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Neutron Polarization Control by Interferometer

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A neutron interference experiment of the magnetic double refraction phenomenon was made in order to control the neutron spins. The experiment was carried out using an LLL type interferometer on HT-11 station at JRR-2 of JAERI where an apparatus for precise neutron optics is installed. A magnetic phase shifter made of Permalloy and a nuclear phase shifter made of Al were inserted between the interferometer's crystal slabs. When the magnetic phase shifter was set at an appropriate angle, an interference fringe produced by rotation of the nuclear phase shifter disappeared due to the magnetic double refraction. However, the fringe was recovered after the neutron beam was reflected from a spin analyzing crystal. This shows that the polarization state of the neutron beam outgoing from the interferometer is continuously changed by controlling the magnetic and nuclear phase shifters.

KEYWORDS: neutron interferometry, spin polarization, magnetic materials

§.1. Introduction

A perfect crystal neutron interferometer usually made of Si crystal is a very accurate instrument for detecting phase shifts of neutron wave functions caused by interactions between neutrons and fields. Measurements of coherent scattering lengths and experiments of fundamental properties of quantum mechanics, such as spinor rotation and gravitational effect, have been successfully performed by the neutron interferometry technique.[1]

We have made a series of neutron interference experiments using an LLL type interferometer to observe double refraction phenomena of neutrons caused by magnetic materials. We used a magnetic phase shifter made of Permalloy or Fe-3%Si crystal, in addition to a usual nuclear phase shifter. When an unpolarized neutron beam was incident on the LLL interferometer, the amplitudes and the phases of the interference fringes of the outgoing beams, called O-beam and H-beam, varied due to the effect of the magnetic double refraction. Although these variations would have been accompanied with changes of neutron spin states of the O-beam and the H-beam, we did not analyze the spin states in the former experiments.[2,3]

In this paper we report on our latest experiment in which the spin state analysis was made and an approach to the neutron spin control by the inerferometry technique was explored.

§.2. Experimental

Our experiment was carried out on HT-11 station at JRR-2 of JAERI where equipment for high precision neutron optics is installed. The arrangement of the experiment, which is nearly the same as those in previous experiments,[2,3] is shown in Fig.1. The modified point of this arrangement is that a spin analyzing crystal (a Heusler alloy crystal) is set on the path of the O-beam when analysis of the spin polarization is needed.

An unpolarized neutron beam of the wavelength of 1.09Å selected by a monochromator was incident on the interferometer. The cross section of the beam was narrowed to 3×10 mm^2 by slits in front of the interferometer. The effective yield of the O-beam in this arrangement was about 3 cps.

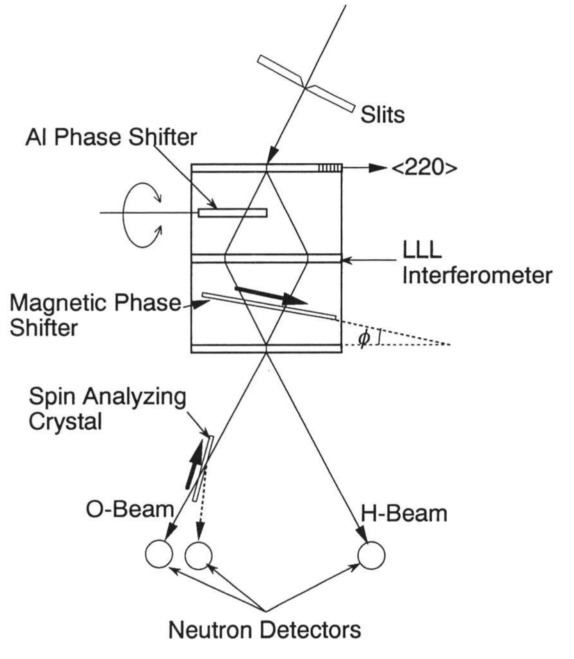

Fig. 1. The arrangement of the experiment. The magnetic phase shifter is a Ni-78% Permalloy plate 0.5mm thick. The thickness of the Al phase shifter is 3mm. The reflection plane of the interferometer is (220) and that of the spin analyzing crystal (a Heusler alloy crystal) is (111).

