

ARTICLES

Coherence and spectral filtering in neutron interferometry

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The coherence length of a neutron wave packet depends on the spectral width of the distribution of wave vectors that make up the packet. The coherent overlap of the wave packets traversing the two beam paths in a perfect-silicon-crystal neutron interferometer (NI) is altered by placing a material with a neutron-nuclear optical potential in one of the beam paths in the NI. If the optical potential is positive, it causes a delay of the wave packet and a loss of fringe visibility. By use of an analyzer crystal, we narrow the spectral distribution *after* the mixing and interference has occurred in the last crystal slab of the NI. This increases the coherence length and restores some of the fringe visibility.

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I. INTRODUCTION

In a recent paper, we described an experiment in which the fringe visibility in a neutron interferometry experiment is restored by means of a neutron-phase-echo effect [1]. In this paper, we describe a related experiment, where the beam coherence can apparently be improved by the use of an analyzer crystal placed immediately in front of the detector. A preliminary discussion of this experiment has already been published [2].

The superposition principle is perhaps the most important assumption of quantum mechanics. It allows us to construct a localized neutron wave packet by a Fourier sum of plane waves, having a (complex) spectrum $a(\mathbf{k})$:

$$\Psi(\mathbf{r}, t) = \int a(\mathbf{k}) e^{i(\mathbf{k} \cdot \mathbf{r} - \omega_{\mathbf{k}} t)} d\mathbf{k}. \quad (1)$$

The phases of the component waves are correlated by $a(\mathbf{k})$, so that they add constructively only in some localized region of space time. Consider a neutron wave packet Ψ_i incident on a perfect-Si-crystal neutron interferometer (NI), as shown in Fig. 1 [3,4]. The first crystal blade of the NI splits the amplitude of Ψ_i into two parts, Ψ_1 and Ψ_2 , which separate and traverse paths I and II, respectively. Both beams pass through a polished, homogeneous aluminum slab, which can be rotated through small angles α about a vertical axis. This slab, called the “phase rotator,” induces a variable phase difference $\phi_p(\alpha)$ between Ψ_1 and Ψ_2 , given by

$$\phi_p(\alpha) = N_p b_p \lambda d \frac{\sin^2 \theta_I \sin \alpha}{\cos^2 \theta_I - \sin^2 \alpha}, \quad (2)$$

where λ is the neutron wavelength, N_p , b_p , and d are, respectively, the atom density, nuclear scattering length,

and thickness of the phase rotator, and θ_I is the Bragg angle of the interferometer. The beam Ψ_2 also passes through a plane-parallel slab of some material, perpendicular to the beam, with atom density N , neutron-nuclear

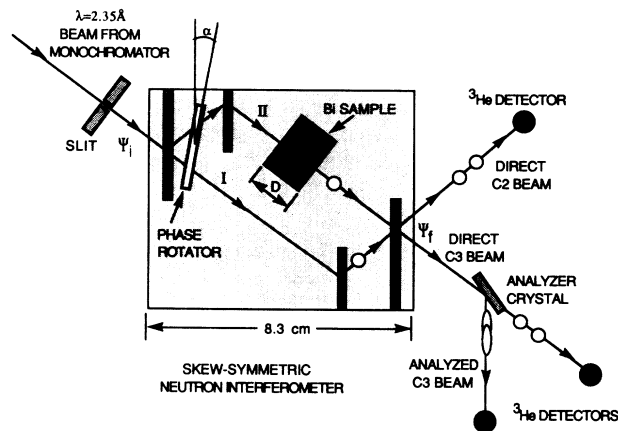


FIG. 1. Schematic diagram of a perfect Si crystal skew-symmetric neutron interferometer. The beam from the monochromator, of nominal wavelength $\lambda = 2.35 \text{ \AA}$, passes through a $8 \times 6 \text{ mm}^2$ slit immediately in front of the NI. The circles represent the coherence length of the wave packets resulting from one neutron entering the NI and traversing the two beam paths. The beam on path II passes through one or two bismuth slabs, which spatially delay the wave packet due to the positive optical potential of Bi. The packets recombine, interfere, and are detected by one of the ^3He detectors. The C3 beam is detected after reflection by a Si analyzer crystal. The interference contrast is measured by rotating the aluminum phase shifter in steps α about a vertical axis.

