The cyclotron-based neutron sources and projects at NARI

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Abstract. A compact accelerator-driven neutron source is being developed in Taiwan to fill the need in neutron scattering experimental facilities. The National Atomic Research Institute (NARI) is spearheading two neutron projects to deliver neutron services to both the industrial and academic sectors. These services encompass personnel training, scientific experiments, and soft error rate tests for semiconductor devices. Currently, optimization efforts are underway for a 30 MeV cyclotron neutron source, and several radiation services have already been executed using quasi-monoenergetic fast neutrons. Moreover, a white spectrum fast neutron source is under trial, and a neutron imaging system is undergoing evaluation. As a part of Phase I of the 70 MeV cyclotron project, two neutron targets—a fast neutron target and a thermal neutron target—will be installed. Planning for Phase II is expected to commence shortly.

1 Background

The Institute of Nuclear Energy Research (INER) was Taiwan’s sole nuclear energy research institution and was restructured into the National Atomic Research Institute (NARI) on September 27, 2023. NARI holds the national mission to advance atomic science and technology in Taiwan.

Neutrons are crucial for the development of advanced materials and processes, a fact that is widely recognized in Taiwan. To address the issue of lacking a neutron scattering experiment facility, several projects have been initiated in the past. Figure 1 illustrates the historical timeline of Taiwan’s neutron-related projects.

Constructed in 1959, the Tsing Hua Open Pool Reactor (THOR) stands as Taiwan’s inaugural neutron source. For six decades, this facility has rendered services in neutron imaging, medical isotope production, boron neutron capture therapy (BNCT), and various

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irradiation processes. Particularly noted for its BNCT, THOR has established a distinguished reputation, successfully treating over 300 cases.

Among these initiatives, the Taiwan Research Reactor II (TRRII) was the most significant. It aimed to replace the Taiwan Research Reactor (TRR) and establish numerous neutron scattering instruments. Unfortunately, the project was terminated in 1998.

The SIKA program (2006-2009), a collaboration with the Australian Nuclear Science and Technology Organization (ANSTO) to build a cold triple-axis spectrometer, was notably successful. It allowed Taiwanese researchers to conduct experiments with highly bright neutrons during reserved beam times.

Despite the TRR II program being inactive for over 20 years and INER lacking a high-flux neutron source, a plan was set in 2019 to produce neutrons from a cyclotron in Taiwan, which provides over 50% of isotopes. In 2021, a four-year project commenced, developing a thermal neutron source for imaging purposes and a fast neutron source for testing the soft error rate.

In 2019, with the outbreak of the COVID-19 pandemic, air flights were blocked to cause a significant isotope shortage. To stabilize the isotope supply, the Legislative Yuan in Taiwan supported, and the Executive Yuan approved, a project to construct a new 70 MeV cyclotron. This initiative, known as the “70 MeV cyclotron project,” was initiated in 2023. The main objectives of the project are to: (1) maintain a stable supply of nuclear medicine to benefit the nation's health; (2) expand radiation resistance testing technologies for satellites and semiconductors; (3) develop new drugs and technologies for precise cancer diagnosis and treatment; and (4) broaden the neutron application to develop advanced materials.

We carried out a series of surveys focused on neutron technology among Taiwan’s academic community. The results reveal that neutron instruments and applications are primarily directed towards magnetic materials, with supplementary research in superconductor technology, lithium batteries, and archaeology. Industrially, there is a demand in Taiwan for soft error rate testing for semiconductor devices, strain measurement in metals, and neutron imaging for lithium batteries, heat pipes, and other devices. Strain measurements are predominantly carried out in industries such as welding, shipbuilding, and construction. Moreover, neutron imaging holds substantial promise for applications in hydrogen energy, energy storage, and information computing.

