, with flight paths up to 7 m and time resolution reaching 1 ns. The spectrometer is equipped with deuterium and tritium gas target systems, enabling experiments in the neutron energy range of 5–42 MeV.

2.2 HPGe Detector Array on the HI-13 Tandem Accelerator

This detector array [11] is mainly used for measuring gamma production cross-sections from neutron inelastic scattering and $(n, xn\gamma)$ reactions. As shown in Figure 2 [Figure 2: see original paper], the array consists of six Clover detectors and six planar detectors, with each Clover detector comprising four high-purity germanium detectors with 38% relative detection efficiency, equipped with BGO anti-Compton shields.

2.3 Spherical He-3 Neutron Detector Array on the CIAE Cockcroft-Walton Accelerator

This system is primarily used for online measurement of $(n, 2n)$ reaction cross-sections by directly detecting the two outgoing neutrons from the $(n, 2n)$ reaction. Figure 3 [Figure 3: see original paper] shows a photograph of this detection system [12], which consists of 110 He-3 tubes uniformly embedded in a spherical polyethylene moderator. The detection system achieves a detection efficiency of 30% for neutrons from ^{252}Cf spontaneous fission, offering both high detection efficiency and insensitivity to gamma rays compared to large liquid scintillation detectors.

2.4 Fission Fragment Identification Spectrometer at CIAE

As shown in Figure 4 [Figure 4: see original paper], this spectrometer [13] is mainly used for measuring fission fragment mass distributions. The spectrometer consists of a high-resolution time-of-flight detector and high-energy-resolution fission fragment energy detectors. The time-of-flight detector achieves a time resolution of 150 ps, while the energy detector provides energy resolution better than 0.5% (for Cu ions at 80 MeV). The system's mass resolution is better than 1 for the light peak around $A=90$ and reaches 1.4 for the heavy peak around $A=140$.

2.5 BaF2 Detector Array (GTAF-II) at CSNS Back-n

As shown in Figure 5 [Figure 5: see original paper], this facility [14] is primarily used for (n, γ) reaction cross-section measurements. It consists of 12 pentagonal and 28 hexagonal BaF2 crystals forming a spherical detector array with an inner cavity diameter of 20 cm for sample placement. Each crystal is 15 cm thick with a maximum diameter of 14 cm. The system's total detection efficiency for cascade gamma rays following (n, γ) reactions approaches 100%.

2.6 C6D6 Spectrometer at CSNS Back-n

This spectrometer [15] is also mainly used for (n, γ) reaction cross-section measurements, consisting of four deuterated liquid scintillation detectors ($\text{Ø}12.7 \text{ cm} \times 7.62 \text{ cm}$) with associated electronics and data acquisition systems. This

spectrometer complements the GTAF-II facility: the C6D6 spectrometer is primarily used for measuring (n, γ) reaction cross-sections of stable nuclides with relatively large cross-sections, while GTAF-II, with its extremely high detection efficiency, is mainly used for small-cross-section reactions or microsamples (such as rare isotopes or unstable nuclides).

2.7 LPDA Spectrometer at CSNS Back-n

This spectrometer [16] is primarily used for nuclear data measurements of charged-particle emission reactions induced by neutrons. The spectrometer consists of a 16-unit ΔE - ΔE -E telescope system installed in a vacuum target chamber with a diameter of 1 m. Each telescope unit comprises a low-pressure multi-wire proportional chamber, a 300 μ m thick Si detector, and a 3 cm thick CsI crystal detector. For protons, the spectrometer covers an energy range of 0.5–100 MeV with a wide dynamic range.

2.8 FIXM Fission Cross-Section Measurement Spectrometer at CSNS Back-n

This spectrometer [16] is mainly used for fission cross-section measurements, consisting of an 8-unit multi-layer fast fission ionization chamber that can accommodate eight fission samples for simultaneous measurement. Fission samples are electroplated onto 20 μ m thick stainless steel or 100 μ m thick aluminum backings with diameters of approximately 5 cm. With fast preamplifiers, the fission ionization chamber achieves signal rise times of about 30 ns, making it suitable for fast neutron time-of-flight measurements.

2.9 Other Facilities

In addition to the above facilities, numerous other experimental systems are used for nuclear data measurements, including a gridded ionization chamber at Peking University for (n, α) reaction cross-section measurements, neutron nuclear data integral experimental facilities at the Institute of Nuclear Physics and Chemistry (China Academy of Engineering Physics) and China Institute of Atomic Energy, nuclear data measurement facilities at the Shanghai Institute of Applied Physics (Chinese Academy of Sciences), and charged-particle-induced nuclear reaction data measurement facilities at the Institute of Modern Physics (Chinese Academy of Sciences).

