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The spin-echo spectrometer at the Spallation Neutron Source (SNS)

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ABSTRACT

A novel neutron spin-echo spectrometer with superconducting main coils enabling enclosure by a double walled μ-metal magnetic shielding chamber has been built and set into operation at the spallation neutron source in Oak Ridge. The layout of the spectrometer is described. Performance with emphasis on the superconducting main solenoids and the time-of-flight operation is described. Data on resolution, stability and first experiments are shown.

1. Introduction

Neutron spin-echo (NSE) spectrometers offer the unique possibility to extend the energy resolution of neutron spectrometers significantly beyond the μeV limit, which is reached by back scattering spectrometers utilizing Bragg reflection by perfect crystals as filters [1–5]. NSE uses a different approach, encoding tiny velocity changes, which the neutrons suffer during the scattering process, into spin precession angles allows the use of a broad velocity distribution in the incoming beam [6,7]. The latter yields a large flux at the sample position. At the pulsed spallation source this property causes a decoupling of the proper spin-echo resolution in terms of Fourier-time from the time-of-flight wavelength resolution that depends on the effective neutron pulse duration. The instruments need an incoming beam of polarized neutrons. In the generic spin-echo spectrometer type the polarization is longitudinal, the spin direction is along the flight path. The spin precession sections that code neutron velocities into precession angles before and after the sample are realized by magnetic solenoids. Start, reversal and end of the spin-precession is effected by flippers before and after the solenoids. The first $\pi/2$-flipper rotates the spin direction perpendicular to the solenoid field such that precession can start. In the vicinity of the sample a π-flipper reverses the precession angle and – if the neutron velocity did not change – in the following symmetric decoding solenoid the reverse precession ends at the same direction, in which the neutron spin started immediately after the first $\pi/2$ flipper. The polarization that was lost due to the accumulation of different precession angles by neutrons with different velocities is restored at the position of the second $\pi/2$-flipper due to the symmetric back-precession after inversion of the accumulated precession angle in the first arm by the π-flipper close to the sample. This restoring effect is independent of the initial neutron velocity, and is the the name giving *spin-echo* effect. The last $\pi/2$-flipper performs a spin-rotation that effectively stops the time-keeping precession. The $\pi/2$-flipper converts the spin projection along a perpendicular axis (e.g. z) in front of the flipper to the spin-projection along the longitudinal beam axis behind the flipper. Further precession due to the longitudinal guide and analyzer field do not affect this projection, which is the parameter that determines the neutron transmission probability through the analyzer.

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As the sample scattering changes the neutron velocity, the symmetry between coding and decoding precession is more or less violated and the echo amplitude is reduced due to the dephasing of different neutrons. The spin echo technique yields an effective energy resolution in the neV regime. However, the results are not obtained as the spectral representation of the scattering function $S(Q,\omega)$ as for backscattering and time-of-flight spectrometers, but rather in terms of the intermediate scattering function $S(Q,t)$, the (cosine)-Fourier transform of $S(Q,\omega)$. The normalized scattering function $S(Q,t)/S(Q)$ pertains to the final polarization $P_{\rm echo}(t)$ of the scattered neutrons at the echo condition

$$P_{\rm echo}(t) = \frac{1}{S(Q)} \mathcal{R} \int \cos\left(\underbrace{J\lambda^3 \frac{\gamma m_n^2}{2\pi h^2}}_{t} \omega \right) S(Q,\omega)\, d\omega \qquad (1)$$

where $0 < \mathcal{R} < 1$ denotes the resolution function, $J = \int |B|\, dl$ the magnetic field integral of a neutron path through the spin precession region, $\gamma = 2\pi \times 2.91306598 \times 10^7\ \mathrm{s}^{-1}/\mathrm{T}$ the Larmor constant of the neutron, m_n the neutron mass, h Planck's constant and t the Fourier time. During an experiment the Fourier time may be scanned by variation of the magnetic field that determines J, $t \simeq 0.18 \times \mathrm{J/Tm} \times (\lambda/\mathrm{Å})^3$. The largest possible Fourier time is a measure of the maximum resolution of the spin echo spectrometer; the current technical limit approaches $t = 10^{-6}$ s, which according to the relation $\Delta\omega t = 1$ corresponds to $\hbar\Delta\omega = 0.7$ neV. Besides by the maximum available field integral $J_{\max}$ the maximum Fourier time is limited by the resolution function $\mathcal{R} = \mathcal{R}(\lambda, t)$. Ideally this factor should be equal to one. Because of differences in the exact values of the field integrals for different neutron paths in the beam the real value is < 1. In Appendix A it is shown that if the distribution functions are approximated by Gaussians an estimate for the resolution may be written as

$$\mathcal{R} \simeq \exp\left[-\left(\frac{\Sigma t}{\lambda^2} \right)^2 \right] \qquad (2)$$

where Σ is a measure for the relative field integral homogeneity. If $t_{\max}$ is limited by the maximum available field integral it scales with λ^3, whereas if the drop of $\mathcal{R}$ below a given limit (e.g. 0.5 or $1/e$) is the limiting factor, $t_{\max}$ scales with λ^2. For high resolution, i.e. large Fourier times, it is necessary to add correction elements to the main precession solenoids in order to reduce their intrinsic field integral inhomogeneity. The other measure to maximize the Fourier time is the use of a long wavelength.

