Development

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Date: 2026-01-20T16:28:07+00:00

Abstract

In contrast to conventional neutron imaging, which relies on attenuation contrast, polarized-neutron imaging (PNI) has proven to be a powerful tool for investigating the spatial distribution of magnetic fields inside and around bulk samples owing to the intrinsic magnetic moment of neutrons. This technique exploits the measurement of the cumulative precession of the neutron polarization as it traverses a magnetic field.

We report the recent development of PNI capabilities at the China Advanced Research Reactor (CARR), where two neutron-imaging instruments (thermal and cold) have been established. To further advance and implement the PNI technique, a dedicated PNI facility—comprising a double-crystal pyrolytic graphite monochromator, a supermirror polarizer with three parallel V-cavities, and an in situ optically pumped (^3)He neutron spin filter serving as a neutron spin analyzer—has been successfully developed and tested on an existing cold neutron-imaging instrument. This setup is expected to significantly enhance neutron imaging and neutron optics at CARR in the future.

Full Text

Preamble

Development of a Polarized-Neutron Imaging Technique at the China Advanced Research Reactor

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In contrast to conventional neutron imaging that relies on attenuation contrast, polarized-neutron imaging (PNI) has proven to be a powerful tool for investigating the spatial distribution of magnetic fields inside and around bulk samples, owing to the intrinsic magnetic moment of neutrons. This technique benefits from measuring the cumulative precession of neutron polarization as it passes through a magnetic field. We report the recent development of PNI capability at the China Advanced Research Reactor (CARR), where two neutron-imaging instruments (thermal and cold) have been established. To further develop and realize the PNI technique, a PNI facility consisting of a double-crystal pyrolytic graphite monochromator, a supermirror polarizer with three parallel V-cavities, and an in-situ optically pumped ^{3}He neutron spin filter as a neutron spin analyzer was successfully developed and tested based on an established cold neutron-imaging instrument. This setup will be beneficial for enhancing neutron imaging and neutron optics capabilities at CARR in the future.

Keywords: Neutron radiography, Polarized-neutron imaging, Magnetic imaging, Magnetic field, Polarizing supermirror

Introduction

Neutrons, having no net electric charge, primarily interact with atomic nuclei, enabling them to penetrate deeply into thick samples with adequate contrast. Moreover, neutrons are sensitive to light elements (such as H and Li) in many condensed matter samples and can distinguish adjacent elements in the Periodic Table and isotopes (such as ^{1}H, ^{2}H, and ^{3}H). Consequently, similar to X-ray imaging, neutrons serve as ideal probes for the nondestructive detection of internal structural defects in objects at the macroscopic level.

Distinct from X-rays and electrons, these unique properties have made neutron radiography and tomography, primarily in transmission mode, a valuable complement to X-ray imaging techniques for material analysis. Since its first report in 1935, this method has been extensively developed over the past few decades using white beams. Conventional neutron-imaging techniques rely on measuring the intensity attenuation of a transmitted neutron beam as it passes through a sample [?]. In recent years, advances in neutron-imaging techniques and data processing across various neutron sources have significantly expanded their applications [?]. These developments, including both direct and indirect methods [?], have been particularly important in many scientific research fields such as materials science [?, ?], renewable energy [?, ?], lithium-ion battery technology [?], civil engineering [?], and the preservation of cultural heritage [?, ?]. Moreover, to satisfy various nondestructive requirements in several targeted scientific fields, several specific neutron-imaging methods have been exploited.

For example, energy-selective neutron imaging and neutron Bragg-edge imaging are currently used to investigate crystal-engineered materials. In addition, a neutron phase-contrast imaging method employing a grating interferometer has been introduced [?, ?]. Beyond conventional imaging with thermal and cold neutrons, fast neutrons with relatively high energies have also been exploited for imaging applications such as isotope analysis [?].

