Polarized neutron beam at the SANS diffractometer KWS2 of the JCNS

A.Ioffe*, A.Feoktystov, S.Staringer, A.Radulescu, E.Babcock, Z.Salhi

Abstract

This article describes a high-efficiency transmission polarizer that has been installed at the high-intensity SANS diffractometer KWS2 of the Jülich Centre for Neutron Science. The polarizer is primarily designed to be used in the low resolution/high Q-range mode of this diffractometer for the purpose of the separation of coherent scattering on biological objects from an intrinsic background caused by incoherent scattering on their hydrogen atoms.

The polarizer operates with a rather divergent incident beam and is placed at about 2m from the sample (upstream in the beam). The diffuse spin-flip scattering that would become critical for such geometry is suppressed due to the use of a strong, about 0.14T, magnetic field. The polarizer has been characterized by a $^3$He neutron spin filter and provides very high polarization - 93% at 4.5Å and 99.7% for neutrons with wavelength above 6Å – for the SANS collimation 4m. The polarizer transmission at 4.5Å amounts to 94% of the desired spin component.

The polarizer is placed in the collimation base of the instrument and can be easily put in and out of the beam thus allowing for "an instant" switch between polarized and non-polarized neutron beams.

* Corresponding author. E-mail address: a.ioffe@fz-juelich.de.
1. Introduction.

Polarized neutron small-angle scattering (SANS) with the polarization analysis of the scattered beam becomes an important and requested tool for studies of (self-organized) magnetic nanostructures, as it allows for the separation of magnetic and nuclear contributions, and for the retrieving of complicate magnetic structures [1, 2]. From other hand, neutron polarization analysis is also very valuable for studies of soft matter or biological nanoobjects where it can be used for the separation of coherent and incoherent scattering [3], effectively suppressing the background mainly created by incoherent scattering of neutrons on hydrogen atoms (the incoherent cross section of 80 barn per atom), which always constitute a significant part of atoms in any polymer or biological molecule.

Thus, incoherent neutron scattering is a source of a strong intrinsic (and unavoidable) background accompanying the coherent scattering from non-deuterated biological objects. This fact makes polarization analysis of the scattered neutron beam useful for studies of such objects at high values of momentum transfer, Q. Practically, for Q>0.3Å⁻¹ the coherent signal is usually deep below in the incoherent noise, so that the useful structural information in the SANS spectra is masked by an overwhelming background and the resulting signal-to-noise ratio is very low. Moreover, because the incoherent background is created by the sample itself, the conventional approach - to subtract the results of measurements with the sample and without and to consider their difference as the scattering from the sample – does not help in this Q-range. It was shown in experiments on SANS from biological objects (e.g. proteins lactoferrin and alpha-lactalbumin) that the separation of incoherent background by its precise determination using the polarization analysis allows to effectively increase the signal to noise ratio by factor of about 100 [4-6] thus opening new and exiting possibilities for the structural studies of biological objects by providing the structural information in a wide length range in a single experiment.

Aiming to provide such experimental possibilities we are currently equipping the high-intensity SANS diffractometer KWS2 [7] of the Jülich Centre for Neutron Science in Garching (Germany) with a polarized neutron option. In this article we will describe a high efficiency neutron polarizer built into the collimation base of the instrument rather close to the sample position and demonstrate results of its experimental tests.

2. Description of the polarizer

To carry out the structural studies of biological objects in a wide length range, the SANS spectra should be taken in a wide Q-range, up to 1Å⁻¹. Considering a quick drop of the intensity of the scattered signal with the increase of Q, the transmission of the polarizer should be maximized to keep the intensity of the incident beam as high as possible and, subsequently, the time of a polarized SANS experiment at an acceptable level. Moreover, because the measurement at high Q-values will be carried out with a low Q-resolution, i.e. with a relatively divergent incident neutron beam, the angular acceptance of a polarizer should match a large incident beam divergence.

We have used a transmission polarizer [8, 9] where the spin-up component of the incident neutron beam is deflected by a reflecting surface, while the spin-down component propagates forward without any distortions (Fig. 1). Thus, the spin components are spatially separated and if the deflected reflected beam is stopped by a neutron absorber, then such device will work as a neutron spin filter allowing for the transmission of the spin-up component in a single experiment.

