Proc. Int. Symposium on Neutron Optics and Related Research Facilities, Kumatori, 1996
J. Phys. Soc. Jpn. **65** (1996) Suppl. A pp. 210–213

A New Neutron Polarizer for Neutron Inteferometry Experiments

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(Received 1 February 1996; accepted 5 July 1996)

We report here on the construction of a neutron polarizer by the neutron optics group at the University of Missouri Research Reactor for use in neutron interferometry experiments. The device is based on the polarization dependence of the neutron index of refraction in a magnetic medium and the arc second angular resolution of Bragg reflection from a perfect single crystal of silicon.

KEYWORDS: polarized neutron, birefringence, Darwin width, neutron interferometry

1. Introduction

A new neutron polarizer is being constructed by the neutron optics group at the University of Missouri Research Reactor (MURR) for polarized neutron interferometry experiments. The method we use to produce polarized neutrons is different from the conventional methods which employ reflections from magnetized crystals like Fe_3O_4, $Co_{92}Fe_{08}$, the Heusler alloy Cu_2MnAl, or magnetic supermirrors.[1,2] Our method is similar to the neutron optical technique historically used in the Vienna neutron interferometry group's setup at the ILL.[3]

It is well-known that in magnetic media the different polarization states of the neutron exhibit birefringence. If we combine the angular separation of the two neutron polarization states upon passing through a magnetized iron wedge with the arc second angular resolution of the Bragg reflection from a perfect single crystal of silicon, we have the means by which to select a perfectly polarized neutron beam from an incident unpolarized beam. This paper is a progress report on the implementation of this concept. We intend to first use this device in a scalar Aharonov-Bohm experiment using longitudinally polarized neutrons.[4]

A schematic drawing of the polarizer and the interferometer is shown on Fig. 1. The setup consists of a nominally monochromatic neutron beam from a vertically focusing PG monochromator incident on a two blade double-bounce neutron reflector. The reflector is cut from a perfect single crystal of silicon. The crystal Bragg reflects neutrons from each blade in turn, acting as a double-crystal monochromator, selecting only rays that fall within arc second angular range from the exact Bragg angle. In transit between the double-bounce reflector and the four blade skew-symmetric interferometer, the neutron beam passes through a series of prism-shaped magnetic fields and undergoes birefringence. The neutron beam splits into two perfectly polarized beams with opposing polarization. The two beams travel along separated paths a few arc seconds apart. The interferometer downstream, also cut from a perfect single crystal silicon, selects one of the two perfectly polarized beams. The principles of the device can best be described in terms of the momentum space or k-space, as shown in Fig.2 below. The details will now be explained.

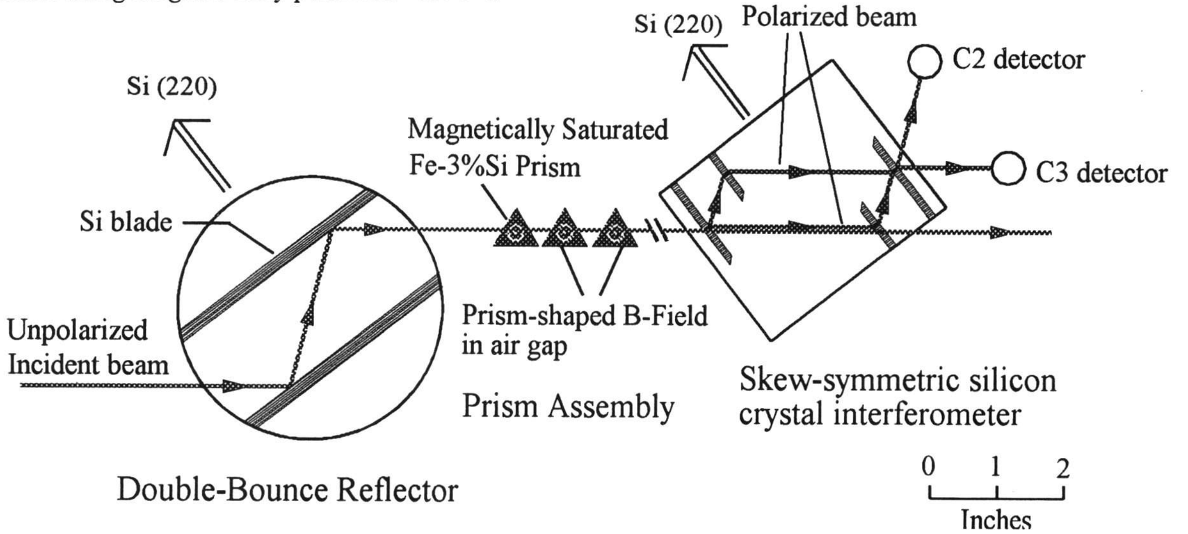

Fig. 1. Schematic drawing of the polarizer - skew-symmetric interferometer assembly. The double-bounce neutron reflector selects a monochromatic beam with arc-second angular divergence. The beam undergoes birefringence through a series of prism-shaped magnetic field which leads to an arc-second angular separation of the two polarization states. The interferometer downstream then selects one of the two perfectly polarized beams. The distance between the prism and the interferometer is 175mm.

