NORTH-HOLLAND
PHYSICS
PUBLISHING

THE NEW VERY-COLD-NEUTRON OPTICS FACILITY AT ILL

K. EDER, M. GRUBER and A. ZEILINGER *

Atominstitut der Österreichischen Universitäten, Schüttelstr. 115, A-1020 Wien, Austria

R. GÄHLER

Physik-Department E21, Technische Universität München, D-8056 Garching, FRG

W. MAMPE and W. DREXEL

Institut Laue – Langevin, BP 156X, F-38042 Grenoble, France

At the vertical neutron guide from the cold source of the ILL an optical table with vibration isolation has been installed. The beam of very cold neutrons (VCN) has a nominal wavelength of 100 Å. We discuss the operational principles of an interferometer operating with VCN. This interferometer will be based on phase gratings as optical elements. VCN-diffraction at these gratings has been studied in great detail. Finally we list the experiments envisaged.

Reprinted from NUCLEAR INSTRUMENTS AND METHODS
IN PHYSICS RESEARCH A

Nuclear Instruments and Methods in Physics Research A284 (1989) 171–175
North-Holland, Amsterdam

THE NEW VERY-COLD-NEUTRON OPTICS FACILITY AT ILL

K. EDER, M. GRUBER and A. ZEILINGER *

Atominstitut der Österreichischen Universitäten, Schüttelstr. 115, A-1020 Wien, Austria

R. GÄHLER

Physik-Department E21, Technische Universität München, D-8056 Garching, FRG

W. MAMPE and W. DREXEL

Institut Laue–Langevin, BP 156X, F-38042 Grenoble, France

At the vertical neutron guide from the cold source of the ILL an optical table with vibration isolation has been installed. The beam of very cold neutrons (VCN) has a nominal wavelength of 100 Å. We discuss the operational principles of an interferometer operating with VCN. This interferometer will be based on phase gratings as optical elements. VCN-diffraction at these gratings has been studied in great detail. Finally we list the experiments envisaged.

1. General

The new vertical neutron guide tube originating from the liquid deuterium cold source at the ILL high-flux reactor (see ref. [1], which also contains technical details of the curved neutron guide) has been designed primarily to feed a Steyerl-turbine [2] in order to produce intense beams of ultracold neutrons. This neutron turbine utilizes only half of the cross section of the vertical guide. Therefore the neutron guide, just before entering the turbine vessel, is split into two guides, one of which feeds the turbine and the other one passes by the wheel in a curved nickel guide of 13 m radius curvature and 3.4×7 cm^2 cross section. This setup provides for a beam of very-cold neutrons with a peak intensity around 80 Å wavelength. It is this beam which is being exploited in the new very-cold-neutron optics setup.

Very-cold neutrons (VCN) may operationally be defined to be of energy and wavelength in between the standard cold neutron regime and the ultracold neutrons. Conventional cold neutrons are characterized by having wavelengths smaller than about 10 Å, making them useful for the investigation of condensed matter. Ultracold neutrons, on the other hand, are defined such as to have kinetic energies too small to overcome the mean optical potential of matter and thus are subject to critical external total reflection under all angles of incidence. This sets the minimum wavelength of ultracold neutrons to about 500 Å. Thus, in wavelength and energy the range of very-cold neutrons may be approximately defined as follows:

$$10\ \text{Å} \lesssim \lambda_{\text{VCN}} \lesssim 500\ \text{Å},$$

$$10^{-6}\text{eV} \lesssim E_{\text{VCN}} \lesssim 10^{-3}\ \text{eV}.$$

From a practical point of view, this is just the range of neutron energies and wavelengths where neither crystal diffraction may be used for beam handling as for thermal neutrons nor totally reflecting mirrors as for ultracold neutrons. In contrast, for VCNs just those beam handling devices may be used that are customary for visible light:

1. The refractive index may deviate significantly from unity and still remain noncomplex. This makes the use of refraction devices such as lenses and wedges feasible.
2. The wavelength, though still an order of magnitude smaller than that of visible light, is already large enough to permit the use of microfabricated structures with positional definition of micrometer magnitude. This makes the use of diffraction devices such as gratings feasible.
3. Combining both above features diffraction gratings may be used in the transmission mode.

