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WAVE OPTICS WITH COLD NEUTRONS

A.G. Klein and A. Zeilinger*

School of Physics, University of Melbourne, Parkville, 3052, Australia
and Physics Department, MIT, Cambridge, MA 02139, U.S.A.
**Physics Department, MIT, Cambridge, MA 02139, U.S.A. and Atominstitut*
der Österreichische Universitäten, A-1020 Wien, Austria

Résumé - Plusieurs expériences d'optique ondulatoire ont été effectuées avec des neutrons de 20 Å du faisceau H-18 à L'ILL; par exemple des figures de Fresnel d'un bord, d'une fente et d'une double fente ainsi que la focalisation avec des réseaux zonés et l'interférométrie par division de front d'onde.

Ces expériences sont passées en revue et discutées du point de vue de leurs motivations et de leurs futures possibilités.

Abstract - Various classical wave optics experiments carried out with 20 Å neutrons on the H-18 facility at I.L.L. are reviewed, namely Fresnel diffraction from a straight edge, single slit and double slit; focussing with zone plates and interferometry by wavefront division.

The motivation of the above experiments is discussed and future extensions and applications are proposed.

A long optical bench built by Gähler, Kalus and Mampe /1/ was set up on the cold neutron beam-line H-18 at the High Flux Reactor of the Institut Laue-Langevin in 1979-80 and was originally used for setting a new upper limit of $q_n \leq -1.5 \pm 1.4 \times 10^{-20}$e on the charge of the neutron. The apparatus was subsequently used by Gähler and various collaborators for a series of wave - optical experiments which will be briefly reviewed here.

The optical bench supported a quartz prism monochromator and associated slits with the aid of which a beam of 15 Å < λ < 30 Å and $\Delta\lambda \sim 1$ Å could be selected. An evacuated flight path of 10 m, in two sections of L = 5 m, was followed by an extremely well shielded detector, in front of which a fine slit could be scanned in 1 μm steps. The overall layout is shown in Fig. 1. This apparatus was found to be very well suited for Fresnel diffraction studies at $\lambda \sim 20$ Å; the characteristic Fresnel length was $\sqrt{\lambda L} \sim 100$ μm.

The diffraction pattern of an opaque straight-edge was measured by Gähler, Klein and Zeilinger /2/ and was found to be in excellent agreement with theory (Fig. 1a). From this result it was possible to deduce an upper limit for the strength of a hypothetical nonlinear term in the Schrödinger equation, of the type proposed by Bialynlicki-Birula and Mycielski /3/. Following the suggestion of Shimony /4/, a neutron interferometer experiment by Shull et al /5/ placed an upper limit of $b < 3.4 \times 10^{-13}$ eV on the strength of such a term. However, the Fresnel diffraction experiment reduced this by a further two orders of magnitude. Using the same set-up, the diffraction pattern of an absorbing wire was also measured. A high precision experiment by Zeilinger, Gähler, Shull and Treimer measured the diffraction patterns of a single slit and of a double slit /6/. The latter experiment showed agreement with standard, linear theory to within 6 parts in 10^3 and represents the most serious challenge to any "heretical" versions of quantum mechanics, such as any nonlinear variants or any of the evolutionary schemes of wave packet reduction /7,8/.