To check a basic performance of the interferometer we measured interference fringes by rotating the Al plate without the magnetic phase shifter and the spin analyzing crystal. The obtained interference fringes are shown in Fig.2(a).

For the O-beam, the visibility of the oscillation defined by $(I_{max} - I_{min})/(I_{max} + I_{min})$ where I_{max} and I_{min} are the maximum and the minimum of the oscillation, was

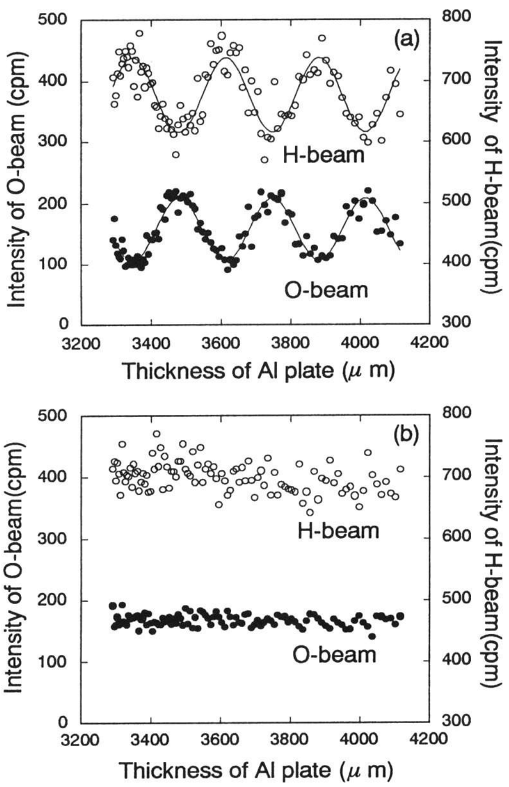

Fig. 2. Inerference fringes of the O-beam and the H-beam measured without the spin analyzing crystal. A yield of the H-beam is higher than that of the O-beam since the shield of the detector for the H-beam was not adequate; (a): The magnetic phase shifter was not inserted. Solid lines are fitting curves; (b): The magnetic phase shifter was inserted. The angle ϕ in the Fig.1 was around -11.5°. Fringes completely disappeared owing to the magnetic double refraction.

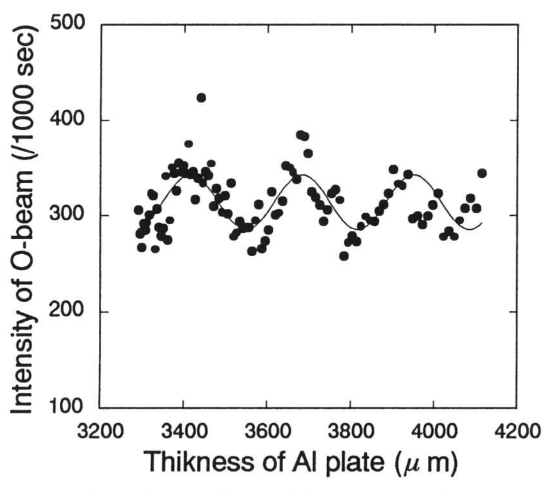

Fig. 3. The interference fringe of the O-beam which is recovered by the spin analyzing crystal.

32%. This result ensures a high performance of the interferometer.

