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An overview of polarized neutron instruments and techniques in Asia Pacific

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Abstract

Polarized neutron scattering is an indispensable tool for exploring a vast range of scientific phenomena. With its dynamic scientific community and significant governmental support as well as the rapid economic growth, the Asia–Pacific region has become a key player in the worldwide neutron scattering arena. From traditional research reactors to cutting-edge spallation neutron sources, this region is home to a myriad of advanced instruments offering a wide range of polarized neutron capabilities. This review aims to provide a comprehensive overview of the development and current status of polarized neutron instruments and techniques in the Asia–Pacific region, emphasizing the important role of the Asia–Pacific region in shaping the landscape of global polarized neutron scattering development.

1 Introduction

Not too long after the discovery of the neutron by James Chadwick [1], physicists realized that neutrons could be a very useful tool to study condensed matter because the wavelength of slow neutrons is on the order of interatomic distances and the energy is comparable to many excitations in condensed matter. Therefore, neutron scattering can provide abundant information on the chemical structure and the dynamics of atoms. The neutron has no charge so it can penetrate deep into matter and directly interact with nuclei, whereas X-rays mainly interact with orbital electrons in atoms. Following the world's first nuclear reactor Chicago Pile-1 reaching criticality in 1942 led by Enrico Fermi, the nuclear age started. A year later in 1943, the Graphite Reactor at the Oak Ridge National Laboratory (ORNL) went critical. Physicist Ernest Wollan and Cliff Shull quickly realized the great potential of the neutrons produced by the Graphite Reactor and embarked on a series of neutron diffraction experiments including the diffraction experiments showing the direct evidence of antiferromagnetism in MnO below its Curie temperature [2] and confirming the ferrimagnetic model for Fe_3O_4 [3]. These pioneering works opened the gate to a new era in neutron scattering. Between the 1950s and 1970s, a great number of research reactors were built and put into use across the world, some of which are still running nowadays. Table 1 lists the major neutron research reactors built between this time frame. Nuclear reactors provided a reliable way of getting high-flux neutrons, which greatly advanced the development of neutron scattering both in technique and instrumentation beyond diffraction. Bertram Brockhouse developed neutron spectroscopy to study the dynamics of a material by building the first triple-axis spectrometer in the world at the Chalk River Research Reactor in Canada. Both Shull and Brockhouse were awarded the Noble Physics Prize in 1994

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Table 1 Major reactor neutron sources built between the 1950s and 1970s

Reactor name	Organization	Country	Power (MW)	Start year	Operation status
High Flux Isotope Reactor (HFIR)	Oak Ridge National Laboratory	USA	85	1966	Yes
National Bureau of Standards Reactor (NBSR)	National Institute of Standards and Technology	USA	20	1967	Yes
High Flux Beam Reactor (HFBR)	Brookhaven National Laboratory	USA	40	1965	Decommissioned
National Research Universal Reactor (NRU)	Chalk River laboratories	Canada	135	1957	Decommissioned
High Flux Reactor (HFR)	Institut Laue-Langevin	France	58	1972	Yes
BER II	Helmholtz-Zentrum Berlin	Germany	10	1973	Decommissioned
High Flux Australian Reactor (HFIR)	Australian Atomic Energy Commission	Australia	10	1958	Decommissioned
JRR-3	Japan Atomic Energy Agency	Japan	20	1962	Yes
IBR-2	Frank Laboratory of Neutron Physics	Russia	4 (pulsed)	1978	Yes

Table 2 Major spallation neutron sources around the world

Source name	Organization	Country	Proton beam power	Start year	Operation status
KENS	High energy Accelerator Research Organization	Japan	4.5 kW	1981	Decommissioned
Japan Spallation Neutron Source (JSNS)	J-PARC	Japan	1 MW	2008	Yes
China Spallation Neutron Source (CSNS)	Institute of High Energy Physics	China	100 kW, upgradable to 500 kW	2018	Yes
Intense Pulsed Neutron Source (IPNS)	Argonne National Laboratory	USA	7 kW	1981	Decommissioned
Los Alamos Neutron Science Center (LANSCE)	Los Alamos National Laboratory	USA	56 kW	1983	Yes
Spallation Neutron Source (SNS)	Oak Ridge National Laboratory	USA	1.7 MW, upgradable to 2 MW	2006	Yes
ISIS	ISIS Neutron and Muon Source	UK	160 kW	1984	Yes
SINQ	Paul Scherrer Institute	Switzerland	1 MW (continuous)	1996	Yes
European Spallation Neutron Source	European Research Infrastructure Consortium	Sweden	Up to 5 MW		Under construction