scattering length b , and thickness D . This slab, which we call the “sample,” induces a phase shift

$$\chi_s(D) = k \Delta l = -\frac{2\pi N b D}{k} = -N b D \lambda \quad (3)$$

and a spatial delay

$$\Delta l = -\frac{D V_{\text{op}}}{2E} \quad (4)$$

in Ψ_2 , where E is the neutron’s kinetic energy and the optical potential is

$$V_{\text{op}} = 2\pi \hbar^2 N b / m, \quad (5)$$

where m is the neutron mass. We assume for now that the sample does not attenuate the beam. The two waves recombine in the last perfect crystal blade of the NI, and form two exit waves, which are linear combinations of Ψ_1 and Ψ_2 . If the optical path lengths of beams I and II are nearly equal, the two packets overlap and coherently interfere, giving rise to interference effects.

As discussed in our recent paper (Ref. [1]), and elsewhere [5], one can show that if a detector is placed in an exit beam, the time-averaged intensity it will measure is

$$I(D, \alpha) = A \int_{-\infty}^{+\infty} |a(\mathbf{k})|^2 d\mathbf{k} + B \int_{-\infty}^{+\infty} |a(\mathbf{k})|^2 \cos[\phi_0 + \phi_P(\alpha) + \chi_S(D)] d\mathbf{k}, \quad (6)$$

where ϕ_0 is some constant, initial phase (under ideal conditions, $\phi_0 = 0$). We explicitly note the dependence of the time-averaged counting rate $I(D, \alpha)$ on the thickness of the sample D and the angle α of the phase rotator, since these are the parameters that are varied in the experiment. The parameters A and B are constants that depend on which exit beam, C_2 or C_3 , is being considered, and also on how well the interferometer is working. In the C_3 beam, we usually find $B_{C_3} \approx (0.5) A_{C_3}$, and in the C_2 beam, $B_{C_2} \approx (0.17) A_{C_2}$. To conserve neutrons, $B_{C_3} = -B_{C_2}$, but $A_{C_2} \approx (2.7) A_{C_3}$.

The first integral term in Eq. (6) is a constant. The second term, however, oscillates as we vary $\phi_P(\alpha)$. For example, if the spectral distribution $|a(\mathbf{k})|^2$ is a Gaussian of standard deviation σ_k , then Eq. (6) yields an intensity

$$I(D, \alpha) = A + B \cos[\phi_0 + \phi_P(\alpha) + \chi_S(D)] e^{-(N b D \sigma_\lambda)^2 / 2}, \quad (7)$$

where $\sigma_\lambda = 2\pi \sigma_k / k^2$ is the width of the spectral distribution in terms of wavelength.

As we vary $\phi_P(\alpha)$, we trace out a sinusoidal intensity pattern $I(D, \alpha)$, called an interferogram. The contrast (fringe visibility) of the interferogram is defined to be the amplitude of the oscillation divided by the mean value of the pattern. As Eq. (7) shows, the contrast $C(D)$ diminishes as the sample thickness D increases; its maximum value $C(0)$ occurs when $D = 0$, that is, when there is no sample in the beam. In principle, the maximum contrast $C_{C_3}(0)$ in the C_3 beam may vary from 0% to 100%, depending on how well the interferometer performs; experi-

mentally, we find $C_{C_3}(0) \approx 50\%$. It is the relative contrast, $C_R(D) \equiv C(D)/C(0)$, that is of interest in these experiments. The relative contrast can be calculated from the magnitude of the complex mutual coherence function $\Gamma(D, \alpha)$ [6]:

$$C_R(D) = \frac{C(D)}{C(0)} = \frac{|\Gamma(D, \alpha)|}{|\Gamma(0, 0)|}, \quad (8)$$

where

$$\begin{aligned} \Gamma(D, \alpha) &\equiv \langle \Psi_1^*(0) \Psi_2(\Delta l) \rangle \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} |a(\mathbf{k})|^2 e^{i[\phi_0 + \phi_P(\alpha) + \chi_S(D)]} d\mathbf{k}. \end{aligned} \quad (9)$$

