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Applications of Neutron Spin Interferometry for New Spectrometers

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Neutron spin interferometry is a developing method based on the principle that a polarized neutron can be transformed to a superposition of field-parallel and -antiparallel spin state. From this point of view, several types of neutron spin echo spectrometer are suggested or realized. In this presentation, applicability of these spectrometers to a pulsed neutron source is discussed. A new type of small angle neutron scattering method applying neutron spin echo method is also discussed.

KEYWORDS: slow neutron, spin interferometry, spin echo, spectrometer

§1. Introduction

Neutron spin interferometry, in which neutron is divided and superposed in spin states, is a developing method.[1)] Since it requires less beam collimation and less monochromatization comparing neutron interferometry with single crystals, it is more effectively applicable to some experiments using longer wavelength neutron and higher intensity.

As shown in Fig. 1 in neutron spin interferometry, polarized neutron (P:polarizer) is converted to superposition of parallel and antiparallel spin states ($\pi/2$:$\pi/2$ rotated in historical description), with the definite phase between the two states (Pr1). Next the spin states are reversed (π flipper) and some interaction is received (I). Then the two states are superposed each other by the second $\pi/2$ flipper and spin-up component of the superposed state is measured with the spin analyser (A) and the detector (D). The effect of the interaction appears in the shift and the change of contrast of the interference pattern at the detector.

The advantages of the neutron spin interferometry are the followings:

1. it requires less position precision comparing to the Si single crystal interferometer,
2. it is applicable to wider range of neutron wavelength,
3. since neutrons with longer wavelength are available, the phase shift can be deteremined more precisely,
4. more intense neutron beam is available.

There are three methods to introduce the phase difference between the two states: 1. kinetic energy difference between spin-up and spin-down states due to the static magnetic field; 2. kinetic energy difference between the two states due to the rf-spin flipper; 3. reflection by the multilayer spin splitter (MSS), which consists of a magnetic mirror, a gap layer and a non-magnetic mirror. For each method, one or two types of Neutron Spin Echo (NSE) spectrometer and small angle neutron scattering (SANS) instruments are designed.[2–4)]

In the followings, applicability of some of these new types of spectrometers to pulsed neutron sources is discussed. And the new types of SANS instruments including advantages and disadvantages are also discussed.

§2. Applicability of New Types of NSE Spectrometers to Pulsed Sources

In the present stage, three types of new NSE spectrometers are constructed or suggested. In the followings, τ_{NSE} is the Fourier time for each spectrometer.

1. Neutron resonance spin echo (NRSE):[5)] replacing precession magnet by a radio-frequency (rf) spin flipper pair. In NRSE, whole system except in the flippers, is kept in zero magnetic field. Hence, the effects due to the disturbance from outside of the system can be eliminated.
$$\tau_{\mathrm{NSE}} = \frac{\hbar\omega L}{mv^3}, \tag{2.1}$$
ω:the rf frequency for the spin flipper, L: the length between two flippers; m:neutron mass; v:neutron velocity.
2. MIEZE type spin echo:[6)] As in NRSE, magnetic field is zero for whole system. The main feature of this spectrometer is that the sample is placed after the spin analyzer, and hence the spin echo contrast is free from spin-incoherent scattering in the sample.
$$\tau_{\mathrm{NSE}} = \frac{\hbar\Delta\omega L}{mv^3}, \tag{2.2}$$
$\Delta\omega$:frequency difference between two spin flippers, L: the length from the sample to the detector.
3. NSE with multilayer spin splitter:[7)] A set of new device called multilayer spin splitter (MSS) is used instead of precession magnet. Since the 'precession angle' is independent of the flight path length of neutron and the intensity of the magnetic field in this set up, the whole system can be quite small without losing the resolution.
$$\tau_{\mathrm{NSE}} = \frac{4D\sin\theta}{v} \tag{2.3}$$
D:thickness of the gap layer in MSS; θ:neutron incident angle to MSS.

