

A PHASE-GRATING INTERFEROMETER FOR VERY COLD NEUTRONS

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An interferometer for very cold neutrons using three phase gratings sputter-etched into quartz-glass plates has been developed for fundamental physics experiments. The lines of the phase gratings were aligned parallel to $1\ \mu\text{rad}$ by light interferometry. A prototype interferometer with an overall length of 50 cm has been tested for $\lambda = 102\ \text{\AA}$ ($v = 38.7\ \text{m/s}$) neutrons.

Since the first successful experimental tests by Maier-Leibnitz and Springer [1] of a biprism neutron interferometer and by Rauch, Treimer and Bonse [2] of a perfect-crystal neutron interferometer numerous experiments have been performed, most of them aimed either at precision measurements of properties like scattering lengths or at tests of fundamental predictions of quantum mechanics. The field of neutron interferometry is already so wide that for details the reader has to be referred to the proceedings of a recent conference [3]. The majority of these experiments has been done with the three-crystal Laue-case interferometer, the so-called LLL-interferometer [2], yet there exist also other types of neutron interferometers. With perfect crystals, two-crystal interferometers both of the Laue-case (LL) [4] and of the Bragg-case (BB) [5] type have been tested successfully. These interferometers exploit the distinct advantage of large perfect crystals: all optical elements (beam splitters and mirrors) can be cut out

of one and the same crystal. This implies perfect alignment of the elements with respect to each other. Clearly, since Bragg diffraction is the physical process by which these perfect-crystal interferometers operate, their field of application is essentially limited to neutrons of thermal energies. For some applications it is desirable to have very large, i.e. meter-size, interferometers. In that case the construction of a perfect-crystal interferometer poses severe alignment problems. Thus it is of considerable significance that neutron interferometers based on more conventional optical principles have been demonstrated to operate. For $\lambda = 3.15\ \text{\AA}$ neutrons Ioffe, Zabiyaikin and Drabkin [6] have developed an interferometer based on a combination of mirrors and reflection gratings. For $\lambda = 20\ \text{\AA}$ neutrons both a Billet-type split-lens interferometer [7] and a double-slit interferometer [8] could be operated. In contrast to the perfect-crystal interferometers, these interferometers have found no or little application due to various limitations. It is the purpose of the present Letter to report the successful development of an interferometer for $\lambda = 100\ \text{\AA}$ neutrons which is based

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on transmission phase gratings as optical elements and which has several distinct advantages over the interferometer types developed so far.

The interferometer operates on the new optical table on Niveau D of the high-flux reactor at the Institut Laue-Langevin, Grenoble. There, a beam of very cold neutrons emerging through the vertical neutron guide tube from the liquid D₂ cold source [9] is available. The peak wavelength of 102 Å with a FWHM bandwidth of 22% was determined by a time-of-flight method. The details of the general setup including the necessary vibration isolation provided by the optical table have been published recently [10].

In principle, a neutron interferometer operating in the 100 Å wavelength range could be based on a variety of different optical elements. Of all these, transmission gratings were chosen because a relatively wide neutron beam may be used, thus relaxing somewhat the severe intensity limitations resulting from the significant drop of the Maxwellian intensity distribution at that wavelength. It may be noted that $\lambda = 100$ Å neutrons correspond to a temperature of 0.1 K which is in the low-energy tail even of the 25 K Maxwellian distribution emerging from the D₂ cold source. For the same reason it was decided to employ phase gratings. Also, if operated in the symmetric transmission mode, the alignment requirements of the interferometer are less stringent than in other geometries and, as is well known from optics, a grating interferometer is free of dispersion and aberration^{#1}.

