Preliminary experiment of magnetic imaging using polarized pulsed neutrons at HUNS

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Abstract

Imaging using polarized neutrons is one of the most attractive techniques in the neutron imaging field, because of its capability to visualize magnetic field inside materials or spaces by analyzing neutron polarization. An advanced method, which can quantify the magnetic field by combining the time-of-flight method with a polarization analysis of pulsed neutrons, has been developed at J-PARC. To introduce this method to the compact accelerator-driven neutron source, we have started the magnetic imaging experiments at Hokkaido University Neutron Source (HUNS). Using an experimental system consisting of a pair of magnetic super-mirrors as a polarizer and an analyzer, a spin flipper, and a two-dimensional neutron detector, we obtained the polarization of 90\% at the wavelength over 6 Å. The first demonstration experiments were performed for coil samples. As a result, an oscillatory behaviour of polarization depending on the wavelength due to the neutron spin’s Larmor precession was clearly observed.

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1. Introduction

There are various ways to observe magnetic field such as ferrofluids, Hall devices, Lorentz microscopes, and so on. However, most of these methods have capability to obtain magnetic information only from the surface or superficial area of materials. On the other hand, because the neutron has a magnetic moment and penetrates deeply into the materials, it is possible to observe inside of bulk materials or inaccessible spaces. Most of the magnetic imaging studies have been performed at reactor neutron sources, while a study using pulsed neutron source has been done only at J-PARC. Usage of pulsed neutrons enables us not only to study the wavelength dependence of neutron polarization efficiently but also to quantify the magnetic field. However, at large facilities there are a lot of difficulties to perform test experiments such as the developments of new techniques or devices due to inconvenience to access and restricted beam time. The compact accelerator-driven neutron source plays a significant role for performing the fundamental technical development and the low resolution measurements. Compensate such difficulties and supplies a place for the enough time to perform fundamental experiments. Thus, we recently started preliminary imaging experiments using polarized pulsed neutrons at Hokkaido University Neutron Source (HUNS) based on a compact electron accelerator to establish the magnetic imaging technique.

2. Principle

The magnetic imaging technique using neutron beam is based on the interaction between the magnetic moment of a neutron and the magnetic field. The motion of neutron spins in the magnetic field is expressed by a torque equation as follows:

$$\frac{d}{dt} S = \gamma [S \times B]$$

where \(S\) represents a vector of the neutron spin, \(B\) the magnetic field and \(\gamma\) the gyromagnetic ratio of the neutron. Consequently, Eq. (1) describes the rotation of neutron spin around the magnetic field. Because neutrons have magnetic moment due to its spin 1/2, they undergo a precession called Larmor precession in a magnetic field. The precession angle of this motion is expressed as follows:

$$\varphi = \frac{1}{\lambda} \int_{\text{path}} B \frac{\mu}{m} ds$$

where \(\lambda\) is the neutron wavelength, \(B\) the strength of magnetic field \(B = |B(t)|\), \(t\) the residence time in the magnetic field, and \(\omega_L\) the Larmor frequency. From Eq. (2) rotation angle \(\varphi\) is described as the traversing path integral of the magnetic field. When the incident neutron is monochromatic, the strength of magnetic field can be evaluated using the neutron spin rotation angle. For this measurement, polarized neutron beam is used since the motion of the neutron spin in a magnetic field depends on its spin polarity. Magnetic imaging technique maps the distribution of cumulated magnetic field by detecting the rotation angle \(\varphi\). However, it is not possible to detect the rotation angle directly, so that change of the polarization due to the neutron spin rotation is measured. The neutron polarization is defined by the following expression,

$$P = \frac{n_t - n}{n_t + n}$$

where \(n_t\) is the number of spin-up neutrons, \(n\) is the number of spin-down neutrons. And also, the relation between polarization and the rotation angle \(\varphi\) is represented by,

$$P = 1 - (1 - n^2)(1 - \cos \varphi)P_0,$$
where $P$ is the neutron polarization after the neutrons pass through the magnetic field, $P_0$ is the initial polarization, $n$ is direction cosine of magnetic field from quantized axis. Because the polarization is a projection of the spin rotation angle, there is a periodicity of $2\pi$, and the rotation angle can't be decided uniquely only from the polarization value.

According to the Eq. (2) and (4), the oscillatory behavior of neutron polarization depending on the neutron wavelength due to the Larmor precession is deduced. Therefore, analysis of the frequency of polarization oscillation makes it possible to evaluate the absolute value of rotation angle $\phi$ and to obtain the quantity of path integral of magnetic field strength. Moreover, the tilt angle of the magnetic field from the quantized axis of neutron spin is derived from the offset of polarization oscillation. Because the pulsed neutrons can be regarded as a succession of monochromatic neutrons at each instant, a polarization change depending on the neutron wavelength can be obtained easily by using the time of flight (TOF) method. Consequently, we can obtain both the strength and the direction of the magnetic field quantitatively by analyzing wavelength dependence of polarization using pulsed neutrons. This is the most important advantage of polarized pulsed neutrons in the magnetic imaging.