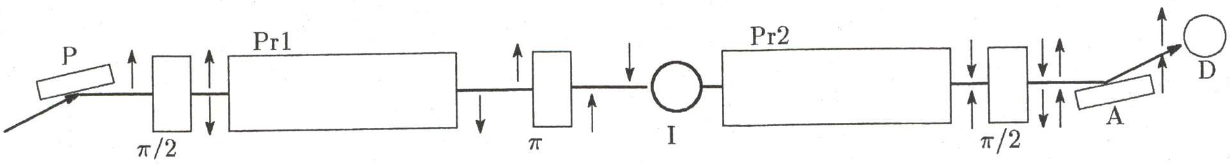

Fig.1. Typical arrangement of neutron spin interferometry.

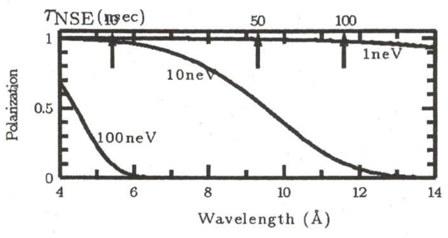

Fig.2. Polarization of NSE signal for NRSE via neutron wavelength.

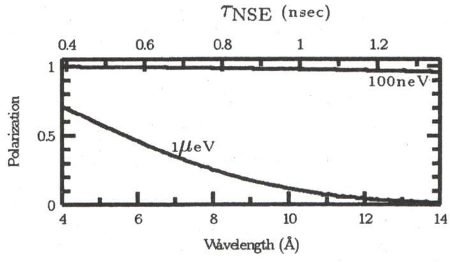

Fig.3. Polarization of NSE signal for MSS-NSE via neutron wavelength.

Since all the above spectrometer require zero or low magnetic field, tight constraint for magnetic field uniformity is relaxed.

The Fourier time τ_{NSE} for the above two spectrometers is proportional to v^{-3}. The relation is equivalent to that in conventional spin echo spectrometer. Indeed, since τ_{NSE} for conventional NSE is given by

$$\tau_{NSE} = \frac{2\mu BL}{mv^3}, \tag{2.4}$$

where μ:neutron magnetic moment, B:magnetic field, L:length of the magnetic field, hence the magnetic field 1T is equivalent to the rf-frequency of 29.2MHz in eq.(2.1).

For these spectrometers, installation to pulsed neutron sources gives advantage that wide τ_{NSE} can be covered in single measurement.

In general, if we assume that the quasi-elastic scattering in the sample obeys Gaussian distribution with standard deviation σ, the polarization P_{NSE} of the spin echo signal is represented with τ_{NSE},

$$P_{NSE} \propto \exp\left[-\frac{\tau_{NSE}^2\sigma}{\hbar^2}\right]. \tag{2.5}$$

Polarization of NSE signal for NRSE via neutron wavelength is shown in Fig. 2. Here rf-frequency and length between flippers are taken as 10MHz and 1m, respectively.

Here three curves are plotted corresponding to the standard deviation of quasi-elastic scattering of 1, 10, 100neV. τ_{NSE} is shown in upper axis of the figure. As can be seen, the range of τ_{NSE} is wide (4.1 to 175nsec).

In contrast, for NSE with MSS, the same plot as Fig. 2 is shown in Fig. 3.

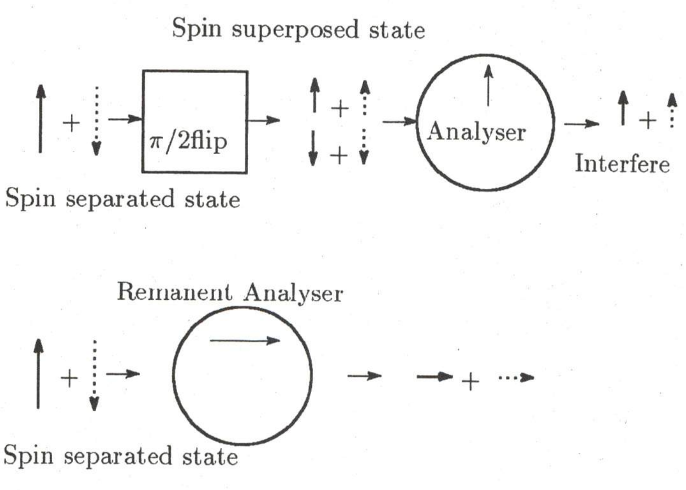

Fig.4. Schematic representation for the way to omit the second $\pi/2$ flipper in NSE spectrometer.

