EXPERIMENTAL STATUS AND RECENT RESULTS OF NEUTRON INTERFERENCE OPTICS

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ABSTRACT

Up to the present time, perfect crystal interferometers of both two-crystal and three-crystal Laue-case variety have been used to explore the optical characteristics of neutrons of diffracting wavelength. In addition, very recently the classical optical experiments on the diffraction by an absorbing edge, by an absorbing wire and by single and double slit assemblies have been performed for cold neutrons. These experiments show with high precision the validity for matter waves of the standard Fresnel-Kirchhoff approach to diffraction.

PERFECT CRYSTAL NEUTRON INTERFERENCE OPTICS

After its invention in 1974, the three-crystal or LLL interferometer[1] has found numerous interesting applications. The experiments performed up to 1978 have been reviewed at the International Workshop in Neutron Interferometry.[2] Since the time of this conference, measurements with this type of interferometer of the coherent scattering lengths of various gases including tritium have been performed by the Vienna-Dortmund[3] group at the ILL, and an improved version of the experiment on the effect of Earth's rotation on neutron interferences was performed by the Missouri[4] group. Thus, we can state that LLL neutron interferometry has become in the few years since its invention a very well established technique.

The LLL interferometer corresponds topologically to the standard Mach-Zehnder interferometer for light if one modifies the particular type of beam splitter used, i.e. if the mirrors of the Mach-Zehnder interferometer are considered to be replaced by the perfect

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crystals in Laue geometry (Fig. 1). An important advantage of the LLL interferometer is that one can, as in the Mach-Zehnder interferometer, use large apertures in the incident beam and still obtain macroscopically well separated beams.

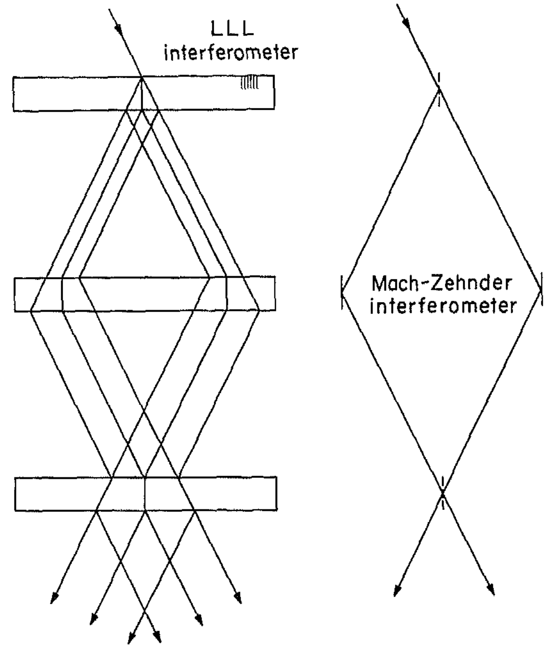

Fig. 1. LLL-interferometer showing central ray propagation and the Borrmann fan limitation within the system is topologically equivalent to the Mach-Zehnder interferometer.

Of other types of possible perfect crystal interferometers discussed in the literature[5], only the two-crystal or LL interferometer has found experimental application[6,7] up to now. For the operation of this interferometer type the mutual coherence properties of radiation following different optical paths within the Borrmann fan are crucial. Even without possible coherence between different components in the incident radiation, there will still be coherence left between rays which follow symmetric paths within the crystal with respect to the lattice planes. If the thickness of the second crystal plate is identical to that of the first one, corresponding rays meet at the exit face of the second crystal plate forming a focus where they coherently superpose (Fig. 2). Therefore this interferometer type can be viewed as being a thermal neutron analog of the standard Rayleigh interferometer. This interferometer type has been successfully employed in experiments[8] aimed at limiting the size of hypothetical nonlinear terms in the Schroedinger equation by three orders of magnitude as compared to Lamb-Shift experiments[9] and for a search for an Aharonov-Bohm effect for neutrons.[10]