Aiming to provide such experimental possibilities we are currently equipping the high-intensity SANS diffractometer KWS2 [7] of the Jülich Centre for Neutron Science in Garching (Germany) with a polarized neutron option. In this article we will describe a high efficiency neutron polarizer built into the collimation base of the instrument rather close to the sample position and demonstrate results of its experimental tests.
Such a polarizer has already been used for a double-crystal SANS diffractometer which has demonstrated a remarkable performance [10], being also simple in the construction and allowing for the fast (practically “instant”) switch between non-polarized and polarized operation modes just by moving it in or out of the neutron beam.

3. Design of polarizer

The polarizer is installed at a distance of 2m from the sample (Fig.2) and the maximum acceptable incident beam divergence $\beta_{\text{max}} = \pm 0.21^\circ$ is determined by the collimation geometry: the aperture of (20x20)mm² at the end of the neutron guide is separated by 4m from the sample aperture of (10x10)mm². $\beta_{\text{max}}$ determines the geometrical parameters of the polarizer: the supermirror should be tilted at the angle $\alpha$ satisfying the condition $(\alpha+\beta_{\text{max}}) < \theta_c = 0.1^\circ m\lambda$ for the shortest wavelength ($\lambda-\Delta\lambda$) in the neutron beam with the monochromaticity of $\Delta\lambda/\lambda$.

As the polarizing mirror has to overlap a convergent neutron beam with a cross-section is smaller than that of the neutron guide, the required length of the polarizing mirror is not large. Thus, we use the 900mm long $m=3$ supermirror made of nine double-side coated 0.3mm thick Si plates of 100mm length (produced by Neutron Optics Berlin, GmbH). The mirror is tilted by $\alpha=1.11^\circ$ with respect to the neutron beam axis to provide total reflection of the spin-up neutrons of the divergent beam with $\Delta\lambda/\lambda=20\%$ that is later absorbed by
a boron-containing material (Fig. 3). Because of the small wafer thickness, $t=0.3\text{mm}$, a low neutron beam attenuation can be achieved (see Sect. 4.2).

For such calculated settings of the polarizer, the above-mentioned total reflection of the spin-down component should take place for neutrons with $\lambda>11\text{Å}$.

Another effect that has been taken into considerations is the spin-flip diffuse neutron scattering that results from a non-perfect alignment of magnetic domains in ferromagnetic layers of supermirrors [11].

Because the aim of the polarization analysis is to measure the spin-flip cross-section caused by incoherent scattering, the spin-flip diffuse scattering would create an undesirable background on the whole area of the large neutron detector of a SANS machine and may impose limits on the accuracy of the determination of the spin-flip cross-section at high $Q$. Such background can be suppressed either by the placement of the polarizer far away from the detector thus reducing the solid angle subtended by the detector (practically before a long collimation base of a SANS instrument) or by applying a strong magnetic field on the supermirror for a better alignment of magnetic domains. As in the case of our polarizer which
has been installed rather close to the detector, the supermirror is immersed in a strong, 0.14T, magnetic field created by NdFeB permanent magnets. According to [11] such field is sufficient to suppress the diffuse scattering to the negligible for our applications level.

4. Experimental test

4.1 Polarization analysis

The polarizer performance has been characterized by means of a $^3$He neutron spin filter. We have used the in-house made $^3$He cell labeled J8 (Jülich-8) with the length $l=6$ cm and containing $^3$He at a pressure of about $p_{He}=1.9$ bar. This cell is practically opaque for the spin state antiparallel to the direction of the $^3$He polarization in the whole wavelength range used at KWS2, i.e. its polarizing efficiency

$$P_n(\lambda) = \tanh(0.0733 \cdot l \cdot p_{He} \cdot P_{He} \cdot \lambda)$$

(1)

is close to unity for the $^3$He polarization of $P_{He}=65\%$ maintained during the experiment (Fig.5). Indeed, such neutron spin filter is practically an ideal analyzer, so that corrections to be applied for a short wavelength part of the beam are very small and changes in $P_n$ are weak with respect to the absolute value of $P_{He}$ for the $P_{He}$ levels of our measurements.