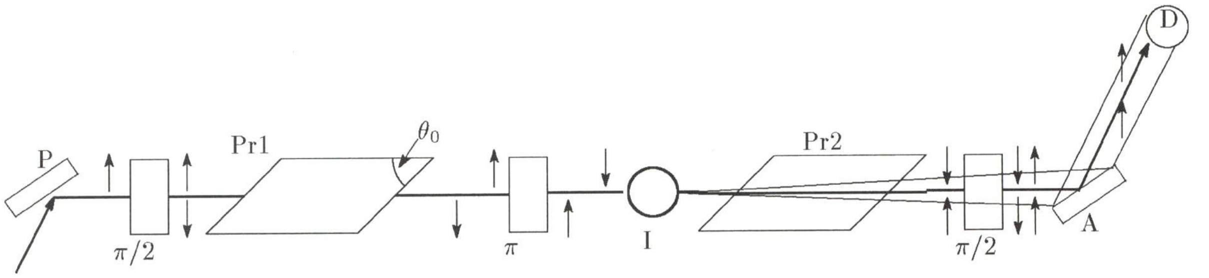

Fig.5. Typical arrangement of neutron spin interferometry.

Comparing to NRSE, the range of τ_{NSE} is much narrower (0.39-1.359nsec), since τ_{NSE} is proportional to λ. For MSS-NSE several sets of MSS with different gaps are required to cover certain range of τ_{NSE}.

From the point of view of the spin interferometry, the second $\pi/2$ spin flipper on conventional NSE and MSS-NSE can be omitted as shown in Fig. 4.

In these spectrometers, the second $\pi/2$ flipper superposes spin-down state to spin-up state, and vice versa (expressed by dotted arrow in Fig. 4). The analyzer selects spin-up state after superposition and the interference can be detected.

Such 'superposition and select' can be realized using vertically magnetized remnant analyzer mirror. When the spin-up state of neutron is incident to the analyzer mirror, since the spin-up state is the superposition of the spin-right and -left state, only a half of these states is reflected. The same applies to the spin-down state. Hence we get the superposition of the former spin-up and -down states.

§3. New Types of SANS Instruments

Application of NSE system to SANS, it is required that small angle change affects the phase difference between the spin-up and -down states of neutron. Such a requirement is realized with the tilted magnetic field (for Mezei NSE), tilted rf-spin flipper (for NRSE) and single reflection from MSS as shown in Fig. 5.

For the NRSE, the phase difference $\delta\phi$ is proportional to the scattered angle and the neutron wavelength,

$$\delta\phi = \frac{2\pi\omega L \tan\theta_0 \delta\theta}{v} = \frac{m\lambda^2\omega L \tan\theta_0}{4\pi\hbar} q, \tag{3.1}$$

where θ_0, ω and L are tilt angle of the flipper, rf-frequency and length between rf-flippers. $q = 4\pi\delta\theta/\lambda$ is the momentum transfer. The above equation indicates that $q \sim (4\pi\hbar)/(m\lambda^2\omega L \tan\theta_0)$ is the measurable range, which corresponds to 10^{-4}Å^{-1} for $\omega = 10$MHz, $L = 1$m, $\lambda = 4$ Å and $\theta_0 = 30$ deg.

The difficulty of this new SANS spectrometer is the separation of scattered component from the incident component. In NSE spectrometer, the polarization at the echo point is inevitably lower than unity due to imperfection of spin flippers, polarizer and analyzer, and imhomogenity of precesson area. Even if the polarization equals 0.9, about 5% of the incident neutrons come into the detector. For most of the samples, such contamination of the incident neutrons is much more intense than the scattered component.

§4. Conclusion

The discussions on the new spin echo spectrometers and the new small angle scattering spectrometer are presented. The NRSE spectrometer shows quite similar property to the conventional NSE spectrometer. It can cover quite wide range of τ_{NSE} if it is installed to a pulsed neutron source, as shown in Fig. 2. The MSS-NSE spectrometer will not cover such wide range of τ_{NSE}. However it has possibility of constructing quite small NSE spectrometer, with the usage of remnant magnetic mirror.

The difficulty of practical application of the NSE small angle scattering spectrometer is also pointed out.

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