Then we set the magnetic phase shifter between crystal slabs of the interferometer as shown in Fig.1. According to the scattering theory of thermal neutrons,[4,5] the refractive indices n_+ and n_- for two spin states in the ferromagnetic material are given by

$$n_{\pm} = 1 - (\delta_{\mathrm{n}} \pm \delta_{\mathrm{m}}),$$

with

$$\delta_{\mathrm{n}} = \frac{2\pi}{k^2}\sum_i n_i b_{\mathrm{n},i} \quad , \tag{1}$$

$$\delta_{\mathrm{m}} = \frac{2\pi}{k^2}\sum_i n_i b_{\mathrm{m},i} \quad , \tag{2}$$

where + and - correspond to the spin states parallel (+) and antiparallel (-) to the magnetization of the ferromagnetic material, respectively. Here k is the wave number of the neutrons, the summation over i involves all kinds of atoms in the ferromagnetic material, n_i is the number of the i-th atom per unit volume, and $b_{\mathrm{n},i}$ and $b_{\mathrm{m},i}$ are the nuclear scattering length and the forward magnetic scattering length of the i-th atom, respectively.

In this case the essential phase factors $\psi_{\pm}$ for the neutron waves in the O-beam are given by

$$\psi_{\pm} = \exp(-i\delta_{\mathrm{n,Al}}kt_{\mathrm{Al}}) + \exp\{i(\delta_{\mathrm{n,M}} \pm \delta_{\mathrm{m,M}})kt_{\mathrm{M}}\} \ ,$$

where the meaning of ± is the same as above. Here subscripts Al and M signify the Al phase shifter and the magnetic phase shifter, respectively, δ's are given by eq.(1) and eq.(2), and t's are effective thickness of the phase shifters created by rotations. Consequently the intensities of the (+) state neutrons and the (-) state neutrons $|\psi_{\pm}|^2$ are given by

$$|\psi_{\pm}|^2 = 2 + 2\cos(\delta_{\mathrm{n,Al}}kt_{\mathrm{Al}} + \delta_{\mathrm{n,M}}kt_{\mathrm{M}} \pm \delta_{\mathrm{m,M}}kt_{\mathrm{M}}). \tag{3}$$

When ($\delta_{\mathrm{m,M}}\ k\ t_{\mathrm{M}}$) = $n\pi/2$), oscillations of $|\psi_{\pm}|^2$ become completely out of phase, namely

$$|\psi_{\pm}|^2 = 2\{1 \pm \sin(\delta_{\mathrm{n,Al}}kt_{\mathrm{Al}} + \delta_{\mathrm{n,M}}kt_{\mathrm{M}})\}. \tag{4}$$

and they cancel out each other.

This condition was satisfied when $\phi \approx$ -11.5°, where ϕ is the angle between the magnetic phase shifter and the crystal slab as shown in Fig.1, and the fringes completely disappeared as shown in Fig.2(b). However, as indicated by eq.(4), it is in this case that the spin state perfectly parallel or antiparallel to the direction of the magnetization can be obtained. Therefore, the fringes are recovered if the intensities of $|\psi_+|^2$ part and $|\psi_-|^2$ part of eq.(3) are measured selectively by a spin analyzer.

Thus, we set the spin analyzing crystal at the position depicted in Fig.1 and measured the intensity of the O-beam. The result is shown in Fig.3 where the fringe is recovered clearly.

The visibility of the interference oscillation, which is estimated to be 9%, is rather small because the directions of the magnetizations of the magnetic phase shifter and the spin analyzing crystal are not parallel in the arrangement of our experiment. A correction for this geometrical effect is given by dividing the visibility by the cosine of the angle made by the directions of the two magnetizations. We obtained a corrected value of 28% for the visibility. This value is close to the basic visibility 32%. This indicates that the magnetic phase shifter and the spin analyzing crystal worked fairly well and an almost perfectly polarized neutron beam was created from an unpolarized incident beam by using the LLL interferometer.

§.3. Summary and Discussion

We made the experiment on the magnetic double refraction phenomenon of neutrons using the LLL interferometer of a high performance. The interference fringe, once disappeared when the magnetic phase shifter was set between crystal slabs of the interferometer at an appropriate angle, recovered by the spin analyzing crystal and this ensures the change of the spin state.

Since the result of the spin analysis indicates that the polarization of the beam is very high, this method can be applied to the experiments which need a highly polarized and coherent neutron beam.

Acknowledgments

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