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Neutron Spin Quantum Precession Using Multilayer Spin Splitters and a Phase-spin Echo Interferometer

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Neutron spin quantum precession by multilayer spin splitter has been demonstrated using a new spin interferometer. The multilayer spin splitter consists of a magnetic multilayer mirror on top, followed by a gap layer and a non magnetic multilayer mirror which are evaporated on a silicon substrate. Using the multilayer spin splitter, a polarized neutron wave in a magnetic field perpendicular to the polarization is split into two spin eigenstates with a phase shift in the direction of the magnetic field. The spin quantum precession is equal to the phase shift, which depends on the effective thickness of the gap layer. The demonstration experiments verify the multilayer spin splitter as a neutron spin precession device as well as the coherent superposition principle of the two spin eigenstates. We have developed a new phase-spin echo interferometer using the multilayer spin splitters. We present successful performance tests of the multilayer spin splitter and the phase-spin echo interferometer.

KEYWORDS: Neutron spin quantum precession, coherent superposition, spin eigenstates, multilayer spin splitter, spin interferometer, phase echo, phase-spin echo interferometer

§.1. Introduction

We have developed cold neutron optics and interferometry using multilayer mirrors.[1-3,9,13] The advantages of multilayer mirrors are their applicability to long neutron wavelength and a great variety of mirror performances as neutron optical devices. Here we present a study on spin interferometry using multilayer spin splitters.

A polarized neutron in a magnetic field perpendicular to the polarization creates Larmor precession in the plane perpendicular to the direction of the magnetic field. In quantum theory the polarized neutron is expressed as the coherent superposition of the two spin eigenstates in the direction perpendicular to the polarization and the precession angle is equal to the phase difference between the two eigenstates. The coherent superposition of the two spin eigenstates was proposed by E.P. Wigner as thought experiment first[4] and later by A. Zeilinger as feasible experiment using silicon interferometer.[5,6] J. Summhammer et al. demonstrated experimentally the coherent superposition principle using a silicon interferometer.[7,8].

Quantum theory on spin coherent superposition predicts that we could have another precession device as well as Larmor precession in magnetic field, if we develop a spin splitter of the neutron wave with phase difference. We can realize such a spin splitter with multilayer spin splitters[9] and call the precession by the spin splitter quantum precession. In this paper we describe the structure and principle of multilayer spin splitters, and give the successful performance test results of the spin splitter. A phase-spin echo interferometer was proposed as an application of the spin splitter.[9]. We demonstrate experimentally the performance of the phase-spin echo interferometer.

§.2. Multilayer spin splitter and neutron spin quantum precession

We consider a polarized neutron in the X-Y plane in a vertical magnetic field. We take the X-Y plane in the horizontal plane and the Z-axis in the vertical direction. The polarized neutron creates Larmor precession in the X-Y plane. Quantum theory gives the equation (2.1) for the polarized neutron $S_{xy}(\Theta)$.[5,6]

$$\left|S_{xy}(\Theta)\right\rangle = \frac{1}{2}\left\{\left|\uparrow_z\right\rangle + e^{i\Theta}\left|\downarrow_z\right\rangle\right\}$$
$$= \frac{1}{\sqrt{2}}e^{i\Theta/2}\left\{\cos\left(\frac{\Theta}{2}\right)\left|\uparrow_z\right\rangle - i\sin\left(\frac{\Theta}{2}\right)\left|\downarrow_z\right\rangle\right\} \quad (2.1)$$

where Θ is the precession angle.

This equation shows that the polarized neutron is equivalent to the coherent superposition of the two spin eigenstates along the Z-axis. The phase difference Θ between the two spin states is equal to the precession angle Θ of the polarized neutron. Therefore, if we can produce the two spin eigenstates with a phase difference by a multilayer spin splitter, we could have another precession device besides the conventional Larmor precession in a magnetic field.[9]

We consider a multilayer spin splitter which consists of a magnetic multilayer mirror on top, followed by a Ge gap layer and a non magnetic multilayer mirror, as shown in Fig.1. When a polarized neutron in the *X-Y* plane is incident on the multilayer, +1/2 spin component of the neutron is reflected by the magnetic mirror on the top side and -1/2 spin component is reflected by the non magnetic mirror on the bottom side. The phase difference ϕ between the two spin states is produced by the effective gap