2. The Double-Bounce Reflector and The Interferometer

As shown in Fig. 1, nominally monochromatic neutrons from a vertically focusing pyrolytic graphite (0002) monochromator are incident upon the inner surface of the first silicon blade of the polarizing crystal and are Bragg reflected by the (220) crystal planes. The perfect single crystal reflection takes a thin slice out of the incident neutron volume in *k*-space (Fig. 2(a)). The thin slice of scattering volume consists of neutrons with a wide selection of wavelengths, each with an appropriate nominal incident angle. But for each wavelength, the perfect crystal rocking width, called the Darwin width, is very narrow (Fig. 2(b)). A reflectivity profile for rocking a thick crystal across the Bragg reflection at a definite wavelength is shown in Fig. 3(a). Only those monochromatic neutrons that fall within the Darwin width of the reflectivity profile are reflected by the first blade. The full Darwin width $\Delta\theta_D$, derived from dynamical diffraction theory, is given by[5]

$$\Delta\theta_D = \frac{2\lambda^2 F_{220}}{\pi V \sin 2\theta_B}, \qquad (1)$$

where F_{220} is the structure factor for the (220) reflection, V is the volume of the silicon unit cell and θ_B is the Bragg angle. For λ=2.35Å, θ_B=37.72°, the corresponding Darwin width $\Delta\theta_D$=1.55 arc seconds.

The neutrons that are reflected by the first blade are then incident upon the inner surface of the second blade. Since the two blades are cut from the same single crystal and still attached to the same base, the crystal planes in the two blades are aligned perfectly. The neutrons are Bragg reflected again by the (220) planes of the second blade, which brings the neutrons back parallel to the incident direction. A calculation of the intensities using dynamical diffraction theory shows that 73% of the neutrons reflected by the first silicon blade will be reflected by the second blade.[5] Thus, a collimated neutron beam that is parallel to the incident beam emerges from the double-bounce reflector. Rocking the double-bounce reflector against the PG monochromator selects different slices of the neutron volume in k-space (Fig. 2(c)).

The two 5mm thick blades of the polarizer crystal are 38mm apart with their surfaces parallel to the Si(220) planes, and were machined from a single-crystal silicon ingot. The blades remain attached to the 12.7mm thick base of the ingot so that the crystal planes in one blade are perfectly aligned to the crystal planes in the other blade (Fig. 4). The thickness chosen is much larger than the Pendellösung length, typically of the order of a few tens of microns [6], guaranteeing the total Bragg reflection intensity. After the machining, the reflector was etched to remove the surface work damage.

The neutron beam from the double-bounce reflector eventually goes through the skew-symmetric interferometer (Fig. 1). The interferometer consists of four blades cut out of a perfect single silicon crystal. Neutrons undergo Laue reflection from the (220) crystal planes. Similar to the double-bounce reflector, the perfect single

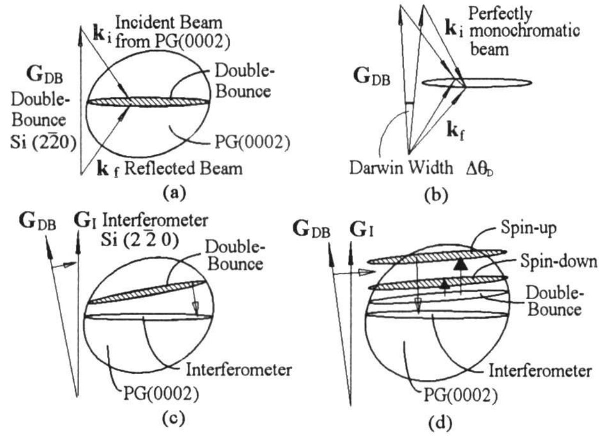

Fig. 2. (a) Perfect single crystal reflection of the double-bounce reflector takes a slice out of the k-space volume of neutrons from the PG(0002) monochromator; (b) Perfect single crystal rocks against a perfectly monochromatic beam, the rocking width is the Darwin width; (c) Rocking the double-bounce reflector against the PG(0002) monochromator and the interferometer; (d) Birefringent splitting of the neutron k-space volume by the prism-shaped magnetic field. Rocking the double-bounce crystal allows the interferometer to select either spin-up or spin-down neutrons.