A principal sketch of the diffraction gratings^{#2} may be seen in fig. 1. On a piece of 2.5 mm thick quartz glass two gratings are arranged side by side. The grating which is used for neutron diffraction has been sputter-etched into the quartz glass. The grating for light is an absorption grating which is produced by evaporation of chromium onto the quartz substrate. Both gratings are parallel to each other better than 0.1 µm over the whole length of the lines. Each grating is 8 cm larger and 1 cm wide. Both have a 1:1 ratio of line to slit width: this geometry suppresses

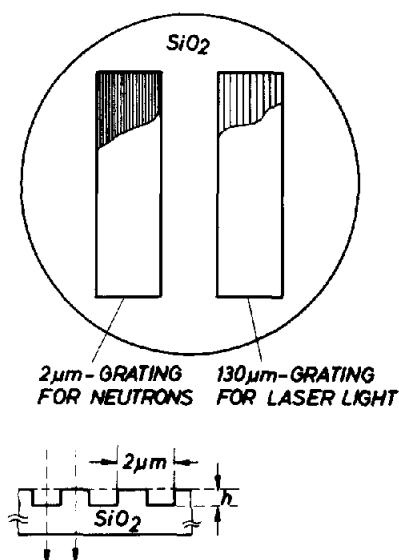


Fig. 1. Quartz glass plate with a phase grating for neutrons and a light-absorption grating (top, not to scale) and a cross-section of the phase grating (bottom). The height h determines the phase shift.

all even order diffractions. In practice this means that only diffraction into zero-order maximum and the two first order maxima is of significance, thus improving again the neutron "economy" of the interferometer. The grating constant for the absorption grating was chosen to be 130 µm in order to obtain the same diffraction angle (5 mrad) for He-Ne laser-light as for the $\lambda = 102$ Å neutrons at the 2 µm phase gratings. Phase gratings provide the further advantage of a phase-dependent intensity distribution for different orders. The relative phase between two beams passing through the lines and the slits of the grating respectively (fig. 1) is

$$\chi = 2\pi h / D_\lambda, \quad (1)$$

where D_λ is the λ -thickness for neutrons of the material used. For $\lambda = 102$ Å neutrons the λ -thickness of quartz glass is 1.8 µm. The zero order maximum is a superposition of the waves with relative phase χ . Clearly, if the amplitudes of the two waves are of equal magnitude, which is the case for a 1:1 grating, and if $\chi = \pi$, the zero order maximum is canceled. For intensity reasons we choose a phase shift of π for the second grating in the interferometer and of $\pi/2$ for

^{#1} For diffraction-grating neutron interferometers this case has been discussed by Ioffe [11].

^{#2} The gratings were made by Heidenhain, D-8225 Traunreut, FRG.

the first and the third grating. These phase shifts can be achieved for one wavelength only.

The setup for our experiment is seen in fig. 2. The slits S_1 and S_2 define the neutron beam and its angular width (0.6 mrad) incident on the first grating G_1 . Slit S_3 which is 1.25 mm off axis shields off neutrons from other interferometer arms. After a flight path of 1.6 m the O-beam, i.e. the beam parallel to the incident beam, is separated by 8 mm from the H-beam, thus only O-beam neutrons are detected by the BF_3 counter. The He-filled tubes are used to minimize loss of neutrons due to scattering and absorption.

The interferometer employs three diffraction gratings in parallel geometry (fig. 3). For adjustment purposes the gratings are mounted on combinations of precision rotation and translation tables permitting rotation around all three axes in space and translation in a direction along the periodicity vector of the gratings. The precision required for the parallel adjustment of the three gratings is quite different for the three angular directions. Interferometer operation is most sensitive to relative rotational misalignment of the gratings around the direction of the neutron beam. There, microradian-precision is required, whereas for the other directions milliradian-precision is satisfactory.