However, visualizing the magnetic distribution and flux generated by a magnet using conventional neutron-imaging techniques represents a significant challenge. Neutrons possess another unique property in the form of a nonzero intrinsic magnetic moment that lies antiparallel to their internal angular momentum. This allows neutrons to interact with magnetic fields deep inside solid matter, which is not possible with traditional field probes. Therefore, the distribution of magnetic induction inside a solid magnetic material and in free space can be nondestructively visualized (through magnetic interaction with spin-polarized neutrons) via imaging with polarized neutrons (only one spin state). The polarized-neutron imaging (PNI) technique was first realized by the CONRAD instrument at the Helmholtz Centre, Berlin, enabling clear observation and quantitative analysis of the trapped three-dimensional magnetic flux distribution within a polycrystalline lead cylinder below the critical temperature [?]. Subsequently, various PNI facilities have been designed and constructed using different neutron sources [?]. Established PNI is employed to investigate spatial magnetic fields inside and outside matter, magnetic domains and magnetic phase transitions, inhomogeneous ferromagnets, the Meissner effect, and flux pinning, where conventional neutron imaging is not suitable [?]. For example, the skin effect in a bulk aluminum conductor has been observed and theoretically calculated, indicating an inhomogeneous distribution of electric current and resulting magnetic field [?]. Owing to the severe polarization loss of polarized neutrons passing through ferromagnetic materials, PNI has also been used to investigate the phase transition process from the ferromagnetic to the paramagnetic state [?].

Polarized Neutron Physics

Neutrons are subatomic particles with spin quantum number $s = 1/2$ and an angular momentum of $\pm\hbar/2$. The neutron spin is therefore easily influenced by a magnetic field due to its intrinsic magnetic moment ($\mu = -9.66 \times 10^{-27}$ J T^{-1}), which is usually aligned antiparallel to the neutron spin. When neutrons pass through an applied external magnetic field ($\vec{B}$), their interaction with the magnetic field can change their motion behavior. According to the Schrödinger wave equation, the time-dependent motion of the spin vector ($\vec{S}$) of neutrons can be expressed as follows [?, ?]:

$$\frac{d\vec{S}(t)}{dt} = \gamma[\vec{S}(t) \times \vec{B}(t)]$$

where γ represents the gyromagnetic ratio of the neutrons (-1.832×10^8 rad s^{-1} T^{-1}). The change in neutron spin in an external magnetic field is known as Larmor precession, which always occurs at a specific frequency $\omega_L = \gamma B$, where B is the scalar magnitude of the magnetic field ($B = |\vec{B}|$).

When neutrons with wavelength λ travel through a magnetic field with velocity ($v = h/m\lambda$) adiabatically, the wavelength-dependent precession angle ($\phi(\lambda)$) can be described by a path integral [**?**, **?**, **?**]:

$$\phi(\lambda) = \omega_L t = \int \gamma B \frac{ds}{v} = \frac{\gamma m \lambda}{h} \int B ds$$

where t represents the time required for neutrons to pass through the magnetic field ($t = \int ds/v$), m represents the rest mass of a neutron (1.675×10^{-27} kg), and h represents Planck' s constant ($h = 6.626 \times 10^{-34}$ J s). Therefore, the precession angle is related to the wavelength (λ) and is proportional to the magnetic field strength (B), according to Eq. (2), indicating the strong impact of the applied magnetic field strength on Larmor precession. As neutrons propagate through an applied magnetic field caused by either an external current source or localized magnetization, the Larmor precession of neutron polarization is closely dependent on the magnetic field distribution along the neutron' s motion trajectory. Therefore, as defined in Eqs. (1) and (2), the magnetic field distribution can be deduced by analyzing the accumulated shift in neutron polarization.

The PNI technique, which combines neutron polarization analysis and neutron-imaging techniques, can be used to visualize magnetic flux by measuring variations in neutron polarization. In comparison with conventional attenuation-based neutron imaging, the intensity of the transmitted neutrons is further modulated by neutron polarization (P) [**?**, **?**, **?**]. Polarization P can be obtained through polarization analysis owing to only two possible neutron spin orientations, including the spin-up and spin-down states caused by Zeeman splitting in a magnetic field:

$$P = \cos\phi(\lambda) = \frac{I_{\text{up}} - I_{\text{down}}}{I_{\text{up}} + I_{\text{down}}}$$

where I_{up} and I_{down} are the neutron intensities recorded in spin-up and spin-down states, respectively. The polarization analysis process introduced during imaging tests first generates polarized neutrons before the sample and then examines the polarization change along a certain direction after passing through the studied sample. When performing polarization analysis, the neutron polarization information is converted into an additional intensity with respect to the conventional transmission attenuation contrast $I_a(x,z)$. According to Eq. (3), the contrast variation introduced by Larmor precession of the polarization vector in front of the polarization analyzer within a magnetic field can be described as $I_m(x,z)$ [**?**, **?**]:

$$I(x,z) = I_0(x,z) \cdot \exp\left(-\int \mu(s)ds\right) \cdot \frac{1}{2}[1 + \cos\phi(x,z)]$$

$$I_a(x,z) = I_0(x,z) \cdot \exp\left(-\int \mu(s)ds\right)$$

$$I_m(x,z) = \frac{1}{2}[1 + \cos\phi(x,z)]$$

where $I(x,z)$ and $I_0(x,z)$ are the recorded intensities after the polarization analyzer and the intensity of the incident beam, respectively. μ is the linear attenuation coefficient of the studied sample caused by conventional neutron imaging and (x,z) is the corresponding coordinate in the detector plane of the imaging detector system. Note that the polarization vector can be viewed as the average of all spin states for a neutron beam. Using this method, variations in the polarization orientation for a given path are indicative of the magnetic field distribution when polarized neutrons traverse the magnetic field.

Design of the PNI Facility

Developing neutron-imaging techniques requires a high-quality source, as high-flux neutron sources can reduce measurement time for dynamic processes [?, ?, ?]. The China Advanced Research Reactor (CARR), a high-flux research neutron source, focuses on neutron-imaging capability. Two neutron-imaging instruments have been established at the China Institute of Atomic Energy (CIAE). The cold neutron-imaging instrument at the CNGC beamline provides a maximum neutron flux of 1.87×10^8 n cm^{-2} s^{-1} at 30 MW of CARR. The aperture system enables L/D values from 160 to 3200, suitable for energy-selective and high-resolution imaging. L/D is the ratio of distance (L) between aperture system and sample to diameter (D) of applied aperture. Various PNI facilities have been constructed at different neutron sources using optical devices such as neutron polarizers and spin flippers since the first report by the CONRAD instrument at Helmholtz Centre Berlin [?]. To enhance neutron-imaging capability, developing PNI technique on the cold neutron-imaging instrument at CARR is urgent, considering future research on magnetic domains, phase transitions, and Meissner effect in superconductors.

The PNI setup consists of a double-crystal graphite monochromator after an aperture system, a supermirror polarizer with three V-shape cavities coupled with an RF-flipper, a guide magnetic field, electromagnetic coils, and a polarized ^{3}He neutron spin filter (NSF) using a spin-exchange optical pumping (SEOP) ^{3}He cell as analyzer, followed by an imaging detector system [?, ?, ?]. An aperture system of 7 holes with varying sizes in the upstream tunes the incident beam profile. A pinhole with different radii behind the supermirror polarizer tunes spatial resolution, L/D (where D is the pinhole diameter), and neutron flux, as shown in Fig. 1 [Figure 1: see original paper]. The beam generates coverage of 100 mm diameter at the sample position and a field-of-view (FOV) of 110 mm × 110 mm at the camera, illuminating the neutron camera scintillator. To reduce background noise and activation, the monochromator, polarizer, pinhole, guide field, and NSF system are covered by ^{10}B-doped rubber shielding.

