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High angular resolution neutron interferometry

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ABSTRACT

The currently largest perfect-crystal neutron interferometer with six beam splitters and two interference loops offers novel applications in neutron interferometry. The two additional lamellas can be used for quantitative measurements of a phase shift due to crystal diffraction in the vicinity of a Bragg condition. The arising phase, referred to as "Laue phase," reveals an extreme angular sensitivity, which allows the detection of beam deflections of the order of 10^{-6} s of arc. Furthermore, a precise measurement of the Laue phase at different reflections might constitute an interesting opportunity for the extraction of fundamental quantities like the neutron–electron scattering length, gravitational short-range interactions in the sub-micron range and the Debye Waller factor. For that purpose several harmonics can be utilized at the interferometer instrument ILL-S18.

1. Introduction

Perfect crystal X-ray and neutron interferometry has a long history [1–3], but an interesting feature of crystal interferometers, namely their extreme angular sensitivity, has been exploited only by intensity measurements [4,5] but not yet by phase measurements. Only recently, the machining of large-scale crystal interferometers, specially designed [6], opened novel applications in neutron optics and fundamental physics [7]. The interferometer of Mach–Zehnder type has been cut with two additional lamellas L_1 and L_2 in the middle (Fig. 1), which can be used for the measurement of crystal phases due to dynamical diffraction. We refer to this phase as "Laue phase" [8] because the underlying diffraction process is known as Laue transmission in crystallography. Due to the large interferometer dimensions, different prism configurations can be employed for coherent beam deflection with smoothly tunable deflection angles [7]. It turns out that the Laue phase is extremely sensitive to beam deflections in front of the crystal lamellas (Section 2), which become detectable with the new interferometer setup (Section 3). After the first successful tests and phase measurements new applications can be envisaged, like the nice idea presented by Ioffe et al. [9] for measuring the neutron–electron scattering length, or a proposal made by Greene et al. [10] for testing a hypothetical short-range interaction (Section 4).

2. Laue phase and angular sensitivity

A distinct phase shift is generated when the neutron wave passes a perfect crystal plate close to the Bragg condition [11,8]. In the following, we are considering only the diffracted wave in forward direction. The Laue phase is then defined as the argument of the complex transmission amplitude (t) as shown in Fig. 2.

$$\phi_{Laue}(y) \equiv \arg\{t(y)\} \quad y = -\delta\theta \sin 2\theta_B E/|V_{hkl}|. \tag{1}$$

The parameters y and $\delta\theta = \theta - \theta_B$ describe the beam deviation from the Bragg angle θ_B, E the neutron energy and $|V_{hkl}|$ the crystal potential [12]. The Laue phase in an analytical form reads

$$\phi_{Laue}(y) = \phi_{Laue}(0) - A_H y + \arctan\left\{\frac{y}{\sqrt{1+y^2}} \tan\left[A_H\sqrt{1+y^2}\right]\right\}. \tag{2}$$

At certain positions of $\delta\theta$, the arctan term induces a distinct fine-structure to the phase which is extremely sensitive to the Pendellösung length Δ_H. The Pendellösung length is an important parameter in crystal optics because it contains important quantities like the atomic scattering length (b_{atom}) and the Debye Waller factor (W)

$$A_H \equiv \pi D/\Delta_H \quad \Delta_H = \frac{\pi n}{2 d_L N b_{atom}(q) e^{-W(q)} \tan\theta_B} \tag{3}$$

b_{atom} and W depend on the momentum transfer ($q = 2\pi n/d_L$); N denotes the atomic density, d_L the lattices spacing and n the order of reflection. It turns out that the slope of the Laue phase, and hence the angular resolution, reaches its maximum in the vicinity of the Bragg condition $\delta\theta = \theta - \theta_B \to 0$. There ϕ_{Laue} increases linearly with $\delta\theta$ and the angular resolution is determined by the geometric ratio of thickness (D) and lattice

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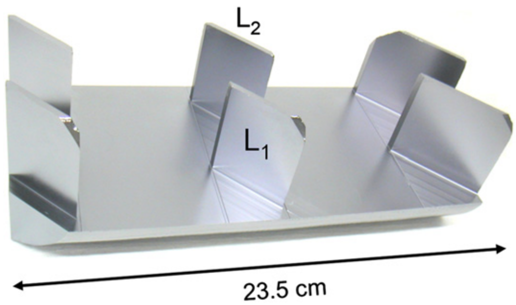

Fig. 1. The currently largest perfect crystal neutron interferometer.

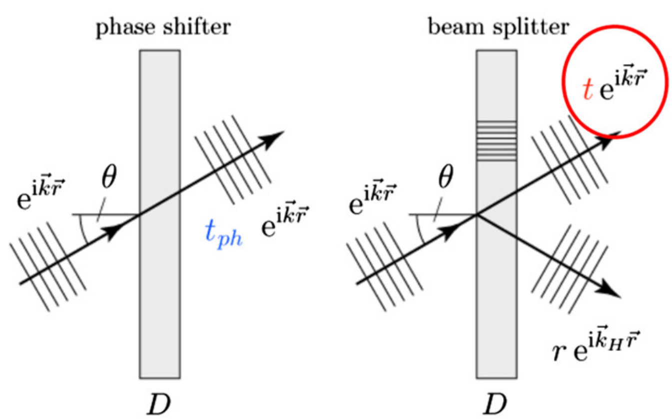

Fig. 2. Comparison of the phase shifter case (left) where only refraction occurs, and the Laue transmission (right) where dynamical diffraction causes strong phase variations.

