Physica B 283 (2000) 314–317

PHYSICA B

www.elsevier.com/locate/physb

Neutron lens and prism

T. Oku*, H.M. Shimizu

RIKEN (The Institute of Physical and Chemical Research), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Abstract

A magnetic neutron lens and a prism using sextupole and quadrupole permanent magnets have been studied. The enhancement of beam intensity by a 2 m sextupole magnet was measured and a maximum gain of 36.5 in the wavelength range 14.0 Å $\leqslant \lambda \leqslant$ 14.8 Å was observed. The prism function of a quadrupole magnet has been experimentally demonstrated by observing a two-dimensional neutron image. We discuss the capability to measure neutron energy by combining the prism and a position sensitive detector and a possible application in neutron scattering experiment.

PACS: 03.75.Be; 29.30.Hs; 41.85.Ew; 41.85.Lc

Keywords: Cold neutron; Focusing; Inelastic scattering; Neutron instruments

Magnetic neutron optics is a refractive optics free from beam attenuation on the basis of precisely calculable kinematics [1–3]. In addition, it has the potential to be applied as neutron polarizer and analyzer according to its neutron spin selectivity. In this paper, we report experimental studies on magnetic neutron lens and prism using permanent sextupole and quadrupole magnets, respectively.

The focusing effect of a permanent sextupole magnet was studied as shown in Fig. 1. 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 aperture. A pulsed neutron beam, which passed through 2 mm diameter holes in cadmium collimator attached on both ends of the magnet, was counted as a function of time of flight, which determined the neutron wavelength. 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 spin of the incident unpolarized neutron is quantized on entry to the magnetic field. We define the z-axis as being parallel to the beam direction, with the x-axis horizontal and the y-axis vertical to it and we set the sextupole magnetic field strength to $|\boldsymbol{B}| = C_S(x^2 + y^2)/2$, where C_S is a constant. 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 $\omega^2 = |C_S\mu/m|$, and μ and m are the magnetic moment and mass of the neutron, respectively. The $\mp$ signs correspond

* Corresponding author. Tel.: + 81-48-467-9723; fax: + 81-48-467-9721.

E-mail address: oku@riken.go.jp (T. Oku)

0921-4526/00/$ - see front matter
PII: S0921-4526(00)00322-7

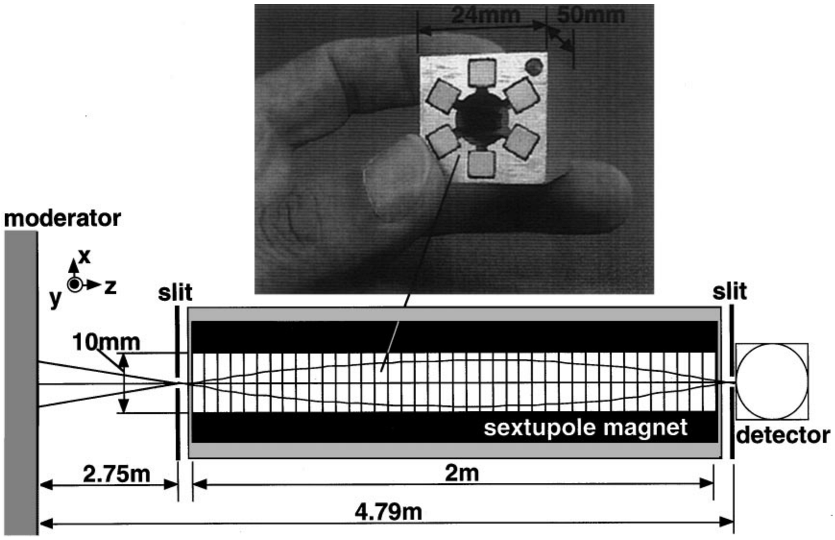

Fig. 1. Experimental setup for the study of a neutron lens. A 2 m sextupole magnet is put together from 40 units of aluminum blocks. Each unit contained six pieces of permanent magnet, 5 mm × 5 mm × 50 mm, as shown in the photograph.

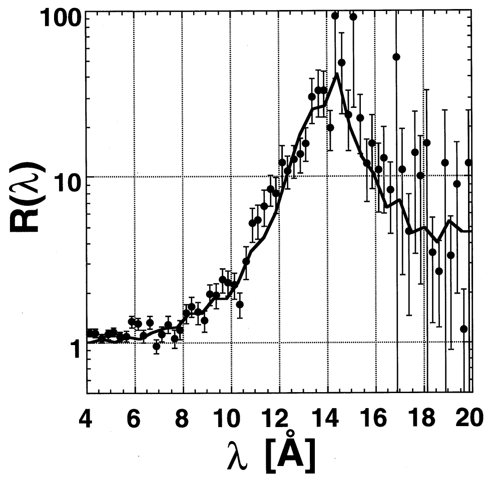

Fig. 2. Magnetic enhancement of the neutron beam intensity as a function of the neutron wavelength.

to neutron spins parallel and anti-parallel to the local field direction. Thus, spin-parallel neutrons are focused onto the axis at the magnet exit when the relation $\omega l = v_z$ is satisfied, where l is the magnet length and v_z the z-component of the neutron velocity.

The focusing effect as a function of wavelength was observed as shown in Fig. 2, and an average gain of $\bar{R} = 36.5 \pm 8.0$ was obtained in the wavelength region of $14.0\,\text{Å} \leqslant \lambda \leqslant 14.8\,\text{Å}$. The focal wavelength of 14.4 Å corresponded to $C_S = 3.2 \times 10^4\ \mathrm{T\,m^{-2}}$. The solid line in the figure 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. From the numerical simulation, $\bar{R} \sim 100$ is expected with a completely absorptive aperture boundary and a complete polarity conservation.