It has therefore been proposed by us [5] to exploit the unique availability of a VCN beam at ILL by installing a general-purpose neutron optics facility. It is the purpose of the present article to report its status as of March 1989.

---

* Presently at Physik-Department E21, Technische Universität München, FRG.

0168-9002/89/$03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

2. The optical table

At the VCN exit port after the turbine an optical table was mounted (fig. 1). This optical table is of a honeycomb structure (RS-series by Newport) and it has a size of 6 m × 1.2 m. The optical table is supported by pneumatic vibration isolation legs. Since the exit port is about 3.5 m above the Niveau D floor at ILL a special stiffened steel beam support structure on which the vibration isolation legs are resting had to be made. This support structure is rigidly connected to the main support beams of Niveau D. These support beams have a height of 1.7 m and a thickness of 0.8 m.

After bypassing the neutron turbine the VCNs are being reflected by a nickel mirror which is set at a grazing angle of approximately 10°. This serves as a monochromator, effectively cutting off short wavelength neutrons and resulting in a peak wavelength around 100 Å. Fig. 2 shows the neutron spectrum obtained as measured by a time-of-flight technique. The sharp narrow minima at short wavelength are fully explained as arising from destructive interference of waves reflected at the front face and at the back face of the 2000 Å thick nickel layer of the mirror.

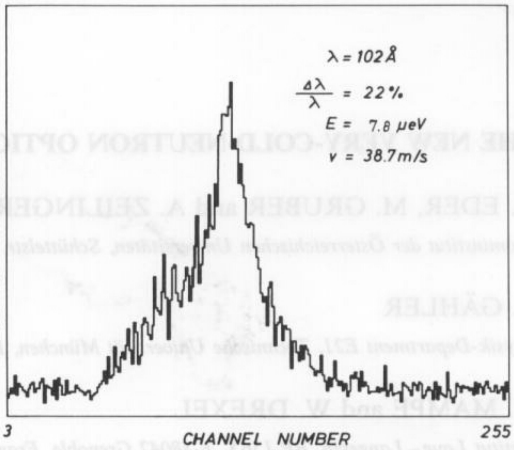

Fig. 2. Neutron spectrum after reflection from a nickel mirror at a grazing angle of nominally 10° measured by a time-of-flight method.

A problem deserving special attention is the effect of background vibration on the operation of any optical devices mounted on the top plate of the optical table. This is particularly important for the operation of interferometers. For the case of a perfect-crystal interferometer a thorough analysis of the influence of ambient vibration noise on interferometer performance has been presented by Shull [6]. Here we will only give a brief quantitative estimate of the maximum permissible vibrational noise level.

Suppose we wish, as is the case for our experiments, to study neutron diffraction effects at micrometer structures including neutron interferometry exploiting gratings of micrometer lattice constant. Then certainly we need the optical table to be stable on a scale much better than 1 μm during the neutron flight time of $t_0 \simeq 0.15$ s over the full length of the setup. This implies that for frequencies of the order of 5 Hz and more the maximum vibration amplitudes should be much less than 1 μm. Measurement of the vibration background on Niveau D indicates that there are a few vibration amplitude peaks in that frequency range which are of the order of 1 μm. These vibrations are very satisfactorily damped by the passive pneumatic vibration isolation legs of the optical table. The situation is somewhat more complicated for lower frequencies, i.e. frequencies in the 1 Hz range. There, certainly, a constant velocity motion of the optical table during the neutron flight time t_0 does not influence the experiment. The critical condition is rather that changes in position due to *accelerations* should be limited:

$$\Delta x \ll 1 \mu\text{m} \quad \text{with} \quad \Delta x = \tfrac{1}{2} a_0 t_0^2.$$