Double-Crystal Graphite Monochromator

Because neutron polarization precession is wavelength-dependent in an external magnetic field according to Eq. (2), a polarized monochromatic neutron beam is required. A white beam with various neutron wavelengths leads to reduced measured polarization through dephasing. Therefore, monochromating the white beam from the reactor is critical for the PNI setup. This can be achieved via the time-of-flight method at pulsed neutron sources or through a monochromatization device. Devices like mechanical neutron velocity selectors and double-crystal monochromators can select neutrons with desired wavelength from white beams at continuous reactor sources like CARR [**?**, **?**]. The mechanical neutron velocity selector' s key component is a rotating drum with helical lamellae coated with neutron absorption material. It allows neutrons with certain velocity to pass through, selecting wavelengths by drum rotation speed. The neutron wavelength (λ) depends on rotation speed: $\lambda = h\Phi/(mL\omega)$, where h and m are Planck' s constant and neutron rest mass, L is rotor length, Φ is lamella helical angle, and ω is rotor angular velocity. The main factors influencing wavelength resolution ($\Delta\lambda/\lambda$) of a velocity selector include distance (d) between adjacent lamellae, radius of rotor (R), and helical angle (Φ), as described by $\Delta\lambda/\lambda = d/(R\Phi)$. A desired wavelength from an incident white beam can be selected through a double-crystal monochromator based on Bragg' s law: $n\lambda = 2d\sin\theta$ (where $n = 1, 2, 3, ...$), with d, θ, and n representing the lattice spacing, diffraction angle, and order of diffraction, respectively. The neutrons are reflected parallel to the incident beam by a second crystal, creating a monochromatic beam. Higher-order reflections generate secondary neutrons, decreasing the final wavelength resolution. Wavelength resolution and neutron flux are key parameters for evaluating monochromatization devices. The selection of a device should be guided by experimental requirements. A double-crystal monochromator offers high wavelength resolution with lower neutron flux, while a neutron velocity selector provides lower resolution but higher flux [**?**, **?**]. High wavelength resolution suits energy-selective imaging and scattering experiments but requires longer measuring time.

A double-crystal graphite monochromator is installed at the cold neutron-imaging beamline, composed of pyrolytic graphite single crystals with a mosaicity of 0.8° and size of 70 mm × 70 mm, as shown in Fig. 2 [Figure 2: see original paper]. Through double reflection by the two crystals, neutrons with a required wavelength can be defined from the incident white beam without changing beam direction. Previous experiments demonstrated a wavelength resolution ($\Delta\lambda/\lambda$) of 2.6% for neutrons with 4 Å wavelength and beam size of

100 mm × 150 mm through time-of-flight measurement [?]. The beam center height is lowered by 90 mm after selecting the desired neutron wavelength compared to the incident beam.

Polarizer Coupled with an RF-Flipper

To develop polarized-neutron techniques and perform polarized-neutron experiments, including scattering and imaging, the production of polarized neutron beams (only spin-up or spin-down) is a prerequisite at the beamline [?]. Currently, three main methods exist for generating polarized-neutron beams, each with unique advantages. The first is the use of polarizing crystals such as $Co_{92}Fe_8$ and Heusler alloys (Cu_2MnAl), which can polarize monochromatic neutrons through preferential Bragg diffraction. Cu_2MnAl has high reflectivity and relatively low absorption in contrast to $Co_{92}Fe_8$ [?]. The second is the use of polarizing supermirrors, mainly including cavity and bender types, which are highly efficient and suitable for a wide neutron wavelength range. However, polarizing supermirrors have difficulty polarizing neutrons with short wavelengths (below 2.0 Å) and neutron beams with large divergence. In addition, the polarizing S-bender (generally in reflection mode) has a small device size and relatively high polarization but can increase beam divergence and decrease the resolution function; therefore, a collimator is always required for imaging applications [?]. A polarizing V-cavity supermirror (generally in transmission mode) can maintain beam direction by transmitting neutrons with only one spin state (spin-up or spin-down). However, it generates low polarization and increases the total device length, which occupies more precious space at the beamline relative to the S-bender [?, ?]. In contrast, the polarized ^{3}He NSF has been rapidly developed and used to polarize neutron beams in recent years owing to its ability to polarize beams with large divergence and neutrons with a broad energy band [?]. Polarized ^{3}He NSF operates on the principle of preferential absorption by polarized ^{3}He nuclei, selectively transmitting neutrons with spin parallel to ^{3}He and absorbing neutrons with spin antiparallel to ^{3}He. The polarized ^{3}He NSF can not only polarize neutrons with various wavelengths but also handle neutron beams with large divergence. One major disadvantage of polarized ^{3}He NSF is polarization loss with increasing operation time, which occurs due to several factors such as collision with the glass cell wall and stray magnetic fields around the device [?].

