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Time Beat Neutron Spin Interferometry before or after Analyser

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We have developed neutron spin interferometry using radio frequency flippers. The time beat of neutron intensity at detector position is created by the coherent superposition of the spin eigenstates of cold neutrons with different energy state, which are produced with two radio-frequency flippers. If we insert an unmagnetized sheet of Permally as a neutron spin depolarizer before the second $\pi/2$ flipper, the beat signal at detector position is completely destroyed while if we insert the magnetic depolarizer after polarization analyser, the beat signal is not influenced by the magnetic potentials.

KEYWORDS: neutron spin interferometry, time beat, magnetic potential, coherence

§1. Introduction

Neutron resonance spin echo method (NRSE) has been developed by Gähler and Golub *et al.*,[1,2] where spin echo phases are created by radio frequency (RF) flippers. As a modified version of NRSE, they apply the echo of time beat for a TOF neutron spectrometer, MIEZE instrument.[3-5] In the MIEZE spectrometer the sample is downstream of the analyser leaving the signal indifferent to magnetic field and spin flips in the sample. Following their principle, we have developed neutron spin interferometry using these radio frequency flippers.[6-8] In this paper we have firstly demonstrated the dependence of these time beat on the position of a neutron spin depolarizer.

The time beat of neutron intensity at detector position is created by the coherent superposition of the same spin eigenstates of neutrons with different energy states, which are produced with two radio-frequency flippers and polarization analyser.

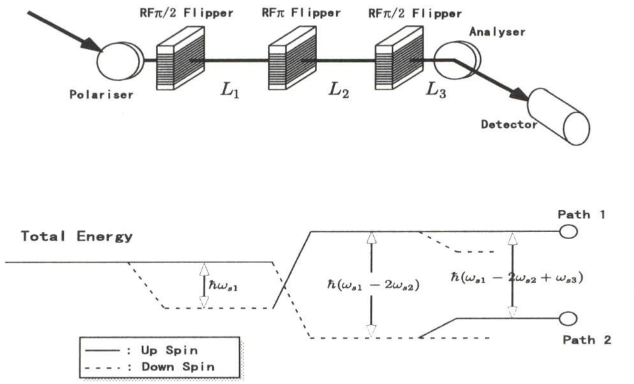

Fig. 1. Arrangement of a time beat neutron spin interferometer with RF spin flippers. The splittings in total energy are given by the exchange of quanta with energies $\omega_{z1}, \omega_{z2}, \omega_{z3}$ by RF flippers.

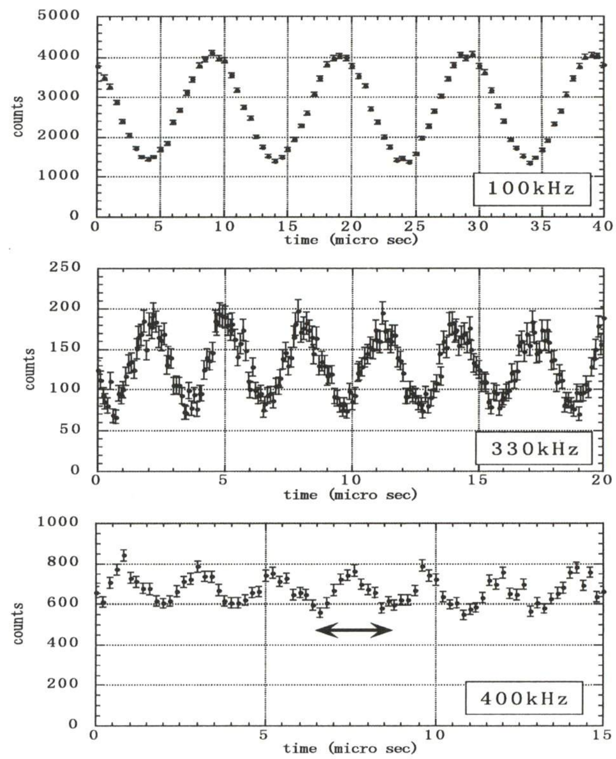

Fig. 2. Typical time beat examples of 100, 330 and 400 KHz.

§2. Quantum Beat

A simple cold neutron spin interferometer using radio frequency flippers (RF flipper) is shown in Fig.1, which is similar to the MIEZE spectrometer.

