

Polarization-analyzed small-angle neutron scattering with an in-situ ^3He neutron spin filter at the China Spallation Neutron Source

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Abstract

Polarization-analyzed small-angle neutron scattering (PASANS) is an advanced technique that enables the selective investigation of magnetic scattering phenomena in magnetic materials and distinguishing coherent scattering obscured by an incoherent background, making it particularly valuable for cutting-edge research. The successful implementation of PASANS in China was achieved for the first time at the newly commissioned Very Small Angle Neutron Scattering (VSANS) instrument at the China Spallation Neutron Source (CSNS). This technique employs a combination of a double-V cavity supermirror polarizer and a radio frequency (RF) neutron spin flipper to manipulate the polarization of the incident neutrons. The scattered neutron polarization is stably analyzed by a specially designed in-situ optical pumping ^3He neutron spin filter, which covers a spatially symmetric scattering angle coverage of about 4.8° . A comprehensive PASANS data reduction method, aimed at pulsed neutron beams, has been established and validated with a silver behenate powder sample, achieving a maximum momentum transfer coverage of approximately $0.25 \text{ \AA}^{-1}$.

Full Text

Preamble

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Polarization-analyzed small-angle neutron scattering (PASANS) is an advanced technique that enables the selective investigation of magnetic scattering phenomena in magnetic materials and the distinguishing of coherent scattering obscured by incoherent background, making it particularly valuable for cutting-edge research. The successful implementation of PASANS in China was achieved for the first time at the newly commissioned Very Small Angle Neutron Scattering (VSANS) instrument at the China Spallation Neutron Source (CSNS).

This technique employs a combination of a double-V cavity supermirror polarizer and a radio frequency (RF) neutron spin flipper to manipulate the polarization of the incident neutrons. The scattered neutron polarization is stably analyzed by a specially designed in-situ optical pumping ³He neutron spin filter, which provides spatially symmetric scattering angle coverage of about 4.8°. A comprehensive PASANS data reduction method, tailored for pulsed neutron beams, has been established and validated with a silver behenate powder sample, achieving a maximum momentum transfer coverage of approximately 0.25 Å⁻¹.

Keywords: neutron polarization analysis, small angle neutron scattering, ³He neutron spin filter

INTRODUCTION

As a method for studying material structure on nano- to micro-scales, small-angle neutron scattering (SANS) complements X-ray and light scattering techniques, as neutrons exhibit high transmittance, sensitivity to magnetism and nuclei, and are commonly used in materials research such as proteins, polymers, and magnetic nanoparticles [?]. When neutron spins are polarized, SANS can further distinguish the contributions of nuclear coherent scattering, incoherent scattering, and magnetic scattering due to the different interactions between

polarized neutrons and materials [?], which benefits measurements requiring accurate structural parameter extraction or clarification of magnetic domain distributions in materials [?]. This capability is critical for advanced applications such as resolving spin textures in skyrmion materials or quantifying hydrogen/deuterium exchange dynamics in biomolecules. Polarized neutron small-angle scattering instruments are therefore essential facilities at neutron sources worldwide.

With the development of the ^3He neutron spin filter (NSF) [?], the challenge of analyzing the polarization of scattered neutron beams by the polarization-analyzed small-angle neutron scattering (PASANS) method was overcome. Traditional polarization analyzers, such as polarizing supermirrors, suffer from limited angular coverage and require precise angular alignment, whereas ^3He NSF provides a tunable, wide-angle solution adaptable to both reactor and spallation sources. The properties of a ^3He NSF can be customized for a specific neutron wavelength band by optimizing the geometrical parameters and ^3He gas pressure, enabling analysis of neutron polarization after scattering for both pulsed and single-wavelength neutron beams. Furthermore, the ^3He NSF offers better accessibility for scattered neutrons in a SANS instrument compared to polarizing supermirror arrays by increasing the coverage of the analyzing angle. This is a crucial aspect of SANS experiments, as it affects the range of reciprocal space that can be measured and the available sample scale in PASANS experiments.