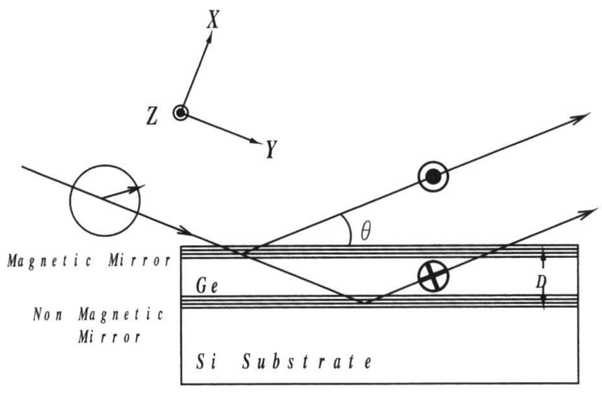

Fig. 1. Structure and principle of a multilayer spin splitter. The spin splitter consists of a magnetic multilayer on top, followed by a gap layer and a non magnetic multilayer on a well polished silicon substrate, and produces coherent superposition of the two spin eigenstates of the z axis with phase difference ϕ.

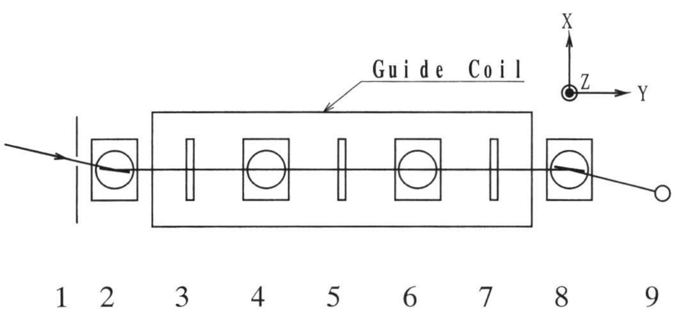

Fig. 2. Structure of a new spin interferometer, which is analogous optically to a spin echo equipment with vertical precession field; 1 Slit, 2 Polarizer, 3 First π/2-flipper, 4 First Precession Coil (PC-1), 5 π-flipper, 6 Second Precession Coil (PC-2), 7 Second π/2-flipper, 8 Analyzer, 9 Detector. Two goniometers in the two precession fields 4 and 6 allow us to mount a multilayer interferometer with the phase echo condition.

thickness D and given by, taking $n(\theta)$ as the average refractive index of the effective gap layer,

$$\phi = \frac{4\pi D n(\theta)\sin\theta}{\lambda} \quad (2.2)$$

$$n(\theta) = \sqrt{1 - \frac{Nb_c}{\pi}\left(\frac{\lambda}{\sin\theta}\right)^2} \quad (2.3)$$

where θ is the neutron incident angle, λ the neutron wavelength, N and b_c are the average atomic density and coherent scattering length of the effective gap layer, respectively.

The above description shows that the multilayer spin splitter could be another spin precession device and the non magnetic gap layer of the multilayer spin splitter gives rise to neutron spin quantum precession, which depends on the gap layer thickness, the neutron incident angle and the neutron wavelength.

It should be noted that in the silicon interferometer a whole neutron creates no precession, because the forward beam of the interferometer is complementary to the deviated beam and both precessions of the two subbeams are canceled by each other.[6,8].

§.3. Performance tests on multilayer spin splitters

Performance tests of multilayer spin splitters were made with a new spin interferometer.[10] The spin interferometer is analogous optically to a conventional spin echo system with vertical precession field. The interferometer has a polarizer, two π/2-flippers, a π-flipper, two vertical precession fields, a vertical guide field, an analyser and two goniometers in the two precession fields, as shown in Fig.2. Three flipper consist of the same Mezei coils and the other vertical magnetic field are prodeced by coils of the Helmholz type.

The polarized neutron along the Z-axis is turned to the Y-axis by the first π/2-flipper. Then, neutron spin in a vertical magnetic field, which is produced by a guide coil and two precession coils creates precession in the X-Y plane. We can measure the neutron spin precession angle using the second π/2-flipper and the analyser.

The spin interferometer has notable features different from conventional spin echo systems, as follows:

(a) Magnetic mirrors used in the interferometer function in a very low magnetic field less than 10 Oe.[11]
(b) A very low magnetic field is applied to the system, and the spin precession in the system has a very low rotation number. This allows us easy observation of the optics and interferometry related to the coherent superposition.
(c) Neutron spin states are controllable by multilayer mirrors.
(d) A multilayer interferometer can be mounted in the system.