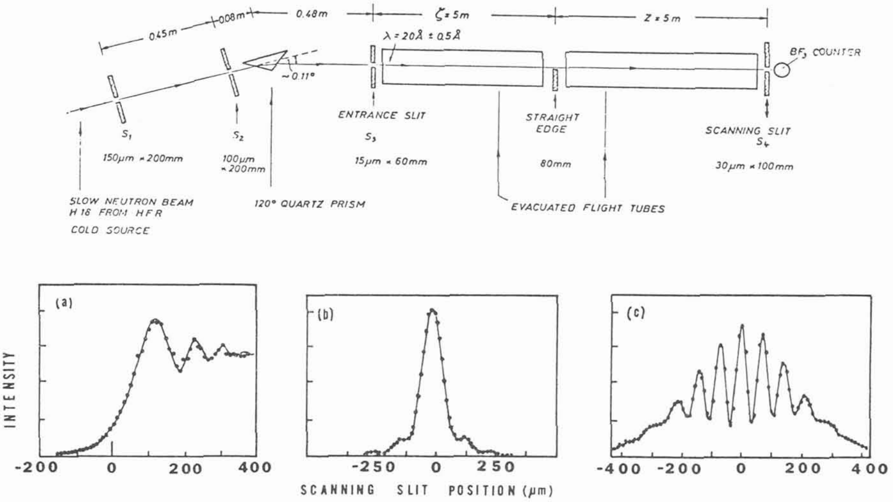

Fig. 1 - Schematic layout of optical bench assembly on long-wavelength beam H-18. Diffraction patterns of a) straight edge b) single slit c) double slit.

The various diffraction patterns are shown in Fig. 1 a, b and c.

In a further application of Fresnel diffraction, the experiments of Kearney et al /9/ and Klein et al /10/ have demonstrated the focussing and imaging of slow neutrons by Fresnel zone plates, Fig. 2; both spherical and cylindrical focussing structures were found to work in accord with the design. The zone plates were manufactured on silicon substrates by means of photo-lithographic techniques of the kind used in micro-electronics. Alternate zones were plated with a 2.4 µm layer of copper which gives a 180° phaseshift for neutrons of 20 Å wavelength.

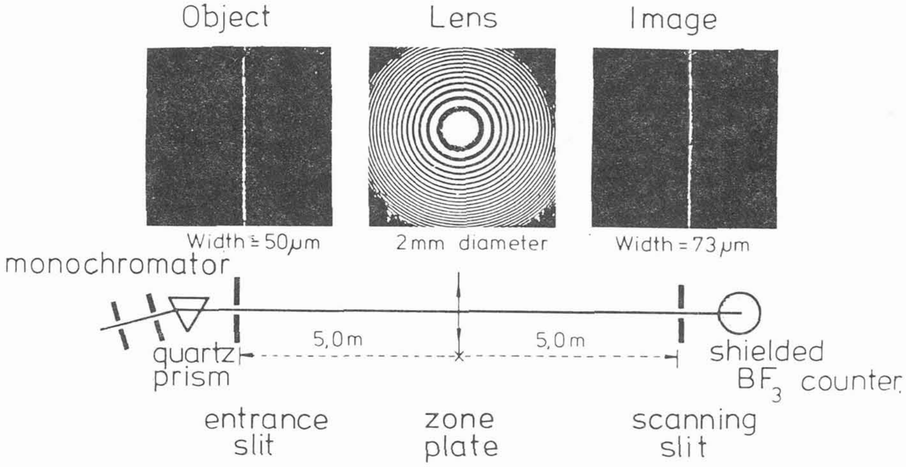

Fig. 2 Focussing of 20 Å neutrons by a Fresnel zone plate.

Following the successful demonstration of focussing by zone plates, the special configuration shown in Fig. 3, which corresponds to a split lens, was used by Klein et al /11/ as an interferometer analogous to the Billet experiment in classical optics. This type of interferometer, which operates by division of the wavefront rather than amplitude division (which is the case in the perfect crystal interferometers) suffers from the disadvantage that with the wavelengths available the separation of the interfering beams was rather small, of the order of a few 100 μm or less. On the other hand, it has the advantages that it is suitable for long wavelengths and is considerably less sensitive to mechanical and thermal disturbances.