The maximum acceleration due to a given mode $x = x_0 \cos(\omega t)$ with amplitude x_0 and frequency $\nu = \omega / 2\pi$ is $a_0 = -x_0 \omega^2$. This implies a limit to the maximum amplitude of a given mode

$$x_0 \ll 2 \Delta x / (t_0 \omega)^2,$$

or, for our numbers,

$$x_0[\mu\text{m}] \ll 2 / (\nu[\text{Hz}])^2.$$

Measurement of the ambient vibration level on Niveau D at the ILL demonstrates that in this frequency range a peak of vibrational noise at approximately 1 Hz frequency and slightly below exists. This peak has an amplitude of about 10 μm which certainly would de-

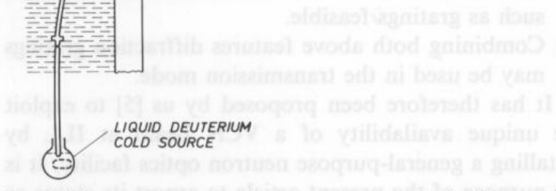

Fig. 1. The arrangement of the neutron optical table at the vertical guide at the Institut Laue–Langevin.

teriorate interferometer action. If measured on top of the steel support structure the same levels of ambient vibrational noise are found as may be expected from the property that the support structure does not employ any damping mechanism. Yet, if measured on top of the optical table, all vibrational amplitudes are significantly reduced with the critical 1 Hz frequency peak still having an amplitude of a few μm. This still implies displacements of the order of 1 μm due to acceleration during the neutron flight time. Thus additional low-frequency vibration damping is required. For this purpose an active feedback system of novel design was constructed whose features will be published elsewhere. Here it suffices to state that in a test of a preliminary version we could successfully demonstrate the reduction of the vibrational amplitudes at low frequencies to the order of 0.1 μm. This, combined with the passive pneumatic vibration isolation legs which reduce high-frequency noise, is expected to result in satisfactory optical table performance even for large-scale interferometers.

3. Neutron interferometer design

The first instrument planned to operate on the optical table will be a large-scale neutron interferometer. For VCN it is impossible to use perfect crystals as beam splitting devices. Hence, one could base an interferometer on the use either of mirrors or of gratings or of a combination of both. The latter was chosen in the successful demonstration of an interferometer with cold neutrons [7]. Yet, an interferometer based solely on gratings is preferable over an interferometer based on mirrors since it is achromatic and aberration-free. This fact, which is well from optics, clearly also holds for neutrons [8].

The interferometer geometry is basically the same as that of the first electron interferometer [9] which has also been employed in the perfect-crystal LLL interferometer [10,11] (fig. 3). Instead of the crystals, as was the case in these papers, we will employ transmission gratings with a lattice constant of 2 μm. The manufacture of such gratings is current technology. From a practical point of view the main difference as compared to the LLL interferometer is that, while there the individual crystal plates acting as beam splitters and mirrors respectively are already well aligned due to the monolithic design, in our case the three diffraction gratings have to be aligned by external means. This is done by employing interferometers operating with laser light. To that end, on the same plate of quartz glass a diffraction grating for the neutrons with a lattice constant of 2 μm and a grating for photons with a lattice constant of 130 μm are arranged (fig. 4). Diffraction of standard He–Ne-laser light at the latter grating results in the same diffraction angles as the diffraction of 100 Å wavelength neutrons at the 2 μm grating. Because of the size and the vertical divergence of the neutron beam a minimum of three independent laser interferometers operating at different height levels and different inclinations is necessary for sufficient alignment. Details of this and of an alternative alignment procedure proposed by Ioffe [12] will be published elsewhere.