The first spin interferometer was set up at Kyoto University research reactor in the last autumn. Another spin interferometer was installed at the C3-1-2 beam port of JRR-3 reactor. This beam port is for cold neutron optics and interferometry.[12] Incident neutrons are monochromatized by four sequential Bragg reflections using four multilayer monochromators. The neutron wavelength is 12.6Å and the wavelength resolution is 3.5%.

In order to make performance tests of a multilayer spin splitter, we set it in the second precession field. Spin echo profiles were measured as function of the current of the first precession coil PC-1, in order to check the contrast of spin echo profiles.

When we change the neutron incident angle θ of the multilayer spin splitter by $\Delta\theta$, the phase difference changes also . The change $\Delta\phi$ is given by the equation, satisfying $\theta \langle\langle 0$ and $\Delta\theta \langle\langle 0$

$$\Delta\phi = \frac{4\pi D}{\lambda}\{n(\theta)\sin\theta - n(\theta+\Delta\theta)\sin(\theta+\Delta\theta)$$
$$\approx \frac{4\pi D\Delta\theta}{n(\theta)\lambda} \quad (3.1)$$

$\Delta\phi$ is equal to the change of neutron spin precession angle, which brings the shift of the measured spin echo profile. The goal of the performance test is to demonstrate experimentally whether or not the shift of the spin echo profile measured for angle displacement $\Delta\theta$ corresponds to the change of the phase difference $\Delta\phi$ by the angle displacement .

We prepare two kinds of multilayer spin splitters with effective gap thickness D of 3700Å and 6700Å for performance tests. The multilayer spin splitters are deposited on well polished silicon substrates which are placed in magnetic field of about 100 Oe.[11] The magnetic multilayer on top consists of 7 bilayers of 45-permalloy(Pa) and germanium(Ge) of 100Å thickness in optical length, which function as a magnetic mirror in a low magnetic field of 5Oe. The non magnetic multilayer on the bottom side is a conventional Ni/Ti multilayer, which has the same optical design as the magnetic multilayer. The actual thicknesses of deposited layers are 152Å, 132 Å, 108Å and 98Å for the Pa layer, Ni layer, Ge layer and Ti layer, respectively, taking their refractive indices into account. The gap layer thicknesses of germanium are 2000Å and 5000Å for D of 3700Å and 6700Å, respectively. Their thickness is equal to the gap thickness added to half the total thickness of the two multilayers.

Fig.3 shows the spin echo profile measured for the multilayer spin splitter with D=6700 Å. The abscissa indicates the PC-1 current and the ordinate the neutron counts. The current of PC-2 is 4.5 amp. The spin echo condition for the Larmor precession in the magnetic field is satisfied at PC-1 current=4.5 amp, where we can not observe any contrast of the spin echo profile. We, however, find the contrast restored in lower current region of PC-1. The measured profile shows that the system has the mechanism to restore contrast of the profile, which is related to a kind of echo phenomena between phase difference and Larmor precession. The following experiments are made in the current region of PC-1 which gives a maximum contrast of spin echo profile.

Typical measured spin echo profiles for the spin splitter of D=3700Å are shown in Fig.4 together with fitted curves for sequential angle displacements of 0.03 deg. step. The abscissa is the current of PC-1 precession coils. The solid line indicates the standard case without angle displacement. The dotted line is for an angle displacement of 0.03 deg., which shifts by 0.036 amp. to lower current than the standard profile. The broken line for the next angle displacement of 0.03 deg., which shifts by a further 0.033 amp. to lower current than the dotted echo profile. The sequential shift of measured spin echo profiles demonstrate a good agreement with the prediction from Eq.(3.1) for the sequential angle displacements. Averaged period of 0.116 amp. of the measured echo profiles corresponds to neutron spin precession angle of 2π. Measured data are summarized in Fig.5 for the two kinds of multilayer spin splitters. The ordinate is the measured shift of spin echo profiles and the abscissa is the angle displacement. The solid line and the broken line are the data for the two multilayer spin splitters with deposited effective gap thickness of 3700Å and 6700Å, respectively.

