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A large-area neutron-interferometer optimized for coherent beam deflection: Applications

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ABSTRACT

A large perfect crystal interferometer with two interference loops offers novel applications in neutron interferometry. Coherent beam manipulation with special prism and phase shifter arrangements is discussed and prism materials that are able to preserve beam coherence in case of thicker prisms are investigated. A set of four identical prisms has been used to determine the vertical coherence function in an experiment performed at instrument ILL-S18. Several proposals for new experiments are outlined for (a) squeezing in momentum space, (b) precise measurement of gravitational induced phase shifts, and finally, (c) the simulation of a split crystal interferometer.

1. Introduction

With the large-area six-plate perfect crystal interferometer introduced in Ref. [1] new experimental methods become feasible in different fields of neutron interferometry. A key feature of the instrument is the use of higher order reflections without change of beam geometry. The available monochromatic beams cover a range from λ=0.68 Å up to 2.72 Å. The use of different wavelengths will be convenient in a variety of systematic studies, for example, for a new approach to distinguish between geometrical and dynamical phase shift [2], for scattering length measurements [3,4], for gravitation experiments [5], or for simulation of a split-crystal neutron-interferometer.

Another important feature of the instrument is the much larger available sample space which considerably facilitates the experiments presented here. Especially for thick samples there are, nevertheless, stringent requirements on the homogeneity of the prism material. Several materials with thicknesses more than 1 cm and suitable for coherent beam deflection have been investigated and are discussed in Section 2. A set of four identical prisms has been fabricated for measuring the vertical coherence function at instrument S18 [6] at Institute Laue-Langevin (ILL), Grenoble, France, and these results are described in Section 3. Additional beam deflection experiments are presented in Section 4.

2. Materials suitable for coherent beam manipulation

Most of the materials used in the past for neutron interferometry consisted of rather thin slabs with only a few millimeters of thickness [7,3]. In the coherent deflection experiments two prisms are used in every path, the first prism for beam deflection, and the second for phase compensation and to avoid defocusing. The optical path length through two prisms can be several centimeters, depending on the prism opening angle. The requirements for the prism material are therefore much more

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stringent than for thin phase plates [3]:

$$V_S = \exp\left\{-\left[\left(\frac{\delta t}{t_S}\right)^2 + \left(\frac{\delta N}{N}\right)^2\right](Nb_c\lambda t_S)^2/2\right\}V_0 \quad (1)$$

where V_0,V_S denote the visibilities without and with sample in one interferometer path, t_S is the sample thickness, with δt the thickness variation of the sample, and δN describes the fluctuation in the number of nuclei per volume. The influence of δN strongly increases with t_S^2 in the exponent. Especially inhomogeneities $>1\,\mu$m affect the visibility [4] and cause ultra-small angle scattering (USANS), which can be analyzed with the same setup (Fig. 1). The visibility reduction is wavelength dependent, i.e., smaller wavelengths maintain higher visibility in thick samples. Table 1 lists a representative selection of prism materials considering the following criteria:

- Homogeneity: visibility reduction and USANS negligible
- Absorption negligible
- Large scattering length density Nb_c for strong beam deflection
- Machinability with high geometric accuracy and good surface quality
- Reasonable material and production costs

Several of the listed materials have been used for preparation of thick phase shifters for visibility (Table 2) and USANS measurements at instrument S18. Typically, USANS investigations are performed by using a channel-cut analyzer, but with our instrument these can be accomplished in the interferometer without changing the setup (Fig. 1). Especially the good applicability of single crystal materials (MgF_2, sapphire) should be noted. Different aluminium alloys, as well as different types of fused silica, have shown a large variance of visibility. Stronger USANS correlates with a pronounced visibility reduction and this confirms density fluctuations δN as main source of dephasing in the samples (Fig. 1, Table 2).

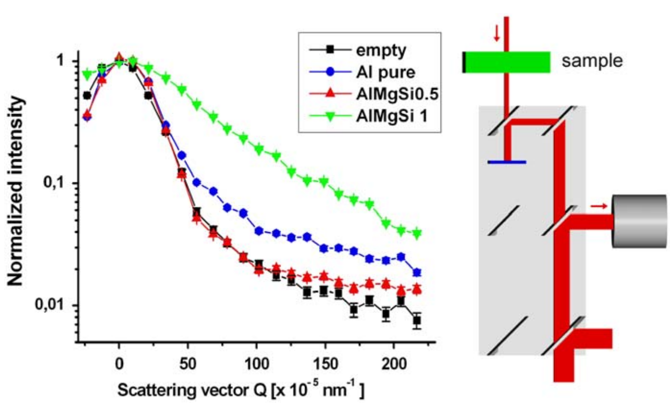

Fig. 1. Arrangement for USANS detection using the interferometer in Laue reflection. The aluminium plate with the highest visibility, AlMgSi0.5, shows the lowest ultra-small angle scattering ($Q=4\pi/\lambda \cdot \sin\theta/2$, θ=scattering angle).

