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A Modified Spin Echo System of Mieze Type Using RF Flippers for Incoherent Inelastic Scattering

Toru Ebisawa, Seiji Tasaki, Dai Yamazaki[1], Norio Achiwa[2], Gou Shirozu[2], Toshiharu Kanaya[3], Naoya Torikai[4], Masahiro Hino, Takeshi Kawai and Kazuhiko Soyama[5]

Research Reactor Institute Kyoto University, Kumatori, Osaka 509-0494, Japan
[1] *Department of Nuclear Engineering Kyoto University, Japan*
[2] *Department of Physics, Kyushu University, Japan*
[3] *Institute for Chemical Research, Kyoto University, Uji, Kyoto, Japan*
[4] *Neutron Science Laboratory, High Energy Accelerator Research Organization, Japan*
[5] *Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan*

We propose a modified spin echo system of Mieze type using RF flippers for incoherent inelastic scattering. Performances of this system are discussed from a viewpoint of spin interferometry.

KEYWORDS: neutron spin echo, rf flipper, Mieze, time beat, spin echo time, incoherent inelastic

§1. Introduction

The neutron spin echo method (NSE) proposed by Mezei has been considerably improved as a powerful tool for high resolution spectroscopy in quasi elastic neutron scattering phenomena.[1,2] Gähler and Golub *et al.* have developed neutron resonance spin echo methods (NRSE) with wide applicability using radio-frequency flippers coupled zero field, which enable to avoids the very precise homogeneity of the magnetic field in NSE.[3,5]

We have been developing new spin echo systems using multilayer spin splitter and RF flippers[6–8] based on cold neutron spin interferometry.[9] We here discuss a new spin echo system of Mieze type[5,10,11] using RF flippers from a viewpoint of neutron spin interferometry. A neutron is split into the two spin eigenstates and superposed based on the coherent superposition principle of a particle with 1/2 spin.[12] The physical process of the spin interferometry is quite analogous to the conventional silicon interferometer with Mach-Zehnder type. So far spin echo method have been treated by classical Larmor precession of neutron spin. Spin states of neutron, however, is always observed by 1/2 or -1/2. This shows that behavior of neutron spin should be treated not classically but quantum mechanically, as pointed out by Mezei.[13] It should be noted that the classical behavior of neutron spin using Larmor precession is approximately valid in the meaning that it is consistent with the expected value by quantum mechanics. In the case of spin echo methods using multilayer spin splitters or RF flippers which have no classical analogs, the description by the spin interferometry is required for the evaluation of the methods and brings us easy understanding of the methods.

§2. Method

The structure of the principle of the spin echo method are illustrated in (a) and (b) of Fig. 1, respectively. The guide field of a several mT is applied parallel in the direction of neutron traveling. The resonance field of the RF flippers are applied perpendicular in the guide field. These perpendicular fields bring us the zero field effect[3] without magnetic shielding. The polariser and analyser mirrors are operated by the low guide field. The entrance edge of the 1st RF flipper and the exit edge of the third RF flipper are non-adiabatic $\pi/2$ flipper, and function as wave splitter and superposer, respectively.

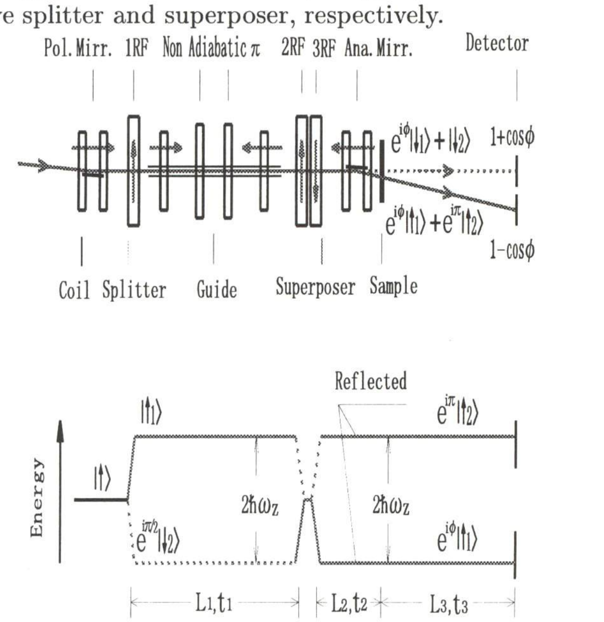

Fig. 1. (a) An arrangement of a Mieze type spin echo method with RF flippers. The guide field is applied in the perpendicular direction to the magnetic field of the RF flippers, as shown by bars with arrow, and non adiabatic spin flipping is used for $\pi/2$ flippers. (b) Illustration of the method by spin interferometry.