Progress in Nuclear Data Experimental Research

Relying on the aforementioned neutron sources and experimental facilities, extensive nuclear data experiments have been conducted over the years, yielding fruitful results. The main achievements are summarized below.

3.1 Secondary Neutron Differential and Double-Differential Cross-Section Measurements

Secondary neutron differential and double-differential cross-sections are crucial for testing nuclear data theoretical models and determining model parameters, as well as for neutron transport calculations in nuclear device design. Early work established fast neutron time-of-flight spectrometers based on China's first cyclotron and later on Cockcroft-Walton accelerators, completing measurements of secondary neutron double-differential cross-sections for several important nuclides. Following the construction of the HI-13 tandem accelerator and multi-detector fast neutron time-of-flight spectrometer, extensive experimental measurements have been completed for numerous nuclides at various energy points. Particularly in the 8–14 MeV energy region, secondary neutron double-differential cross-section measurements have become an international challenge due to the presence of breakup neutrons from common neutron sources (such as p+T and d+D reactions), which severely interfere with low-energy regions of secondary neutron spectra. The China Institute of Atomic Energy has pioneered an unconventional fast neutron time-of-flight spectrometry method [17] that effectively avoids breakup neutron interference while maintaining energy resolution by combining conventional and unconventional spectrometers. Major completed works are listed in Table 2 . Figure 9 [Figure 9: see original paper] shows partial secondary neutron double-differential cross-section results for ${}^6\text{Li}$ reactions induced by 10.27 MeV neutrons [18,19].

3.2 Fission Yield Measurements

Fission product yield data are important for fission physics research, reactor design and operation, and nuclear material detection. China has established both radiochemical and direct gamma spectrometry methods for fission yield measurements, completing numerous experimental measurements (Table 3). In recent years, the China Institute of Atomic Energy, Northwest Institute of Nuclear Technology, and Institute of Nuclear Physics and Chemistry (China Academy of Engineering Physics) have all developed fission fragment mass distribution measurement techniques. The China Institute of Atomic Energy has completed measurements of fission fragment mass distributions for thermal neutron-induced fission of ${}^{235}\text{U}$ and ${}^{239}\text{Pu}$ using the FFIS spectrometer [20], obtaining high-quality experimental data. Figure 10 [Figure 10: see original paper] shows the measured mass distribution for ${}^{235}\text{U}$ fission induced by thermal neutrons.

3.3 Excitation Function Measurements

Excitation functions for reactions such as $(n, 2n)$, $(n, 3n)$, (n, γ) , (n, p) , and (n, α) have important applications in nuclear physics research, neutron field parameter diagnostics, and nuclear technology applications. For example, $(n, 2n)$ and (n, γ) reaction cross-sections play significant roles in neutronics calculations for nuclear device design and are widely used for neutron fluence rate

and spectrum measurements. Excitation function measurements are generally divided into offline and online methods. The offline method (activation method) involves irradiating samples in a neutron field and determining reaction cross-sections by measuring the activity of product nuclei. This method is simple and reliable but limited to single-energy points or specific spectra (such as fission spectra), and can only be applied when product nuclei are radioactive with suitable half-lives and measurable properties. The online method determines cross-sections by measuring prompt particle yields during reactions, offering greater universality and enabling efficient measurement of excitation functions across broad energy regions using white neutron sources in a single experiment, though requiring high-purity isotopic samples. China primarily used the activation method in early work, completing extensive measurements of excitation functions for over 100 reaction channels including $(n, 2n)$, (n, γ) , (n, p) , and (n, α) for various nuclides [21,22]. These data have filled some gaps and clarified discrepancies, providing important support for China's excitation function library development. In recent years, online methods have rapidly advanced, including direct neutron detection [12] and prompt gamma-ray methods for $(n, 2n)$ cross-section measurements, (n, γ) cross-section measurements using white neutron sources [23,24], and (n, xn) reaction data measurements using white neutron sources and Peking University's facilities [25], yielding fruitful results.

3.4 Other Types of Nuclear Data Measurements

In addition to the above, China has achieved extensive experimental results in gamma production cross-sections, fission cross-sections, total neutron cross-sections, integral data, and charged-particle-induced nuclear reaction data. Gamma production cross-section measurements have primarily utilized the HI-13 tandem accelerator and HPGe detector array at the China Institute of Atomic Energy, completing numerous measurements of neutron inelastic and $(n, 2n\gamma)$ production cross-sections in the 7–11 MeV energy region. Fission cross-section measurements have mainly been based on the China Spallation Neutron Source, completing measurements of ^{235}U , ^{236}U , ^{238}U , and ^{239}Pu fission cross-sections from eV to hundreds of MeV [26,27]. Total neutron cross-section measurements have also been performed at the CSNS Back-n facility for materials such as Al, Be, and C [28]. Integral data have been obtained primarily by the Institute of Nuclear Physics and Chemistry (China Academy of Engineering Physics) and China Institute of Atomic Energy through numerous shielding integral experiments with spherical and slab samples [29,30], providing important integral experimental data for macroscopic validation of nuclear databases. Charged-particle-induced nuclear reaction data have been measured primarily using the HI-13 tandem accelerator and accelerators at the Institute of Modern Physics (Chinese Academy of Sciences).