The ^3He NSF has primarily been used on neutron beamlines in ex-situ mode, such as the Very Small Angle Neutron Scattering (vSANS) diffractometer at the National Institute of Standards and Technology (NIST) Center for Neutron Research [?], the KWS-1 instrument at the Heinz Maier-Leibnitz Zentrum (MLZ) [?], and the D33 instrument at the Institut Laue-Langevin (ILL) [?]. The ex-situ ^3He NSF is shielded from spatial stray magnetic fields by a cylindrical μ -metal casing. Its compact size makes it feasible for deployment in SANS experiments, as it occupies little space between the sample and detector array. However, powerful neutron sources such as reactor sources and longer polarization decay lifetimes of the NSF are required due to the intrinsic decay of the ^3He polarization in ex-situ mode. Additionally, continuous calibration of the ^3He polarization prior to sample measurements, or periodic calibration during ongoing measurements, is necessary to ensure accurate corrections for each dataset when switching to a new NSF, which inevitably increases the complexity of data reduction.

As a complement to ex-situ mode, the in-situ ^3He NSF allows one to maintain constant ^3He polarization through in-situ optical pumping, thereby greatly simplifying the measurement procedure and making PASANS available at pulsed neutron sources [?].

At the China Spallation Neutron Source (CSNS), years of dedicated efforts in the self-development of polarized neutron techniques have resulted in capabilities encompassing both instrumentation design and methodology establishment for polarized neutron experiments [?, ?, ?, ?]. Notably, the polarizing ^3He capa-

bility at CSNS has been validated in both ex-situ and in-situ modes, allowing for customized designs tailored to specific neutron instruments [?, ?, ?]. In accordance with the pulsed neutron characteristics of CSNS, a geometry-optimized optical-pumping cell (OPC) can be produced internally to meet various requirements for neutron wavelength ranges and scattering angle coverage [?]. Following extensive technological development and verification tests at CSNS, the polarized neutron technology is now equipped for implementation in neutron instruments with small-angle scattering capabilities.

In this paper, we report the design and first successful application of the PASANS technique in China by utilizing polarized neutron instruments, including an in-house customized in-situ NSF at the Very Small Angle Neutron Scattering (VSANS) instrument at CSNS. Additionally, a comprehensive method was established for correcting polarized neutron data for PASANS measurements with a pulsed neutron beam, which has been validated through measurements using silver behenate powders.

II. EXPERIMENTAL INSTRUMENTS

A. PASANS setup on the VSANS beamline

The VSANS instrument at CSNS was designed in its physical configuration to cover studies of materials requiring polarized neutron scattering techniques. As shown in Fig. 1 [Figure 1: see original paper], a rotational exchange drum is mounted upstream of the VSANS beamline, enabling precise switching among three channels: neutron guide, flight tube, and polarizing supermirror. This mechanized drum system achieves mode switching within several seconds, with precise positional repeatability that allows continuous measurements switching between polarized and unpolarized modes. The polarizing supermirror is specifically designed to polarize cold neutrons in the range of 2.2 Å to 11 Å by employing a double-V cavity composed of $m = 5$ Fe/Si supermirrors, optimized based on Monte Carlo simulation results for polarizing efficiency and transmission ratio [?]. The vertical neutron polarization guide field, which maintains neutron polarization after the supermirror, is generated by a combination of permanent magnet bars and iron plate yokes mounted on downstream flight tubes. The magnet assembly is optimized to generate a field strength of 40-70 G and exhibits field direction uniformity better than 1° within the $4\text{ cm} \times 4\text{ cm}$ central area, making it suitable for experiments requiring larger beam sizes or scattered beam angle coverage.

Furthermore, a radio frequency (RF) neutron spin flipper manufactured by SwissNeutronics Inc. is utilized to flip the polarization of incident neutrons by a π angle. The static magnetic field environment adjacent to the flipper (Fig. 1) was optimized using finite element simulations in COMSOL Multiphysics software [?] to achieve a compatible gradient field distribution satisfying the magnetic resonance condition. This optimized field configuration enables the RF spin flipper to attain 98% flipping efficiency at 2.2 Å, significantly simplify-

ing subsequent polarized neutron data reduction procedures.