Or, if the displacement Δl is in the longitudinal direction (parallel to $\mathbf{k}$), we can replace $|a(\mathbf{k})|^2$ by the wavelength spectrum $g(\lambda)$ to calculate $\Gamma(D, \alpha)$, namely

$$\Gamma(D, \alpha) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} g(\lambda) e^{i[\phi_0 + \phi_P(\alpha) + \chi_S(D)]} d\lambda. \quad (10)$$

For this experiment $\chi_S \gg \phi_P$, so that the phase rotator has a negligible effect on the contrast. Thus, for a Gaussian distribution $|a(\mathbf{k})|^2$, the relative contrast falls off as a function of the sample thickness D according to the formula

$$C_R(D) = e^{-(N b D \sigma_\lambda)^2 / 2}. \quad (11)$$

Such relative contrast curves were first measured for neutron interferometry by Kaiser, Werner, and George [7].

Note that Eq. (6) for the intensity $I(D, \alpha)$ depends only on the magnitude $|a(\mathbf{k})|^2$ of the spectrum $a(\mathbf{k})$ [8]. There are therefore two interpretations as to why the relative contrast decreases with increasing sample thickness; both are equally valid and experimentally indistinguishable [9,10]. First, we know that a wave packet spreads as it propagates, with the faster wavelength components tending toward the leading end of the packet, and the slower components toward the trailing end. The sample delays the packet on path II with respect to the packet on path I, so that when they reach the recombination region, the packets are spatially displaced by a distance $\Delta l(D)$, given by Eq. (4). Faster components within one packet then overlap with slower components within the other. The result is that the interference amplitude “washes out” when summed over the packet, which reduces the contrast of the interferogram [11]. If the two packets are displaced by a distance greater than the coherence length, then the contrast disappears.

If one views the neutron beam as consisting of an incoherent superposition of plane waves, then a second conceptual interpretation can be applied. Each plane-wave k component gives rise to its own intensity pattern $I(k, D, \alpha)$; the overall intensity $I(D, \alpha)$ is the integral of $I(k, D, \alpha)$ over the intensity distribution $g(\mathbf{k})$. On passing through the sample, each component experiences a different phase shift $\chi_S(k, D)$. The overall intensity is thus a sum of sinusoidal patterns of differing phases, which leads to a reduction in the interference amplitude. The beam is said to become “dephased” as the sample thickness increases, and the interferogram contrast even-

tually approaches zero.

In this experiment, we wish to measure changes in interferogram contrast due to the coherence properties of a neutron beam. However, there are other effects that also reduce the contrast. These must be understood and corrected for if we wish to isolate the dephasing effects. First, we have to take into account the beam attenuation due to the sample, which we have not discussed so far. If an attenuating sample is placed in beam II, the amplitude of the wave Ψ_{II} is attenuated by a factor $\exp(-\xi)$, due to the absorption and scattering cross sections of the material. As discussed in our phase-echo paper (Ref. [1]), this attenuation leads to a loss in contrast with increasing sample thickness,

$$\left[\frac{C(D)}{C(0)} \right]_{\text{att}} = \frac{e^{-\xi}}{a_I + e^{-2\xi} a_{II}}, \quad (12)$$

where a_I and a_{II} are the fractional beam intensities on paths I and II, respectively ($a_I + a_{II} = 1$). Thus, if we measure a contrast C_{meas} in our experiment, and wish to deduce what the contrast C would be without the sample's attenuation, we merely multiply C_{meas} by an attenuation correction factor f_{att} :

$$C = C_{\text{meas}} f_{\text{att}}, \quad (13)$$

where

$$f_{\text{att}} = e^{\xi(a_I + e^{-2\xi} a_{II})}. \quad (14)$$

This gives us a way to measure the contrast C corrected for the effects of attenuation. The intensity fractions a_I and a_{II} and attenuation parameters ξ were measured experimentally, and from this information we calculated the attenuation correction factors f_{att} for each sample used. The effect of attenuation on the contrast is different for C2 and C3, and therefore the C2 and C3 data must be corrected separately. The details and results of this correction process are given in an appendix in Ref. [1].