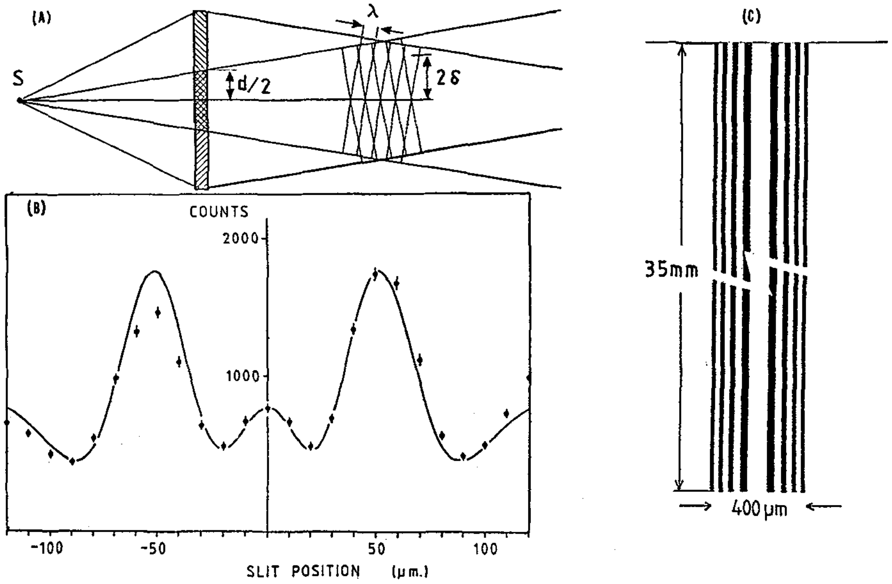

Fig. 3: Split lens interferometer. (A) Schematic of split zone plate (B) Interference patters. (C) Pattern of phase-shifting zones.

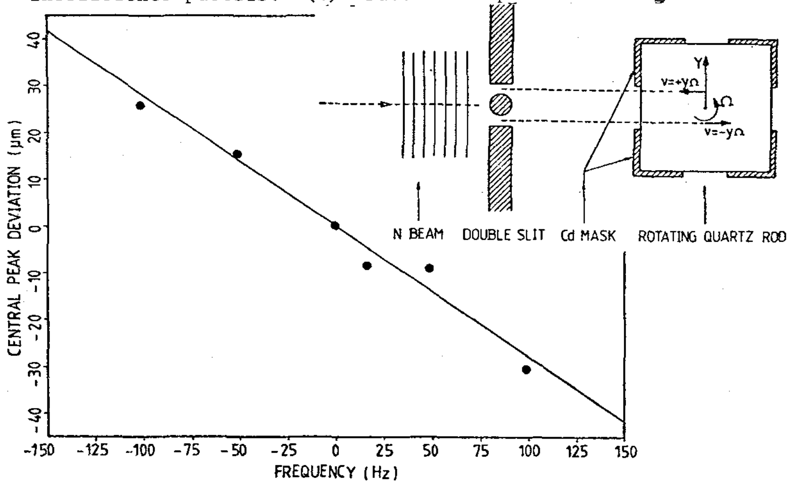

Fig. 4: Results of Fizeau experiment with slow neutrons (points) compared with theory (straight line). Inset: Principle of the experiment.

A double slit interferometer was used by Klein et al /12/ to observe the phase shift induced by the motion of a refracting medium, in an experiment analogous to the classic work of Fizeau. In this experiment, shown schematically in Fig. 4, a quartz prism of square cross-section was rotated in the two beams behind the slits and the resultant fringe shift in the interference pattern was determined. The results were found to be in good agreement with theory and constitute a verification of the transformation laws obeyed by the $(\omega, \vec{k})$ four-vector for de Broglie waves.

All the above experiments may be seen as verifications of quantum mechanical principles and as tests of non-standard quantum mechanical theories. Further experiments along these lines can be envisaged, should a long-wavelength beam line become available again. Among such experiments are the following: a) Time-dependent diffraction effects, aimed at investigating the time-dependent behavior of wave-packets, i.e., experiments directly involving the time-dependent Schrödinger equation. b) The Cavendish experiment with neutrons, i.e., the measurement of the Universal Gravitational constant G by means of an active gravitational mass other than the Earth itself. Such an experiment, which should be feasible with neutrons of $\lambda \gtrsim 100$ Å, would be the first time that active gravitational effects produced by objects of laboratory, rather than cosmic scale, would be observed with elementary particles.

The further development of zone plates as beam-shaping structures would be associated with such experiments. Mention should be made, for example, of the possibility of producing condensing lenses which, because of their dispersive nature, could function also as monochromators when used in conjunction with defining slits placed at the appropriate focus. Furthermore, with alternate zones made of ferromagnetic material, zone plates could fulfill the role of polarizers as well as monochromators and condensing lenses for long wavelength neutrons.

Finally, the use of split-lens interferometers at longer wavelengths could lead to a new set of experiments such as precision measurement of scattering lengths as well as the investigation of further gravitational, inertial and magnetic effects.

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