Summary and Outlook

China's nuclear data measurements have long focused on meeting national defense needs. Initial work completed critical measurements for ^{235}U and ^{239}Pu key nuclear data, $\text{d}+^6\text{Li}$ reaction cross-sections, and $^6\text{Li}(\text{n},\text{t})$ reaction excitation functions, making important contributions to China's "Two Bombs" program. Subsequently, extensive measurements and evaluations of excitation functions, fission yields, secondary neutron differential and double-differential cross-sections, gamma production cross-sections, decay data, and integral data have been completed, filling data gaps and clarifying discrepancies, strongly supporting China's nuclear programs.

In recent years, domestic investment in nuclear data measurement has increased due to the development of new nuclear energy systems. Various institutions have paid increasing attention to nuclear data for fusion reactors, thorium-based molten salt reactors, and ADS systems. Furthermore, the construction of advanced radiation source platforms such as the China Spallation Neutron Source, TMSR-PNS at the Shanghai Institute of Applied Physics (Chinese Academy of Sciences), and the Shanghai Laser Electron Gamma Source (SLEGS) at the Shanghai Advanced Research Institute (Chinese Academy of Sciences) has significantly enhanced China's nuclear data measurement capabilities. As these major facilities are completed and put into operation, they will further promote experimental nuclear data research in China.

Author Contribution Statement

This article was written solely by Ruan Xichao.

References

- [1] Artisyuk V, Broeders C, Gonzalez-Romero E, et al. Challenge of nuclear data for innovative nuclear energy [J]. *Progress in Nuclear Energy*, 2008, 50(2–6): 341–346. DOI: 10.1016/j.pnucene.2007.11.015.
- [2] Harada H. Meeting nuclear data needs for advanced reactor systems[R]. OECD/NEA/NSC/WPEC/DOC. 2014: 446.
- [3] Sartori E. Nuclear data for radioactive waste management [J]. *Annals of Nuclear Energy*, 2013, 62: 579–589. DOI: 10.1016/j.anucene.2013.02.003.
- [4] Fischer U, Batistoni P, Cheng E, et al. Nuclear data for fusion energy technologies: requests, status and development needs[C]. *Proceedings for the International Conference on Nuclear Data for Science and Technology*. Santa Fe (USA): AIP, 2004: 1478–1485.
- [5] Koning A J, Blomgren J, Jacqmin R, et al. Nuclear data for sustainable nuclear energy[R]. *Coordinated action on nuclear data for industrial development in Europe - CANDIDE*, European Commission-Joint Research Center-IRMM, 2009.

- [6] Ge Z G. The CENDL-3.2 version of Chinese general purpose evaluated nuclear data library[J]. EPJ Web of Conferences, 2020, 239: 09001. DOI: 10.1051/epjconf/202023909001.
- [7] Wang H W, Chen J G, Cai X Z, et al. Development of photo-neutron facility driven by electron LINAC[J]. Nuclear Techniques, 2014, 37(10): 100522. DOI: 10.11889/j.0253-3219.2014.hjs.37.100522.
- [8] An Q, Bai H Y, Bao J, et al. Back-n white neutron facility for nuclear data measurements at CSNS[J]. Journal of Instrumentation, 2017, 12(7): P07022. DOI: 10.1088/1748-0221/12/07/p07022.
- [9] Tang J Y, An Q, Bai H Y, et al. China's first high-performance white neutron source: CSNS back-n white neutron source and application[J]. Atomic Energy Science and Technology, 2019, 53(10): 2012–2022. DOI: 10.7538/yzk.2019.youxian.0431.
- [10] Sa J, Tang H Q, Zhou Z Y, et al. Multi-detector fast neutron time of flight spectrometer[J]. Atomic Energy Science and Technology, 1992, 26(6): 1–8.
- [11] Sun Q, Wang Z H, Zhang Q W, et al. Measurement of ^{209}Bi neutron inelastic scattering cross-section with prompt γ ray method[J]. Atomic Energy Science and Technology, 2022, 56(5): 816–824. DOI: 10.7538/yzk.2022.youxian.0189.
- [12] Fan R R, Li Q, Bao J, et al. Detector development at the Back-n white neutron source[J]. Radiation Detection Technology and Methods, 2023, 7: 171–191. DOI: 10.1007/s41605-022-00379-5.
- [13] Liu C, Liu S L, Yang Y, et al. The FFIS spectrometer for determination of fission fragment mass distribution with the energy-velocity method[J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2022, 1041: 167319. DOI: 10.1016/j.nima.2022.167319.
- [14] Zhang Q W, Luan G Y, Ren J, et al. Cross-section measurement of neutron capture reaction based on back-streaming white neutron source at China Spallation Neutron Source[J]. Acta Physica Sinica, 2021, 70(22): 222801. DOI: 10.7498/aps.70.20210742.
- [15] Ren J, Ruan X C, Bao J, et al. The C6D6 detector system on the Back-n beam line of CSNS[J]. Radiation Detection Technology and Methods, 2019, 3(3): 52. DOI: 10.1007/s41605-019-0129-8.
- [16] Ren J, Ruan X C, Jiang W, et al. Neutron capture cross-section of ^{169}Tm measured at the CSNS Back-n facility in the energy region from 30 to 300 keV[J]. Chinese Physics C, 2022, 46(4): 044002.
- [17] Qi B J, Tang H Q, Zhou Z Y. A new method to measure secondary neutron spectra[J]. Physics, 2002, 31(1): 36–39. DOI: 10.3321/j.issn: 0379-4148.2002.01.010.

