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NEUTRON LENSES IN INTERFEROMETRY

Anton ZEILINGER* and Michael A. HORNE**
**Atominstitut der Österreichischen Universitäten, Schüttelstraße 115, A-1020 Wien, Austria*
and
***Stonehill College, North Easton, MA 02356, USA*
and
Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

It is shown experimentally, that the intensity distributed broadly outside the focal spot on the back face of a two-crystal neutron interferometer can be refocused by using properly shaped lenses between the crystals. Generally, these lenses have to be of elliptical cross section and result in focussing of pure single-wave, field radiation.

The closeness to unity of the refractive index for thermal neutrons of all materials or fields has restricted the use of neutron lenses in that energy range to the demonstrational level [1]. This situation is somewhat better for cold neutrons in the 10–30 Å range, where standard cylindrical lenses were used as key elements in a precision optical bench set-up [2] and where also the feasibility of using Fresnel lenses was demonstrated successfully [3].

In the thermal energy region, another principally different avenue for focussing neutrons is opened up by utilizing crystal diffraction. Besides in the well-known case of curved crystals, focussing effects even arise for unbent perfect crystals due to dynamical diffraction. Of these effects, the focussing at the back face of the second one of two equally thick crystals in Laue orientation has been demonstrated and investigated in some detail [4, 5]. In the present paper we present the first results of a new type of focussing which arises due to a combination of crystal diffraction with lens action.

The radiation excited by an incident δ-function ray fills the whole Borrman triangle inside the crystal (see insert of fig. 1). For a non-absorbing crystal, two wave-fields arise, commonly termed α and β wave-fields such that at each point inside the crystal both an α and a β amplitude may be identified. Their relative beat as a function of crystal depth causes the Pendellösung phenomenon. Hence, for the radiation leaving the back face of a crystal of thickness t in Bragg diffracted direction, the phase as a function of exit face position Γ (fig. 1) varies as

$$\Delta\phi_{\alpha,\beta} = \pm \frac{\pi t}{\Delta_0} \sqrt{1-\Gamma^2}\,, \qquad (1)$$

where Δ_0 is the Pendellösung length and the two signs refer to the two wave-fields respectively. Eq. (1) gives the phase at a position Γ relative to the phase of the radiation at the edges of the Borrman-fan, hence it contains all dynamical diffraction effects on the phase besides contributions by the mean refractive index.

As is well known in optics, a focus occurs at

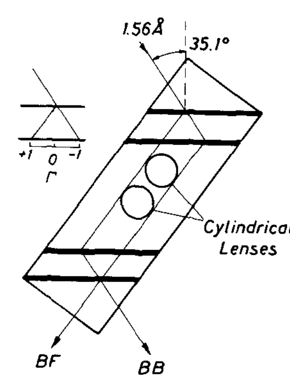

Fig. 1. The two-crystal neutron interferometer with two cylindrical lenses in the beam between the crystal plates.

those points where the variation of the phase upon variation of the path from the source to the focus vanishes. Therefore the focus already observed earlier with the LL interferometer [4] may readily be explained as resulting from neutron radiation which propagates as α wave-field in the first crystal plate and as β wave-field in the second one or vice-versa. This follows, because then the two contributions to the phase resulting from propagation through the two crystals are of equal magnitude, but opposite sign (eq. (1)) and hence cancel each other. In contrast, such a cancelling does not happen for neutron radiation which propagates as the same wave-field in both crystal plates, making it appear as a broad background intensity distribution (fig. 2).

Therefore the interesting question arises, if it is possible to focus those background neutrons propagating as the same type wave-fields in both crystals, i.e. either α–α or β–β wave-fields. In that case the total crystal contribution to the phase is just twice the value of eq. (1), either of positive or of negative sign. In order to achieve focussing of that radiation, this phase contribution has to be compensated. This can be achieved, if the phase correction

$$\Delta\phi_{\text{corr}} = \mp \frac{2\pi t}{\Delta_0} \sqrt{1 - \Gamma^2} \qquad (2)$$

is imparted on the neutron beam on its way

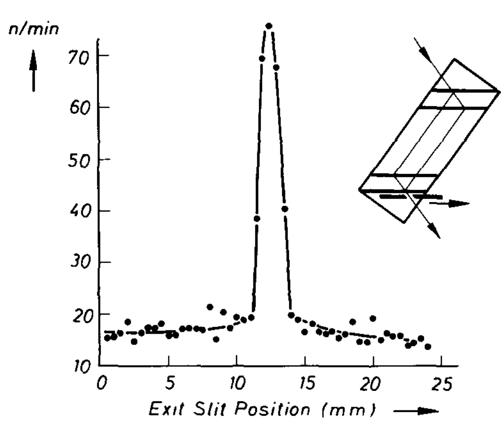

Fig. 2. Intensity distribution at the back face of the second crystal plate for the empty interferometer without phase gradient compensation.