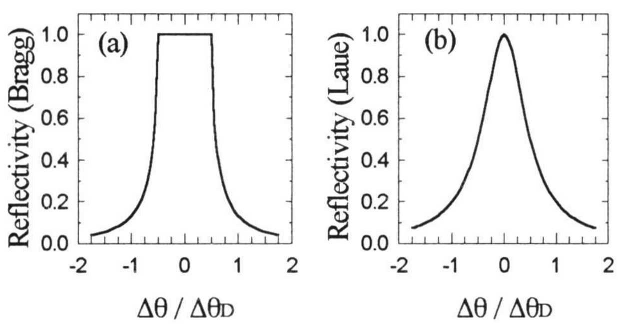

Fig. 3. Reflectivity profile of (a) Bragg reflection and (b) Laue reflection from a thick perfect single crystal slab. The angle Dq is in units of Darwin width, Dq_D, measured from the Bragg angle.

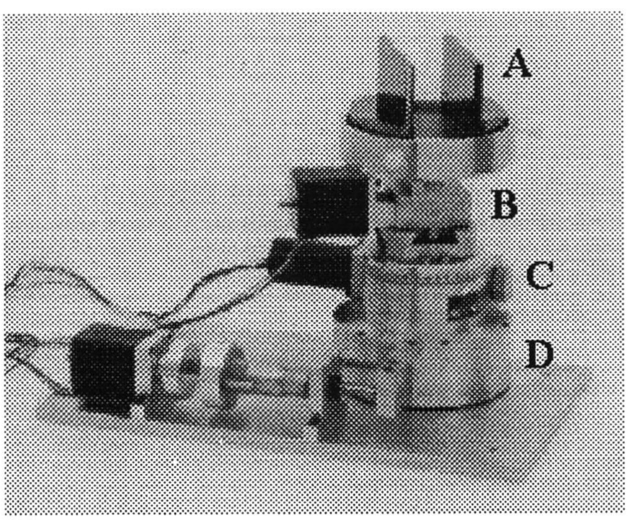

Fig. 4. Double-bounce crystal mounted on a precision rotary table. A: Double-bounce crystal, showing the two blades attached to the same base, the crystal sits in a cradle; B:Tilt stage to optimize the tilt of the crystal; C: Coarse rotary stage to rotate the crystal to the nominal Bragg condition and D: 0.05 arc sec step rotary stage for aligning the double-bounce crystal with the interferometer.

crystal silicon interferometer only accepts incoming neutrons that fall within a thin slice in k-space, with the rocking width for the Laue (220) reflection equal to 2 arc seconds (Fig. 3(b)). For any neutron from the reflector to be accepted by the interferometer, the (220) crystal planes in the double-bounce reflector must be aligned with the interferometer (220) crystal planes to within a fraction of an arc second (Fig. 2(c)), A fine rotary stage with 0.05 arc second step size is constructed for this purpose.

Finally, the double-bounce reflector is mounted on a tilt stage for optimizing the tilt, following by a coarse rotary stage underneath to rotate the reflector to the nominal Bragg angle. The fine rotary stage is located under the coarse rotary stage. A photograph of the double-bounce crystal mounted on the mechanical assembly is shown in Fig. 4.

To maintain the stability of the reflections against misalignment due to thermal fluctuations and vibrations, the reflector-interferometer assembly selects neutrons near the peak maximum of the incident beam from the PG monochromator. A rocking curve and a tilt scan at the optimum alignment is shown in Fig. 5. The full-width-half-maximum is about 2 arc seconds, confirming the calculations using the dynamical diffraction theory.

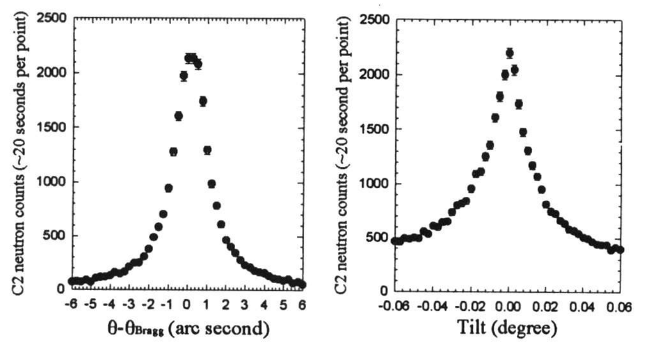

Fig. 5. (a) Rocking curve and (b) Tilt scan for the double-bounce reflector-skew-symmetric interferometer. The Rocking curve is a convolution of the reflector Bragg reflection and the interferometer Laue reflection (FWHM ~ 2 arc seconds).