- [18] Ruan X C, Zhou Z Y, Chen G C, et al. Measurements of neutron emission spectra for neutron induced reactions on ^9Be and $^6,^7\text{Li}$ [J]. *High Energy Physics and Nuclear Physics*, 2007, 31(5): 442–447.
- [19] Ruan X C, Chen G C, Huang H X, et al. Measurement of the secondary neutron emission differential and double-differential cross-sections between 20 and 30 MeV[J]. *Journal of the Korean Physical Society*, 2011, 59(2): 1729–1732. DOI: 10.3938/jkps.59.1729.
- [20] Liu C, Liu S L, Yang Y, et al. Measurement of post-neutron mass distribution for thermal-neutron-induced fission of ^{239}Pu [J]. *Atomic Energy Science and Technology*, 2022, 56(5): 798–804. DOI: 10.7538/yzk.2022.youxian.0054.
- [21] Lu H L, Wang D H, Cui Y F, et al. Fast neutron excitation curves of Al, Ti, V, In and I nuclei[J]. *Atomic Energy Science and Technology*, 1975, 9(2): 113–126.
- [22] Lu H L, Zhao W R, Yu W X, et al. The cross sections of $^{176}\text{Hf}(n, 2n)^{175}\text{Hf}$ and $^{185}\text{Re}(n, 2n)^{184}\text{Re}_{m,g}$ reactions[J]. *Atomic Energy Science and Technology*, 1999, 33(5): 410–414.
- [23] Ren J, Ruan X C, Wang J C, et al. Radiative capture cross-section measurement and resonance parameter analysis for ^{169}Tm based on white neutron source[J]. *Atomic Energy Science and Technology*, 2022, 56(5): 805–815. DOI: 10.7538/yzk.2022.youxian.0125.
- [24] Zhang G H. Progress of experimental researches on neutron induced light charged-particle emission nuclear reactions[J]. *Scientia Sinica (Physica, Mechanica & Astronomica)*, 2020, 50(5): 052005.
- [25] Nie Y B, Ren J, Ruan X C, et al. Benchmark experiments with slab sample using time-of-flight technique at CIAE[J]. *Annals of Nuclear Energy*, 2020, 136: 107040. DOI: 10.1016/j.anucene.2019.107040.
- [26] Sun Q, Wang Z H, Zhang Q W, et al. Measurement of ^{209}Bi neutron inelastic scattering cross-section with prompt γ ray method[J]. *Atomic Energy Science and Technology*, 2022, 56(5): 816–824. DOI: 10.7538/yzk.2022.youxian.0189.
- [27] Ren Z Z, Yang Y W, Wen J E, et al. Measurement of the $^{236}\text{U}(n, f)$ cross section for neutron energies from 0.4 MeV to 40 MeV from the back-streaming white neutron beam at the China Spallation Neutron Source[J]. *Physical Review C*, 2020, 102(3): 034604. DOI: 10.1103/physrevc.102.034604.
- [28] Liu X Y, Yang Y W, Liu R, et al. Measurement of the neutron total cross sections of aluminum at the Back-n white neutron source of CSNS[J]. *The European Physical Journal A*, 2021, 57(7): 232. DOI: 10.1140/epja/s10050-021-00499-8.
- [29] Liu R, Lu X X, An L, et al. Recent progress of neutronics experiments[J]. *Physics*, 2009, 38(12): 889–893.
- [30] Liu R, Lu X X, An L, et al. Recent progress of neutronics experiments[J]. *Physics*, 2009, 38(12): 889–893.

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