An in-situ ^3He NSF system is specially designed for VSANS as the analyzer, which is essential for PASANS since the neutron absorption cross-section of ^3He is spin-dependent and the ^3He NSF can be tailored to provide larger neutron scattering angle coverage for the scattered beam. Additionally, neutron polarization must be manipulated adiabatically by customized guide fields along the beam path [?, ?], indicated by colored arrows in Fig. 1, rotated by 90° before the analyzer to be parallel or antiparallel to the polarized ^3He neutron polarization analyzing direction. The in-situ pumping method for maintaining the ^3He NSF on the beamline ensures stable and continuous analyzing capability throughout measurements. As shown in Fig. 2(a) [Figure 2: see original paper], the PASANS experimental setup at VSANS was developed based on the design described above.

B. In-situ ^3He neutron spin filter

The in-situ ^3He NSF at CSNS was first developed and delivered to neutron beamlines in 2021 [?] and has been successfully utilized as a neutron spin polarizer and analyzer for neutron imaging and reflectometry measurements at CSNS [?]. To accommodate the geometry of the conically scattered neutron beam for the SANS instrument, a new generation of in-situ ^3He NSF, termed in-situ-SANS, was developed based on our innovative prototype designs. This specialized analyzer system was engineered to maintain the high polarization performance of standard in-situ filters while overcoming the geometric constraints imposed by small-angle scattering measurements.

The OPC features an inner diameter of 72 mm and a length of 80 mm, as shown in Fig. 2(b), facilitating a scattering angle of approximately 4.8° (corresponds to θ in the yellow cone) and a maximum q value of about $0.24 \text{ \AA}^{-1}$ when the cell is positioned 37 cm from the sample. Notably, the dimensions of the optics, oven windows, magnetic shielding cavity, and box on their exit sides have been enlarged to allow the analyzed scattered neutron beam to pass through the NSF setup unimpeded. The significant changes, especially the asymmetric magnetic shielding configurations and higher heat dissipation from the sapphire window, pose challenges in improving and maintaining the ^3He polarization. To address these challenges, the system incorporates modifications to improve field and temperature spatial uniformity at the OPC position. This includes a revamped magnetic field sub-system featuring four distinct gradient compensation coils with optimized input currents, improving field homogeneity to the level of $10^{-4}/\text{cm}$ at the OPC position. Furthermore, a proactive air cooling mechanism has been installed at the top of the box to mitigate thermal effects resulting from heat dissipation from the large window on the magnetic shielding materials.

Additionally, neutron-absorbing materials were attached to the exit side of the NSF box to minimize scattering interference beyond the cell coverage area. The

figure of merit (FOM) of the OPC produced for PASANS measurements is optimized to be $11.01 \text{ bar} \cdot \text{cm}$, which involves balancing ^3He neutron polarization and transmission ratio to maximize neutron polarization analysis capability across the instrument's wavelength range of $2.2 \text{ \AA}$ to $6.7 \text{ \AA}$. The Free Induction Decay (FID) method is employed to track the evolution of ^3He polarization, validating a saturated polarization level of 62.3% with the Electron Paramagnetic Resonance (EPR) method, corresponding to a ^3He polarization of 61.1% calibrated through neutron transmission measurements (see Fig. 3 Figure 3: see original paper and (b)). As shown in Fig. 2(a), the new in-situ-SANS also allows for flexible experimental configurations. The main ^3He NSF box can be moved in or out of the beam path by operating the support cart's motor [?]. In combination with the switchable polarizing supermirror at the rotational exchange drum, the whole polarized neutron setup at VSANS enables quick switching between half-polarized SANS, PASANS, and unpolarized SANS. These features underscore the exceptional suitability of in-situ-SANS for PASANS applications, as well as the convenience for users in controlling measurement modes.