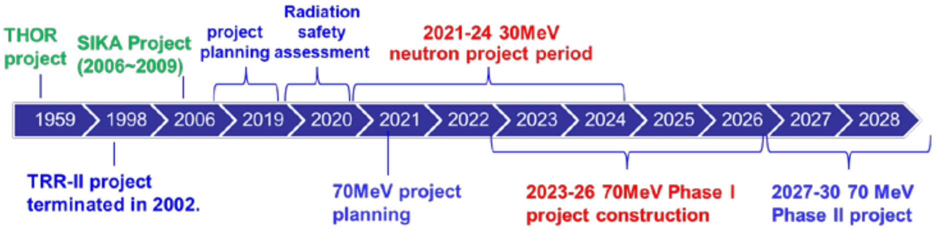


Fig. 1 The history of Taiwan’s neutron-related projects.

2 Instrument survey of users' needs

In 2021, we assigned Taiwan Neutron Science Society (TWNSS) to conduct a survey to ascertain the instruments needed by Taiwan’s industry and academia. According to the results depicted in Fig. 3, the top two required instruments are neutron powder diffractometers and small angle neutron scattering (SANS) devices. Additionally, there's significant interest from the industry in neutron computed tomography (CT). Based on the identified needs, available space, and budget constraints, multifunctional neutron instruments are being developed to support Taiwan's neutron community in personnel training, beam-time competition, and other services. Recommendations include integrating powder diffraction with strain scanners into a single instrument and combining neutron imaging and CT at one station. For the mentioned applications, a continuous wave (CW) mode neutron beam is the preferred choice.

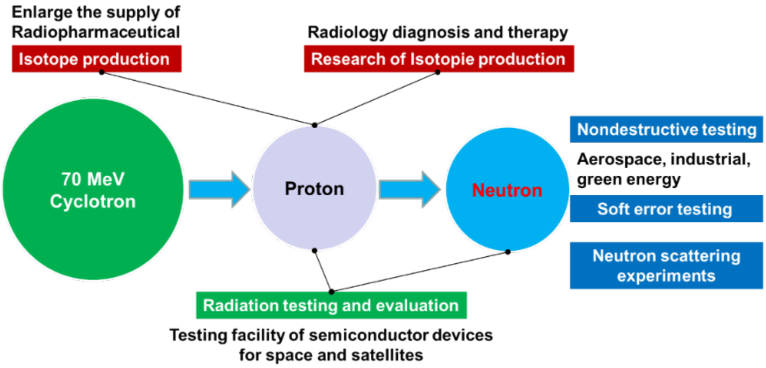


Fig. 2 The four key missions of the 70 MeV cyclotron project.

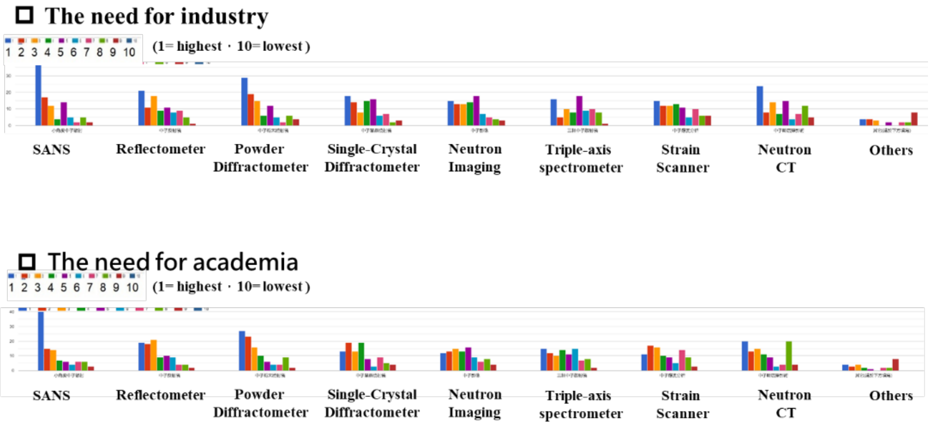


Fig. 3 Survey on desired neutron instruments in Taiwan [1]

3 The 30 MeV Cyclotron Neutron Source

NARI owns a 30 MeV cyclotron that has been producing isotopes for over 30 years. Leveraging this cyclotron, the initial neutron source was established. Two kinds of neutron sources have been successfully developed: a bifunctional target that can generate either white spectrum fast neutrons or thermal neutrons, and another source that produces quasi-monoenergetic neutrons, as depicted in Fig. 4. Accompanying these are two instruments: a thermal neutron imaging station and a neutron-induced radiation testing station.