In such experiments, spatially well separated beams are used which necessitates a limitation of the entrance aperture. But it is interesting to note that the operation of the LL interferometer does not depend on selecting just two symmetric rays at the exit face of the second crystal. In contrast, because any pair of such symmetric rays exhibits essentially the same coherence properties the whole beam can be used between the crystals. An advantage of the LL interferometer stems from the property that only two crystal plates are encountered by the beam. This implies that the operation of that

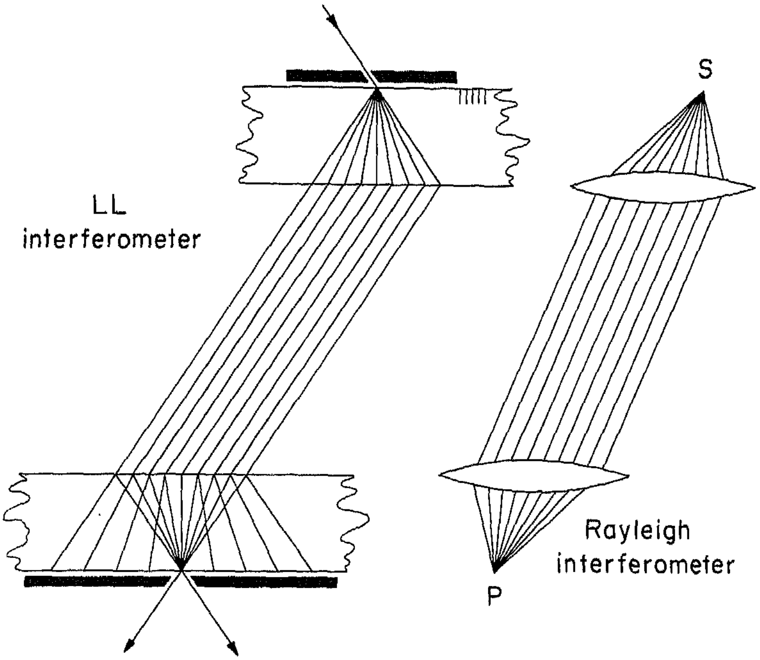

Fig. 2. Ray propagation in the two-crystal or LL-interferometer exhibits focusing action at the backface of the second crystal plate in analogy to the Rayleigh interferometer for light.

interferometer type is insensitive to parallel lateral displacements of the crystal plates relative to each other. On the other hand, it is very sensitive with respect to the relative angular position of these crystal plates the sensitivity being in the range of 10^{-3} arcsec.[11] For experiments sensing a deflection of the whole beam on its way from the first to the second crystal plate a very wide entrance aperture can be used. An experiment exploiting that angle sensitivity feature is at present in progress at MIT. It concerns the neutron analog of the classical Sagnac experiment, an experiment sensing the effect on the interference fringes of active rotations of the interferometer.

Another interesting feature of the LL-crystal set-up is its very high sensitivity (10^{-8}eV) to energy changes of the neutron on its way from the first to the second crystal plate. This has been used in an experiment demonstrating the wavelength change of the neutron when entering a modest magnetic field.[12] The very existence of the two related focal points (Fig. 2) allows one to conclude that the flight time of the neutron from one to the other focal point has to be the same since generally the optical path is of equal length along any path connecting two focal points in an optical system. This property together with symmetry considerations leads to the conclusion that the flight time for a neutron from the entrance face is the same independent of the actual path followed by the neutron within the crystal plate. The experimental result[13] demonstrates this property.

NEUTRON DIFFRACTION AT ABSORBING EDGE, SINGLE SLIT AND DOUBLE SLIT ASSEMBLIES

One of the motivations of introducing a nonlinear term into the Schroedinger equation[9] was to prevent wave packets from spreading without limit. Therefore, it is reasonable to expect that effects of such a nonlinear term may be seen when looking closely on the free space propagation of neutrons. It can be shown[14] that a nonlinear term of the type

$$F = F(\rho), \quad \rho = |\Psi|^2 \quad , \tag{1}$$

would lead to a bending of the wavefront of

$$\frac{d^2y}{dz^2} = \frac{1}{2E}\frac{dF}{d\rho}\frac{d\rho}{dy} \quad , \tag{2}$$