3. Birefringence

Between the reflector and the interferometer, the neutrons pass through a series of prism-shaped magnetic fields (Fig. 1). The interaction potential between the neutron magnetic moment μ and the magnetic field **B** is

$$E = -\mu \cdot B. \qquad (2)$$

This leads to birefringence, a polarization dependent index of refraction given by

$$n_{\pm} = 1 \mp \frac{\mu B}{m v^2} = 1 \mp \varepsilon \qquad (3)$$

with the + sign labeling the spin-up neutrons with the magnetic moment parallel to the field and the - sign for neutrons with opposite spin, where m is the neutron mass and v=1.68mm/μsec for λ=2.35Å neutrons. When passing through a prism, a neutron beam is deflected in the same way light is deflected by an optical prism except that, the refractive index for neutrons is in general less than one, and the neutron beam tends to bend towards the apex angle. The angle of the deviation from the incident direction is

$$\delta_{\pm} = \mu 2\varepsilon \tan(\frac{\alpha}{2}) \qquad (4)$$

where α=60° is the prism apex angle. Thus the neutron beam undergoes birefringence through the prism-shaped magnetic field and splits into two perfectly polarized beam with opposing polarization (Fig. 2(d)). The two beams travel along different paths a few arc seconds apart. For λ=2.35Å (v=1.68mm/μsec) neutrons passing through a α=60° magnetic field, the separation of the two beams amounts to $\delta_{+} - \delta_{-}$=0.097 arcsec/kGauss. A field strength greater than 20kGauss is required to produce a 2 arc second separation, which is the combined rocking width of the reflector-interferometer assembly.

To achieve the 2 arc second separation, a magnetically saturated Fe-3%Si 60° prism carrying a saturation field of 22kGauss and two 60° prism-shaped magnets with air-gap fields equal to 2kGauss and 3kGauss, respectively, are positioned symmetrically along the beam path (Fig. 1).

The 60° iron wedge was machined by the Electrical Discharge Machining (EDM) process from a cylindrical iron-3%silicon single crystal. A single crystal is used due to the large attenuation from Bragg scattering of polycrystalline iron. A quality check of the crystal using neutron diffraction at the (200) reflection revealed three "mosaic" crystal domains within a 2° range. The multi-domain mosaic structure may introduce a small contamination in the polarization of the two transmitted neutron beams. With the prism magnetized along its [001] easy axis, the neutron beam passes symmetrically through the prism, in a direction which is a few degrees away from the [100] crystal axis. Such a geometry avoids back scattering as well as other possible Bragg reflections. The prism was etched in 50%(volume)HNO_3 and polished to remove surface damage that occurred during machining. The transmission of neutrons through the single crystal iron wedge is 75% as compared to 25% for a similar polycrystalline iron wedge.

As indicated above, the iron prism is magnetized along its prism axis, or the [001] easy axis. To produce a clean polarized beam, it is crucial to magnetically saturate the iron prism. Based on the length to diameter ratio of 1.5 for the cylindrical single crystal iron from which we machine the prism, we estimated that a 7kGauss applied field is needed to saturate the iron. Two rectangular $Nd_2Fe_{14}B$ magnets with energy product equal to 35MGOe, residual induction of 11kGauss and a surface field up to 5kGauss are used as the poles at the two ends of the iron prism. A soft iron yoke is used to carry the return field of the magnets. Substantial etching and polishing have been done to reduce the possibility of surface depolarizing effects of the prism. Passing a 100% polarized neutron beam through the magnetized iron, we found that the neutron beam remained 93% polarized, indicating that the iron prism is largely saturated. The fringing field from the magnet pole faces outside the triangular shaped prism is in the same direction as the magnetization and reduces the relative index of refraction by no more than 5%, therefore it does not pose a problem. The nuclear interaction between the neutron and the iron nuclei introduces an extra deviation of 1.78 arc seconds to both polarized beams but has no effect on the separation between the two. As described above, two sets of 60° prism-shaped $Nd_2Fe_{14}B$ magnets produce air-gap magnetic fields with field strengths 3kGauss and 2kGauss, respectively, which further separates the two polarized beams. This setup is equivalent to a 60°, 27kGauss field which separates the two polarized beams by 2.5 arc seconds (Fig. 6).