Such an interferometer is installed at C3-1-2 cold guide, JRR-3M, JAERI. The RF flippers consist of two coils, that is, one creates a magnetic field B_z parallel to the quantized axis and another one creates an oscillating field $B_x(t)$ perpendicular to the quantized axis. Assuming the resonance condition for the RF flipper and expressing the oscillating field as $B_x(\sin\omega_z t + \Delta)$, the

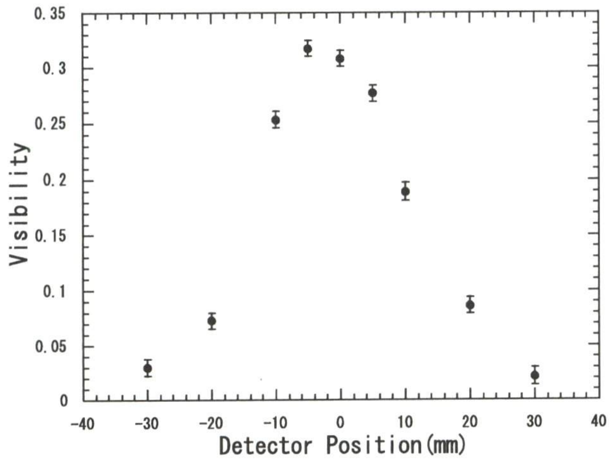

Fig.3. Visibility of the time beat spectrum as a function of the detector position at 330 KHz.

frequency of the oscillating field, ω is given by,

$$\hbar\omega_z = 2\mu B_z \tag{2.1}$$

where μ is the neutron magnetic moment. The RF flippers function as $\pi/2$ and π flippers when the amplitude B_x satisfies eqs.(2.2) and (2.3), respectively,

$$\frac{l}{v}(\mu B_x) = \frac{\pi\hbar}{2} \tag{2.2}$$

$$\frac{l}{v}(\mu B_x) = \pi\hbar \tag{2.3}$$

where l is the length of the RF-flipper and v the neutron velocity.

We consider the following cases for the magnetic fields of the system,

$$B_{z,1} = B_{z,2} = B \gg B_{z,3} = B_g \tag{2.4}$$

where $B_{z,i}$ is the magnetic field along the z axis of the i th RF flipper and B_g the guide field, respectively. The three RF flippers function as $\pi/2, \pi$ and $\pi/2$ in turn. The polarized neutron is split into the two spin eigenstates with energy difference with $\hbar\omega_z$ by the first RF $\pi/2$-flippers. The spin state and energy difference of these partial waves are reversed by the second RF π-flippers. The third $\pi/2$-flipper supersplits into two $\uparrow$ and two $\downarrow$ spin neutron states which can be selected by analyser to give two $\uparrow$ spin states with different energygiving rise to quantum beats of neutron intensity.

The time beat of neutron intensity at the detector positon at $t_d = t_0 + t_1 + t_2 + t_3$ is given by eqs. (2.5).[9] Here, t_0 is the time when the neutron is incident on RF $\pi/2$-spin flipper, and t_i is given by L_i/v.

$$|\psi_t^{out}(+)|^2 = \frac{1}{2} + \frac{\cos[(2\omega_{z2} - \omega_{z1})t_d + \Delta_0 + \Theta]}{2} \tag{2.5}$$

where the effect of B_g is neglected and the wavelength dependent phase is given by

$$\Theta = \frac{\omega_{z1}L_1 - (2\omega_{z2} - \omega_{z1})(L_2 + L_3)}{v}, \tag{2.6}$$

where L_1 is the length between the first and second RF flippers, L_2 the length between the second RF flipper and the sample, L_3 is the length between the sample and the detector. The phase difference created by the magnetic potential among the flippers is quite analogous to the Larmor precession. Accordingly, this term induces a phase dispersion depending on the velocity spread of the incident neutrons. Condition $\Theta = 0$ is required in order to observe the interference pattern with high visibility.[7,9,10] This condition is equivalent to the time focussing in the MIEZE spectrometer by Gähler *et al.*.[2,11]

Figure 2 shows a typical time dependent interference pattern with frequencies of 100, 330 and 400 KHz using a fast time analyser.

These figures show that the time beat appears as a function of the neutron detection time $t_d = t_0 + t_1 + t_2 + t_3$ with frequency $2\omega_{z1} - \omega_{z2}$.

Consequently we would observe a time interference in the time spectra. We should note that the time beat only appears at the position of the time echo where the detector should be located. The positional dependence of the visibility of oscillating time spectra is shown in Fig. 3.