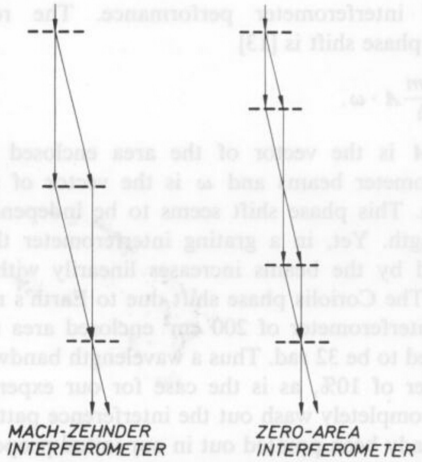

Fig. 3. Two possible topologies of a grating interferometer. The zero-area interferometer has the advantage of being insensitive to certain spurious effects, while the conventional Mach–Zehnder interferometer gives higher separation between the interferometer beams.

A point which deserves specific attention is the fact that the Coriolis force due to rotation of the Earth may

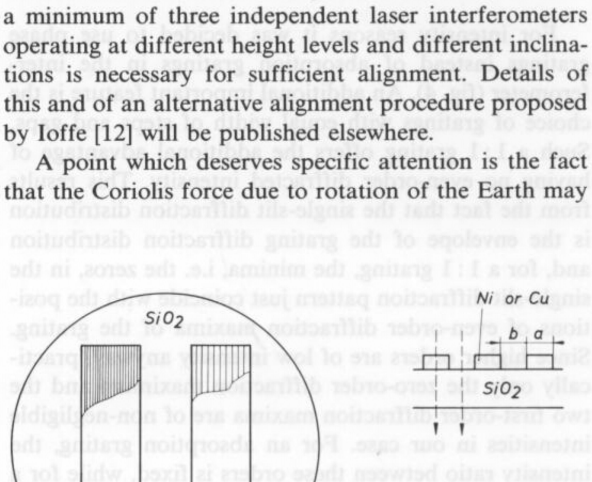

Fig. 4. Sketch of the phase gratings used. On the same quartz-glass plate a neutron grating and a laser-light grating are arranged side by side for alignment purposes (left). Two different types of phase gratings for neutrons were tested (right). In one type (top) the lines of the grating are made of Ni or Cu deposited through an electroplating procedure onto the quartz plate. In the second type (below) the grooves are sputter-etched into the quartz. The grating diffraction action results from the relative phase shift between neighbouring paths.

destroy interferometer performance. The resulting Sagnac phase shift is [13]

$$\Delta\phi = \frac{2m}{\hbar} \boldsymbol{A} \cdot \boldsymbol{\omega}.$$

Here, $\boldsymbol{A}$ is the vector of the area enclosed by the interferometer beams and $\boldsymbol{\omega}$ is the vector of angular rotation. This phase shift seems to be independent of wavelength. Yet, in a grating interferometer the area enclosed by the beams increases linearly with wavelength. The Coriolis phase shift due to Earth's rotation in an interferometer of 200 cm^2 enclosed area may be estimated to be 32 rad. Thus a wavelength bandwidth of the order of 10%, as is the case for our experiments, would completely wash out the interference pattern. As has already been pointed out in our initial proposal [5], a possible way to avoid this would be to use an interferometer of zero enclosed area (fig. 3). Such a design would also have the advantage of cancelling any possible phase shifts due to Earth's gravity, which might result from a vertical misalignment of the interferometer.

4. Neutron diffraction at the phase gratings

For intensity reasons it was decided to use phase gratings instead of absorption gratings in the interferometer (fig. 4). An additional important feature is the choice of gratings with equal width of steps and gaps. Such a 1 : 1 grating offers the additional advantage of having no even-order diffracted intensity. This results from the fact that the single-slit diffraction distribution is the envelope of the grating diffraction distribution and, for a 1 : 1 grating, the minima, i.e. the zeros, in the single-slit diffraction pattern just coincide with the positions of even-order diffraction maxima of the grating. Since higher orders are of low intensity anyway, practically only the zero-order diffraction maximum and the two first-order diffraction maxima are of non-negligible intensities in our case. For an absorption grating, the intensity ratio between these orders is fixed, while for a phase grating this can be manipulated. Especially, if the step height is just $D_\lambda/2$, where D_λ is the λ-thickness, i.e. that material thickness that leads to a phase shift of 2π, then the zero order maximum is cancelled. This is our choice for the middle grating of the interferometer, since the zero-order diffraction intensities would leave the interferometer anyway.