In addition to attenuation, there are other nonideal effects that reduce the interferogram contrast, such as imperfections in the machining of the crystal, vibrations and rotations, thermal gradients, and gravitational warping of the crystal. These effects are also discussed in Ref. [1]. In light of these effects, it is not surprising that we cannot attain 100% contrast with our interferometer. We must content ourselves with a maximum contrast C_0 of order 50% in the C3 beam.

II. THEORY OF CRYSTAL-ANALYZED COHERENCE MEASUREMENTS

A. Gaussian spectrum

Consider a longitudinal coherence neutron interferometry experiment, as shown in Fig. 1. We place a NI in the neutron beam, and it diffracts neutrons with a distribution of wavelengths $g_0(\lambda)$. Let us assume for now that the spectrum is Gaussian, with standard deviation σ_λ^0 :

$$g_0(\lambda) = \frac{1}{\sqrt{2\pi}\sigma_\lambda^0} e^{-(\lambda - \lambda_0)^2 / 2(\sigma_\lambda^0)^2}. \quad (15)$$

When we place samples of varying thickness D in beam II inside the interferometer, the relative contrast is given by Eq. (11), with $\sigma_\lambda = \sigma_\lambda^0$. When the sample thickness D becomes large enough, the beam becomes dephased, and the contrast falls essentially to zero.

Consider now placing an analyzer crystal in the C3 exit beam produced by the arrangement described above. This crystal has a mosaic width η_A , and reflects out of the exit beam a distribution of wavelengths Gaussian in shape and of spectral width σ_λ . The setup for such an experiment in the antiparallel configuration is shown in Fig. 2. The width of the reflected spectrum may be considerably less than that of the overall exit C3 beam σ_λ^0 . It would seem to follow that the contrast in the analyzed beam could be much higher than in the overall beam.

It is a straightforward matter to calculate the spectral width σ_λ that is reflected out of the exit beam by an analyzer crystal of mosaic width η_A . By a geometric argument [11], it can be shown that the analyzer accepts a Gaussian window $W(\lambda)$ of wavelengths

$$W(\lambda) = e^{-(\lambda - \lambda_0)^2 / 2(\sigma_\lambda^A)^2}, \quad (16)$$

of width σ_λ^A ,

$$\sigma_\lambda^A = \lambda_0 \eta_A \left| \frac{\cos(\theta_I) \cos(\theta_A)}{\sin(\theta_I - \theta_A)} \right|, \quad (17)$$

where θ_I is the interferometer Bragg angle. The analyzer Bragg angle θ_A is positive for the parallel scattering configuration, and negative for the antiparallel configuration. We are free to use crystals with different mosaic widths η_A , and can reflect neutrons off of various Bragg planes within a given crystal. In other words, an analyzer window $W(\lambda)$ can be created with almost any width σ_λ^A that we wish.

The spectrum $g(\lambda)$ reflected by the analyzer is the product of the analyzer window $W(\lambda)$ and the incident spectrum $g_0(\lambda)$:

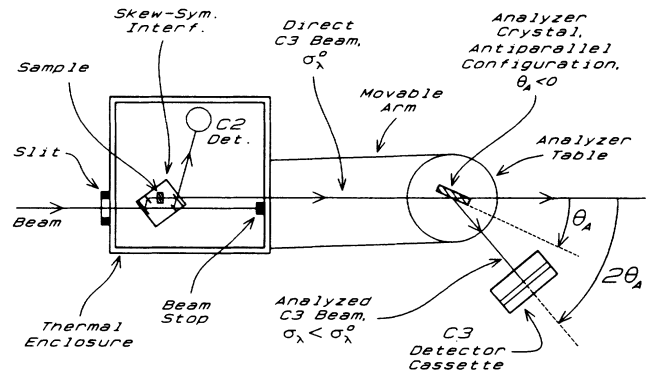


FIG. 2. Setup for analyzing the C3 exit beam with an analyzer crystal in the antiparallel configuration. The nominally monochromatic beam ($\Delta\lambda/\lambda = 1.2\%$) is produced by Bragg reflection from a pyrolytic graphite monochromator ($2\theta_B = 41^\circ$). The Bragg angle of the (220) reflection in the silicon NI is $\theta_B = 37.7^\circ$.