for their significant contributions in neutron scattering. The construction of research reactors has slowed down or even stopped in most part of the world since 1980. Meanwhile, accelerator-based spallation neutron sources have gained popularity among the neutron community. All major spallation neutron sources since the 1980s are listed in Table 2. Unlike reactor sources, which produce a continuous and constant neutron flux, the spallation neutron sources usually send out neutrons in pulses with typical frequencies between 10 and 60 Hz. The time-averaged flux in today's pulsed neutron sources is still lower than that of a high-flux reactor source, but the peak flux is often much higher. For example, the neutron brightness at 1 Å of the High Flux Isotope Reactor (HFIR) at ORNL is about 200 times higher than the time-averaged brightness of the Spallation Neutron Source (SNS), but the SNS's peak brightness at the same wavelength is about 10 times that of HFIR. By taking advantage of the time-of-flight (TOF) technique and optimized instrumentation, a pulsed neutron beamline can provide higher wavelength resolution, access broader (Q, ω) space, and generally have lower background. Over the last 70 years or so, neutron scattering has made huge progress in every aspect including the source, instrumentation, techniques, and applications. Today, neutron scattering has become an indispensable tool in many disciplines of science and technology including physics, biology, chemistry, materials science, engineering, and many interdisciplinary fields.

Compared to X-rays, a unique feature of the neutron is that it has a magnetic moment, which allows the neutron to interact with other magnetic moments and thus serve as an ideal probe of magnetic properties in magnetic materials. The fact that neutrons can be polarized further enhances the capability of neutron scattering in studying magnetism. The first polarized neutron experiment was performed in 1959 by Nathans et al. to study magnetic scattering by iron and nickel in which the incident neutron beam was polarized [4]. The method is now often referred to as the “half-polarized” or “flipping ratio” method, which greatly increases the sensitivity of probing small magnetic scattering amplitudes. In 1969, Moon et al. pioneered the polarization analysis method by adding a neutron polarization analyzer after the sample [5]. This method is now called longitudinal polarization analysis (LPA) because the scattered beam polarization is only measured along the same direction as the incident polarization. LPA provides a convenient way to separate nuclear, magnetic, and spin-incoherent scattering components, which are otherwise hard to decouple. With the advances in neutron optics over the last 50 years, LPA has become the most widely used polarized neutron technique in the world. In the 1970s, Mezei developed the neutron spin echo (NSE) technique based upon Larmor precession of the neutron spin in magnetic fields [6]. NSE encodes the neutron energy transfer in the Larmor precession angle of the neutron polarization to achieve the highest energy resolution in neutron spectroscopy and thus is ideal to study systems with slow dynamics. In the 1980s and 1990s, the polarization analysis method was extended to three-dimensional polarimetry by Tasset [7, 8], now known as spherical neutron polarimetry (SNP). Compared to LPA, SNP exploits the vectorial nature of the neutron polarization and measures the full polarization change in the scattering process, which has found use in determining complex magnetic structures that are otherwise hard to determine unambiguously using other methods [9–12]. There are also many other notable development of polarized neutron techniques including but not limited to XYZ polarization analysis [13], neutron resonance spin echo [14–16], Larmor diffraction [17–19], polarized neutron imaging [20–22], and dynamic nuclear polarization (DNP) [23, 24]. The diverse applications of polarized neutrons in today’s neutron scattering highlight the importance of developing polarized neutron capabilities in modern neutron facilities.

Neutron scattering has a long history in the Asia–Pacific region as well, although it started slightly later than in Europe and North America. Japan emerged as a major player in neutron research in the region in the early 1960s following the completion of the Japan Research Reactor No. 2 (JRR-2) and the Japan Research Reactor No. 3 (JRR-3). Japan also commissioned the world’s first pulsed neutron facility KENS in 1981. With the increasing demand for higher neutron fluxes in the user community, JRR-3 was replenished to run at 20 MW in the 1990, and the new 1-MW Japan Spallation Neutron Source (JSNS) was built to replace KENS and started operation in 2008 at the Japan Proton Accelerator Research Complex (J-PARC). Other countries in the region like Australia, China, India, and Korea have also made significant strides in the development and application of neutron scattering. Today, the Asia–Pacific region has developed a robust neutron scattering community marked by advanced facilities and active international collaborations. Because of the unique power of polarized neutrons, the development of polarized neutron capabilities is also an integral part of the major neutron facilities in the region. In this review, we will survey polarized neutron development in the Asia–Pacific region, highlighting advancements and progress in polarized neutron techniques and instrumentation in the major neutron sources in the region.