III. POLARIZED DATA REDUCTION

In neutron scattering theory, the total scattering amplitude comprises distinct contributions [?, ?]: (1) the nuclear coherent and isotope incoherent scattering, represented by the term N , which are independent of neutron polarization; (2) the nuclear spin-incoherent scattering I , which is dependent on neutron polarization and has an approximate probability of 2:1 for flipping or not flipping the neutron spins; and (3) the magnetic scattering term M , which depends on both neutron spin and the scattering vector, and can be further separated into $M_{\perp}$ and $M_{\parallel}$, where the subscripts indicate that the sample magnetization component is perpendicular to the scattering vector (q) and can be either parallel or perpendicular to the neutron polarization, depending on whether the neutron spin flips. To summarize, concerning neutron spin dependence, the total scattering can be divided into non-spin-flip (NonSF) and spin-flip (SF) scattering components, represented by the red and blue arrows in Fig. 1, respectively. The NonSF scattering comprises the terms N , $1/3 \cdot I$, and $M_{\perp}$, while the SF scattering consists of $2/3 \cdot I$ and $M_{\parallel}$.

In a typical polarized neutron scattering process, information about the NonSF and SF scattering in a sample is collected by manipulating the polarization of the incident and scattered neutrons. Additionally, the polarized neutron data must be corrected for unintended scattering leakage from incorrect spin states in the raw data due to inefficiencies of polarized neutron instruments. To extract the absolute sample scattering amplitude, a derivation based on the efficiencies of polarized neutron instruments is required [?]. For SANS measurements conducted at a pulsed neutron source, the scattering intensity $S(x, y, \lambda)$ is a function of the two-dimensional position within the scattering plane (x, y) and the neutron wavelength λ , which will be simplified as S hereafter. NonSF scattering S_{++} , S_{--} , and SF scattering S_{+-} , S_{-+} , where the subscript in-

icates whether the spin of the incident or scattered neutron is parallel (+) or antiparallel (−) to the guide field direction, in PASANS are typically given as follows:

$$\begin{aligned} S++ = ++ - S-- = ++ - sm+ + sm+ - smf- + smf- - 3He+\sigma++ + \\ - 3He+\sigma-- + + 3He-\sigma++ + - 3He-\sigma-- + + sm+ + sm+ - smf- + \\ smf- - 3He+\sigma-+ 3He+\sigma+- 3He-\sigma-+ 3He-\sigma+- \end{aligned}$$

$$\begin{aligned} S+- = ++ - S-+ = ++ - sm+ + sm+ - smf- + smf- - 3He-\sigma++ + \\ - 3He-\sigma-- + + 3He+\sigma++ + - 3He+\sigma-- + + sm+ + sm+ - smf- + \\ smf- - 3He-\sigma-+ 3He-\sigma+- 3He+\sigma-+ 3He+\sigma+- \end{aligned}$$

where $\sigma_{\pm\pm}$ refers to the simplified description of sample scattering cross sections $\sigma_{\pm\pm}(x, y, \lambda)$ with different neutron spin states, and *** represents the probability that a spin-up (+) or spin-down (−) neutron can pass through a polarized neutron instrument. *** can also be expressed in terms of the combination of wavelength-dependent instrument polarization parameters $P^*(\lambda)$ and transmission ratio $T^*(\lambda)$, simplified as:

$$\begin{aligned} sm/3He+ &= (1 + Psm/cell)Tsm/3HePol \\ sm/3He- &= (1 - Psm/cell)Tsm/3HePol \\ smf/3He- &= (1 - Psmf/cell)Tsmf/3HePol \\ smf/3He+ &= (1 + Psmf/cell)Tsmf/3HePol \end{aligned}$$

where $Psmf = PsmPf$, $Tsmf = TsmTf$. $Psm/cell/f$ refers to the polarizing or analyzing efficiency of a supermirror (Psm), 3He spin filter (Pcell), and the flipping efficiency of the neutron spin flipper (Pf). $Tsm/3HePol/f$ refers to the transmission ratio of an unpolarized neutron beam passing through the polarized neutron devices. However, both Tsm and Tf are reduced in our case since the experimental data (S**) are normalized by the primary beam measured with the supermirror in place. In addition, $Tf = 1$ as an RF flipper is utilized.