where z is measured along the propagation direction of the neutrons and y orthogonal to it. As the effect increases with increasing lateral gradient of the probability density, a precision measurement of the Fresnel diffraction of slow neutrons at a straight absorbing edge was performed.[14] The apparatus used in that experiment and in those mentioned later made use of an optical bench arrangement[15] located at one of the neutron beam lines emerging from the cold source of the High Flux Reactor of the ILL (Fig. 3). Monochromatic neutrons of wavelength 20.0 Å with a spread of ±0.5 Å were used in the experiment and these were prepared by prism refraction. Fig. 4 shows the experimental Fresnel pattern together with a computer generated pattern as calculated with the standard linear Schroedinger equation. As can be seen from these data, any effect due to nonlinear action was found to be below experimental resolution and this permitted a lowering of the limit on the size of nonlinear terms by another two orders of magnitude as compared with the neutron interferometer result. Specifically, for a logarithmic nonlinearity type

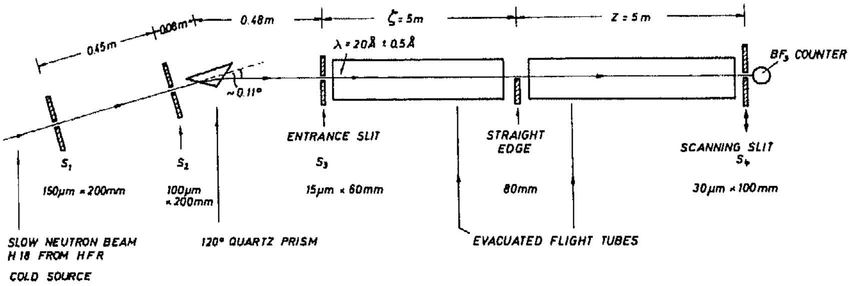

Fig. 3. Cold neutron optical bench set-up (not to scale).

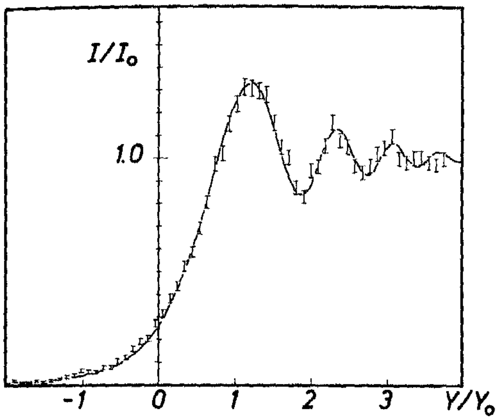

Fig. 4. Experimental Fresnel diffraction pattern of an absorbing straight edge, together with pattern calculated from standard linear Schroedinger equation[14] ($Y_0 = 100\mu m$).

of term $F = -b \ln(\alpha|\Psi|^2)$, the quantity b which measures the strength of the nonlinear term cannot be larger than 3.3×10^{-15}eV in order to be in agreement with the experiment.

Further experiments which have been performed using the same experimental arrangment concerned the diffraction of neutrons at single and double slit assemblies. In slit diffraction, experiments have been performed using slits of width 96μm and 22μm in the single and double slit configurations respectively. Fig. 5 shows the result of the 96μm single diffraction experiment obtained in a measuring time of 11¾ days for the whole pattern which amounts to 192 minutes per point. Also displayed is the computer generated solution of the standard linear Schroedinger equation. This solution was obtained using a Fresnel-Kirchhoff type approach[16] where the entrance slit of the optical bench was assumed to be a plane wave coherent over the full width of that slit. Different wavelength contributions and different incident direction contributions were assumed to be incoherent with each other. It should be noted that in the single slit diffraction pattern the interference maxima up to third order are clearly visible with some indication of the fourth-order maximum.