Extensive experiments were performed to find gratings of sufficient quality for the neutron interferometer [14]. Three different ways of producing such gratings were tested. In the first series we tested gratings with nickel steps which were made by an electroplating process. In the second series the steps were made of copper, again in an electroplating procedure. In both cases the substrates of the gratings were SiO$_2$-glass plates of constant thickness (better than λ/10). None of the gratings produced by the electroplating method were satisfactory. There were significant deviations in the step width, dislocations, unevenness of the photoresist and some oxidation problems. Good quality gratings were finally obtained by a process called sputter etching. In that process sputtering with an etching agent results in a nicely defined grating cut into the quartz-glass substrate (fig. 4). Neutron diffraction studies of these gratings finally demonstrated their satisfactory performance (fig. 5). Detailed results of the neutron diffraction studies at the various phase gratings will be published elsewhere.

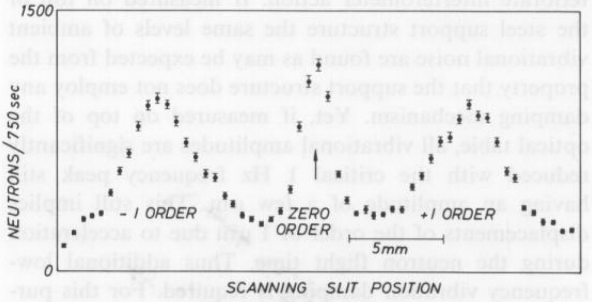

Fig. 5. Measured neutron diffraction for a grating with step height of $D_\lambda/2$, a so-called "π-grating". The presence of zero-order intensity is caused by the wavelength distribution and by small imperfections of the grating.

5. Experiments proposed

A number of experiments have been discussed [15] and proposed [5] by us for the VCN setup and particularly for VCN interferometry. Here we will only give a brief list and the reader is referred to the appropriate literature. The experiments envisaged are:

- Development of new neutron optical devices. Of those, phase gratings have been successfully tested to date. Further work in the development of devices with micron- and submicron-structures is planned.
- Development of a neutron interferometer of meter size. Since the time of the Workshop an interferometer with an overall length of 0.5 m has been tested successfully by us. This will be published elsewhere.
- Improvement of the present limit of a possible nonlinearity of the Schrödinger equation [16].
- Precision tests of the unitarity of quantum mechanics [17].
- Topological quantum effects for neutral particles, specifically the so-called Aharonov–Casher effect [18].
- Improved search for a non-Abelian gauge interaction of the neutron [19].

- Search for a novel neutron Fizeau effect [20].
- Time-dependent neutron optics, specifically with switched fields [21].
- Improvement of the neutron electric charge limit [22].
- Improvement of the neutron magnetic charge limit [23].
- Neutron Cavendish experiment. This would be the first experiment on the action of laboratory created gravity fields on an elementary particle.

Acknowledgements

We would like to thank the Institut Laue–Langevin for giving us the possibility of performing these experiments. We thank Prof. C.G. Shull (MIT) for stimulating discussions and encouragement and Prof. H.J. Bernstein for discussions on possible neutron interferometer applications. We also appreciate the constructive cooperation of Herr Heinz Kraus from Heidenhain Company in the development of the phase gratings. This work was mainly supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung under project no. P 6635 T. Additional support was received from the Bundesministerium für Forschung und Technologie (Bonn), from the US National Science Foundation (grant no. DMR 87-13559 and INT-87-13341) and again from the Austrian Fonds zur Förderung der wissenschaftlichen Forschung under project no. S 42-01.