In the quadrupole field given by $|\boldsymbol{B}| = C_Q(x^2 + y^2)^{1/2}$, neutrons are accelerated following the equations: $\mathrm{d}^2x/\mathrm{d}\theta^2 = \mp x\rho_0/(x^2 + y^2)^{1/2}$, $\mathrm{d}^2y/\mathrm{d}\theta^2 = \mp y\rho_0/(x^2 + y^2)^{1/2}$ for positive and negative spin polarity, where $\theta = \omega t, \omega^2 = |C_Q\mu/m|/\rho_0$ and ρ_0 is the radius of the quadrupole magnet aperture. In the special case of $y = 0$, the equation is simplified as $\mathrm{d}^2x/\mathrm{d}\theta^2 = \mp \rho_0$, which clearly visualizes a prism function according to the constant acceleration.

We have constructed a permanent quadrupole magnet with $\rho_0 = 3.5$ mm [4]. The strength of the magnetic field was $\omega \sim 480\ \mathrm{s^{-1}}$. We measured the

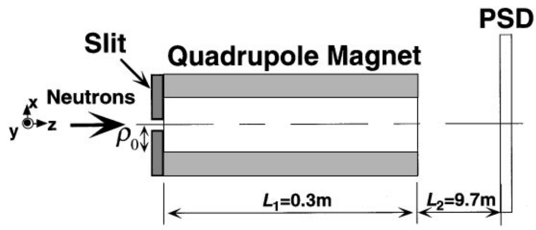

Fig. 3. Experimental setup for the study of the neutron prism. The radius of the magnet aperture is $\rho_0 = 3.5$ mm. The wavelength of incident neutrons is $\lambda = 15$ Å with a resolution of $\Delta\lambda/\lambda = 0.135$. A cadmium collimator with a 1 mm diameter hole is attached at the entrance of the magnet.

prism function of the quadrupole magnet using cold neutrons from a reactor neutron source. The neutron wavelength was $\lambda = 15$ Å with a resolution of $\Delta\lambda/\lambda = 0.135$. The length of the quadrupole magnet was $L_1 = 0.3$ m and the distance between the magnet and the position sensitive detector (PSD) was $L_2 = 9.7$ m as shown in Fig. 3. A two-dimensional neutron image obtained by the PSD is shown in Fig. 4(a). The neutrons are split into two regions due to the spin selectivity of the prism. The experimental image was well reproduced by the numerical calculation with a collimator misalignment of $(x, y) = (-0.25$ and 0.43 mm) as shown in Fig. 4(b).

The prism with PSD is capable of analyzing the neutron energy and is applicable to inelastic scattering instruments using pulsed neutrons. With a non-monochromatic neutron beam, all components of incident and scattered momentum vectors can be measured by tracing back the arrival time of incident neutrons from the timing of PSD signals. 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 estimated energy resolutions using the PSD with position resolution of 1 and 0.2 mm are about 5 and 0.5 μeV, respectively, in the energy transfer range from 10^{-3} to 10 meV, where $L_1 = 0.4$ m, $L_2 = 4$ m, the PSD time resolution of 10 μs and a sufficiently collimated incident beam are assumed.

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 made 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. Moreover, we can measure the elastic scattering simultaneously. In the practical use of the prism, the neutron intensity is still the problem, since the incoming beam must be sufficiently fine and collimated. An improvement of the design of the device and the instruments is necessary to overcome this problem.

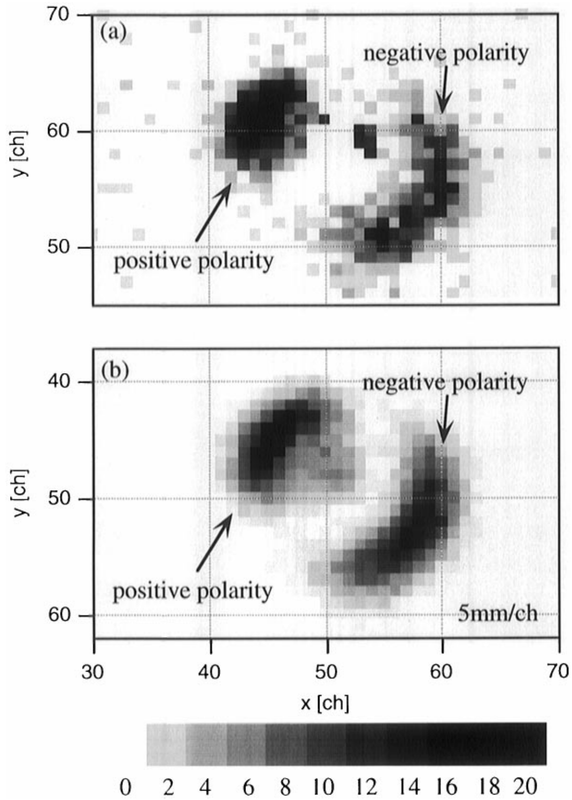

Fig. 4. Two-dimensional image of neutrons at the surface of the PSD: (a) experimental result and (b) numerical simulation.

References

[1] H.M. Shimizu et al., Physica B 241–243 (1998) 172.
[2] H.M. Shimizu et al., Nucl. Instr. and Meth. A 430 (1999) 423.
[3] H.M. Shimizu et al., Proceedings of the 2nd European Conference on Neutron Scattering, 1–4 September, 1999, Budapest, Hungary, Physica B 276–278 (2000).
[4] T. Oku, H.M. Shimizu, Proceedings of the 2nd European Conference on Neutron Scattering, 1–4 September, 1999, Budapest, Hungary, Physica B 276–278 (2000).