$$g(\lambda) = g_0(\lambda)W(\lambda) = \frac{1}{2\sqrt{2\pi}\sigma_\lambda} e^{-(\lambda-\lambda_0)^2/2(\sigma_\lambda)^2}, \quad (18)$$

where the width σ_λ is given by

$$\sigma_\lambda = \sigma_\lambda^0 \frac{\sigma_\lambda^A}{[(\sigma_\lambda^0)^2 + (\sigma_\lambda^A)^2]^{1/2}}. \quad (19)$$

The form of this equation insures that $\sigma_\lambda < \sigma_\lambda^0$. Figure 3 shows the analyzed spectral width σ_λ versus the analyzer Bragg angle θ_A , calculated for several values of the mosaic width η_A .

Now, consider what this means in terms of our contrast measurements. The overall or "direct" C3 beam has a spectral width σ_λ^0 ; as we vary the sample thickness D , its relative contrast $C_{\text{dir}}(D)$ is given by Eq. (11), with $\sigma_\lambda = \sigma_\lambda^0$. However, if we place an analyzer crystal in the C3 beam, we reflect out only a fraction $\sigma_\lambda/\sigma_\lambda^0$ of the overall spectral width, and find that the analyzed relative contrast $C_A(D)$ falls off at a slower rate:

$$C_A(D) = e^{-(NbD\sigma_\lambda)^2/2} \geq C_{\text{dir}}(D). \quad (20)$$

Beyond a given sample thickness, the contrast in the direct C3 beam is nearly zero, indicating that the beam is apparently incoherent. Yet, with the analyzer, we pick out of the "incoherent" beam a certain portion of the neutrons that still yields contrast. The analyzer crystal thus restores the contrast by reducing the wavelength spectrum of the beam after the interference has taken place. In terms of wave packets, we say that the analyzer increases the coherence length Δx by narrowing the momentum spread Δp .

B. Effects of a non-Gaussian spectrum

The discussion in the preceding section assumed, for convenience, that the spectrum was Gaussian. This is nearly, but not exactly, the case in our experiment, as we shall see. From Eq. (10), we see that this affects the behavior of the contrast curves. However, if the incident spectrum $g_0(\lambda)$ is measured, Eq. (10) can be used to predict the shape of the contrast curve $C_{\text{dir}}(D)$.

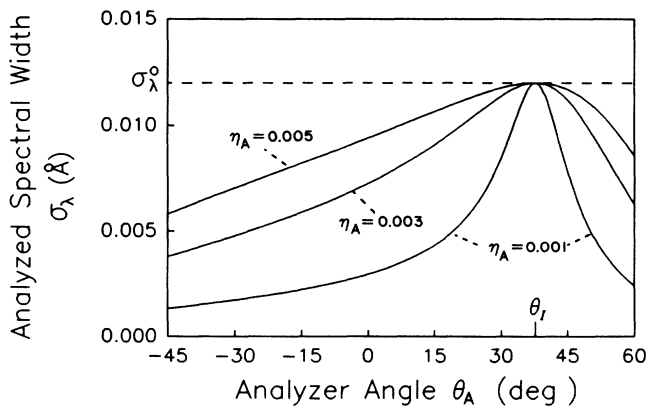


FIG. 3. Spectral width σ_λ of the analyzed beam vs the analyzer Bragg angle θ_A for several values of the mosaic width η_A (in rad).