2 Polarized neutron instrumentation in major neutron facilities in Asia Pacific

Over the last 60 years, the Asia–Pacific region has experienced a remarkable surge in the advancement of neutron scattering instrumentation and techniques, reflecting the growing prominence of this region within the global neutron scattering community. This progress can be ascribed to the establishment of world-class research facilities and the development of cutting-edge neutron sources throughout the region. Figure 1 shows the major neutron sources in the region. Collaborative efforts among researchers, institutions, industries, and nations in the Asia Pacific have fostered a vibrant scientific community, leading to groundbreaking discoveries and advancements in diverse areas. Almost every neutron user facility has invested a significant number of resources in the development of polarized neutron capabilities due to the unique advantages and insights that polarized neutron techniques offer in various fields of research.

2.1 Australia

Australia has a rich history in the field of neutron scattering. A major milestone in the history was the construction of the 10-MW High Flux Australian Reactor (HIFAR) in 1958, which began to be utilized for neutron scattering research in the late 1960s until it was finally shut down in 2007 [25]. In response to the need for a new, state-of-the-art neutron scattering facility, the Australian government initiated the construction of the Open-Pool Australian Lightwater (OPAL) research reactor at the Australian Nuclear Science and Technology Organisation (ANSTO), which became operational in 2007. The OPAL reactor is a modern, 20-MW multipurpose research reactor that provides a reliable and powerful neutron source for a diverse array of neutron scattering instruments. Currently, a total of 15 neutron instruments are available to users, six of which can perform polarized neutron experiments.