References

[1] A. Steyerl, H. Nagel, F.-X. Schreiber, K.A. Steinhauser, R. Gähler, W. Gläser, P. Ageron, P. Astruc, W. Drexel, R. Gervais and W. Mampe, Phys. Lett. A116 (1986) 347.
[2] A. Steyerl and S.S. Malik, Physica B137 (1986) 270.
[3] A. Steyerl, W. Drexel, S.S. Malik and E. Gutsmiedl, Physica B151 (1988) 36.
[4] A. Steyerl, Nucl. Instr. and Meth. 125 (1975) 461.
[5] R. Gähler, W. Mampe, C.G. Shull and A. Zeilinger, ILL Proposal no. 3-12-25 (Feb. 1986).
[6] C.G. Shull, in: Physics as Natural Philosophy, eds. A. Shimony and H. Feshbach (MIT Press, Cambridge, Massachusetts, 1982) p. 167.
[7] A.I. Ioffe, V.S. Zabiyakin and G.M. Drabkin, Phys. Lett. 111 (1985) 373.
[8] A.I. Ioffe, Physica B151 (1988) 50 and references therein.
[9] L. Marton, Phys. Rev. 86 (1952) 585.
[10] U. Bonse and M. Hart, App. Phys. Lett. 6 (1965) 155.
[11] H. Rauch, W. Treimer and U. Bonse, Phys. Lett. A47 (1974) 369.
[12] A.I. Ioffe, private communication.
[13] D.K. Atwood, M.A. Horne, C.G. Shull and J. Arthur, Phys. Rev. Lett. 52 (1984) 1673 and 53 (1984) 1300.
[14] The gratings were made by Heidenhain, 8225 Traunreut, FRG.
[15] A. Zeilinger, NBS Special Publication 711, ed. G.L. Greene (US Department of Commerce, Washington, DC, 1986) p. 112.
[16] R. Gähler, A.G. Klein and A. Zeilinger, Phys. Rev. A23 (1981) 1611.
[17] A. Zeilinger, in: Quantum Concepts in Space and Time, eds. R. Penrose and C. Isham (Oxford University Press, Oxford, 1986) p. 17.
[18] Y. Aharonov and A. Casher, Phys. Rev. Lett. 53 (1984) 319;
H. Kaiser, M. Arif, S.A. Werner, R. Clothier, A. Cimmino, A.G. Klein and G.I. Opat, these Proceedings (Int. Workshop on Fundamental Physics with Slow Neutrons, Grenoble, France, 1989) Nucl. Instr. and Meth. A284 (1989) 190.
[19] T.T. Wu and C.N. Yang, Phys. Rev. D12 (1975) 3845;
A. Zeilinger, M.A. Horne and C.G. Shull, in: Foundations of Quantum Mechanics in the Light of New Technology, eds. S. Kamefuchi et al. (Phys. Soc. Japan, Tokyo, 1984) p. 289.
[20] V.F. Sears, Phys. Rev. A32 (1985) 2524;
A. Cimmino et al., these Proceedings (Int. Workshop on Fundamental Physics with Slow Neutrons, Grenoble, France, 1989) Nucl. Instr. and Meth. A284 (1989) 179.
[21] A. Zeilinger, J. Phys. (Paris) 45, suppl. C3 (1984) 213.
[22] J. Baumann, R. Gähler, A.I. Ioffe, J. Kalus and W. Mampe, these Proceedings (Int. Workshop on Fundamental Physics with Slow Neutrons, Grenoble, France, 1989) Nucl. Instr. and Meth. A284 (1989) 130 and references therein.
[23] K. Finkelstein, C.G. Shull and A. Zeilinger, Physica B136 (1986) 131.