But what about the analyzed beam? We cannot measure the spectrum in the analyzed beam unless we were to add a second analyzer arm and crystal, which would be difficult. For lack of a better option, we decided to model the analyzed spectrum with a single Gaussian. We fit the incident spectrum $g_0(\lambda)$ to a single Gaussian to determine a spectral width σ_λ^0 , and from this calculated the analyzed spectral widths σ_λ using Eq. (19). We feel justified in doing this because the spectrum is restricted by the mosaic analyzer crystal. If the analyzer has a Gaussian mosaic distribution, and if the window $W(\lambda)$ has a narrow width σ_λ^A , then the reflected spectrum $g(\lambda)$ will also be nearly Gaussian. This is not precisely correct, but the approximation is nevertheless a very good one for this experiment, as we shall see.

C. Phase difference between the C2 and analyzed C3 beams

It is a well-known fact that the interferogram patterns in the C2 and C3 exit beams differ in phase by 180° , that is,

$$\begin{aligned} I_{C3} &= A_{C3} + B \cos(\Delta\phi), \\ I_{C2} &= A_{C2} + B \cos(\Delta\phi + \pi), \end{aligned} \quad (21)$$

where $\Delta\phi = \phi_0 + \phi_p(\alpha) + \chi_S(D)$. This is necessary so that the neutron current is conserved. As the phase $\Delta\phi$ changes, the intensity is swapped back and forth between the two exit beams. In the analyzed beam, however, we find that the phase difference between the C2 beam interferogram and the analyzed C3 beam interferogram is not necessarily 180° due to the non-Gaussian nature of the wavelength spectrum.

To see why this is so, consider a non-Gaussian spectrum modeled by the sum of two equivalent Gaussians:

$$g(\lambda) = \frac{1}{\sqrt{2\pi}\sigma_\lambda} (e^{-(\lambda-\lambda_1)^2/2\sigma_\lambda^2} + e^{-(\lambda-\lambda_2)^2/2\sigma_\lambda^2}). \quad (22)$$

Although this is an oversimplification, the physics of the following derivation is the same for this spectrum as for the real spectrum of our experiment. If this spectrum is placed in Eq. (10), the resulting intensity oscillates with increasing D as

$$\begin{aligned} I(D) &= A + B \cos[\phi_0 + \phi_p(\alpha) - Nb_c D \bar{\lambda}] \\ &\quad \times \cos(Nb_c D \Delta\lambda) e^{-(Nb_c D \sigma_\lambda)^2/2}, \end{aligned} \quad (23)$$

where $\Delta\lambda = (\lambda_1 - \lambda_2)/2$, and $\bar{\lambda} = (\lambda_1 + \lambda_2)/2$. The difference between this expression and Eq. (7) is the term $\cos(Nb_c D \Delta\lambda)$, which is a slowly oscillating amplitude envelope. The other cosine term is rapidly oscillating. In a phase rotator scan, we measure the phase of the rapidly oscillating curve. The relative contrast of this intensity pattern is

$$C_R(D) = |\cos(Nb_c D \Delta\lambda)| e^{-(Nb_c D \sigma_\lambda)^2/2}. \quad (24)$$

Figure 4 shows a representative intensity pattern generated from Eq. (23). At the point labeled Q , the oscillation pattern goes through a node; the amplitude envelope $\cos(Nb_c D \Delta\lambda) = 0$, so that $Nb_c D \Delta\lambda = \pi/2$ (modulus 2π).

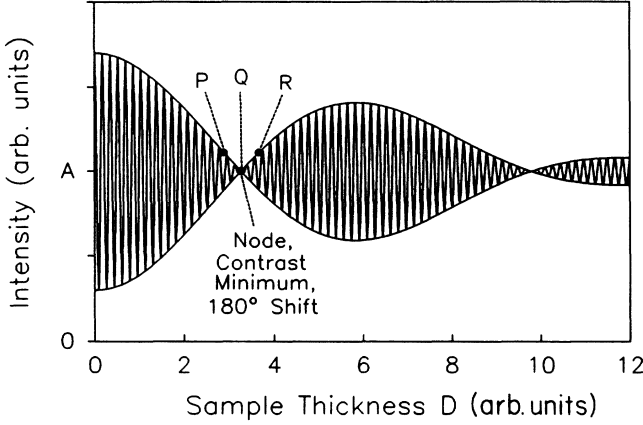


FIG. 4. A representative neutron intensity oscillation pattern, from Eq. (23).