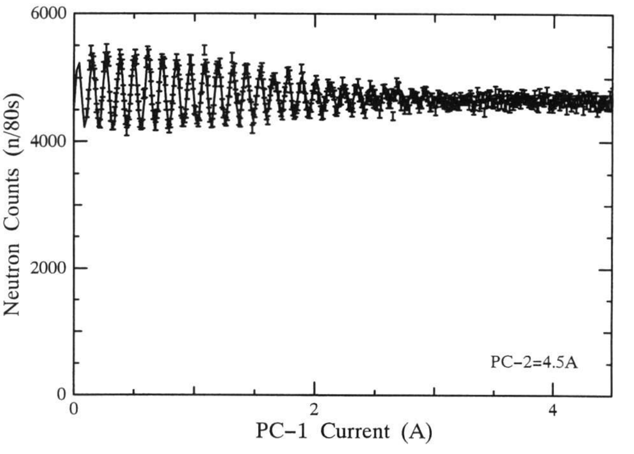

Fig. 3. Measured spin echo profile for a multilayer spin splitter with effective gap thickness of 6700Å mounted in the second precession field PC-2. The data is taken for the constant current of PC-2 of 4.5 amperes. Some recovery of the contrast of spin echo profile is observed in lower current side of PC-1.

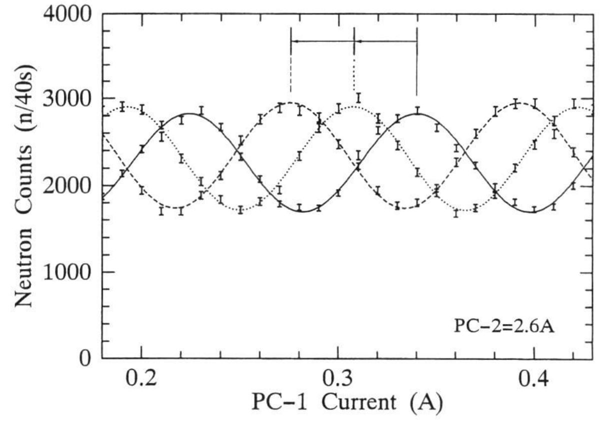

Fig. 4. Typical shifts of spin echo profiles of a multilayer spin splitter with D=3700Å measured for sequential angle displacement of 0.03 deg. step. Solid line, dotted line and broken line are fitted profiles for angle displacements of 0 deg., 0.03 deg. and 0.06 deg., respectively. The data demonstrates that the spin echo profiles shift to lower current side with larger angle displacement.

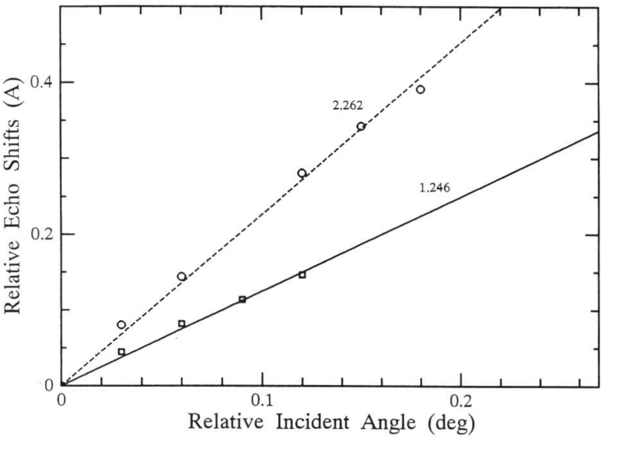

Fig. 5. data between angle displacement and measured shift of the spin echo profiles. Solid and broken lines are the data for the multilayer spin splitter with effective gap thickness of 3700Å and 6700Å, respectively.

The figure shows that the echo profile shifts are proportional to the angle displacements and the effective gap thickness is in good agreement with the quantum precession predicted from Eq.(3). This demonstrates that the quantum precession by a multilayer spin splitter is equivalent to the Larmor precession in a magnetic field.

§.4. Performance tests on a new phase-spin echo interferometer

When we arrange two identical spin splitters parallel to each other in the two precession fields as shown in Fig.6(a), the system satisfies the phase echo[13] and the spin echo phenomenon[14] simultaneously.

The simultaneous occurrence of the two echo phenomena is illustrated in Fig.6(b).[9] A polarized neutron in the X-Y plane is split into the two spin states of the Z-axis, with a phase difference, by the first spin splitter. The π-flipper reverses two subbeams. The reversed subbeams are reflected and superposed by the second spin splitter. The neutron polarization status is restored completely by the phase echo and spin echo phenomena.

So we call this system a phase-spin echo interferometer. The measured spin echo profile for the interferometer is shown in Fig.7 for D=6700Å. Comparison of Fig.4 and Fig.7 demonstrates considerable improvement of the contrast of spin echo profiles by the simultaneous occurrence of phase echo and spin echo phenomena.