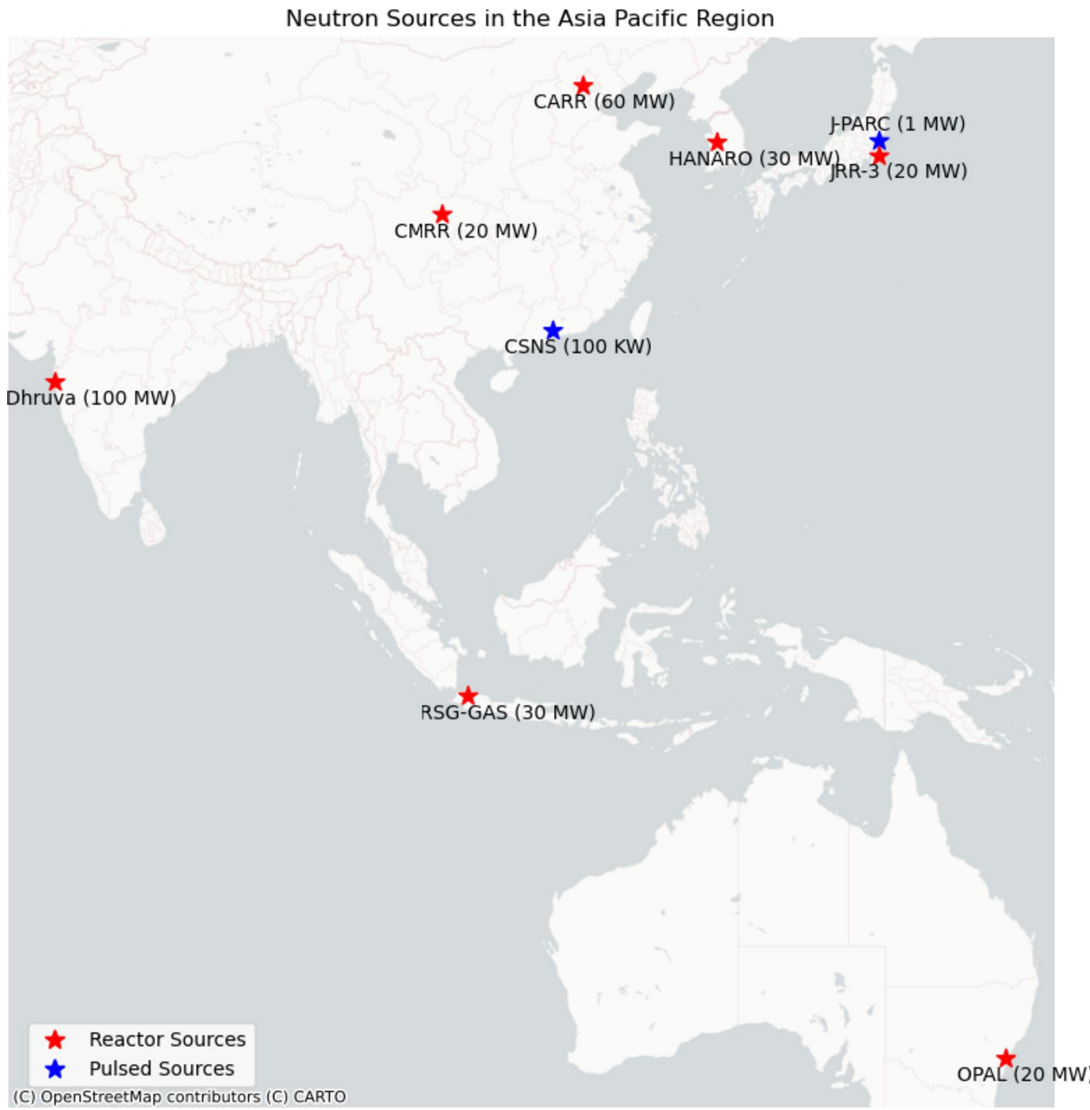

Fig. 1 Major neutron sources in the Asia–Pacific region

- *Platypus*: As the first instrument at OPAL to offer polarized neutron capabilities, Platypus is a versatile TOF neutron reflectometer that provides both unpolarized and polarized modes to cater to a wide variety of experiments [26, 27]. For polarized neutron reflectometry (PNR), Platypus employs two SwissNeutronics Fe/Si supermirrors ($m=3.8$) as the polarizer and analyzer, respectively. The wavelength band for PNR ranges from 2.5 to 13 Å, which is narrower than the unpolarized band (1–21 Å) due to the limitations of the supermirrors [27]. Two RF gradient neutron spin flippers are placed before and after the sample position to realize polarization analysis for the whole polarized neutron wavelength band. PNR has become an integral part of the beamline, enabling researchers to explore magnetic properties of various materials [28–33].
- *Taipan*: Taipan is a versatile thermal triple-axis spectrometer with a high-flux thermal neutron beam [34–36]. Both inelastic and diffraction experiments can be performed on this instrument owing to its high flux and flexible configurations. In recent years, the polarization analysis capability has been added to the instrument by using ex situ polarized ^{3}He neutron spin filters as both the polarizer and analyzer [37]. Users have started to take advantage of this new capability for experiments [38–40].
- *Pelican*: As a direct geometry TOF cold neutron triple-axis spectrometer with a wide detector bank, Pelican was designed with polarization analysis in mind

from the very beginning [41, 42]. The planned polarized mode involves using a combination of a compact solid-state supermirror bender as the polarizer and a wide-angle ^{3}He neutron spin filter as the analyzer. Currently, the wide-angle ^{3}He system is under development. Once completed, Pelican is expected to operate in the polarized mode for a significant amount of time https://www.ansto.gov.au/our-facilities/australian-centre-for-neutron-scattering/neutron-scattering-instruments/pelican-time.

Other instruments, including *QUOKKA*, a SANS instrument, *SIKA*, a cold neutron triple-axis spectrometer, and *WOMBAT*, a neutron diffractometer, are also equipped with polarized neutron capabilities [37, 43, 44]. Much of the polarized neutron instrumentation at ANSTO is focused on employing polarized ^{3}He neutron spin filters. A metastability-exchange optical pumping (MEOP) station, developed by the Institut Laue-Langevin (ILL), is responsible of producing highly polarized ^{3}He for instruments [37]. The MEOP station provides a fast method for producing large volumes of polarized ^{3}He gas and thus is key to the successful deployment of ^{3}He spin filters at ANSTO. As instrument development continues, polarized neutron scattering is expected to play a more significant role at ANSTO.

2.2 China

China's research into neutron scattering dates back to the 1950s. In 1958, the 7-MW Heavy Water Research Reactor (HWRR), the first nuclear reactor in China, reached criticality. Soon after, Chinese researchers constructed a neutron diffractometer at the HWRR [45, 46]. In 1960, they observed and later reported on the effects of piezoelectric oscillation, which resulted in an enhancement of neutron scattering on quartz single crystals [47]. The HWRR underwent several upgrades and reached up to 15 MW in the 1980s. It was finally decommissioned in 2007 after 47 years of operation. China's neutron scattering research has experienced remarkable progress over the last two decades and has rapidly emerged as a significant force in the global neutron scattering community. Three sources have been built during the last 15 years: the China Advanced Research Reactor (CARR), the China Mianyang Research Reactor (CMRR), and the China Spallation Neutron Source (CSNS). The CARR is a 60-MW research reactor located in Beijing [48–50], which went critical in 2010. The CMRR is a 20-MW research reactor in Mianyang, Sichuan province, and has started operation since 2014 [51, 52]. The CSNS, based in Dongguan, Guangdong province, is the first spallation neutron source in China and the second in the Asia–Pacific region [53–56], which has been operating since 2018 and is currently running with a 100-kW proton beam power. The establishment of the three neutron sources serves as a testament to the country's commitment to fostering innovation and collaboration in neutron scattering. In addition to these large-scale neutron sources, China has also constructed a small accelerator-based source, known as the Compact Pulsed Hadron Source (CPHS) at Tsinghua University [57]. Beyond its research capabilities, the CPHS is a dedicated platform for the education and training of the next-generation neutron scattering users, making it an ideal incubator for fostering future talents in the field, which is an ideal place dedicated to education and training of next-generation neutron scattering users.