At point P , slightly to the left of Q , $NbD\Delta\lambda = \pi/2 - \delta$, so that the intensity at P is

$$I(D_P) = A + B \sin(\delta) \cos[\phi_0 + \phi_P(\alpha) - NbD\bar{\lambda}] \times e^{-(NbD\sigma_\lambda)^2/2} \quad (25)$$

At point R slightly to the right of Q , $NbD\Delta\lambda = \pi/2 + \delta$, so that the intensity at R is

$$\begin{aligned} I(D_R) &= A + B[-\sin(\delta)] \cos[\phi_0 + \phi_P(\alpha) - NbD\bar{\lambda}] \times e^{-(NbD\sigma_\lambda)^2/2} \\ &= A + B \sin(\delta) \cos[\phi_0 + \phi_P(\alpha) - NbD\bar{\lambda} + \pi] \times e^{-(NbD\sigma_\lambda)^2/2} \end{aligned} \quad (26)$$

The phase of the function at points P and R differs by π . Thus, when the oscillation goes through a node, or the contrast goes through a minimum, we expect the phase of the intensity pattern to shift of 180° .

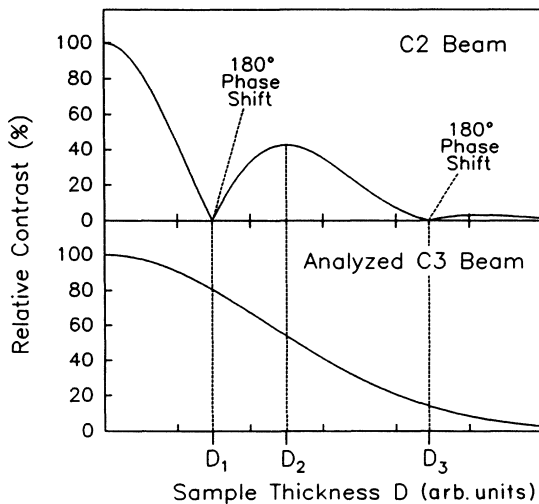


FIG. 5. Representative relative contrast curves in the $C2$ beam and in the analyzed $C3$ beam.

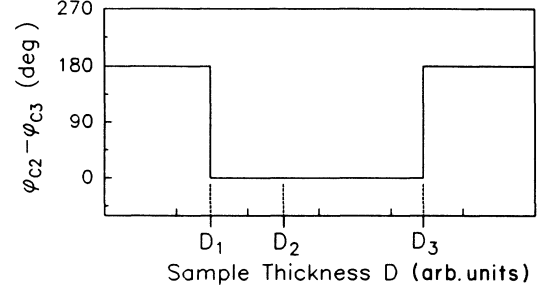


FIG. 6. The phase difference between the $C2$ beam and analyzed $C3$ beam, based on Fig. 5.

In this derivation, we have simplified matters by assuming that the spectrum could be modeled by the sum of two equivalent Gaussian peaks. This actually turns out to be quite a good approximation for the spectrum used in this experiment. Even if this were not the case, we would still expect the phase of the pattern to shift by 180° when the contrast curve goes through a minimum. This should happen in both the $C2$ beam and the overall (direct) $C3$ beam.

Consider what happens, however, if we analyze the $C3$ beam, and compare it to the overall $C2$ beam. We compare these two beams because they were monitored simultaneously in the experiment. The relative contrast in the analyzed $C3$ beam should fall off more slowly than in the $C2$ beam, as shown in Fig. 5. When no sample is in the interferometer, the two beams are 180° out of phase. At some thickness D_1 the $C2$ beam (and the direct $C3$ beam) goes through a contrast minimum, and its phase is shifted by 180° . At this point, however, the analyzed $C3$ beam has not reached a contrast minimum, so its phase is not shifted. Thus, for a range of sample thicknesses between D_1 and D_3 , the $C2$ and analyzed $C3$ beams are in phase with each other. At some greater thickness D_3 , one of the beams reaches another contrast minimum, and experiences another 180° phase shift, so that the two beams are again 180° out of phase. Figure 6 shows the difference in phase between the $C2$ and analyzed $C3$ beams, based on the curves in Fig. 5.