A V-shape transmission cavity is adopted as a neutron supermirror polarizer, instead of a bender polarizer, to produce polarized neutrons while maintaining beam divergence [?, ?]. Various V-shape cavity configurations with different m values were analyzed in the 2–8 Å wavelength range (in Fig. 3 [Figure 3: see original paper]) using McStas software [?, ?]. Considering available space and cost, a supermirror polarizer with three parallel V-shape cavities (Parallel 3Vs) in the horizontal direction was selected, as shown in Fig. 3 [Figure 3: see original paper]. Si-wafers coated with Fe-Si polarizing supermirror ($m = 3.3$) transmit spin-up neutrons and absorb spin-down neutrons. The neutron beam divergence is preserved through the polarizer along the neutron flight path (y-axis), as shown in Fig. 1 [Figure 1: see original paper]. The polarization is parallel to the z-direction. An adiabatic [A6]π radio-frequency flipper (RF-flipper), comprising static vertical and radio-frequency longitudinal magnetic fields, is coupled with the polarizer to tune polarized-neutron spin direction for polarization testing [**?**].

Guide Field and Electromagnetic Coils

A guide field along the polarized-neutron flight path is required to preserve neutron polarization, as neutrons would otherwise depolarize through interaction with Earth' s magnetic field and stray fields, unlike the white beam. A guide field is designed behind the polarizing device, as shown in Fig. 4 [Figure 4: see original paper]. The total length is 6000 mm, consisting of three 2000 mm segments. The segmented design allows manageable installation and convenient switching for different instrument lengths. A series of pure iron rods with NdFeB permanent magnets at both ends is distributed along the z-direction at 100 mm intervals, sandwiched between two pole plates of pure Fe material (in the xy plane). The pole plates and iron rods form a low-reluctance path for magnetic flux from the NdFeB magnets, distributing it uniformly between the polar plates. The vertical guide field strength is 4.7 mT, sufficient to maintain neutron polarization and tolerate external disturbances 10 times stronger than Earth' s field. The magnetic field is directed from the lower pole plate to the upper one. Evacuated aluminum tubes with thin aluminum windows are positioned between the pole plates along the neutron flight path to reduce atmospheric scattering, as shown in Fig. 4 [Figure 4: see original paper].

Owing to the polarization direction of the polarized ^{3}He spin filter and guide field being along the y-axis and z-axis respectively, electromagnetic coils made of pure Cu wires are installed to adiabatically rotate and maintain the polarization along the y-axis, as shown in Fig. 1 [Figure 1: see original paper]. The magnetic field amplitude can be modulated by changing the coil current based on experimental requirements. The coil field strength enables an adiabatic transition between vertical permanent magnet and horizontal coil-magnetized sections. Notably, owing to trigonometric function behavior, a slight non-adiabatic transition with the final polarization vector at 15° from the z-axis causes minimal longitudinal polarization loss of 0.035; however, it maintains a significant transverse component of 0.26. Therefore, careful simulation and implementation of field direction transition are crucial. The simulated adiabatic parameter k exceeds 10 across the beam profile at the shortest operating wavelength, enabling good adiabatic transition with low transverse components.

Polarized ^{3}He Spin Filter as Analyzer

For polarized-neutron techniques, both production and measurement of polarized neutrons require specialized equipment, realized by polarizers before and after the sample. The first polarizer produces polarized neutrons, like the designed polarizing 3V-cavity supermirror, while the second one analyzes polarization changes after neutrons pass through the sample. A polarized ^{3}He spin filter is ideal for PNI experiments, having a large uniform aperture, high polarization across neutron energies, and wide acceptance angle. The polarized ^{3}He NSF is installed after the sample for the PNI setup at CARR as the polarization analyzer. Two methods exist to polarize ^{3}He gas in a boron-free glass cell: metastable-exchange optical pumping (MEOP) and SEOP [**?**]. SEOP produces nuclear polarization slowly at high pressures (0.5-1.3 bar), while MEOP works rapidly at low pressures (mbar level). SEOP is now preferred as it meets most high-pressure applications [**?**].

The polarization of the ^{3}He atoms (P_{He}) can be defined as:

$$P_{\mathrm{He}} = \frac{P_A K_{\mathrm{SE}}[A]}{K_{\mathrm{SE}}[A](1+X)+\Gamma_{\mathrm{He}}}$$

where P_A represents the alkali-metal electron polarization (such as Rb), K_{SE} is the spin-exchange rate coefficient, $[A]$ is the alkali-metal density (such as Rb), X is a parameter that affects P_{He} via a large slope of the relationship between Γ_{He} and alkali-metal density $[A]$ relative to the spin-exchange rate, and Γ_{He} is the spin-relaxation rate of ^{3}He atoms.