A polarized neutron is split into the two spin eigenstates by the sudden change of the magnetic field at the entrance edge of the first RF flipper. These eigenstates are distinguished by "path 1" and "path 2"with $|\uparrow\rangle$ and $|\downarrow\rangle$, respectively. The two spin components with relative phase shift ϕ are superposed in the two pairs of spin states, $\uparrow$, $\uparrow$ and $\downarrow$, $\downarrow$ by the exit edge of the last RF flipper. These pairs are separated as the reflected and transmitted beam by the analyser mirror. The phase shift can be measured by the neutron intensity.

Satisfying the time focusing condition,[4,8,10] a phase shift between the two spin eigenstates, $\Phi_t = 2\omega_z t$, is given bellow,[8]

$$\Phi_t = 2\omega_z t \tag{2.1}$$

where ω_z is the resonance frequency and t the neutron detection time. The above equation shows that a time dependent interference (time beat) is observed by time spectrum measurement.

Expressing the neutron velocity and the velocity change as v and Δv, respectively, the change of the phase shift $\Delta\Phi$ are given bellow,[8]

$$\begin{aligned}\Delta\Phi &= -\omega_z L_3 \frac{\Delta v}{v^2}, \\ &= -\omega\tau_{nse} \end{aligned} \tag{2.2}$$

where ω and τ_{nse} are the energy transfer corresponding to the velocity change and the spin echo time, respectively. They are given by,

$$\omega = \frac{m}{\hbar} v \Delta v \tag{2.3a}$$

$$\tau_{nse} = \frac{\hbar\omega_z L_3}{m v^3} \tag{2.3b}$$

These equations show that this spectroscopy is similar to conventional spin echo method in spite of different spin interferometry. The typical characteristics of this system as a spin echo method can be evaluated from these equations and are shown in Table I. It should be noted that this spin echo method is featured by the sample position after the analyzer mirror as discussed bellow.

TableI. Energy resolution and τ_{nse} *) of a modified spin echo method using RF flippers as a function of neutron wavelength for three frequencies of the time interference, assuming L_3 = 1m. The energy range corresponds to phase shift of 2π.

wavelength(Å)	6	12	24
Frequency : 10KHz			
energy range(μeV)	267	33	4.2
τ_{nse}(nsec)	0.0155	0.124	0.99
Frequency : 100 KHz			
energy range (μeV)	26.7	3.3	0.42
τ_{nse}(nsec)	0.155	1.24	9.93
Frequency : 1 MHz			
energy range(μeV)	2.67	0.33	0.042
τ_{nse}(nsec)	1.55	12.4	99.2

*) In the previous paper[8,11] the values of the energy range and τ_{nse} in this Table were underestimated by factor 8.

§3. Spin Echo with Spin Flipping

When a neutron is scattered by hydrogen or vanadium atoms, two-thirds of the cross section for the incoherent spin scattering is connected with spin flip.[14,15] Neutron transmission through an unmagnetized ferromagnetic material gives rise to the random orientation of the neutron spins. Generally speaking, spin flipping in the spin interferometry process deteriorates the interferometry characteristics as known in the conventional spin echo method. The special arrangement of Mieze spin echo method, however, keeps the interferometry characteristics for spin flip scattering.

We consider spin interferometry depending on spin flipping position (sample position) before and after of the analyser mirror. The situation of the interferometry is illustrated in table II. Table II (a) shows the case without any spin flipping. The two interference patterns reflected and transmitted the analyser mirror are compensated each other as shown in Fig.1.

When neutron spin flips in the interferometry process, we should consider the three cases as follows.

(b) In the case that neutron spin flips before the supersoser (the 2 nd $\pi/2$ flipper), the spin states are superposed in the reversed spin state. The reflected and transmitted components by the analyser mirror are mixed depend on the spin flipping. Consequently, the contrast of the interference pattern is reduced depending on the flipping ratio.

(c) In the case that neutron spin flips between the superposer and the analyser mirror. The reflected and transmitted components are also exchanged. The situation is quite same as the case (b).

(d) In the case that neutron spin flips after the analyser mirror. The reflected and transmitted components are reversed in their spin states. In this case, however, the change of the spin state never give any effect in the interference pattern.