Table 1
Selection of suitable prism materials.

Material	Nb_c (10^{10} cm^{-2})	δ (β=30°)
Silicon	2.07	0.27″
Aluminium	2.08	0.27″
Fused silica	3.46	0.45″
Quartz	4.18	0.54″
Germanium	3.61	0.46″
MgF_2	5.11	0.66″
Sapphire	5.74	0.74″
MgO	5.99	0.77″
Graphite	7.5	0.96″
(Diamond)	11.7	1.5″
(Beryllium)	9.62	1.23″

Nb_c=coherent scattering length density, δ=deflection angle, β=prism opening angle.

Table 2
Test plates placed in both interferometer paths for visibility measurements (λ=2.7 Å, visibility normalized to an empty interferometer).

Material	Specification	Thickness (cm)	Visibility
AlMgSi0.5	Wrought	2	96(1)%
AlMgSi1	Wrought	2	10(2)%
Al99.5	Wrought	2	72(3)%
AlMg4,5Mn	Cast	0.5	35(3)%
Fused silica	Grade 2F	1	94(3)%
MgF_2	VuV, single crystal	1	92(3)%
Sapphire	Single crystal	1	98(2)%

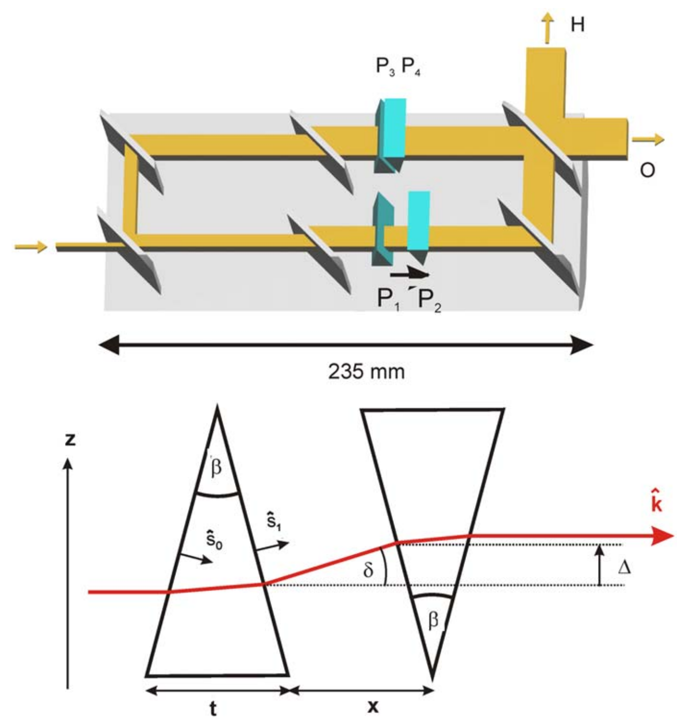

Fig. 2. Prism arrangement for measurement of the vertical coherence function.

3. Vertical coherence

Measurements of the vertical coherence function have first been performed at the MURR facility [8], and more recently, in a more elegant approach, prisms have been employed at the NIST [9] and ILL [10]. The coherence function is given by the autocorrelation function of two overlapping wave functions shifted by a spatial displacement $\vec{\Delta}$ [3]:

$$\Gamma(\vec{\Delta}) = \int \Psi^*(\vec{r})\Psi(\vec{r}+\vec{\Delta})d^3r \quad (2)$$

$|\Gamma(\vec{\Delta})| = V_0$ is the visibility of interference fringes and contains all accessible information about coherence properties. The coherence length in Gaussian approximation is defined as the spatial shift at which $|\Gamma(\Delta_{coh})|$ has decreased by a factor $1/e$. A displacement $\vec{\Delta}$ can be realized by a set of four identical prisms as depicted in Fig. 2. In one path the two prisms are joined together, working like a slab [x=0], in the other beam the two