The neutron polarization (P_n) can be deduced according to the ^{3}He polarization (P_{He}) by measuring neutron transmission in parallel and antiparallel directions when a polarized ^{3}He NSF is used as a spin flipper [**?**]:

$$\frac{T_{\mathrm{up}} - T_{\mathrm{down}}}{T_{\mathrm{up}} + T_{\mathrm{down}}} = \tanh(n\sigma l P_{\mathrm{He}})$$

where T_{up} and T_{down} represent the transmission of neutron polarization parallel and antiparallel to the ^{3}He polarization, respectively. n represents the density of ^{3}He atoms in the cell, σ represents the absorption cross-section of ^{3}He atoms related to neutron energy, and l represents the flight distance of neutrons passing through the ^{3}He NSF.

A polarized ^{3}He NSF using the SEOP method based on transmission through polarized ^{3}He gas in a boron-free glass cell serves as an analyzer to detect polarization change after the polarized beam interacts with the magnetic field of the studied sample. Compared to the off-situ system, the in-situ integrated SEOP ^{3}He NSF system provides long-term (over seven days) and stable ^{3}He polarization of up to 65%, as calibrated in early reports [**?**, **?**, **?**, **?**]. The polarization of the ^{3}He in the spin filter is along the y-axis, as shown in Fig. 1 [Figure 1: see original paper], which is connected to the guide field in the sample region. Through the implicit adiabatic fast-passage AFP-NMR function, the in-situ ^{3}He spin filter selects the neutron spin state after the sample, thus completing the neutron polarization measurement and analysis process. To support PNI experiments, the in-situ ^{3}He spin filter has a compact mobile design to reduce the entire length along the neutron flight direction due to the large distance between the sample and scintillator screen of the detector, which can negatively affect the final spatial resolution. The NSF is composed of a ^{3}He gas-boron-free glass cell with a diameter of 80 mm, covering a 50 mm × 50 mm effective sample area. Consequently, the measured intensity after the NSF contains the superposition of conventional attenuation of neutron imaging and precession angles of the polarization vector. The polarization change and resulting magnetic field information can be obtained through normalization processing and contrast deduction using conventional neutron imaging.

Detector System

A scintillator screen with a thickness of 100 μm and composed of ^{6}LiF/ZnS (Ag) powder was used for neutron detection; it produced a peak emission wavelength of 450 nm. The experimental images were recorded using a water-cooled Andor charge-coupled camera (DW936 IkonL) system with 2048 × 2048 pixels operating at −60 °C to reduce possible electronic noise. Figure 1(b) shows a practical physical picture of the PNI setup at CARR, designed according to the abovementioned series of optical devices.

Measurements of Key Parameters

To evaluate the designed PNI setup, measurements and experiments were conducted. Polarized-neutron experiments use neutrons with longer wavelength, as cold neutrons are suitable. However, the cold source at CARR was not operational during this experiment, resulting in insufficient cold neutrons at the CNGC beamline. Neutrons with wavelength of 2.7 Å were used for polarization tests, balancing polarizer performance and secondary-wavelength neutron contamination, due to minimal contamination from higher-order reflections of the double-crystal monochromator. This leads to lower total polarization due to limitations of the designed supermirror polarizer.

The neutron flux before the aperture system is 4×10^7 n cm^{-2} s^{-1} (thermal neutron spectrum) at 30 MW. A pinhole with diameter $D = 3$ mm after the polarizer provides L/D of 2100 ($L = 6300$ mm, distance between pinhole and sample for PNI setup), improving spatial resolution and reducing beam divergence. Data acquisition takes 15 minutes per polarization test, including high-flux spin state, low-flux spin state, and polarization state flip time. Both the RF-flipper after the polarizing supermirror and the ^{3}He NSF can adiabatically flip polarization state according to Eq. (3). The ^{3}He NSF is used to flip polarization state during experiments, recording images with spin-up and spin-down states. Figure 5 [Figure 5: see original paper] shows initial experiments evaluating the PNI setup.

A Siemens star test shows spatial resolution better than 400 μm [A7], as in Fig. 5(a-b) [Figure 5: see original paper]. The effective FOV exceeds 50 mm × 50 mm, marked by a square frame in Fig. 5(a) [Figure 5: see original paper].