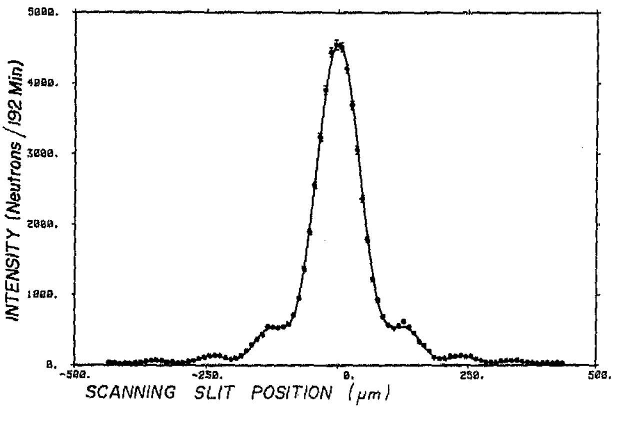

Fig. 5. Experimental 96μm single slit diffraction pattern with pattern calculated from the Schroedinger equation

By mounting a Boron wire of 104μm thickness into the gap of a 148μm wide single slit a double slit assembly was obtained. Fig. 6 shows a drawing to scale of that arrangement. The absorbing edges were made of a borate glass with 10% Gd_2O_3 added to ensure a high neutron absorption action. The flat parts of the edges opposite to

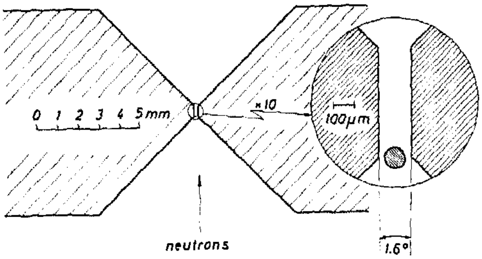

Fig. 6. Double slit arrangement: Boron wire mounted in the gap between absorbing glass edges.

each other were arranged to be slightly divergent as seen from the side of the incident neutrons in order to avoid contamination of the diffraction pattern by surface reflected neutrons. This same approach was also used for obtaining the single slit diffraction patterns. In order to bring once again to attention the scale of the experiment we note that the wavelength of the neutrons (λ = 18.45 Å) was nearly five orders of magnitude smaller than the center-to-center distance ($d \approx 126$ μm) of the two slit openings. Hence the angular distance between two adjacent maxima in the double slit diffraction pattern is only 3 arcsec. In order to obtain acceptable statistical accuracy within a reasonable time, the wavelength band used in that experiment had been increased to ±1.4 Å. This still implied an overall measuring time of 7500 sec per point or of 7½ days for the whole pattern. The slight asymmetry of the diffraction pattern (Fig. 7) can be fully accounted for by the existence of slight asymmetry in the slit widths.

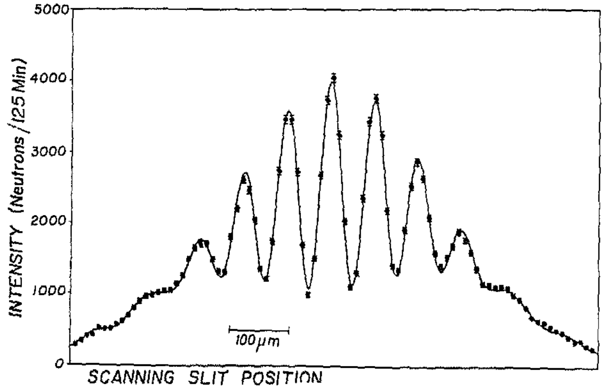

Fig. 7. Neutron diffraction pattern of a double slit with pattern calculated from the Schroedinger equation

This double slit interferometer set-up has also been recently used for a measurement of the Fizeau-effect for neutrons,[17] i.e. the effect of the motion of the phase shifter on the phase of a neutron wave. The result, in agreement with quantum mechanics, may be viewed as a demonstration of the transformation laws of both the deBroglie wavelength and the frequency of a massive particle.

Another interesting group of experiments performed using the optical bench arrangement was performed by Klein et al.[18] In these experiments the operation of both circular and cylindrical Fresnel lenses for thermal neutrons was successfully demonstrated. Furthermore, it could be shown that a Billet split-lens type interferometer[19] using Fresnel lenses can be expected to be operated at a high flux reactor in a sensible intensity range. Furthermore, the introduction of Fresnel lenses into perfect crystal neutron optics[20] seems to open an interesting new field for experimentation.

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