3. Experimental procedure

The position dependent polarization analysis experiments were conducted at HUNS. Fig.1 shows a schematic illustration of the experimental apparatus. The pulsed neutrons emitted from the cold moderator using solid methane were transported through a vacuum flight tube and injected to the double slits to form a neutron beam with a size of 20 mm in height and 10 mm in width. Then, polarization was analyzed using a polarizer, a spin flipper and an analyzer, and through a collimator, the neutrons were detected with a two-dimensional neutron detector. An objective was located at the middle place between the spin flipper and the analyzer. The polarizer and the analyzer consisted of stacked bent magnetic super-mirrors which are magnetized by permanent magnets. These devices spatially separate neutrons with different spin orientation and produce polarized neutrons. The quantized axis was taken along vertical direction. The adiabatic fast passage spin flipper, which inverts spin polarity, was placed behind the polarizer. The neutron intensities were measured in the case with the spin flipper On and Off, the intensities were recorded as the positive or the negative polarity neutrons. Then, the polarization was calculated using result of these two measurements. The polarization of the neutron beam, which passed the objective, was analyzed by the analyzer, and the reflected components were removed by the collimator placed behind the analyzer. The neutrons transmitted through the collimator were detected by a RPMT detector, which is composed of a position sensitive photomultiplier tube with a ZnS/LiF scintillator on the surface. Its spatial resolution was approximately 1.0mm. The repetition rate of pulsed neutrons was 50 Hz, and the exposure time of each measurement was 4.5 hours. We used a solenoid coil with the diameter of 50 mm as a sample (Fig.2 (a)). An electric current of 2.0 A was applied to the solenoid coil and the magnetic field along horizontal axis was produced. Fig.2 (b) shows a simulation result of magnetic field around the solenoid coil for each axis at the distance from neutron source.
4. Results and Discussions

First, we studied the polarization of the experimental system. Fig. 2 shows the results. Fig. 3 (a) are the images of spatial distribution of spin-up and spin-down neutron intensities and polarization at wavelengths of 3.18 Å and 6.35 Å, respectively. In the images at 3.18 Å, the upper figure, the spin-up neutrons were observed as well as spin-down neutrons. On the other hand in the images at 6.35 Å, lower figure, indicate very few intensity of the spin-up neutrons and large intensity from the spin-down neutrons. Fig. 3 (b) shows the wavelength dependence of spin-up and spin-down neutron intensities and the polarization. In this figure, difference between spin-up and spin-down neutron intensities became apparent at the wavelength longer than 3 Å, and consequently the polarization rose up from the wavelength of 3 Å and it reached maximum value of over 90% at around 6 Å. This was slightly lower than the previous value of 96%, which was obtained at BL10 of Materials and Life science experimental Facility in J-PARC, due to the coarse beam collimation of the incident neutron beam and the background noise of the present system.

Next, we measured a magnetic field produced by a solenoid coil with 2.0A current. Fig. 3 (a) shows the spatial distributions of polarization obtained at various wavelengths. Although clear difference was not found among these images, the wavelength dependent polarization calculated from all area of the neutron beam (x = 62 ~ 72ch, y = 40 ~ 88ch) indicated oscillatory behavior obviously as shown in Fig. 3 (b). Here, the polarizability $P_i$ was normalized by incident polarization $P_0$. This periodic oscillation is evidence that neutrons undergo a Larmor precession owing to the interaction with the magnetic field inside the solenoid coil.

Based on the results of magnetic field calculation shown in Fig. 2 (b), we assume that the magnetic field is uniform along $x$ direction and the change in the path integral of magnetic field was expected along $y$ direction due to the
distribution of the magnetic field strength and the difference of the neutron path length in the coil. Then, the beam area was segmented into 8 parts along vertical direction, i.e. the area of 40~80ch in y was divided into 5ch with an x area of 62~72ch, and the polarization was calculated at each area. In Fig.4 (a), typical two results were plotted as a function of the neutron wavelength. The solid lines indicate the results of fitting in the range of neutron wavelength longer than 4 Å using a sinusoidal function written in this figure. The results of evaluated magnetic field strengths from the oscillation frequency obtained by the fitting were shown in Fig.4 (b) together with the results of magnetic field simulation using the finite element method (FEM). In this figure, the same tendency of magnetic field distribution was confirmed thought there still be a difference in the absolute value. The reason of this disagreement may be attributed to the stray field around the coil and the beam divergence. Therefore, improvements of the experimental system and developments of the data analysis methods are needed for the quantitative measurements of magnetic field using polarized pulsed neutron imaging technique.

![Fig. 3 Results on solenoid coil applied the current of 2.0A (a) Distribution of polarization; (b) Wavelength dependent polarization](image)

![Fig.4 Quantification of magnetic field (a) Examples of fitting for polarizabiity; (b) Comparison between experimental and simulated values](image)

5. Conclusion

We started a preliminary experiments of magnetic field imaging using polarized pulsed neutrons at the compact accelerator based neutron source HUNS, and successfully obtained polarized pulsed neutron beam with polarizabiity of 90% over 6 Å. Spatial dependent polarization analysis experiments for a solenoid coil sample were performed and an oscillatory behavior in the wavelength dependent polarization due to the Larmor precession was confirmed. Quantitative analysis of spatial distribution of the magnetic field strength showed similar tendency with the FEM calculation. It is worth to notice that this is the first result of the quantitative magnetic imaging carried out at a small neutron source facility and shows a significant potential of such neutron source to be a powerful station for developing neutron technique.
6. References