Figure 5(c-d) [Figure 5: see original paper] demonstrates 60% uniform neutron polarization across the 80 mm ^{3}He cell region at 2.7 Å, covering the FOV. This polarization results from the supermirror polarizer, guide field, and ^{3}He analyzer. Polarization could improve using a cold source to shift toward cold neutrons, enhancing polarizing supermirror efficiency. Though polarization is moderate due to 2.7 Å neutrons, the PNI setup parameters suffice for extracting magnetic information, albeit requiring longer experimental time.

The magnetic field distribution of a solenoid has been well studied and can examine the practicability of the PNI setup [**?**]. A solenoid generates a controlled magnetic field for PNI measurement, along with motors and superconductors. The solenoid is placed perpendicular to beam direction between the last guide field and in-situ ^{3}He polarization analyzer, as shown in Fig. 6 [Figure 6: see original paper]. The cylindrical solenoid (30 mm in diameter, 80 mm in height) is powered by a DC supply with 50 ppm/°C stability, generating a horizontal magnetic field orthogonal to the guide field. Two electric currents of 1 A and 2 A were applied to the solenoid, corresponding to magnetic fields of 17 G and 34 G at the solenoid center. Though the systematic polarization is not very high compared to other neutron sources, the magnetic field can be detected through contrast across the solenoid body in Fig. 7 Figure 7: see original paper. With increasing current, additional precession is detected at the solenoid center due to longer neutron flight path. For understanding these phenomena, theoretical simulation has been performed. The Larmor precession caused by the solenoid magnetic field is calculated through Eq. (1) and Eq. (2) as:

$$P(\lambda) = \cos\left(\frac{\gamma m \cdot B \cdot \lambda \cdot l}{h}\right)$$

where l denotes the neutron path length within the solenoid. Neutron polarization is related to spin precession inside the solenoid, as defined by Eq. (9), and was calculated and plotted across the centerline of the solenoid in Fig. 7(c-d) [Figure 7: see original paper]. The theoretical results are consistent with the experimentally acquired data, indicating the practicability of the designed PNI setup for CARR.

Discussion and Summary

For several applications in typical macroscopic magnetic samples, such as electrical motors, transformers, superconductor wires, and magnetic materials, the established PNI setup with resolution better than 400 μm and an FOV greater than 50 mm × 50 mm is sufficient to characterize the most significant magnetic behavior. Therefore, the developed PNI setup at CARR can be applied to study magnetic transitions and detect magnetic leakage in motor rotors or transformer cores. It can also be used to observe the Meissner effect in superconductors or quenching in sample environments.

In summary, a PNI facility was successfully designed and constructed for the first time, based on an established cold neutron-imaging instrument in the guide hall at CARR. It is equipped with a double-crystal graphite monochromator, a supermirror polarizer featuring three V-shaped cavities, and an in-situ polarized ^{3}He NSF. The experimental results demonstrate that the designed PNI setup can provide relatively high polarization with 2.7 Å neutrons and good spatial resolution with a large FOV, significantly improving the neutron-imaging capability at CARR. Finally, a clear magnetic field distribution inside the solenoid was easily observed using the designed PNI setup, although the cold source was not operated during the experiments. In addition to the solenoid samples used in this study, a series of other scientific experiments, such as superconductors and motors, were also carried out simultaneously. Detailed results combined with the finite element method are currently being analyzed and will be published elsewhere. In addition, the capability of the designed PNI setup at CARR can be further enhanced in the future through optimization of the gas pressure and length of the ^{3}He cell inside the in-situ ^{3}He NSF, operation of a cold source at CARR, and introduction of different sample environment devices involving temperature, pressure, and/or field conditions.

Declaration of Competing Interest

The authors declare no competing financial interests.

Acknowledgments

The setup of the sample environment was supported by research conducted at the Guangdong Provincial Key Laboratory of Extreme Conditions. The authors would like to thank Andreas Ostermann and Felix Rucker for providing the McStas code for the supermirror polarizer. The authors also appreciate discussions with Peter Boni and Michael Schneider at SwissNeutronics and Prof. Peng Cheng at Renmin University of China.

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