Figure 5 shows the schematic for the operation of the bifunctional target. The target is made of a 0.4 cm-thick Beryllium disk surrounded by HDPE, which serves as a moderator and reflector. This target can provide thermal neutrons for neutron imaging downward. By drawing away the right-hand side HDPE, white spectrum fast neutrons can be generated for irradiation tests, as shown in F5(a).

The licenced white spectrum fast neutrons from the bifunctional target operates at 30 MeV with a maximum current of 20 μA. The neutron flux of fast neutrons simulated with MCNP is noted to be 4×10^6 n/cm^2/s at a distance of 1 m from the beryllium target.

When conducting neutron imaging, these thermal neutrons are directed vertically downward to the basement. It operates at a proton energy of 25 MeV with a maximum current of 50 µA. The L/D ratio can be adjusted from 50 to 65. At an L/D ratio of 50, the maximum thermal neutron flux at the sample position surpasses 1×10^5 n/cm²/s. Figure 6 illustrates a test image captured using this thermal neutron imaging instrument. The imaging area is adjustable to accommodate various applications, with sizes ranging from 15 cm × 15 cm to 43 cm × 43 cm. Efforts are ongoing to enhance the resolution of neutron imaging.

The Quasi-Monoenergetic Neutrons (QMN) had been successfully developed and commenced industrial [4, 5] and academic services for neutron-induced soft error rate (SER) testing in early 2023. The soft error rates measured by QMN align with those obtained in tests at LANSCE, affirming the practicality of QMN.

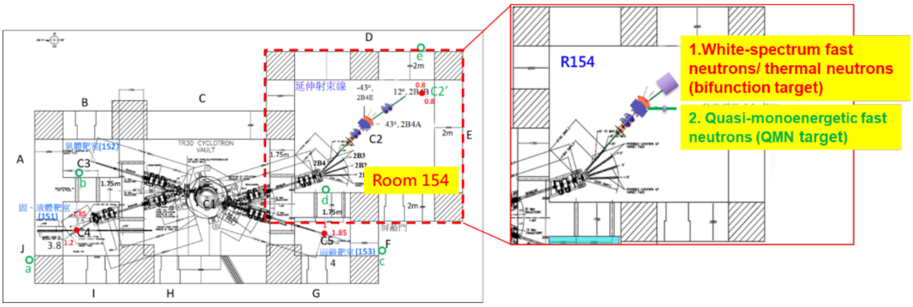
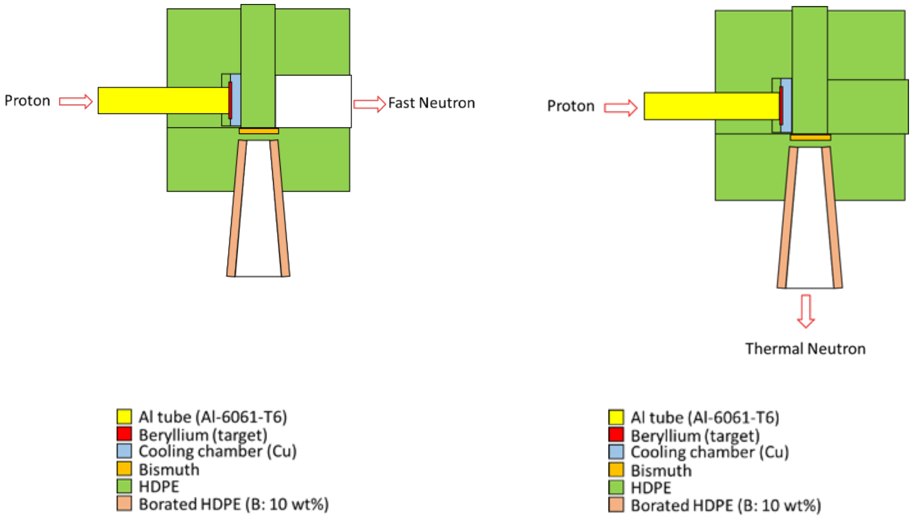