The parallel alignment of the three gratings was performed in two steps. First, the three plates were arranged parallel by an autocollimation telescope. The alignment achieved that way is sufficient for all directions except rotation around the neutron propagation direction. Around that direction using telescope sighting, the lines of the phase gratings may be set in parallel to within 50 μm over the 80 mm length

of the lines. The final alignment is then performed by laser-light interferometry using the light-absorption gratings. Three such interferometers are operating simultaneously (fig. 3), two are parallel to each other with beam passage through the top and the bottom parts of the gratings respectively and one passes at an oblique angle. The alignment procedure consists of scanning one of the three gratings along the scattering vector measuring the relative phase of the three light interference patterns. This information is then used to realign the gratings with differential micrometers until the three laser-light interferograms coincide within 0.1 μm in their phase position, which translates into parallelism of the grating lines within 1 μrad or 0.2 arcsec.

The neutron interference pattern may then be measured in principle in two different ways. Either, as is conventional, a phase shifter is inserted into one of the interferometer arms or, alternatively, one of the diffraction gratings is scanned along the scattering vector. These two methods are equivalent to zero order in λ because in both cases the variation of the intensities of the output beams leaving the interferometer results from the relative positional shift between the third diffraction grating and the standing-wave pattern formed there by the superposition of the two interfering beams. The second method has the advantage of being non-dispersive.

In our case the first diffraction grating was shifted by 0.2 μm steps. The intensity of the O-beam was measured for 30 min each step. The distance from the first to the third grating was 50 cm. Fig. 4 shows a typical interference pattern. If all experimental parameters were ideal, one would expect 100% modulation of the O-beam. This can easily be seen as fol-

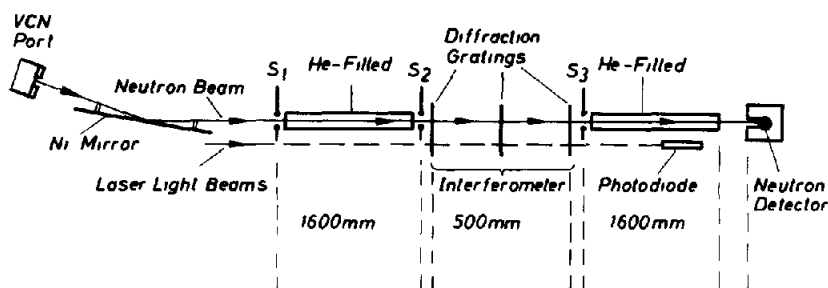


Fig. 2. Overall setup of the experiment (drawn not to scale).

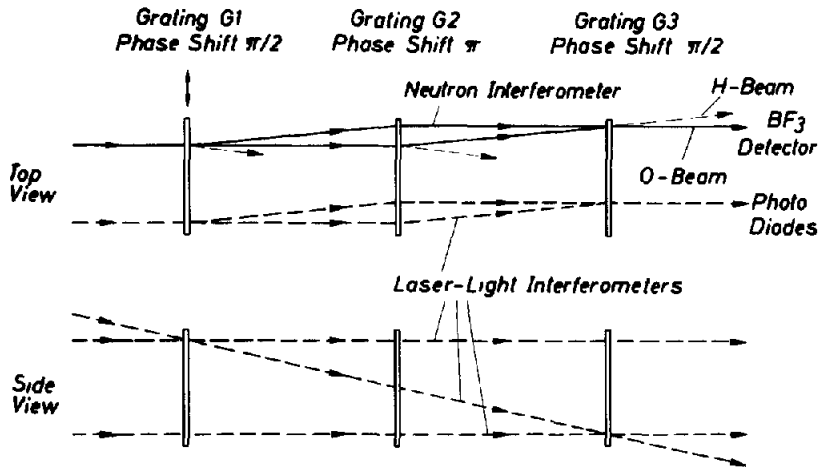


Fig. 3. Top and side view of the beam trajectories in the interferometer. The laser-light interferometers are used to align the neutron interferometer.