According to the above equations, to extract the scattering cross section of samples, the instrument parameters P^* and T^* need to be calibrated in advance by conducting direct transmission measurements with an unpolarized neutron beam. Benefiting from the time-independent 3He polarization of an in-situ 3He NSF, the polarizing efficiencies of the instruments can be denoted as:

$$\begin{aligned} Pcell &= 1 - (T3HeDepol/T3HePol) \\ Psm &= (I++ - I+-)/(I-- - I-+) \end{aligned}$$

where T3HePol and T3HeDepol represent the transmissions of an unpolarized neutron beam passing through a polarized or depolarized 3He cell, and I^{**} refers to the neutron transmission ratio for different neutron spin states. All P^* and T^* parameters will be calibrated before each experimental cycle on the beamline.

Furthermore, measurements of blocked-beam (Sbk, spin-independent), the transmission ratio of the sample (Ts), and scattering from the sample holder (Sh**) are also necessary to determine the absolute scattering intensity of

the sample. Since a typical sample holder is always non-magnetic, its spin-independent scattering measurements could be reduced when Pf is assumed as 1. Both Sh** and Ss** need to be normalized to remove the effects of incident neutron flux and Tsm before polarization correction. The absolute scattering intensity of the sample in reciprocal space can then be expressed as:

$$\begin{aligned}\sigma_{s++}(q) &= (1/C) [B1Scor++ + B4Scor+- + A3Scor-+ + A2Scor] \\ \sigma_{s--}(q) &= (1/C) [B3Scor++ + B2Scor+- + A1Scor-+ + A4Scor] \\ \sigma_{s-+}(q) &= (1/C) [B2Scor++ + B3Scor+- + A4Scor-+ + A1Scor] \\ \sigma_{s+-}(q) &= (1/C) [B4Scor++ + B1Scor+- + A2Scor-+ + A3Scor]\end{aligned}$$

where

$$\begin{aligned}A1 &= (P_{cell} + 1)(P_{sm} + 1) \\ A2 &= (P_{cell} - 1)(P_{sm} - 1) \\ A3 &= (P_{cell} + 1)(P_{sm} - 1) \\ A4 &= (P_{cell} - 1)(P_{sm} + 1) \\ C &= 2P_{cell}P_{sm}(P_f + 1)T3HePol\end{aligned}$$

Tsh and Th refer to the transmission ratios of the sample with holder and an empty holder, respectively. B1 to B4 are presented by replacing Psm with Psmf in A1 to A4 in equation (13). For non-magnetic materials such as polymers and proteins, we have $M_{-} = M_{+} = 0$, which further simplifies equation (12) to:

$$\begin{aligned}\sigma_{s+-} &= \sigma_{s-+} = mI \\ \sigma_{s++} &= \sigma_{s--} = N + (1 - m)I\end{aligned}$$

IV. RESULTS AND DISCUSSION

A. Performance of the PASANS setup

The polarized neutron efficiencies of the instruments were calibrated through neutron transmission measurements without samples on VSANS at CSNS. The procedure involved systematic measurements of transmission ratios for both spin states under various instrument configurations, ensuring comprehensive characterization of the polarization system. Neutron data from PASANS measurements were collected with a wavelength range from 2.2 Å to 6.7 Å, employing a collimation length of 8.31 m. The #3 detector array was positioned 12.2 m downstream from the sample to collect transmission data, while a 2 mm pinhole B₄C slit was mounted before the sample position to define the beam size.