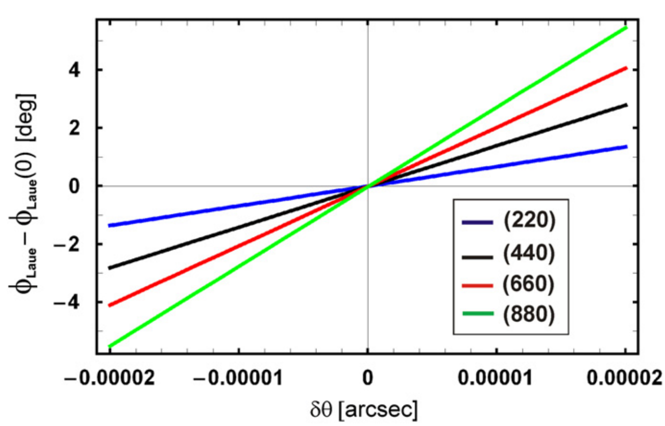

Fig. 3. Laue phase calculated for collimated beams in the vicinity of the Bragg condition. Higher reflections orders (shorter wavelengths) yield higher angular sensitivity (D=15 mm).

spacing (d_L)

$$\phi_{Laue}(\delta\theta) \approx \phi_{Laue}(0) + \delta\theta\,\frac{\pi n D}{d_L} + O(\delta\theta^3) \tag{4a}$$

or alternatively it can be written as a function of momentum transfer

$$\phi_{Laue}(\delta\theta) \approx \phi_{Laue}(0) + \delta\theta\,\frac{qD}{2} + O(\delta\theta^3). \tag{4b}$$

Higher order reflections (nh,nk,nl), or equivalently larger momentum transfers, are therefore more sensitive to beam deflections (Fig. 3).

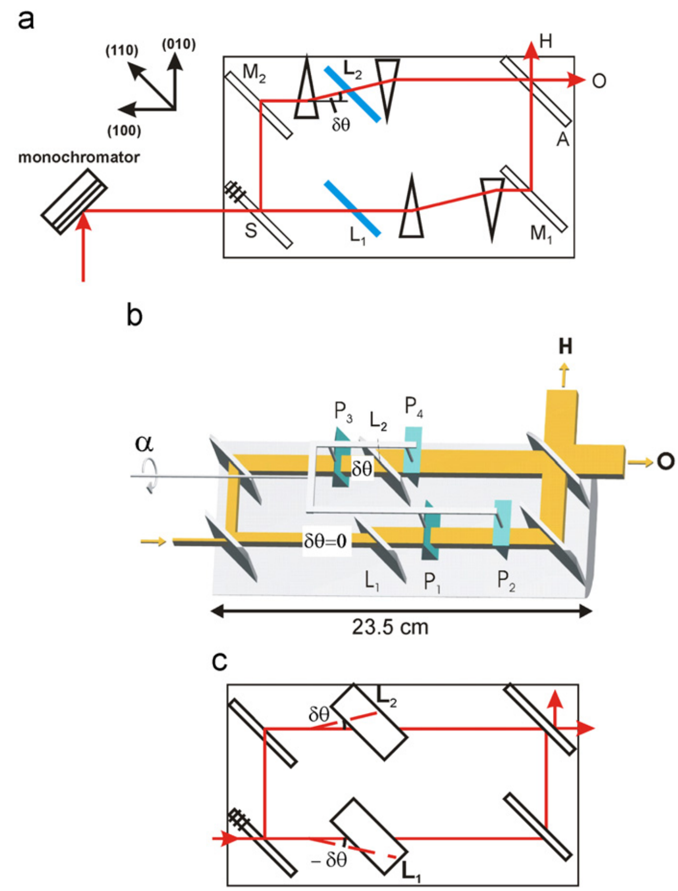

Fig. 4. Setup for detecting small beam deflections $\delta\theta$ in the six plate interferometer: (a) Present setup with four identical prisms and 3 mm thick lamellas. The prism in front of L_2 creates a beam deflection and thereby a phase difference between L_2 and L_1. The other prisms are necessary to avoid dephasing and defocusing; (b) Experimental realization at ILL-S18; (c) Proposal for a new design to enhance phase sensitivity and angular resolution.

3. Angular resolution in the perfect crystal interferometer

First measurements of the Laue phase have been performed at an instrument ILL-S18 with the configuration shown in Fig. 4a. The fine-tuning of beam deflection $\delta\theta$ was achieved with a simultaneous rotation of four aluminium prisms about the axis α (Fig. 4b). The averaging of the Laue phase over the angular distribution slightly reduces the instrumental resolution yielding an angular sensitivity of

$$\frac{\phi(\delta\theta)}{\delta\theta} \cong \frac{8.5^\circ}{0.001''}(440) \text{ and } \frac{\phi(\delta\theta)}{\delta\theta} \cong \frac{6^\circ}{0.001''}(220) \tag{5}$$

near the Bragg condition [13]. In fact, the current interferometer geometry in Fig. 4b is a compromise because further experiments are intended, in which the two-loop feature becomes essential [7]. The angular sensitivity would further be enhanced by machining a new interferometer with thicker lamellas, for example $L_1 = L_2 = 15$ mm as sketched in Fig. 4c, and by generating two opposite beam deflections. Assuming a realistic phase resolution of 0.1°[1] and considering all possible improvements an angular resolution of 10^{-6} s of arc (5×10^{-12} rad) seems feasible.

[1] The phase resolution $\Delta\phi$ is limited mainly by quality and mounting of the interferometer crystal, the count numbers and the thermal stability of the whole setup. A phase resolution of 0.1° could be reached statistically without one day at instrument ILL-S18 by applying an interleaved scanning procedure, where systematic phase drifts are largely suppressed. Currently, the systematic uncertainty due to thermal instability reduces the phase resolution to approximately 0.5°.