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Permanent magnetic field-prism polarizer for perfect crystal neutron interferometers

G. Badurek^{a,*}, R.J. Buchelt^b, G. Kroupa^c, M. Baron^b, M. Villa^b

^a*Institute of Nuclear Physics, University of Technology, Stadionallee 2, A-1020 Vienna, Austria*

^b*Atomic Institute of the Austrian Universities, Vienna, Austria*

^c*Institut Laue-Langevin, Grenoble, France*

Abstract

Spin-dependent bi-refrindexence of neutrons upon passage through the air gap of a prismatically shaped permanent magnet yoke is used to split a thermal neutron beam in two polarized sub-beams with slightly different directions. This method is ideal to polarize the neutrons within perfect crystal interferometers without loss of intensity. Using a sequential arrangement of two such prisms a splitting larger than twice the rocking-curve width of a perfect crystal Mach–Zehnder-type neutron interferometer has been achieved, yielding a beam polarization of about 97%. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Neutron polarizers; Perfect crystals; Neutron interferometry

1. Introduction

Mach–Zehnder-type neutron interferometers based on Bragg/Laue diffraction at perfect crystal lattice planes allow to split matter waves coherently and to separate them by a distance of several centimeters prior to their subsequent coherent superposition [1]. Perfect crystal neutron interferometry has become a key technique for experimental verification and demonstration of basic concepts of quantum mechanics [2]. In most of those experiments which refer explicitly to the spinor character of the neutron wave function the use of polarized incident neutrons is indispensable [3]. The ex-

tremely narrow width of perfect crystal rocking curves provides for an elegant method to polarize thermal neutrons by exploiting the tiny spin-dependent momentum changes these particles experience upon traversing a static magnetic field region with boundaries inclined to each other. The first dedicated polarizer of this kind was realized with electromagnetic fields prisms [4]. Here we report on a novel concept using permanent magnetic fields only, which due to zero energy dissipation is of great advantage with respect to the extreme temperature sensitivity of perfect crystal interferometers.

2. Theoretical background

Upon entering a magnetic field B neutrons of wavenumber k_0 experience a spin-dependent

* Corresponding author. Tel.: + 43-1-72701-229; fax: + 43-1-58801-14199.

E-mail address: badurek@ati.ac.at (G. Badurek)

change of momentum

$$\frac{\Delta k}{k_0} \simeq \pm \frac{m\mu B}{\hbar^2 k_0^2}, \quad (1)$$

due to the different Zeeman energies $\mp \mu B$ of the eigenstates $|\uparrow\rangle$ and $|\downarrow\rangle$ of the Pauli spin operator. Here m is the mass of the neutron and μ its magnetic moment. Thus the field acts as a bi-refracting medium with a spin-dependent refractive index

$$n_{\uparrow\downarrow} = \frac{k}{k_0} \simeq 1 \pm \frac{m\mu B}{\hbar^2 k_0^2}. \quad (2)$$

When an unpolarized neutron beam crosses the boundary between a field-free region and the magnetic field the $|\downarrow\rangle$ spin state is refracted 'towards' a direction perpendicular to the boundary, whereas the $|\uparrow\rangle$ state undergoes refraction 'from' this direction. If two successive boundaries are traversed which are inclined to each other by an angle Φ so as to form a 'field prism', the two spin states propagate in different directions separated by an angle [4]

$$\delta(\Phi, \varepsilon, B, E_0) = \frac{2\mu B}{E_0} \frac{\sin(\Phi)}{\cos(\Phi) + \cos(2\varepsilon)}. \quad (3)$$

Here $E_0 = \hbar^2 k_0^2 / 2m$ is the kinetic energy of the incident neutrons, and the asymmetry angle ε describes the deviation of the prism orientation from symmetric neutron passage. For thermal neutrons a field of about 1 T causes an angular splitting of the order of a few arcseconds. Exploiting the extremely narrow width of perfect crystal Bragg reflections, Schneider and Shull [5] determined the refractive power of iron prisms, whereas refraction by pure magnetic fields was demonstrated in Ref. [6]. The first dedicated neutron polarizer of this kind, using the field ($B = 1.55$ T) within the 5 mm air gap of an electromagnet with prismatically shaped iron yoke (apex angle: 90°) was described in Ref. [4]. A polarizing system using single-crystalline Fe-3% Si prisms is reported in Ref. [7].

