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Neutron Interference by Division of Wavefront

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A novel type of neutron interferometer was constructed and tested employing a split cylindrical zone plate with neutrons of 20 Å wavelength. Its performance and relative merits are discussed.

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The highly successful perfect-crystal neutron interferometer of the type first developed by Bonse and Rauch[1] exhibits interference by amplitude division. It relies on dynamical Bragg diffraction in a highly perfect single crystal to provide the beam splitting. This type of interferometer, topologically analogous to the Mach-Zehnder interferometer of classical optics, has been employed in a variety of interesting experiments with use of thermal neutrons.[2] Its shortcomings, however, are its extreme sensitivity to mechanical and thermal disturbances, and its applicability only to wavelengths shorter than the Bragg cutoff (6.27 Å in silicon).

In this paper we discuss an alternative class of neutron interferometers, namely those that work by division of the wavefront, and report on recent experiments with one such device.

Interference by division of the wavefront, analogous to Young's experiment, has been demonstrated with thermal and cold neutrons in several different ways. The very first neutron interferometer,[3] built by Maier-Leibnitz and Springer in 1962, was of this type; an adaptation of the Fresnel biprism with use of quartz prisms as refracting elements for cold neutrons. The experiments of Klein and Opat[4] on Fresnel diffraction of neutrons by domain walls in ferromagnetic foils are also examples of interference of spatially separated parts of a wavefront, as is the case for the high-precision Fresnel diffraction experiments carried out more recently at the high-flux reactor of the Institut Laue-Langevin in Grenoble, France.[5,6] One of these was, in fact, an exact version of the classical two-slit experiment.[6]

Following the successful demonstration of the use of Fresnel zone plates as focusing and imaging elements for slow neutrons,[7] we recently carried out experiments on a split-lens interferometer, based on the classical model of Billet.[8] It is particularly applicable to cold and very cold neutrons and presents certain advantages, to be discussed later.

The basic layout of a Billet split-lens interferometer is shown in Fig. 1(a). The points S_1 and S_2 mark the positions of two coherent real images of a primary source S, produced by the two halves of the split lens L_1 and L_2. Nonlocalized interference fringes are produced in the region of overlap of the cones diverging from these

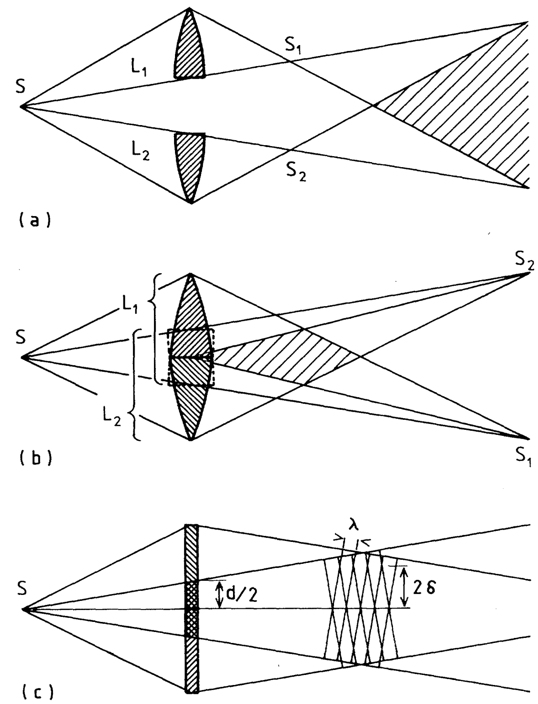

FIG. 1. Split-lens interferometer configurations: (a) positive separation of lens, (b) negative separation with overlapping region removed, (c) special case of (b) which gives constant fringe spacing and employing a zone plate instead of a lens.

images. An alternative geometry is shown in Fig. 1(b); here the separation of the two halves of the lens is negative, i.e., a strip has been removed from the center of the lens and the remaining parts pushed together. Figure 1(c) is a special case of 1(b), with S_1 and S_2 at infinity, giving rise to fringes at uniform spacing throughout the region of overlap. The realization of these schemes for neutrons is made possible by the use of Fresnel zone plates.