The NSE instrument at the SNS is the first high resolution spin-echo instrument at a pulsed spallation source. Its design aims at the optimum usage of the pulsed neutron beam at the highest possible resolution. The necessity to utilize a sizable wavelength frame even at the repetition rate of 60 Hz calls for a short moderator-to-detector distance forcing the instrument into a relatively narrow sector space close to the target block. Thus the sectors claimed by the other neighboring instruments limit the available space and thereby limit the maximum scattering angle. The design features described in the following are chosen to optimally cope with these boundary conditions and at the same time realize a large (Q,t) range. The need to access also higher momentum transfers is satisfied by a variable moderator detector distance allowing for an extension of the scattering angle range. Furthermore the vicinity of other instruments that will use magnetic fields, the iron target block and the crane and other magnetic sources triggered the decision to install a unique magnetic shield around the instrument space [8].

2. Beam transport

The instrument is located at the SNS in Oak Ridge and occupies the beam line 15, BL15 sector there [9]. Neutrons emerge from a cold coupled H_2 moderator with a pulse frequency, f, of 60 Hz. The fast repetition rate calls for a short detector–moderator distance, L, in order to get the largest possible wavelength bandwidth, $\Delta\lambda = (h/m_n)/(Lf)$, within a frame between two pulses. The smallest possible detector–moderator distance is $L = 18$ m yielding $\Delta\lambda = 3.6$ Å. At that short distance the beam-line sector is too narrow to allow for larger scattering angles than $\Phi = 23^\circ$. In order to also enable larger scattering angles the instrument can be positioned along the beam direction at three other positions with $L = 21$,24, and 27 m (see Fig. 1). The highest achievable scattering angle of $\Phi = 81^\circ$ is available at the 27 m position.

2.1. Neutron guide system

The neutron guide system starts at a distance of 2.5 m from the moderator. The first piece of guide is located inside the main beam shutter (indicated by S in Fig. 2). Dimensions of the guide are width $w = 40$ mm and height $h = 80$ mm, the coating is Ni ($m = 1$). Outside the target shielding block at 5.6 m a first frame overlap chopper is positioned, immediately after this chopper a revolver drum that contains three different solid state benders and a beam shutter block follows. The benders effect a beam direction change of 3.5°. Thus a direct view from the sample position to the moderator is avoided. In addition the benders act as neutron beam polarizers. Neutron guide sections interrupted by three further chopper gaps follow up to the distance of 11 m, where the guide exits the primary shielding and enters the instrument enclosure. Three optional 3 m guide sections follow. These can be removed by lifting them to the enclosure ceiling by motorized winches when not used. The secondary spectrometer is then moved to the end of the last active guide section. The secondary spectrometer carrier contains a last – slightly diverging – guide piece of 0.5 m length, extending the guided section to a position close to the first $\pi/2$-flipper. This diverging guide section delivers a few more longer wavelengths neutrons on the sample with a slightly higher divergence corresponding to the increase in output area (42.5 mm × 80 mm). Between the end of the neutron

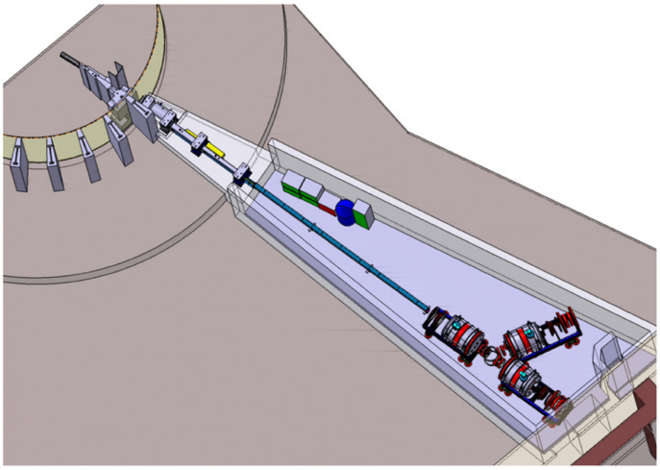

Fig. 1. Layout of the spectrometer showing the full span from moderator (upper left side) to the proper spectrometer. The secondary arm of the spectrometer is shown for two different scattering angles. Besides the shown 27 m position the spectrometer can be positioned also at 24 m, 21 m and 18 m by the removal of one or more 3 m guide segments. The closer positions have a greater effective intensity due to the larger wavelength frame, however, are more restricted with respect to the scattering angle.