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Development of optical devices based on neutron refractive optics

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Abstract

We have been developing neutron optical devices based on neutron refractive optics, such as a neutron lens and prism to improve neutron scattering methods. Prototypes of a compound Fresnel lens, a magnetic lens and prism for neutrons have been developed. The functions of each devices were verified by experimental and numerical simulation studies, and their improvement and applications are still being investigated. The recent progress in our work is reviewed and perspective of their application to neutron scattering experiments is described.

1. Introduction

Neutron scattering method is essential in a study of internal structure and dynamics of material because of the exclusive nature of a neutron. However, its application is limited due to the extremely low intensity of the neutron beam compared with the synchrotron-radiation photoemission. To improve this situation, we have been developing neutron optical devices such as a neutron lens and prism based both on compound and magnetic refractive optics [1-6]. In this paper, a review is presented of the considerable recent progress in our work on the neutron optical devices.

2. Compound Refractive Lens

A neutron optics at an interface between materials is treated in the same way as that for visible light by introducing refractive index $n = 1-bN\lambda^2/2\pi$, where b is the bound coherent scattering length, N the number density of the nuclei and λ the neutron wave length. In general, the refractive indexes of nucleus are nearly unity, and neutron absorption by materials is not negligible. Thus, careful choice of materials is necessary to develop a material lens for neutrons.

Recently, a neutron beam focusing experiment using a compound refractive lens (CRL) was reported[7]. In their experiment, the CRL was made of MgF_2 and had a symmetric concave shape. Considerable neutron intensity gain more than 30 was obtained due to the focusing effect of the CRLs. However, neutron transmission was drastically decreased with increasing the neutron beam size due to the lens shape effect, i.e., the effective lens thickness increases with the neutron beam size.

To overcome this problem, we have fabricated a Fresnel lens made of vitreous silica with an effective potential of $(90.1\text{-}2.7\times10^{-4}i)$neV[6]. The cross section of the lens is depicted in Fig.1. The characteristics of the lenses were investigated with cold neutrons using a

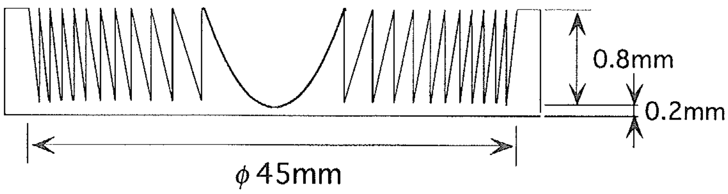

Fig. 1. Cross section of a Fresnel lens.

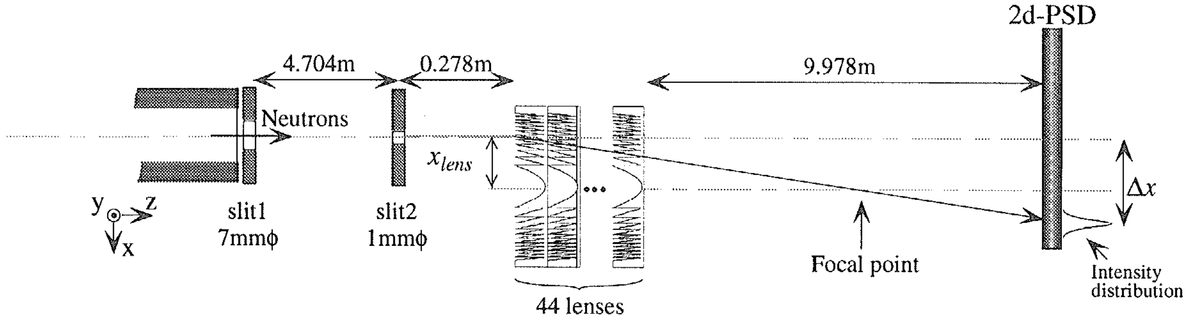

Fig. 2. Experimental setup for the lens characterization.

neutron spectrometer SANS-J installed at JRR-3M of Japan Atomic Energy Research Institute. The small-angle neutron scattering from the vitreous silica, which could reduce the lens performance, was measured. The neutron transmission of the 1-mm-thick vitreous silica was also measured to be 0.973±0.006 for 6.5 Å neutrons, which was significantly lower than the theoretical value of 0.9987. The experimental setups for the lens characterization are shown in Fig. 2. The refracting power of a lens is insufficient to investigate the lens performance, thus a 44-element series of the lenses was used.