Figure 3(a) shows the wavelength dependence of T3HePol and Pcell, where the latter is derived from equation (9). To verify the stabilization of the polarization analyzing capability of the in-situ-SANS, we measured T3HePol approximately every 30 hours. A difference of less than 0.4% in T3HePol was observed, which corresponds to a fluctuation of P3He of less than 1.2%, and the weighted average difference in Pcell was approximately 0.5% based on the primary beam flux distribution. These results demonstrate the exceptional stability of the in-situ optical pumping system, a crucial advantage over conventional ex-situ ³He analyzers that typically require frequent recalibration. It also indicates that

the in-situ-SANS can be used as a stable analyzer at the beamline, allowing Pcell and T3HePol to be treated as constants during the polarization correction process. The corresponding saturated ^3He polarization P3He was also fitted to $61.1\% \pm 0.1\%$ during the experiment [?, ?] (Fig. 3(b)). This high polarization level, maintained consistently throughout the measurements, validates the effectiveness of the modifications to the ^3He NSF sub-systems.

The polarizing efficiency (Psm) of the supermirror was calibrated according to equation (10) by flipping the ^3He polarization while keeping the flipper off. As shown in Fig. 3(c), Psm exceeds 95% at 2.6 Å and reaches about 97.5% at longer wavelengths, which is similar to our simulation result of $\text{Psm} > 95\%$ at 2.4 Å; the difference may arise from the collimation accuracy of the installation. The spin-dependent transmission ratio (Tsm) of the supermirror also exceeds 32% across the experimental wavelength range. Moreover, the flipping efficiency (Pf) of the RF flipper mounted at the VSANS beamline was optimized to be over 98% for neutron wavelengths above 2.2 Å, with optimization involving careful balancing of RF frequency, power, and static magnetic field gradient to achieve maximum flipping efficiency across the entire wavelength band. The excellent performance of the flipper allows us to simplify the polarized neutron data reduction process during the experiment.

B. Sample measurement

Silver behenate (AgBE) has been well established as a standard sample for wavelength calibration in SANS instruments [?], as its first three Bragg reflection peaks are accessible within the SANS scattering angle range. Since it is non-magnetic and hydrogen-rich, its nuclear scattering components N and I can be effectively distinguished through NonSF and SF measurements. The PASANS experiment at VSANS was performed with a silver behenate powder sample encased in a quartz cell with an optical path length of 2 mm, placed 4.5 m and 12 m away from the middle-angle (#2) and small-angle (#3) detectors, respectively. Considering the compact design of the ^3He NSF and the increased cross-section of the in-house fabricated ^3He OPC, the polarization-analyzed scattered neutrons are detected by the entire #3 detector and part of the #2 detector (Fig. 1).

Fig. 4 [Figure 4: see original paper] shows the comparison between the NonSF and SF results measured over a neutron wavelength range of 2.2 Å to 6.7 Å. A distinct symmetrical ring at $q = 0.11 \text{ Å}^{-1}$ was observed in both two-dimensional patterns in the reciprocal space of the #3 and #2 detectors, corresponding to nuclear coherent scattering at small q . Additionally, the second Bragg peak at $q = 0.22 \text{ Å}^{-1}$ was captured by the inner part of the middle-angle detector. The coverage of the q range discussed here is influenced by both the distance separating the detector and OPC cell, as well as the cross-sectional area of the cell. SANS instruments at other neutron sources choose the compact ex-situ ^3He NSF to minimize this distance, such as vSANS at NIST [?, ?] and D33 at ILL [?], allowing them to access a maximum q value of 0.1 Å^{-1} to 0.28 Å^{-1} , but

at the expense of time independence of the analyzing capability. TAIKAN at J-PARC [?], on the other hand, employs the in-situ ^3He NSF as the analyzer, effectively observing the second Bragg peak of AgBE with a maximum q value of around $0.25 \text{ \AA}^{-1}$ by off-setting the OPC cell. Fig. 3(b) and 4 illustrate the PASANS achieved at CSNS compared to others, showing a balance between competitive, spatially symmetrical q coverage and constant analyzing efficiency.

As shown in Fig. 4(a) and (b), compared to the NonSF, the SF also exhibits weak isotropic scattering at the same q positions. These unexpected scattering signals result from leakage of scattered neutrons with incorrect spin states due to imperfect efficiency of the polarized neutron instruments. By implementing the polarized data correction method introduced above, the scattering intensity corresponding to each spin state is allocated to the correct scattering state. Fig. 4(c) and (d) illustrate the corrected NonSF and SF information in reciprocal space, where the nuclear coherent scattering in the SF has been removed, making the SF scattering information, which is mostly contributed by hydrogen in the AgBE, homogeneous and independent of q . This successful separation validates the effectiveness of the polarization correction algorithm, particularly its handling of instrument efficiency factors and background contributions.