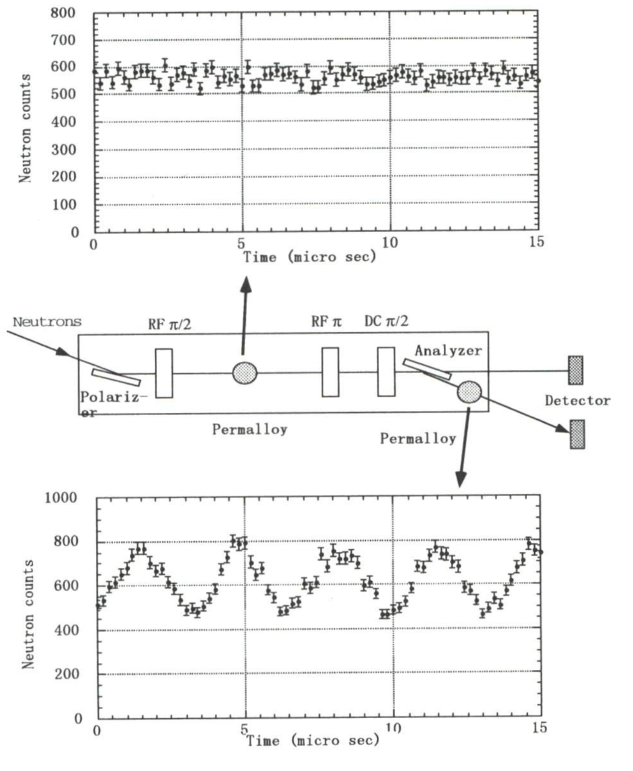

Fig.4. Two kinds of set up to test the effects of unmagnetized Permalloy sheet of 1 mm thickness inserted upstream of the π flipper or downstream of the analyser as a neutron spin depolariser. The time beat of 400 KHz is completely destroyed by randum magnetic domains in the unmagnetized Permalloy film in the former site while the time beat is unchanged in the latter site. Though as the third flipper, DC $\pi/2$ is used instead of RF $\pi/2$ flipper different from Fig. 3, the role of superslitting into two $\uparrow$ and two $\downarrow$ spin neutron states is similar with each other.

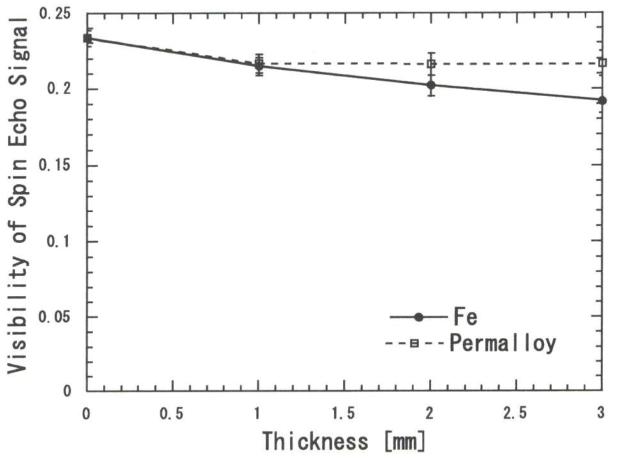

Fig. 5. Tickness dependence spin echo visibility through unmagnetized Permalloy or iron sheet located at behind the analyser for the time beat of 400 KHz .

§3. The Effect of Magnetic Potential before and after Analyer

When we insert a magnetic phase shifter between $\pi/2$ and π spin flippers, the phase of time beat is shifted by the following equation.

$$\Delta\Phi = 2\frac{\mu B_z d}{v}. \tag{3.1}$$

This phase shift corresponds to Larmor precession and it does not depend on the frequency of the RF flippers. In order to measure precisely the phase shift in good visibility of time beat, the frequency is not necessarily high. Here we demonstrate the effect of an unmagnetized Permalloy sheet of 1mm thickness inserted between the $\pi/2$ and the π flippers or inserted between the analyser and the detector as a neutron spin depolariser. The time beat of 400 KHz is completely destroyed by the random magnetic potential of Permalloy domains in the former site while the time beat is almost unchanged in the latter site as shown in Fig. 4.

Thickness dependence of spin echo visibility through unmagnetized Permalloy and iron sheets inserted after the analyser for the time beat of 400KHz is shown in Fig. 5. A small decrease of visibility with increasing thickness was observed both for the iron and the permalloy sheets. Multiple small angle scattering effects by magnetic domains bring path length differences of neutrons in the sample. This might explain the decrease of the visibility. Another possibility is due to the inelastic spin flip multiple scattering. But the frequency dependence of the visibility is required for the proof of these interpretations.

Due to the fact that the time beat of neutron intensity is created by a superposition of $\uparrow$ spin neutron wave functions with different total energies, magnetic potentials downstream of the analyser do not influence the time sygnal. Even if neutron spin is flipped by the random magnetic potentials in the unmagnetized Permalloy sheet, the superposition of both $\uparrow$ spin states changes simultaneously keeping the coherence between them. MIEZE type spectrometer utilizing echo of time beat will be very effective for the measurement of quasi-elastic scattering of ferromagnetic substances and for samples see reference.[12] Similarly, the time beat from the incoherent spin scattering from vanadium sample is demonstrated by Ebisawa in this proceedings.[13]

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