Illustrated in Fig. 2(d) is the birefringent splitting of the scattering volume in k-space for the spin-up and spin-down neutrons. With the interferometer downstream being fixed within the range of optimum orientations, rocking the double-bounce reflector overlaps the reflector scattering volume, i.e., the two polarized beam scattering volumes, with different parts of the neutron k-space volume from the PG monochromator. Eventually, one of the polarized beam scattering volume matches that of the interferometer and a polarized neutron beam is reflected through the interferometer. Switching between the spin-up and the spin-down neutrons can be done by rotating the reflector to the appropriate angle. A spin-flipper is installed between the prism assembly and the interferometer to rotate the neutron spin to the longitudinal direction for the scalar Aharonov-Bohm experiment. Another spin-flipper between the interferometer and a $Co_{.92}Fe_{.08}$ analyzer allows for polarization analysis.

4. Results

A rocking curve of the double-bounce reflector is shown in Fig. 6. The C2 detector detects the neutron beam that goes through the interferometer. Two peaks are detected by C2, showing the birefringent splitting of the neutron beam. A magnetically saturated $Co_{.92}Fe_{.08}$ crystal reflects only the spin-up neutrons in the C3 beam into another detector, leading to the disappearing of the first of the two peaks in the analyzer counts. By comparing the intensities with a depolarizing iron shim placed first before and then after the prism assembly, we determine the polarization to be 99.3%.

An interferogram using the spin-up neutrons is shown in Fig. 7. The 65% contrast of C3 interferogram shows that the polarizing device can be used in neutron interferometry experiments. Alignment and phase stability over several days have been demonstrated.

5. Characteristics of the Polarizer

The characteristics of this polarizer are: (1) Switching from a polarized beam to an unpolarized beam by removing the prisms and rotating the reflector; (2) Selecting spin-up or spin-down neutrons by rotating the double-bounce reflector; (3) Insensitivity to misalignment of the prisms; (4) The beam from the monochromator and the beam from the reflector are parallel; (5) Occupies much less space than a supermirror polarizer; (6) Produces high intensity polarized beam for neutron interferometry experiments as compared to using highly absorbing $Co_{.92}Fe_{.08}$ crystals.

Acknowledgment

This work is supported by the National Science Foundation, Physics Division, grant #9024608.

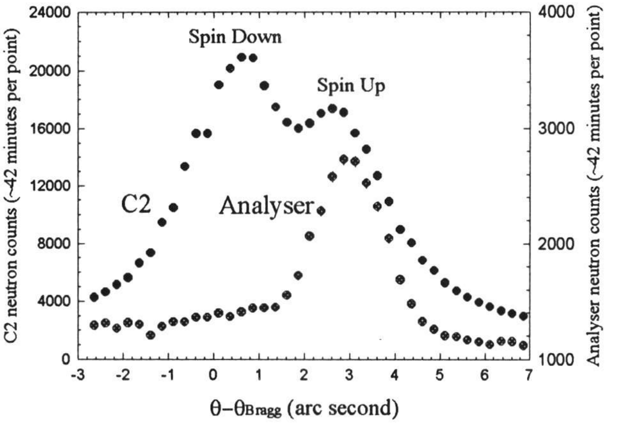

Fig. 6. Double-bounce rocking curve. C2 counts show the splitting of the two beams with opposite polarization. An analyser in the C3 beam detects only the spin-up neutrons, leaving only the second of the two peaks.

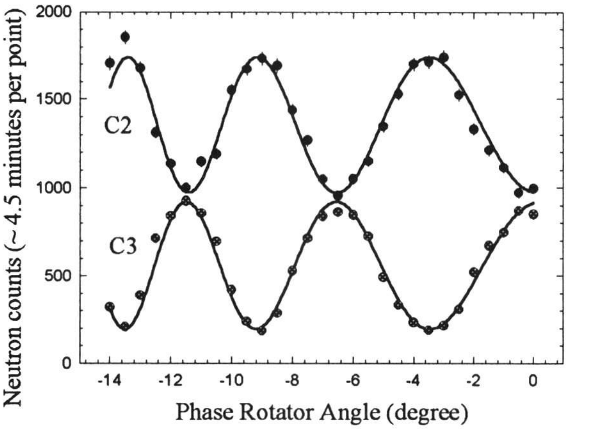

Fig. 7. Interferogram using the spin-up polarized neutron beams. C3 contrast is 65%.

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