To investigate the lens characteristics carefully, a neutron beam collimated by a 1 mmϕ pinhole was used. The neutron image was measured while varying the lens position, x_{lens}, perpendicular to the neutron beam (Fig. 2). Figure 3 shows the neutron image obtained by the PSD. The intensity distribution along the x-axis is shown in Fig. 4(a). The peak of the intensity distribution shifts as the lenses move away from the center position. This indicates that the neutron beam is refracted by the passage through the lenses and that the lenses function as focusing lenses for neutrons. The focal length was estimated to be 14 m for 10 Å neutrons. At x_{lens} =15 mm, the intensity distribution becomes asymmetric and possesses a tail in the direction opposite to the peak shift (Fig. 4(a)). To understand these results comprehensively, we performed numerical simulation, where measured values of the lens

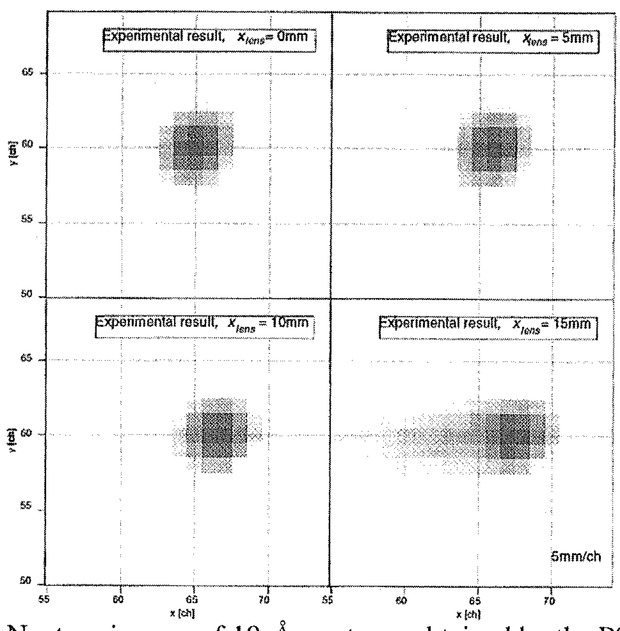

Fig. 3. Neutron images of 10 Å neutrons obtained by the PSD.

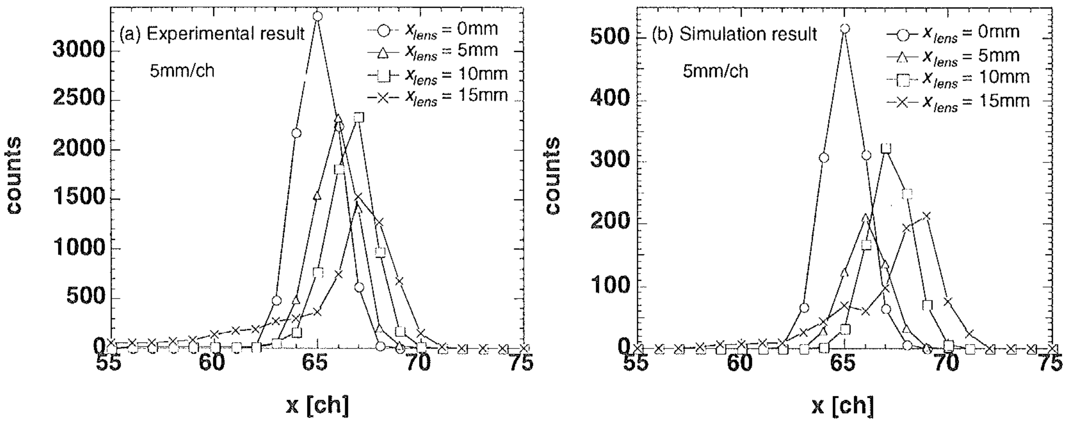

Fig. 4. Intensity distribution along the x-axis at the peak position in y-axis, (a): experimental result, (b): simulation result

shape, small-angle neutron scattering and neutron transmission of the vitreous silica, and gravity effect and reflection at the lens surface were taken into account. The experimental results were approximately reproduced in the numerical simulation (Fig. 4(b)), and it is found that the tail of the intensity distribution results from blunt shape of the lens. By sharpening the lens shape, such kind of refraction can be sufficiently suppressed.

3. Magnetic Lens

Since a neutron has a magnetic dipole moment, it is accelerated in a magnetic field gradient. Thus, we can control neutron beam free from beam attenuation using the magnetic field gradient. Moreover, its spin dependence of the acceleration is profitable in case of using the polarized neutron beam.

