First Sub-arcsecond Collimation of Monochromatic Neutrons

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Abstract. We have achieved the tightest collimation to date of a monochromatic neutron beam by diffracting neutrons from a Bragg prism, viz. a single crystal prism operating in the vicinity of Bragg incidence. An optimised silicon {111} Bragg prism has collimated 5.26Å neutrons down to 0.58 arcsecond. In conjunction with a similarly optimised Bragg prism analyser of opposite asymmetry, this ultra-parallel beam yielded a 0.62 arcsecond wide rocking curve. This beam has produced the first SUSANS spectrum in Q ~ 10^{-6} Å^{-1} range with a hydroxyapatite casein protein sample and demonstrated the instrument capability of characterising agglomerates upto 150 μm in size. The super-collimation has also enabled recording of the first neutron diffraction pattern from a macroscopic grating of 200 μm period. An analysis of this pattern yielded the beam transverse coherence length of 175 μm (FWHM), the greatest achieved to date for Å wavelength neutrons.

1. Introduction

The sharpest [1] and narrowest [2] angular profiles for well separated up- and down-spin neutron[3] peaks were attained five years ago. For tightening the collimation further, we explored neutron diffraction from a single crystal prism. In the vicinity of a Bragg reflection, a fraction of neutrons incident on such a prism propagates through the crystal [4,5] and exits its side face [6-9] in forward diffracted and diffracted beams (Fig. 1). We have coined the term Bragg prism for this device.

2. Bragg prism

By judiciously optimising the Bragg reflection, asymmetric configuration, apex angle of the prism and incident beam position on the front face, the diffracted beam can be collimated down to a fraction of an arcsec [9]. An analyser prism can likewise be designed to accept an extremely narrow neutron angular profile. Fig. 2 depicts such an optimised Si {111} monochromator-analyser Bragg prism pair for 5.26 Å neutrons. A monochromator with the asymmetry angle \( \theta_s = 50.1^\circ \) and apex angle \( A = 172^\circ \) yields a beam collimated to 0.53 arcsec FWHM. An analyser with \( \theta_s = -51^\circ \) and \( A = 16^\circ \) is expected to accept a pair of 0.22 arcsec wide neutron peaks separated by 2.13 arcsec. Fig. 3 displays these predicted angular profiles, incorporating the appropriate Debye Waller factor and their convolution, comprising two 0.57 arcsec wide peaks separated by 2.35 arcsec. The single crystal prism combination thus produces and analyses a neutron beam with sub-arcsec collimation.
3. Experimental

Several monochromators with $\theta_s$ close to 50° and one analyser with $\theta_s = -51°$ were fabricated with the specified apex angles at BARC. A <100> single crystal silicon ingot was aligned using {111} and {220} reflections of 1.2 Å neutrons at the triple axis spectrometer (TAS) in the Dhruva reactor. Cuts at the desired orientations and dimensions were made on this ingot on a Blohm precision grinding machine and subsequent surfacing achieved with a diamond polishing wheel at the Centre for Design and Manufacture (CDM). Final sub-micron polishing and a long (20 minute) and slow etching, to remove all residual strains, operations were performed at the Chemical Laboratory of Hahn-Meitner-Institut (HMI) in Berlin.

The experiment was carried out at the V12b Double Crystal Diffractometer set-up of BENSC (HMI) in Berlin. The analyser rotation could be adjusted in two stages; first in 1 arcsec steps with a geared step motor and then with a piezocrystal driven stage, with the smallest step size of 0.156 arcsec. Direct Bragg reflections, being much stronger and wider than prism diffractions, were first used, facilitating a quick and easy alignment of the analyser. For a monochromator prism ($\theta_s = 50.1°$), a 3.1 arcsec wide nearly triangular rocking curve was recorded (Fig. 4). The monochromator was then translated along the incident beam (see Fig. 2) to illuminate the analyser with its prism diffraction to obtain a 2.5 arcsec wide curve (Fig. 5). After optimising the analyser alignment, a cadmium sheet was introduced before the detector to stop Bragg reflected neutrons from the analyser. With these Bragg prism diffractions, the analyser tilt adjustment became even more critical and had to be made in 0.9 arcsec steps. The rocking curve (Fig. 6) comprising a pair of 0.62 arcsec wide peaks separated by 2.2 arcsec (squares), implies a 0.58 arcsec FWHM for each peak in the beam emanating from the monochromator and is in
This super collimated neutron beam can probe wave vector transfers $Q \sim 10^{-6}$ Å$^{-1}$. The first SUSANS (Super Ultra-Small Angle Neutron Scattering) spectrum in this $Q$-range was recorded with a hydroxyapatite casein protein sample (Figs. 7-8) placed between the monochromator and analyser. The log-normal size distribution of spherical agglomerates in the sample inferred [10] from the SUSANS spectrum has a 53 μm median radius and 46 μm FWHM between half maxima of 27 and 73 μm. The greater half-maximum radius implies the instrument capability of characterising agglomerates upto about 150 μm in size.

Fig. 7 First SUSANS spectrum over $Q \sim 10^{-6}$ Å$^{-1}$

Fig. 8 Left (left) and right (right) peaks in Fig. 7 on the $Q$-scale. Sample: hydroxyapatite casein
Fig. 9 First neutron diffraction pattern with a grating of 200 μm period (inset) and fitted curve (right)

Fig. 9 is a SUSANS pattern of a grating of ~ 200 μm period made by winding a steel wire of 100 μm diameter tightly on a 50x50 mm² aluminium frame (inset). The peaks, considerably broadened due to multiple scattering and refraction in the cylindrical wires, are modulated by clearly resolved diffraction oscillations. The transverse coherence length of 175 µm (FWHM) derived from the least squares fit (Fig.9 right) to the data far exceeds the previous best value of 80 µm [11] obtained for a 1.4 arcsec wide beam as well as the highest (5µm) observed in neutron interferometry [12].

6. Conclusion

We have presented the narrowest, viz. the first sub-arcsec, angular profile for a neutron beam having the highest transverse coherence length and affording SUSANS studies down to Q ~ 10⁻⁶ Å⁻¹.

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