3. Experimental realization

In the course of refurbishing the perfect crystal neutron interferometer facility S18 at the ILL Grenoble, which is operated as a CRG-C instru-

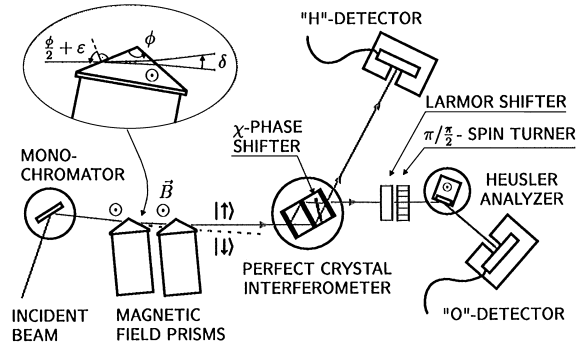


Fig. 1. Sketch of the experimental setup.

ment under the authority of the Atomic Institute of the Austrian Universities, a new type of prism polarizer was developed. It consists of a prismatically shaped permanent magnet yoke (apex angle $\Phi = 116^\circ$), produced by VAC-Hanau/Germany. Inside its air gap of 10 mm height a magnetic field of 0.88 ± 0.02 T is established. Two such prisms of baselength 10 cm each are inserted sequentially between monochromator and interferometer crystal, as indicated in Fig. 1. A B_4C diaphragm in front of the interferometer confines the neutron beam to a horizontal width of 5 mm. The largest possible asymmetry angle of the two prisms is $\varepsilon_{\max} = \pm 25^\circ$. Rotating the interferometer crystal through the (220)-reflection in steps of 10^{-4} degrees yields the rocking curves of the forward ('O-beam') and the diffracted beam ('H-beam') shown in Fig. 2, for both prism set at an asymmetry angle $\varepsilon = 25^\circ$. At a neutron wavelength of 1.895 \AA the two peaks corresponding to the $|\uparrow\rangle$ and the $|\downarrow\rangle$ state are separated by an angle $\delta_{\text{exp}} = 5.3 \pm 0.2''$, which is considerably smaller than $\delta_{\text{calc}} = 8.5 \pm 0.2''$ calculated from Eq. (3). This pronounced deviation of the experimental splitting from the theoretical expectation originates essentially from the small spacing of slightly less than 10 cm between the two magnet yokes, which causes their stray fields to overlap and reduces the achievable field gradients. However, in a previous experiment at the high-resolution SANS instrument of the Vienna research reactor with about 20 cm distance between the two prisms it was proven that the second one indeed