Fig. 4 The set-up of 30 MeV cyclotron-based neutron source [2]



(a) Fast neutron mode (b) Thermal neutron mode

Fig. 5 A schematic for the operation of bifunctional target [2, 3]

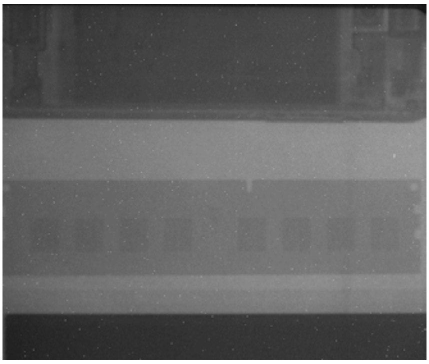


Fig. 6 A neutron image of a computer RAM

4 70 MeV Cyclotron-based Neutron Facility

Fig. 7 depicts the layout of the first floor of the 70 MeV cyclotron-based neutron facility. The cyclotron operates with a beam energy range of 28 to 70 MeV and can achieve a maximum current of one mA. There are a total of six proton beamlines, with two dedicated to neutron applications. One beamline is used for neutron scattering and imaging, while the other is utilized for fast neutron irradiation. The cyclotron has the capability of dual-beam extraction, allowing for the simultaneous production of isotopes and the conduct of neutron scattering experiments.

The planning for the neutron laboratory aims to meet the requirements of both Taiwan’s academic and industrial sectors while ensuring the longest possible beam time, an affordable budget, ample space, and the development of a sustainable business model. In 2021, statistics indicate that 80% of the proton beam time of NARI’s 30 MeV cyclotron was allocated for Tl-201 production, as presented in Table 1. To maximize beam time of NARI’s 70 MeV cyclotron, the neutron operation energy will be set to 28.5 MeV, compatible with Tl-201 production.

Table 2 outlines the potential needs in Taiwan, categorized into three main instruments: neutron powder diffractometers, Small Angle Neutron Scattering (SANS), and neutron imaging. These instruments have various applications, including stress and diffraction measurements with neutron powder diffractometers, as well as computer tomography with neutron imaging.

Considering the above information, Fig. 8 illustrates a conceptual layout of the instruments within the facility, which will be developed in three phases due to budget constraints. Phase I (2023-2026) now focuses the installation of fast neutron targets, thermal neutron targets, and a thermal neutron diffractometer. Phase II (2027-2030) will involve on enhancing the flux of fast neutron targets and establishing neutron imaging. Phase III (2031~) will include the setup of a cold neutron target and SANS instruments.

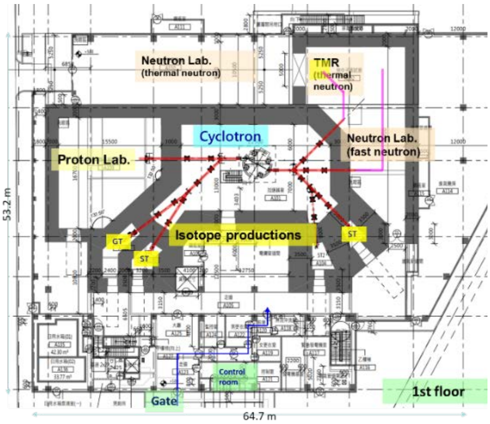


Fig. 7 The first floor layout of 70 MeV cyclotron-based neutron facility [6]