The azimuthally averaged absolute intensity of the corrected NonSF and SF curves is displayed in Fig. 5 Figure 5: see original paper. Two peaks stand out in the NonSF curve, dominated by nuclear spin-coherent scattering, in contrast to the flat SF curve, which is contributed solely by nuclear spin-incoherent scattering. The peak positions at $q = 0.107 \text{ \AA}^{-1}$ and $0.216 \text{ \AA}^{-1}$ match well with the unpolarized neutron scattering results for silver behenate, confirming proper wavelength calibration of this polarized neutron instrument. To estimate the effect of multiple scattering in a hydrogen-rich thick sample, the contribution weight of I in the SF curve is denoted as m , which can be determined by fitting the ratio of σ_{s-+} to σ_{s++} in the low q range, where the N contribution in the NonSF curve could be neglected. Our measurements yield a ratio of $m = 0.569$, consistent with strong multiple scattering occurring in a thicker sample, which has been evidenced by Monte Carlo simulation [?], providing additional validation of the data interpretation. Fig. 5(b) also presents the comparison of calculated N and I based on equations (14-15):

$$\begin{aligned}\sigma_{s++}(q) &= \sigma_{s--}(q) = N + (1 - m)I \\ \sigma_{s-+}(q) &= \sigma_{s+-}(q) = mI\end{aligned}$$

where the nuclear spin-coherent and spin-incoherent scattering are well separated in silver behenate below $q = 0.25 \text{ \AA}^{-1}$.

V. CONCLUSION

In this paper, we report the first successful implementation of the PASANS technique at the newly commissioned VSANS instrument at CSNS. The polarized neutron equipment has been deployed along the neutron path to accomplish the full process of neutron spin polarizing, flipping, and analyzing in PASANS.

The integrated system achieves 97.5% polarization efficiency at $\lambda > 2.6 \text{ \AA}$ and maintains 61.1% ^3He polarization stability with $<1.2\%$ fluctuation over 75 hours of operation [?, ?], setting a new benchmark for polarized SANS instruments at pulsed neutron sources. By utilizing the in-situ ^3He NSF as the neutron spin analyzer, a large symmetric scattering cross-section coverage was achieved in both real and reciprocal spaces, with a maximum q value of approximately $0.25 \text{ \AA}^{-1}$ under an incident neutron wavelength range of $2.2 \text{ \AA}$ to $6.7 \text{ \AA}$. This q -range coverage indicates state-of-the-art performance with the time-independent PASANS technique compared with other neutron facilities.

This capability enables studies focusing on characteristic length scales larger than 2.5 nm , making it particularly suitable for investigating magnetic nanostructures in condensed matter systems or obtaining macromolecular information in polymers. The efficiencies of the polarizing supermirror, spin flipper, and in-situ ^3He NSF have been calibrated, demonstrating a highly efficient and stable neutron polarization capability on VSANS. Moreover, a detailed process for polarized neutron data reduction is introduced, considering a pulsed neutron beam as the incident beam. Silver behenate powder served as a standard sample during the PASANS commissioning, highlighting clear differences between its nuclear spin-coherent scattering and spin-incoherent scattering. This distinction allows its smeared-out Bragg peak at larger q to be differentiated from the background.

The PASANS capability at VSANS opens new opportunities for studying complex magnetic orders in quantum materials and magnetic correlations in nanoparticles. Building on the interfaces developed initially for upgrading the in-situ ^3He NSF, future enhancements will focus on integrating the PASANS method with integrated sample environments, including multi-axis magnetic fields with strong field strength. This integration is expected to broaden scientific applications in magnetic materials with complex magnetic orders, such as magnetic skyrmions, by utilizing polarized neutrons on VSANS.

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