Fig. 5. Wavelength dependence of the polarizing efficiency of $^3$He neutron spin filter.

4.2 Transmission

The neutron attenuation of the polarizer in our case of low energy neutrons and perfect crystal Si substrates carrying the polarizing supermirrors, is mostly determined by the neutron capture and single-phonon scattering processes in Si. An additional attenuation is caused by the coherent scattering and absorption in Fe and amorphous Si layers of the supermirror coatings.

The total cross-section $\sigma_{tot}$ of these processes varies in the range from 0.4 barn to 1.3 barn for neutrons with $\lambda=(4.5-20)\,\text{Å}$ [12] and is presented in Fig. 6.

Indeed, the total attenuation can be written as
where $t_{sub}=0.3\text{ mm}$ is the thickness of Si substrates, $N$ is the atomic density, $\sigma_a$ and $\sigma_{tot}$ are absorption and total cross-sections (indices are related to Fe and Si). $t_{Fe}=3.6\text{ μm}$ and $t_{Si}=2.4\text{ μm}$ are the total thickness of Fe and Si in the double-side supermirror coating.

The plot of the $\lambda-$dependent transmission for the polarizer in question is also presented in Fig. 6, where one can see that it amounts to 94% at $\lambda=4.55\text{Å}$ and is slightly reduced, to 90%, at $\lambda=20\text{Å}$. The neutron transmission has been checked experimentally at a wavelength of 4.55 Å and has been found to be (94±1)% in an excellent agreement with the above-calculated value.

4.3 Polarization.

The polarization of the neutron beam passing through transmission polarizer measured by a $^3$He neutron spin filter (see Sect. 4.1) is presented in Fig. 7. One can see that the polarizer provides a high neutron beam polarization over the whole wavelength range and all incident beam collimations available at KWS2 (92% at 4.5 Å and above 98% for (6÷20)Å). However, a reduced polarization at $\lambda=4.5\text{Å}$ means that the mirror is not perfectly adjusted in the beam: obviously the incident angle $\alpha$ is slightly exceeding the calculated one (1.11°) for neutrons with the shortest wavelength, $\lambda-\Delta\lambda$, impinging on the mirror at the largest possible angle ($\alpha+\beta_{max}$). Indeed, a slight admixing of the spin-up neutrons to transmitted spin-down neutrons has occurred. This conclusion is confirmed both by a higher than expected polarization observed above $\lambda=11\text{Å}$ (see Sect. 3) as well as by measurements with a longer, 14m, collimation base (Fig. 7). In the latter case $\beta_{max}$ is decreased by the ratio 4m/14m = 0.29 and amounts to ±0.06°. This results in the reduction of the largest angle of incidence on the mirror (see Fig. 3) by 0.15° and improves the polarization by 2%.
Fig. 7. Polarization of the beam transmitted through the polarizer vs. the wavelength measured at the shortest collimation of 4m. The point corresponding to the collimation of 14m is shown at 4.5Å as well.

5. Conclusions.

We have designed a transmission neutron polarizer for the SANS diffractometer KWS-2 of the JCNS at the reactor FRM II in Garching. The polarizer is designed to be used for low Q-resolution measurements and therefore is optimized for the short wavelength range of \( \lambda = (4.5-8)\text{Å} \). It has showed a remarkable performance for the rather divergent neutron beam used in this case – the achieved polarization is very close to 100% for neutrons with wavelength above 6Å; some extra final adjustment work has to be carried out to achieve such high level neutron beam polarization for \( \lambda = 4.5\text{Å} \). The beam characterization has been carried out using the \(^3\text{He} \) neutron spin filter that was practically opaque for the undesired spin component and therefore has functioned as a practically ideal analyzer.

The polarizer also demonstrates a very high transmission for the desired spin component, so that the beam attenuation for the desired spin component is measured to be about 94% at \( \lambda = 4.55\text{Å} \) and will be slightly reduced, to 88% for \( \lambda = 20\text{Å} \). It has a simple construction and allows for the fast (practically “instant”) switch between non-polarized and polarized operation modes just by moving the polarizer in or out of the neutron beam.

References