Refractive lenses, although possible,[9] are severely limited in applicability because for all known materials, the refractive index for neutrons departs only very slightly from unity [e.g., $n-1\sim 10^{-4}$ for $\lambda = 20$ Å]. Nevertheless, the thickness of a layer which gives rise to an optical path difference of half a wavelength is of the order of some micrometer, and hence easily realizable. This forms the basis of our zone plates for neutrons. Unlike ordinary zone plates, in which alternate Fresnel zones are blocked out by absorption,[10] we introduce a phase shift (ideally 180°) in alternate zones by passage through thin layers of copper deposited in the appropriate geometric pattern. This gives rise to a much higher intensity in the focused beams. Furthermore, since a primary source in the form of a narrow slit is preferable to a pinhole, cylindrical zone plates were used in order to get a higher intensity.[11] Instead of physically splitting the zone plates, it is easier to manufacture special zone plates with the appropriate geometric patterns corresponding to split lenses.

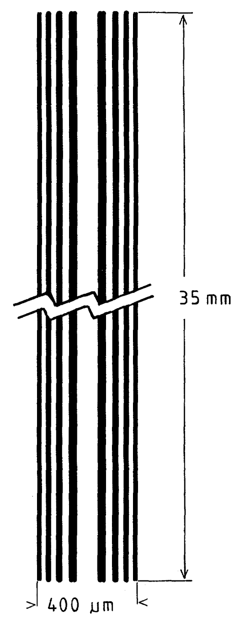

FIG. 2. Split-lens geometric pattern for a cylindrical zone plate.

Such zone plates were produced in our laboratories by means of photomicrolithographic techniques of the kind used in the microelectronics industry. Computer-drawn geometric patterns of the type shown in Fig. 2 were reduced in scale and photographed, with use of uv light, onto a thin layer of photoresist on a silicon-wafer substrate. The developed photoresist acts as a mask through which copper is electrolytically deposited to the required thickness.

For a material with N scattering centers per unit volume, each with a scattering length b, the thickness required to give a phase shift of 180° is given by

$$D(\tfrac{1}{2}\lambda) = \tfrac{1}{2}\lambda/(n-1),$$

where the refractive index n is given by

$$n = 1 - \lambda^2 N b/2\pi.$$

For example, for copper at $\lambda = 20$ Å, we have $D(\frac{1}{2}\lambda) = 2.4$ μm. Departures from a 180° phase shift give rise to corresponding amounts of zeroth-order (i.e., undiffracted) amplitude which, in the case of the split lens, alter the interference pattern in a calculable way. Figure 3 shows the expected interference patterns resulting from several different thicknesses of copper, i.e., different phase shifts in alternate zones in a particular geometry of split-lens interferometer.

The experimental tests of the split-lens interferometer were carried out at the high-flux reactor of the Institut Laue-Langevin on the long-wavelength beam line H-18. A quartz-prism monochromator illuminated a vertical entrance slit of 20 μm width with neutrons of wavelength ~20 Å. A 10-m-long optical bench[9] carried the split lens at a distance of 5 m from the entrance slit and the interference pattern was scanned by a BF_3 counter behind a 20-μm-wide movable slit situated a further 5 m away. Because of the constraints imposed by the construction of the optical bench, the split lens was designed with a focal length of 5 m, corresponding to the limiting condition of constant fringe spacing shown in Fig. 1(c). The effective aperture of the split lens was masked down with cadmium strips so that all the waves crossing the aperture would arrive in the region of overlap in the plane of detection and contribute to the interference pattern.

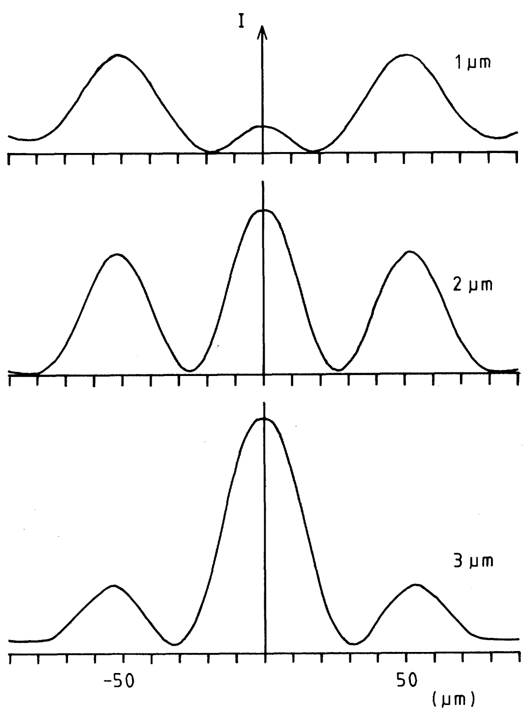

FIG. 3. Calculated interference pattern for different copper thicknesses, i.e., different relative phase shifts.