We propose two applications of phase-spin echo interferometer. One is the alternative development of a high resolution and compact spin echo spectrometer, because the phase difference of 1 mm gap thickness corresponds to about 10^5 rotations of neutron spin precessions. Another is the development of a Jamin type cold neutron interferometer with variable separation of the subbeams, which could be very useful tool for coherency study of neutron waves.

It should be noted that it is not easy to develop a multilayer spin splitter with wide gap width of 1 mm or variable width.

§.5. Conclusion

The multilayer spin splitter was proposed recently as a neutron spin quantum precession device, based on the quantum mechanical coherent superposition of the two spin eigenstates. The performance of the multilayer spin splitters has been demonstrated experimentally with a new spin interferometer. The experiments verified the multilayer spin splitter as a neutron spin precession device as well as the coherent superposition principle of the two spin eigenstates. The multilayer spin splitter consists of a magnetic multilayer mirror on top, followed by a gap layer and a non magnetic multilayer. The structure of the spin splitter produces coherent superposition of spin eigenstates with a spacial phase shift, which gives quantun precession angle.

We have developed a phase-spin echo interferometer using a pair of multilayer spin splitter, which are arranged to satisfy phase echo and spin echo simultaneously in the new spin interferometer. A high resolution and compact spin echo spectrometer and a Jamin type multilayer interferometer for cold neutrons are proposed as

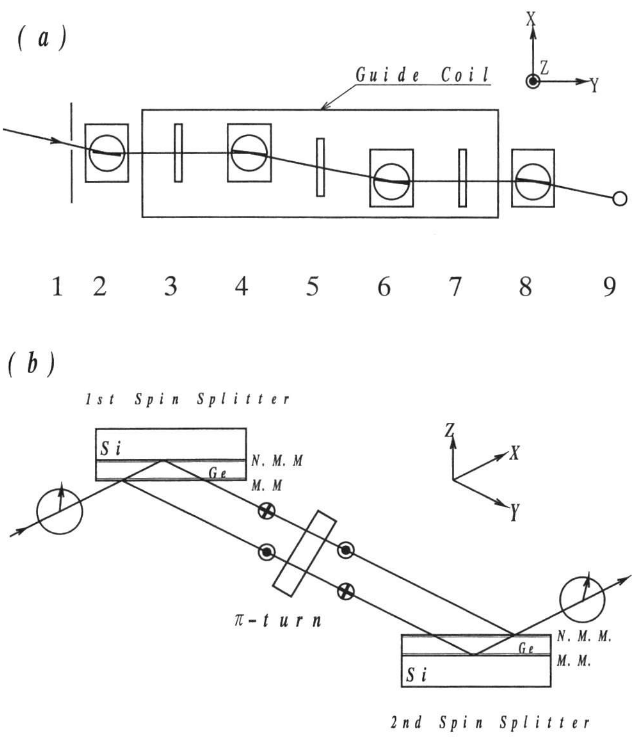

Fig. 6. (a) An arrangement of a phase-spin echo interferometer using two identical multilayer spin splitters, which are mounted in the first precession field 4 and the second precession field 6. The ordinal numbers indicate the same devices that are indicated in Fig.2. (b) Illustration of the simultaneous occurrence of phase echo and spin echo phenomena. The phase echo requires a π-turn flipper as well as a pair of the identical multilayer spin splitters.

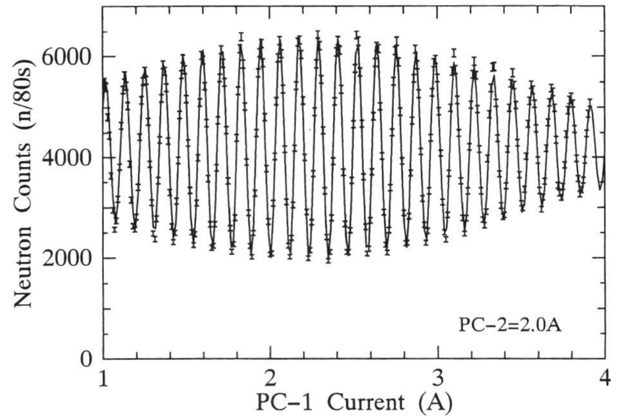

Fig. 7. Measured spin echo profile for a phase-spin echo interferometer with effective gap thickness of 6700Å. Contrast of the spin echo profiles are restored nearly perfectly by the simultaneous occurrence of the phase and spin echo phenomena.

applications of the phase-spin echo interferometer.

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