The CMRR is a high-performance, multipurpose research reactor with dedicated halls for thermal and cold neutrons, supporting a diverse range of scientific investigations through various experimental facilities and instruments, including neutron radiography, radiopharmaceuticals neutron activation analysis, and neutron scattering. Currently, 8 instruments have been built (4 in the reactor hall and 4 in the cold scattering hall) and are open to users [52]. Among these instruments is a polarized TOF neutron reflectometer, *Diting*, in the cold scattering hall [58]. The TOF mode of the reflectometer enables the individualized optimization of the instrument flux and resolution for each experiment. Diting takes advantages of a high-efficiency transmission supermirror ($m = 2.7$) to polarize the incident neutron beam and another transmission supermirror ($m = 3.85$) to analyze the beam. Two adiabatic fast passage RF spin flippers are implemented to flip the upstream and downstream neutron polarizations and thus enact polarization analysis. The polarized mode works over a wide wavelength band from 2.5 to 12.5 Å and covers a Q range from 0 to 0.5 Å^{-1} [51, 52, 58], and users have started to perform polarized neutron reflectometry (PNR) experiments at the instrument to study various science cases [59–62]. Meanwhile, the CMRR has established a dedicated polarized ^{3}He team, which has played a significant role in advancing polarized neutron capabilities in China by developing polarized ^{3}He systems for neutron instruments [63–65]. The use of polarized ^{3}He can realize the rapid deployment of polarized neutron capabilities on typically unpolarized neutron instruments. They have also performed fundamental studies using relevant techniques to make precision measurements in the search for exotic spin-dependent interactions mediated by axion-like particles [66–68]. The CMRR is still fast growing. New neutron instruments are under construction and will join the user program soon. A polarized SANS (PSANS) instrument [52] and two neutron spin echo instruments, the longitudinal neutron resonance spin echo (LNRSE) spectrometer [69] and the spin echo SANS (SESANS) instrument

[70], will be the latest additions to polarized neutron scattering at the CMRR.

The CSNS is large accelerator-based pulsed neutron facility operating with a 1.6-GeV proton beam and 25-Hz proton pulses [55, 56]. It represents a significant leap forward in China's dedication to neutron scattering. The proton beam power is running at 100 kW and can be upgraded to 500 kW in the future. The current facility can accommodate up to 20 neutron instruments, with four beamlines already in the user program and more under construction or planning http://english.ihep.cas.cn/csns/fa/in/. The multipurpose reflectometer (*MR*) is one of the three day-1 instruments at the CSNS and comes equipped with the polarized neutron reflectometry (PNR) capability [71]. This reflectometer utilizes two transmission Fe/Si supermirrors ($m=4.4$) as the polarizer and analyzer in PNR experiments, along with a pair of RF spin flippers positioned before and after the sample. Since its commissioning, the MR instrument has become one of the most productive instruments at the CSNS with PNR experiments being routinely conducted [72–78]. Additionally, the CSNS has a dedicated neutron polarization group and a development beamline (BL-20) contributing to the advancement of polarized neutron devices and techniques [79]. The group has developed both ex situ and in situ polarized ^{3}He neutron spin filters [80–82], built and tested flippers [83], and realized TOF polarized neutron imaging [84]. The development beamline BL-20, equipped with a V-cavity polarizing supermirror to provide a highly polarized incident neutron beam, has become the go-to place for testing neutron polarization devices and exploring new concepts. For the future very small angle scattering (*VSANS*) instrument, efforts are being made to develop a magnetic sextuple lens to focus the incident polarized cold neutron beam onto the sample position [85, 86].

The construction of the three neutron sources is far from complete. Despite the rapid progress and achievements in neutron scattering research in China, there is still considerable potential for further development and expansion. As these facilities continue to expand, more instruments with polarized neutron capabilities will be added to the current instrument suite. The ongoing advancements in polarized neutron scattering technology will enable breakthroughs across a wide range of disciplines. With a steadfast commitment to innovation and collaboration, China is poised to become a leading player in neutron scattering research, pushing the boundaries of scientific exploration and discovery.

2.3 India

India constructed Asia's first research reactor, Apsara, in 1956 at the Bhabha Atomic Research Centre (BARC) in Mumbai. Following Apsara's successful operation, Indian researchers began to explore the potential of neutron scattering in various fields of study. The commissioning of the second, more powerful research reactor, Cirus, in 1962 further accelerated the growth of neutron scattering research in India. The demand for higher neutron flux and better instruments propelled India to build Dhruva, a 100-MW reactor that went critical in 1985 and was designated as the National Facility for Neutron Beam Research (NFNBR) https://www.barc.gov.in/reactor#nav-4. Currently, Dhruva is home to 12 neutron instruments, two of which have polarized neutron capabilities [87].