A sextupole magnetic field functions as a lens for neutrons. The magnetic field strength is expressed as $|B| = C_S(x^2 + y^2)/2$, where C_S is a constant. Here, we define the z-axis as being parallel to the beam direction, with the x-axis horizontal and y-axis vertical to it. As long as the magnetic field is sufficiently large so that the neutron spin polarity about the local magnetic field is conserved, the equation of motion is given by $\ddot{x} = \mp \omega^2 x$, $\ddot{y} = \mp\omega^2 y$, where $\omega^2=|C_S\mu/m|$, μ is the magnetic moment and m the mass of the neutron. The $\mp$ signs correspond to neutrons whose spins have positive and negative polarity to the local field direction. Thus, neutrons with positive polarity spins are focused onto the axis at the magnet exit when the relation $\omega \ell = v_z$ is satisfied, where ℓ is the magnet length and v_z the z-component of the neutron velocity.

The focusing effect of a permanent sextupole magnet was experimentally studied as

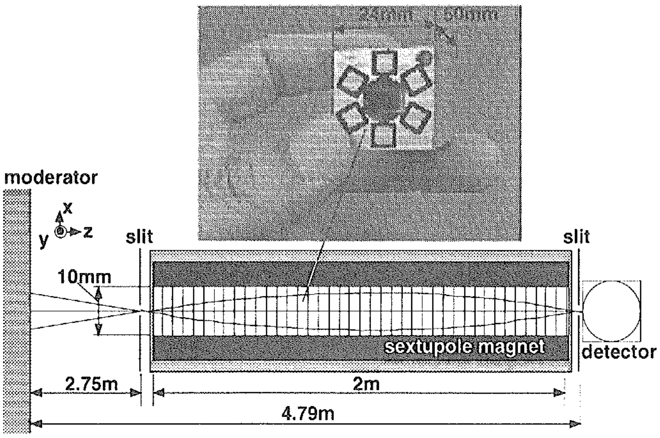

Fig. 5. Experimental setup for the study of a neutron lens. A 2 m sextupole magnet is put together from 40 units of aluminum blocks. Each unit contained six pieces of permanent magnet, 5mm x 5mm x 50mm.

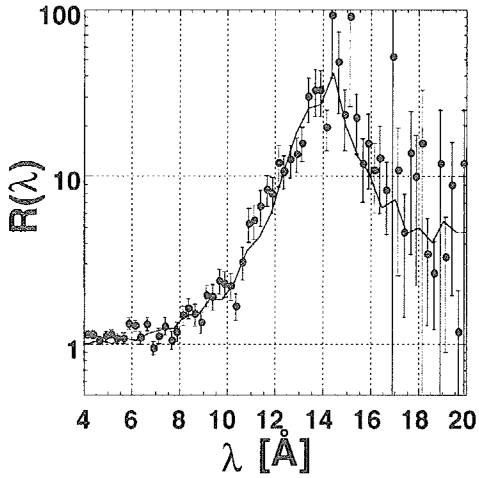

Fig. 6. Neutron intensity gain as a function of the neutron wavelength

shown in Fig. 5[1-3,5]. The magnet was 2 m long and the aperture was 10 mm in diameter. Cadmium cylinders of 9 mm diameter apertures suppressed the neutron reflection on the inner surface of the magnet. A pulsed neutron beam, which passed through 2 mm diameter holes in cadmium collimators attached on both ends of the magnet, was counted as a function of time of flight. We carried out another measurement with an identical configuration with non-magnetized magnet pieces. We denote the ratio of neutron transmittances through the magnetized set and non-magnetized set as $R(\lambda)$ and measured the magnetic effect as the deviation of $R(\lambda)$ from unity. The focusing effect as a function of wavelength was observed as shown in Fig. 6, and an average gain of $\bar{R} = 36.5 \pm 8.0$ was obtained in the wavelength region of 14.0 Å $\leq \lambda \leq$ 14.8 Å. The focal wavelength of 14.4 Å corresponded to $C_S = 3.2 \times 10^4$ T m^{-2}. The solid line in Fig. 6 shows calculated values, taking into account the neutron reflection and absorption at the magnet aperture boundary and the neutron spin polarity loss around the magnet axis. According to the numerical simulation, the neutron intensity gain of ~100 is expected with a completely absorptive aperture boundary and a complete polarity conservation.

4. Magnetic Prism

The distribution of the quadrupole field strength is express as $|B| = C_Q(x^2+y^2)^{1/2}$. Neutrons are accelerated in the quadrupole filed as following the equations: $d^2x/d\theta^2 = \mp x\rho_0/(x^2+y^2)^{1/2}$, $d^2y/d\theta^2 = \mp y\rho_0/(x^2+y^2)^{1/2}$ for positive and negative spin polarity, where $\omega^2 = |C_Q\mu/m|/\rho_0$ and ρ_0 is the radius of the quadrupole magnet aperture. Limiting the neutron motion in xz-plane for simplicity, the equation of the neutron motion is simplified as $d^2x/d\theta^2 = \mp \rho_0$, which clearly indicates a prism function according to the constant acceleration.