Table 1 Production time for a variety of isotopes in NARI

Year	I-123	Tl-201	Ga-67	In-111
2015	2.1%	59.1%	23.2%	5.3%
2016	1.2%	50.2%	23.5%	9.6%
2017	1.4%	55.7%	15.5%	16.7%
2018	1.3%	55.8%	18.3%	14.4%
2019	0.2%	63.7%	18.9%	12.8%
2020	1.5%	64.9%	9.0%	8.7%
2021	2.7%	87.4%	1.2%	6.6%
MeV	30.0	28.5	25.0	22.0
mA	0.1	0.2	0.165	0.16

5 Summary and Outlook

The neutron project at NARI aims to offer neutron services for both industrial and academic applications. These services encompass personnel training, conducting pre-study experiments, and facilitating soft error rate testing for the semiconductor industry. Currently, the project involves optimizing a 30 MeV cyclotron neutron source and developing a neutron imaging system. There's also a significant undertaking known as the “70 MeV project,” scheduled for completion in 2026. The design work for this project is currently in progress, and plans for Phase II are expected to commence shortly. This initiative underscores Taiwan's commitment to advancing neutron-related research and technology in various sectors.

Table 2 three planned instruments for the potential needs in Taiwan

Instrument	Service items	Applications
1	Powder diffractometer/ Strain scanner	Magnetic diffraction/ crystal diffraction/ residual strain measurements
2	High spatial/temporal imaging/ Tomography/ Hybrid images of neutron and X-ray	Non-destructive testing: lithium batteries, engine blades, cooling elements, etc.
3	Small angle neutron scattering/ Reflectometer	Biomaterials and coatings inspection

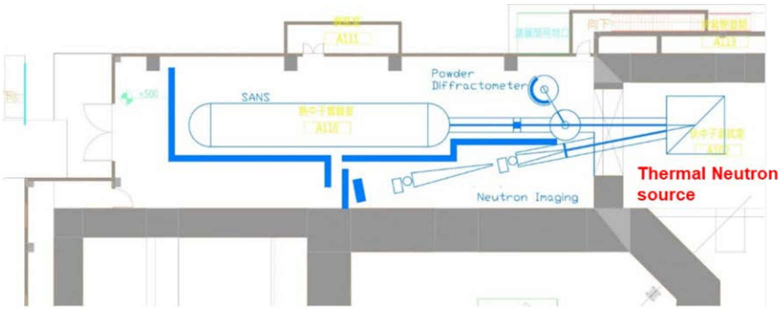


Fig. 8 A conceptual layout of the neutron instruments

References

1. Taiwan Neutron Science Society, Survey of Neutron Instruments in Taiwan, Taoyuan City, Taiwan (2021). (in Chinese)
2. C.C. Hsia, K.Y. Chu, H.M. Lee, W.S. Kuo, Y.F. Chioeu, J.N. Wang, Radiation Safety Assessment for INER Cyclotron-based Neutron Source and its Applications (new quasi-monoenergetic neutron target), INER Report: INER-PC-0373R (2023). (in Chinese)
3. Y. Kiyanagi, Neutron Imaging at Compact Accelerator-Driven Neutron Sources in Japan. Journal of Imaging, 4(4), 55. (2018) https://doi.org/10.3390/jimaging4040055
4. K.Y. Chu, W.S. Kuo, H.M. Lee, Y.K. Fuh, "A 30 MeV-cyclotron-based quasi-monoenergetic neutron source, " Nuclear Engineering and Technology, 55(5), 1559-1566 (2023) https://doi.org/10.1016/j.net.2023.01.020
5. How-Ming Lee, "Fast-Neutrons-Induced Single Event Upsets of 65 nm SRAM Tested by Using NARI's Neutron Sources," Proceedings of 2023 TWNSS Annual Meeting and Neutron Scattering Workshop, Nov. 3-5, 2023, Hengchun, Taiwan (2023)
6. S.S. Farn, T.S. Duh, K.Y. Chu, H.M. Lee, T.Y. Yung, S.L. Jeng, C.H. Chen, J.N. Wang, H.W. Chou, "National Neutrin and Proton Science Applied Research: 70 MeV Medium Cyclotron Construction Project," INER Report: INER-PC-0369R (2023). (in Chinese)