- *Polarized neutron spectrometer*: This instrument is housed in the reactor hall of Dhruva and is a polarized neutron workhorse. It uses Heusler crystals as both the monochromator and polarizer to provide a polarized thermal neutron beam of 1.2 Å and a $Co_{0.92}Fe_{0.08}$ crystal as the polarization analyzer [88, 89]. Two RF spin flippers are employed to enable polarization analysis at this beam line. Notably, this instrument has been extensively utilized for experiments employing the neutron depolarization technique, which is a well-established method to study ferromagnetic materials [90–93]. The one-dimensional neutron depolarization technique of the instrument provides a way to investigate the domain magnetization and magnetic inhomogeneity on a mesoscopic scale in the sample and serves as a useful addition to conventional neutron diffraction [88, 94–101].
- *Polarized neutron reflectometer*: As in other neutron facilities, PNR has become an indispensable tool in studies of magnetic thin films. Situated in the cold guide laboratory next to the reactor hall, the reflectometer at Dhruva can switch between unpolarized and polarized modes and delivers an incident neutron beam with a wavelength of 2.5 Å [102]. In the polarized mode, a polarizing supermirror is used to polarize the incident beam and a Mezei flipper to flip the incident neutron polarization. Although the option to insert a supermirror analyzer to perform polarization analysis is available, it is generally not implemented because of the relatively low neutron flux of the instrument [102]. Nevertheless, the reflectometer remains productive, applying PNR to a diverse range of samples [103–108].

Neutron scattering in India continues to evolve. With the ever-growing demand for better resolution, higher neutron flux, and more modern neutron instruments, a new spallation neutron source has been proposed to be built in India [109–111]. Polarized neutron capabilities will be no doubt a significant part of the new instruments at the spallation neutron source. With the continued growth of the neutron scattering community and enhanced international collaborations, neutron scattering in India looks even brighter.

2.4 Japan

Japan has played a significant role in the development and advancement of neutron scattering research since the 1960s. Japan has also been a front-runner in developing and utilizing polarized neutron techniques. Currently, two major neutron facilities in Japan, the JRR-3 and JSNS, are providing neutron beams for users across the world. The two sources are located within walking distance to each other in Tokai, Japan, which helps users take advantage of the complementary capabilities of both facilities to perform more comprehensive and diverse experiments. The research reactor JRR-3 first went critical in 1962 with a power of 10 MW and was later upgraded to 20 MW in 1990. JSNS at J-PARC is a 1-MW accelerator-based pulsed neutron source debuted in 2008. Both facilities serve as hubs for regional and international collaboration in neutron scattering research, attracting users from all over the world.

Currently, the JRR-3 has a total of 31 neutron instruments currently running https://jrr3.jaea.go.jp/jrr3e/2/21.htm, many of which have polarized neutron capabilities. Here, we highlight several notable polarized neutron instruments:

- *TAS-1*: This instrument is a conventional thermal triple-axis spectrometer with unpolarized and polarized modes. The spectrometer utilizes doubly focusing Heusler crystals (Cu_2MnAl) in polarized mode to polarize neutrons and analyze polarization, thereby enabling longitudinal polarization analysis (LPA) [112]. Moreover, TAS-1 has also been equipped with an advanced spherical neutron polarimetry (SNP) device called CRYOPAD, which was developed at the Institut Laue-Langevin (ILL) [113]. The addition of CRYOPAD, along with versatile sample environment, has enabled the instrument to perform more complicated experiments [114–116].
- *PONTA*: PONTA is another thermal triple-axis spectrometer at JRR-3 with the polarization analysis capability. Like at TAS-1, Heusler crystals are used as the polarizer and analyzer for PONTA [117]. In addition to LPA, PONTA has also tested thermal neutron spin echo spectroscopy [118–120]. Compared to classical triple-axis spectroscopy, the spin echo addition provides a unique way to achieve higher energy resolution without sacrificing neutron flux. Recently, PONTA has added an option to use a V-cavity supermirror as the polarizer, which, in combination with a pyrolytic graphite monochromator, can lead to higher flux and incident neutron polarization.
- *SUIREN*: SUIREN is a magnetic reflectometer dedicated to studying magnetic films and solid–liquid interfaces [121, 122]. SUIREN can choose to run between the unpolarized mode and the polarized mode. The polarized mode enables polarized neutron reflectometry (PNR) by using one Fe/Ge reflection supermirrors as the polarizer and the other one as the analyzer [121, 123]. Together with two Mezei flippers, one before and one after the sample, four cross sections ($++, +-, -+$, and $--$) can be measured, where the first $+$ or $-$ sign in the cross sections represents the incident neutron polarization direction and the second sign denotes the analyzed neutron polarization direction.
- *iNSE*: This is a conventional neutron spin echo spectrometer designed to mainly study dynamics in soft matter [124–127]. The two specially designed symmetric main precession coils responsible for spin echo provide homogeneous field integrals as well as strong magnetic fields [124]. The neutron beam is polarized by a polarizing supermirror bender guide and analyzed by a multichannel supermirror bender, both manufactured by Swiss-Neutronics and working well for neutron from 4 to 15 Å [126].
- *SANS-J-II*: This is a 20-m-long small angle neutron scattering (SANS) instrument capable of doing polarized neutron experiments [128, 129]. The uniqueness of this beamline lies in utilizing focusing lenses to achieve an accessible minimum scattering vector Q_{min} on the order of 10^{-4} Å^{-1} and thus enable ultra-small angle scattering [129, 130]. Polarization analysis is available at high Q with a supermirror analyzer and a high-angle detector, mainly used to separate the coherent and incoherent signals [131]. In addition, a dynamics nuclear polarization (DNP) device has been developed for SANS-J-II to polarize sample nuclei [132], providing an increased signal-to-noise ratio, especially in neutron crystallography of proteins.