From the geometry of Fig. 1(c), we calculate the fringe spacing as $\delta = \lambda f/d$, where d is the width of the central portion removed from the lens of focal length f. This is a special case of the more general formula

$$\delta = (\lambda/\rho d)[f\rho - r(\rho - f)],$$

where ρ and r are the distances from the lens to the source and plane of detection, respectively. The width d was chosen to be 200 μm thus giving a fringe spacing of 50 μm for $\lambda = 20$ Å.

The split lens was placed on the optical bench and aligned with the slits with use of a theodolite. The true wavelength of the neutron beam was checked by time-of-flight measurement and found to be centered on 19.3 Å with a spread of ±0.5 Å. This alters the lens focal length to give a new fringe spacing of 51.8 μm.

The observed interference pattern is shown in Fig. 4, together with the theoretical curve. The theoretical pattern was fitted to the data by subtracting a small amount of background and varying the phase shift between adjacent zones of the split lens. The experimental phase shift was found to correspond to an effective copper thickness of 1.3 μm. Better control over the copper deposition would have given a thickness close to the design figure of 2.4 μm which corresponds to 180° phase shift. We note, however, that the relative phase shift does not influence the basic spatial frequency of the interference pattern, though it controls the overall intensity, and fringe visibility, especially of the central fringe.

We now discuss the comparative merits of split-zone-plate neutron interferometers:

(a) They are easily designable, and are readily manufactured at low cost.

(b) They are most useful at long wavelengths and are therefore complementary to the perfect-crystal interferometer which is applicable only to wavelengths below the Bragg cutoff.

(c) Even though the interference pattern is somewhat smeared out by the wavelength spread, a wide range of wavelengths still gives a high fringe visibility. Therefore very coarse monochromatization is usable, resulting in a relatively high intensity.

(d) Unlike perfect-crystal neutron interferometers, they are relatively insensitive to mechanical vibrations and thermal gradients. This is because diffraction by elements in a plane is much less constrained than is dynamical diffraction from a three-dimensional crystal (which is sub-

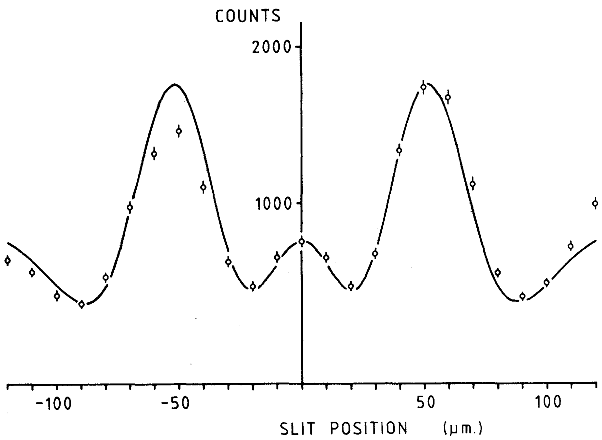

FIG. 4. Experimentally determined interference pattern fitted to theoretical pattern for a Cu thickness of 1.3 μm.

This simply produces a prism deflection, the interference pattern merely producing the required marker for the beam.[13] In practice a variable compensating prism of known refracting index would be employed, in a null method, to eliminate chromatic effects. Calculations show that scattering lengths could thus be measured to accuracies of a few parts in 10^3.

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ject to the Bragg conditions).

(e) Compared with the biprism interferometer of Maier-Leibnitz and Springer[3] the split-zone-plate interferometer has the advantage that it can be designed to concentrate neutrons into the region of overlap of the two beams, i.e., the interference region.

A serious disadvantage of this type of interferometer is the close spacing of the interfering beams. This makes it difficult to include phase shifters in one beam without encroaching on the other. It was this difficulty which limited the applicability of the biprism interferometer as has recently been shown.[12] However, a different mode of employing the interferometer may be found in some cases, which overcomes this difficulty. If the test object produces a phase gradient across both beams instead of presenting a discrete phase shift to only one of them, an easily detected deflection of the interference pattern results. A simple example of such an application would be in the measurement of refractive indices (i.e., scattering lengths) by using a wedge of the material to produce the phase gradient.

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[13]For another example of this kind, see A. G. Klein *et al.*, to be published.