We have constructed a permanent quadrupole magnet with ρ_0 = 3.5 mm [4,5]. The strength of the magnetic field was $\omega \sim 480$ sec^{-1}. We evaluated the prism function of the quadrupole magnet using cold neutrons from a reactor neutron source JRR-3M of Japan Atomic Energy Research Institute. The neutron wavelength was defined by a neutron velocity selector with resolution of $\Delta\lambda/\lambda = 0.129$. The length of the quadrupole magnet was L_1 = 0.45 m and the distance between the magnet and the position sensitive detector (PSD) was L_2 = 9.7 m as shown in Fig.7. The neutron beam was collimated with 1 mmϕ pinhole which is positioned at (x, y) = (-1.0 mm, 0 mm). A two-dimensional neutron image obtained by the PSD is shown in Fig. 8 (a) and (b). The neutrons are split into two regions due to the spin dependence of the prism function. The experimental image was well reproduced by the numerical calculation with a collimator misalignment of (x, y) = (-1.0 mm, 0.45 mm) as shown in Fig.8(c) and (d).

The prism with PSD is capable to analyze the neutron energy and is applicable to inelastic scattering instruments using pulsed neutrons. In a conventional inelastic scattering method using pulsed neutrons, energy of scattering neutrons to detect, E_S, is fixed. Thus, energy transfer, ε_0, can be measured against the incident neutron with energy, E_i (= E_S - ε_0). If

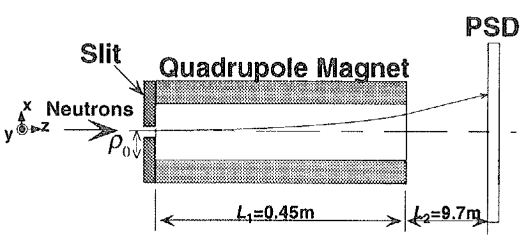

Fig. 7. Experimental setup for the study of the neutron prism.

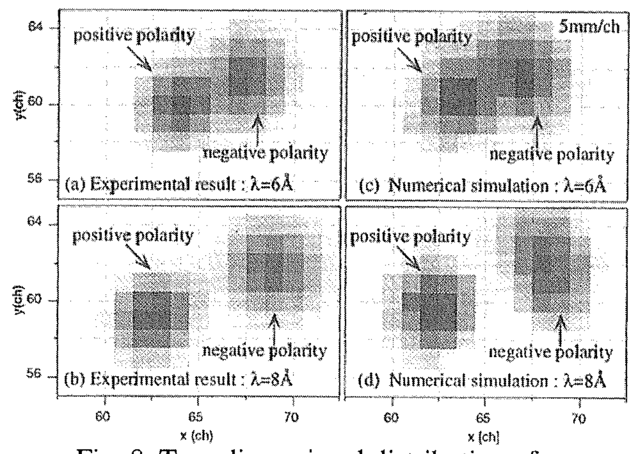

Fig. 8. Two-dimensional distribution of neutron intensity at the PSD position, (a),(b): experimental results, (c),(d): numerical simulation results.

the scattering neutron energy can be analyzed together with time information, energy transfer, ε_0, can be measured against in a range of incident neutron energy. A favorable energy resolution can be achieved in a wide range of energy transfers using a highly collimated incoming beam and a PSD with good position and time resolution. The energy resolutions using the PSD with position resolution of 0.2 mm are about 4 μeV using 10 Å neutrons where L_1 = 1 m, L_2 = 10 m, the PSD time resolution of 10 μsec and incident neutron beam divergence less than 0.02 mrad are assumed.

5. Summary

We have been developing optical devices based on neutron refractive optics to improve the neutron scattering method. We have fabricated Fresnel lenses for neutrons. Its function as a neutron focusing lens were evaluated by the experimental and numerical simulation studies. It is found that compound refractive lenses for practical use can be realized by choosing the lens shape and material. In the future, we will develop compound refractive lenses to apply to neutron scattering experiments by investigating the lens shape and materials. The magnetic neutron lens can produce a polarized beam by transporting the spin polarity of focused neutrons into a dipole field adiabatically. The functions of convex and concave lenses can be switched by reversing the spin polarity and a magnetic multiplet lens is possible. Hybrid optics of reflective optics, compound refractive optics and magnetic optics introduce more variety and flexibility in optimizing beam manipulation. The magnetic neutron prism can offer a novel method in the inelastic neutron scattering experiment. By utilizing the prism, a good energy resolution could be achieved in a wide energy range. In the practical application of the prism, the neutron intensity is still the problem, since the incoming beam must be sufficiently fine and collimated. The improvement of the design of the device and the instruments is necessary to overcome this problem.

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