Some other instruments at JRR-3 also have polarized neutron capability or have tested it. For example, TOPAN is another triple-axis spectrometer with the capability of polarization analysis, and the powder diffractometer HERMES also tried polarized neutron diffraction using a polarized ^3He polarizer [133]. The neutron optics beamline NOP has served as a test bed for the development of polarized ^{3}He neutron spin filters [134–136] as well as other neutron optics like magnetic neutron lenses [137, 138].

The JSNS is located at the Materials and Life Science Experimental Facility (MLF) in J-PARC, which provides high peak neutron brightness at 25 Hz to 21 currently installed neutron instruments [139]. Since its inception in 2008, several state-of-the-art instruments with polarized neutron capabilities have been constructed, offering unique capabilities to users:

- *SHARAKU*: SHARAKU is a TOF-polarized neutron reflectometer. Compared to its counterpart at JRR-3, SHARAKU enables the measurement of reflectivity profiles over a wide range of scattering vector *Q* values. Polarizing Fe/Si supermirrors are installed as the neutron polarizer and analyzer. A Drabkin two-coil spin flipper effectively flips the incident neutron polarization [140], and a Mezei flipper is used to flip the downstream neutron polarization [141, 142]. Additionally, an in situ polarized ^{3}He system has also been tested at the instrument to serve as an analyzer for off-specular scattering [143, 144]. The ^{3}He analyzer can work as a high-efficiency spin flipper to replace the original Mezei flipper.
- *VIN ROSE*: This instrument consists of two types of spin echo spectrometers: a neutron resonance spin echo (NRSE) beamline and a Modulated Intensity by Zero Effort (MIEZE) beamline [145–148]. NRSE and MIEZE are two variations of the neutron spin echo technique. In NRSE, high-frequency spin flippers replace the long, large, and strong magnetic precession coils as seen in the conventional spin echo setup [14, 16], making NRSE instruments more compact than conventional NSE ones. MIEZE is a single-arm NRSE technique in which the polarization analyzer is placed upstream before the sample to avoid polarization manipulation after the sample, and the modulated signal would not be affected by a depolarizing sample or high magnetic fields around the sample [149–151]. At VIN ROSE, the TOF MIEZE beamline is already in the user program [152–154], while the NRSE beamline is still under tuning.
- *TAIKAN*: This is a TOF SANS instrument that covers a wide Q range (0.0008–17 Å^{-1}) for unpolarized neutrons at a single configuration setup [155, 156]. For polarized neutrons, TAIKAN has a V-cavity transmission supermirror installed as the polarizer [157, 158]. Polarization analysis is enabled by adding a polarized ^{3}He analyzer or a supermirror analyzer to separate coherent and incoherent scattering for organics samples [158, 159] or to study magnetic phenomena in magnetic materials [160–162]. Half polarized diffraction experiments without polarization analysis have also been performed on magnetic materials [163–165]. Moreover, DNP was also tested on the instrument to provide spin contrast variation for the sample [166].
- *POLANO*: POLANO is a dedicated direct geometry polarized neutron spectrometer with a wide detector bank aiming to perform polarization analysis for neutrons up to 100 meV [145, 167–169]. An in situ polarized ^{3}He neutron spin filter has been developed as the neutron polarizer [170, 171], which can also work as a neutron spin flipper. A wide-angle supermirror array has been made to serve as the polarization analyzer for neutrons up to 40 meV with an angle coverage of up to 40° [172]. In addition to the supermirror analyzer, POLANO also plans to use a wide angle polarized ^{3}He analyzer to reach higher neutron energies, covering more science cases [173].