The above discussion have been verified by the spin interferometry experiments accompanying spin depolarization induced by a thin plate of iron and Parmalloy.[16] The spin interferometry measurements show that the contrast of the interference pattern did not change by the spin depolarization after the analyser mirror. On the other hand, The interference pattern disappeared depending on the spin depolarization in the upstream side of the analyser mirror.

Unique characteristics of this spin echo method is applicability to incoherent inelastic scattering. Figure 2 shows time beat data for neutrons scattered by vanadium setting up in a direction of 90 deg. just after the analyser mirror. The data showed that the contrast of the time beat did not changed by the incoherent elastic scattering by Vanadium, which is a typical atom with large incoherent elastic scattering cross section based on spin incoherent. Contrast of the time beat profile will be reduced for the conventional method owing to the neutron spin flip in the incoherent scattering. In this arrangement, however, the time beat profile is kept unchanged for the neutron spin flip process. This method, therefore, will bring us a spin echo method applicable to a condense matter including hydrogen atoms which have a large incoherent inelastic scattering.[5]

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Table II. Spin interferometry accompanying spin flip by scattering; (a) without any spin flipping, (b) neutron spin flipping before the superposer, (c) neutron spin flipping between the suposer and the analyser mirror and (d) neutron spin flipping after the analyser mirror.

(a)

Pol.M.	Splitter	Phase shifter	Superposer	Ana.M.	Detector
$\lvert\uparrow\rangle$	$\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + e^{i\pi}\lvert\uparrow_2\rangle$	Reflected	$1-\cos\phi$
			$e^{i\phi}\lvert\downarrow_1\rangle + \lvert\downarrow_2\rangle$	Transmitted	$1+\cos\phi$

(b)

Pol.M.	Splitter	Phase shifter	Spin flip	Superposer	Ana.M.	Detector
$\lvert\uparrow\rangle$	$\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\downarrow_1\rangle + e^{i\pi/2}\lvert\uparrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + \lvert\uparrow_2\rangle$	Reflected	$1+\cos\phi$
				$e^{i\phi}\lvert\downarrow_1\rangle + e^{i\pi}\lvert\downarrow_2\rangle$	Transmitted	$1-\cos\phi$

(c)

Pol.M.	Splitter	Phase shifter	Superposer	Spin flip	Ana.M.	Detector
$\lvert\uparrow\rangle$	$\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\downarrow_1\rangle + \lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + \lvert\uparrow_2\rangle$	Reflected	$1+\cos\phi$
			$e^{i\phi}\lvert\uparrow_1\rangle + e^{i\pi}\lvert\uparrow_2\rangle$	$e^{i\phi}\lvert\downarrow_1\rangle + e^{i\pi}\lvert\downarrow_2\rangle$	Transmitted	$1-\cos\phi$

(d)

Pol.M.	Splitter	Phase shifter	Superposer	Ana.M.	Spin flip	Detector
$\lvert\uparrow\rangle$	$\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + e^{i\pi/2}\lvert\downarrow_2\rangle$	$e^{i\phi}\lvert\uparrow_1\rangle + e^{i\pi}\lvert\uparrow_2\rangle$	Reflected	$e^{i\phi}\lvert\downarrow_1\rangle + e^{i\pi}\lvert\downarrow_2\rangle$	$1-\cos\phi$
			$e^{i\phi}\lvert\downarrow_1\rangle + \lvert\downarrow_2\rangle$	Transmitted	$e^{i\phi}\lvert\uparrow_1\rangle + \lvert\uparrow_2\rangle$	$1+\cos\phi$

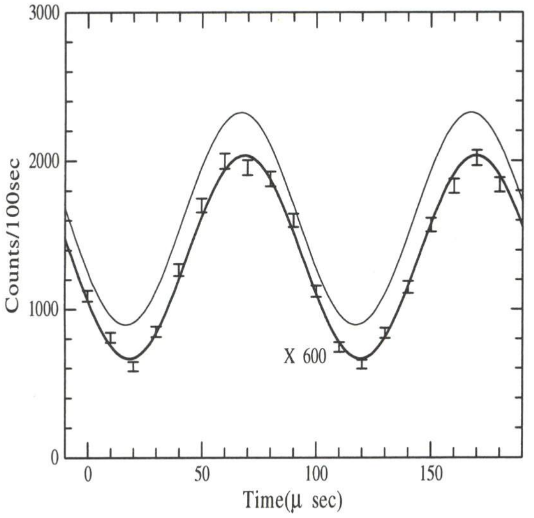

Fig. 2. Time beats measured for incoherent elastic scattering by vanadium by thick solid line and non sample by thin solid line. Both data with frequency of 30 KHz show the same contrast.

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