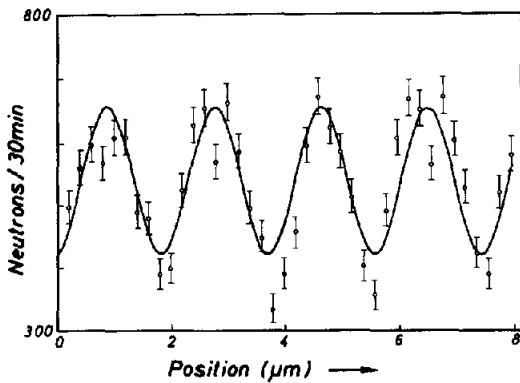


Fig. 4. Neutron interference pattern of the $2\mu\text{m}$ -phase-grating interferometer for $\lambda = 102 \text{ \AA}$ neutrons. The pattern was obtained by translation of the first grating G_1 along the scattering vector. The solid line represents a least-squares sine approximation.

lows: Ψ_0 is the superposition of amplitudes due to the two different trajectories through the interferometer:

$$\Psi_0 = \Psi_1 + \Psi_2 e^{i\chi}, \quad (2)$$

where the two amplitudes Ψ_1 and Ψ_2 may be written as

$$\Psi_1 = r_{-1}(G_3) r_{+1}(G_2) t(G_1) \Psi_i$$

and

$$\Psi_2 = t(G_3) r_{-1}(G_2) r_{+1}(G_1) \Psi_i, \quad (3)$$

where Ψ_i is the incident wave, $t(G_n)$ is the amplitude for transmission at the grating G_n , $r_{+1}(G_n)$ is the amplitude for diffraction into the maximum of order +1 at the grating G_n etc. If the gratings G_1 and G_3 are identical and if all gratings are symmetric we may write

$$|r_{-1}(G_3)| = |r_{+1}(G_1)|, \quad |r_{+1}(G_2)| = |r_{-1}(G_2)|, \\ t(G_1) = t(G_3), \quad (4)$$

i.e., the reflection amplitudes may only differ by a phase factor. These conditions imply that

$$|\Psi_1| = |\Psi_2| \quad (5)$$

and, hence, 100% intensity modulation of the O-beam upon variation of χ . Clearly, conditions (4) hold in the ideal case for each wavelength separately, thus implying the dispersion-free property of the interferometer.

Presently we are working on the extension of the length of the interferometer. The ultimate goal is to achieve a separation of 4 m between the first and the third grating. Experimentally the main problem there stems from the fact that our neutrons are slow enough (40 m/s) to fall already appreciably in the gravitational field of the earth (5 cm over 4 m). If the neutrons used were monochromatic, this would not pose new alignment requirements. Yet, because of the rather large width of the wavelength distribution

in the neutron beam, the neutrons spend different times in the interferometer which results in a variation of the fall height of the order of 2 cm between different neutrons. This implies that the lines of the diffraction gratings have to be aligned in parallel to the local g -vector with an angular precision $\delta\theta \ll 2 \mu\text{m}/2 \text{ cm}$ which again is arcsec precision. Also, care has to be taken to compensate for the Sagnac phase shift due to the Earth's rotation which, for a grating interferometer of the type used here, is dispersive.

A number of different experiments have already been proposed for the new VCN-interferometer [10]. They use one of its advantages or combinations thereof. These advantageous new features and the respective gain factors for a 4 m size interferometer over existing crystal interferometers are

- larger neutron wavelength (factor 30–100),
- larger neutron flight time (1000–3000) and
- larger enclosed area between the beams (20–50).

Yet, clearly, the considerable intensity advantage of the crystal interferometers makes it advisable to use the new VCN-interferometer only in applications which otherwise could not be reached. Of the experiments proposed so far we consider most interesting:

- the measurement of the predicted variation of the neutron refractive index with neutron wavelength at low energies (a Fizeau-type effect [12]),
- the measurement of the action on the neutron beam by a laboratory-created gravitational force (the elementary particle analog of the Cavendish effect),
- the improvement of the present limit of the neutron electric charge [13],
- the reduction of the present upper limit on a possible nonlinear term in the Schrödinger equation [14] and
- the precision measurement of the phase shift due to the earth's gravity [15].

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