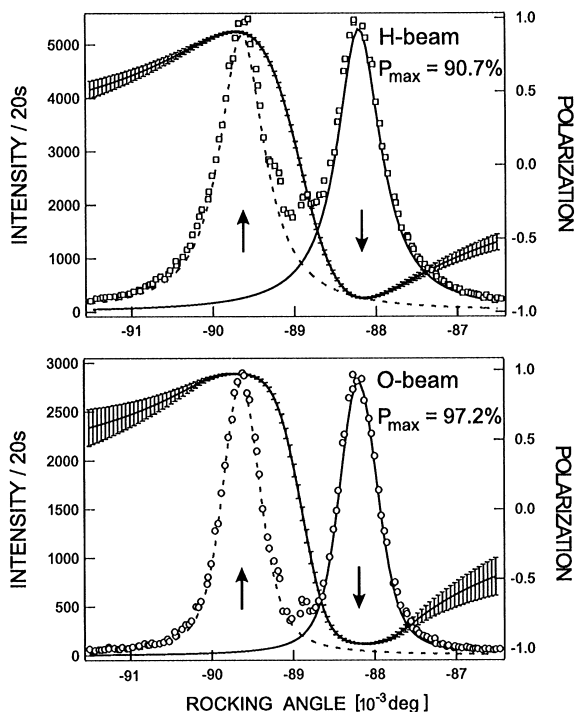


Fig. 2. Interferometer rocking curves and calculated degree of polarization of the forward ('O') and the diffracted ('H') beam for asymmetric neutron passage at $\varepsilon = 25^\circ$ ($\lambda = 1.895 \text{ \AA}$). The relative intensity portions of both beams depend on the size of the nuclear phase shift χ between the interfering subbeams.

doubles the splitting, provided there is no stray-field overlap. But even there the observed splitting was about 20% smaller than that calculated from Eq. (3), which is valid only if the isofield contours at both sides of a prism are straight and not curved. From a least-squares fit of the individual peaks the intensity ratio of both spin states and thus the degree of polarization can be derived for each angular position of the interferometer. The maximal polarization $P_{O,\max} = 97.2 \pm 0.3\%$ of the O-beam is higher than the corresponding value $P_{H,\max} = 90.7 \pm 0.3\%$ of the diffracted beam because of its intrinsically narrower rocking curve. A magnetized Heusler crystal can be inserted in either of the two emerging beams to analyze their spin state. A so-called Larmor shifter coil allows to compensate for the inevitable spin precession which is caused by the guide field along the neutron trajectories, in case one of the interfering subbeams

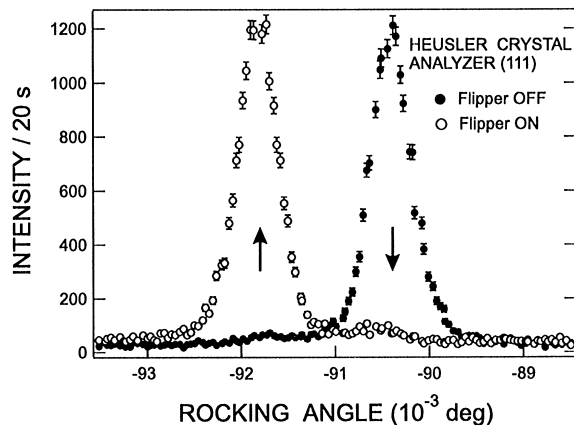


Fig. 3. O-beam intensity distribution behind the Heusler crystal without and with activated spin flipper.

experiences some magnetic interaction so that the final state is no longer oriented along the field. Two crossed DC coils in front of the Heusler crystal, which act either as a π -flipper or as a $\pi/2$ -spin rotator, are necessary to determine all three spatial components of the final polarization vector in successive order. As a typical example the results of a longitudinal (i.e. along the guide field) spin analysis of the O-beam are shown in Fig. 3.

4. Outlook

The achieved degree of polarization is sufficient for most of our scheduled experiments. Nevertheless, we will modify our setup in order to increase the distance between the magnet yokes and to minimize their mutual disturbance. The angular splitting should then become large enough to obtain a polarization of about 99%. Our new method of successive permanent magnetic prisms might even be useful to polarize cold neutrons without the need of perfect crystal reflections. Consider an arrangement of prisms attached closely to each other with alternating orientation of both their wedges and field directions similar to the concept of magnetic wigglers, so that the achievable field gradients are twice as large. However, careful field design would be required in order to minimize depolarization by parasitic transverse field components in the

transition regions between the prisms. The total length of such a polarizer consisting of, say, 100 prisms would be about 10 m, which is not unrealistically large if one considers the available flight paths of neutron spectrometers installed at pulsed sources. For 4 Å neutrons the angular splitting would be as large as 1° . Such a device could not only serve as an efficient beam splitter but simultaneously as a coarse monochromator providing two spatially well separated fully polarized beams.

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