In addition to these instruments dedicated to polarized neutrons, several other instruments at JSNS can also be utilized for polarized neutron experiments. The neutron imaging beam line RADEN has an option to do polarized neutron imaging to visualize magnetization distribution [174–177]. Polarized neutron imaging can also be performed at the instrument NOBORU [178–180], which is a development and test beam line for new techniques and devices. A 7 T DNP apparatus has been successfully tested at the diffractometer iMATERIA by achieving high proton polarizations and is now available for industrial users [181, 182]. The neutron optics and fundamental physics beamline NOP have a polarized neutron branch by using a polarizing supermirror [183, 184], which has been used to measure the neutron lifetime [185] and test other neutron polarization devices [144, 186]. The neutron-nucleus reaction measurement instrument ANNRI has also utilized polarized neutrons for nuclear physics [187, 188].

Japan has a long history of excellence in the field of neutron scattering, contributing to groundbreaking research across various disciplines. The development of polarized neutron scattering instrumentation and techniques has further expanded the scope of research conducted at Japanese facilities. To date, the neutron facilities in Japan have enabled polarized neutron capabilities in almost every category, covering hard matter, soft matter, and fundamental physics. Japan has expert teams dedicated to developing new polarized techniques and instrumentation. For example, the ^{3}He team has developed both in situ and ex situ polarized ^{3}He systems for various instruments [136, 144], and the supermirror team has the capability to fabricate high-performance supermirrors [123, 189]. As facilities like the JSNS and JRR-3 continue to invest in new polarized neutron instruments and methodologies, Japan's role as a leading player in neutron scattering research is set to strengthen further.

2.5 Others

In addition to the aforementioned neutron facilities, both the 30-MW High-flux Advanced Neutron Application Reactor (HANARO) in South Korea [190, 191] and the 30-MW Reaktor Serba Guna G.A. Siwabessy (RSG-GAS) in Indonesia [192, 193] are two major neutron sources in the region. At HANARO, polarized neutron experiments can be performed on the polarized neutron reflectometer REF-V [191, 194] and the 40-m SANS instrument [195]. Polarized ^{3}He neutron spin filters have also been developed at HARARO [196, 197] and will be applied to the triple-axis spectrometers and the neutron imaging beamline in the future [197, 198]. New instruments are still being commissioned or constructed at HANARO, which will expand the scope of applications for polarized neutrons.

The neutron scattering program at RSG-GAS in Indonesia is relatively small compared to other large neutron facilities in Asia–Pacific, but it still managed to equip the triple-axis spectrometer with the polarized neutron capability [193]. Despite the challenges often faced by developing countries like Indonesia, such as limited funding and lack of experienced researchers in the field of neutron scattering, the country has shown a strong commitment to improving its research capabilities in this area, which bodes well for its future advancements in neutron scattering.

3 Conclusions

Over the years, polarized neutron scattering has emerged as a powerful tool in a variety of scientific domains. Fields ranging from physics, chemistry, and materials science to earth science and biology have leveraged the capabilities of polarized neutron scattering to gain significant insights into their respective domains of study. For instance, in the field of magnetism, polarized neutron scattering has been invaluable in the study of magnetic structures, spin dynamics, and magnetic phase transitions, and in the field of soft matter, neutron spin echo has been instrumental in studying the dynamics of polymers and proteins.

The Asia–Pacific region, with its vibrant economic growth and scientific advancements, has been seeing rapid development and utilization of polarized neutron techniques. The region, though a relatively late entrant, has now become an active participant in the global neutron scattering community. The extensive neutron facilities across the region collectively demonstrate a broad engagement in neutron scattering research. The region has embraced almost all polarized neutron techniques, including longitudinal polarization analysis, spherical neutron polarimetry, conventional and resonance neutron spin echo, dynamic nuclear polarization, magnetic lenses, and polarized neutron imaging. This impressive breadth of technique adoption showcases the region's adaptability and eagerness to keep pace with the global trends.

The government support within the region has been vital to these advancements, with significant investment in the construction of new facilities and the upgrading of existing ones. For example, over the past two decades, this region has seen the construction and successful operation of two new large state-of-the-art spallation neutron sources. These facilities account for half of the spallation neutron sources currently operating globally. The increasing accessibility to these facilities, in turn, has opened up many opportunities for collaboration both within the region and with international partners.

In the coming years, as more new facilities and modern instruments come online, and as new polarized techniques become more available, the Asia–Pacific region is expected to play a leading role globally in the applications of polarized neutron scattering.

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