between the two crystals. Clearly, this may be done by some kind of lens action*. Then eq. (2) implies that the lens be of elliptical cross section. The width of the lens in a direction normal to the neutron beam should just be the beam width. The thickness in a direction along the neutron beam is given by the condition, that the phase shift of neutrons propagating through the lens center should be just $\Delta\phi_{\text{corr}} = \mp 2\pi t/\Delta_0$. From that the thickness of the lens D follows as

$$D = 2 \frac{V_G}{V_O} t/\cos\theta_B , \qquad (3)$$

where V_O is the mean potential of the lens material for neutrons, V_G is the Fourier transform of the neutron crystal interaction potential including the Debye–Waller factor e^{-W}. For Al as the lens material and Si (400) reflection at a Bragg angle of $\theta_B = 35.1°$ as used in the experiment it follows that the thickness of such a lens should be just twice its width. Equivalent to such a single elliptical lens is a system consisting of two identical lenses of circular cross-section.

Experiments to demonstrate the re-focussing effect were performed using the M.I.T. two-crystal neutron interferometer (fig. 1). It follows from the two signs of the phase acquired by the neutron wave upon propagating through the crystal, that both full or hollow lenses may be used. The experiments did successfully demonstrate the focussing action in either case. For reasons of space limitation only the experimental results of the full cylinder lenses are presented and discussed here**. The lens material used in the present work was Al for which the neutron refractive index is smaller than unity. This results in a refocussing of the α wave-field, i.e. that wave-field which is closer to the Laue point.

Fig. 2 shows the focussing effect already present in the empty interferometer. The focus is produced by those neutrons which propagated as

* The lens action is analyzed here in terms of phase effects. Alternatively, but equivalently, the lens may be analyzed in terms of angular deflection of the neutron rays between the crystal plates.

** A more complete account of the experiments will be given elsewhere.

different wave-fields in the two crystals. Introduction of one cylindrical lens then leads to a reduction of that focus as shown in fig. 3. In that and in the following experiment, the cylindrical lens was positioned well-centered with respect to the beam. This was achieved by scanning the lens slowly across the beam and monitoring the interferometer output intensity.

Adding then a second cylindrical lens resulted in a reappearance of the focus as may be seen from fig. 4. The intensity of that focus now is only half the intensity of the empty interferometer focus. This is to be expected on the basis of the fact, that here the focus contains one wave-field only anymore. We mention, that the interferometer itself was not compensated for the intrinsic phase gradient present in the empty interferometer and that the illumination conditions were certainly not of spherical wave type because a 1 mm wide entrance slit was used. For these reasons, no interferometer action is to be expected with the cylindrical lenses in place.

The possibility of producing a pure wave-field focus, besides its basic interest for the study of dynamical diffraction itself, should facilitate the development of perfect crysal interferometers of highly absorbing materials. There, the anomalously transmitted wave-field could be utilized in both crystals of a two-ear interferometer, if a proper lens is employed.

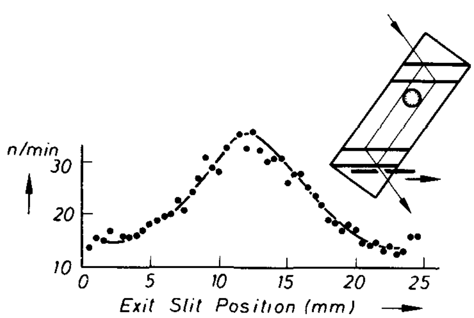

Fig. 3. As fig. 2, but with one cylindrical lens in place. The destruction of the focus of fig. 2 is clearly visible.

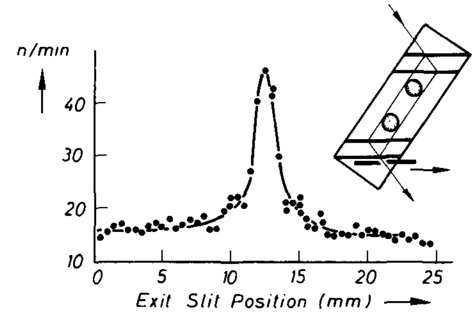

Fig. 4. Positioning of two cylindrical lenses in the beam between the two crystals results in reappearance of a focus.

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