Although this effect makes sense in a mathematical way, it runs contrary to our normal experience in neutron interferometry. For a certain range of sample thicknesses, the $C2$ and analyzed $C3$ beams are in phase. That is, if the counts go up in the $C2$ detector as we rotate the phase shifter, they will also go up in the analyzed $C3$ beam. This seems to contradict the conservation of neutrons, but it does not, because the counts in the *overall* (direct) $C3$ beam must go down. The mean phase of the neutrons in the analyzed $C3$ beam is different than in the $C3$ beam as a whole.

III. EXPERIMENT

A. Apparatus

To begin the experiment, we had to select some analyzer crystals to work with and decide which Bragg

reflections to use. We had at our disposal two silicon crystals, one nearly perfect [$\Delta\theta=0.02^\circ$ full width at half maximum (FWHM), $\eta_A=0.00015$ rad], and the other a pressed silicon crystal with a relatively broad mosaic width [$\Delta\theta=0.47^\circ$ (FWHM), $\eta_A=0.0035$ rad]. We labeled these crystals "NP" and "PR," for "nearly perfect" and "pressed silicon." We decided to work with three different analyzer configurations. We used the PR analyzer in both the (111) parallel and (111) antiparallel configurations, and used the NP analyzer in the (111) antiparallel configuration. With $\lambda=2.35$ Å, the Bragg angle of these reflections is $\theta_A=\pm 22.0^\circ$, where the plus sign is for the parallel configuration, and the minus sign is for the antiparallel. The interferometer Bragg angle for the (220) reflection was $\theta_I=37.7^\circ$. From this, we calculated the analyzed spectral widths σ_λ expected from the crystals in each configuration; the values are given in Table I.

We next had to have a suitable set of phase shifting samples. We chose to make the samples out of bismuth, because Bi has a large, positive scattering length $b=8.533$ fm, an atom density $N=2.82\times 10^{28}$ m $^{-3}$, and a relatively low absorption cross section ($\sigma_a=0.0388$ b and $\sigma_s=9.156$ b). Initially, five slab-shaped samples of bismuth and titanium were machined, polished, and etched, and then epoxied onto aluminum mounting brackets. The samples were made so that their nominal thicknesses were multiples of 4 mm (4, 8, 12, 16, and 20 mm). The exact thicknesses of the samples are given in Table III. In addition, we made a sixth sample that was thinner than the others (2.1 mm thick). Since this sample was about half as thick as sample 1, it was dubbed "sample $\frac{1}{2}$." This sample was used in combination with larger samples to give finer increments in thickness. For example, bismuth samples 1 and $\frac{1}{2}$ could be used simultaneously to place 6.10 mm of Bi in the beam; we called such a combination "bismuth sample $1\frac{1}{2}$." The thin samples in set $\frac{1}{2}$ could also be combined with the other samples to create "sample $2\frac{1}{2}$," sample $3\frac{1}{2}$," and so on. This effectively doubled the number of data points that we could obtain.

The basic setup for the experiment is shown schematically in Fig. 2. A slit, 8 mm wide by 6 mm high, was mounted ~ 7 cm in front of the interferometer to restrict the beam size. When no sample was in the beam, this

produced a counting rate of ~ 1030 counts/min with $\sim 46\%$ contrast in the C3 exit beam, and a rate of ~ 3430 counts/min with $\sim 16\%$ contrast in the C2 detector. The samples were affixed by means of their mounting brackets to an aluminum bar, which held the samples at the right height and position to intercept the beam. The bar was attached to a translation table, so that the samples could be driven in and out of beam II by a computer-controlled stepping motor.

The analyzer crystal was mounted on a goniometer, whose tilt and rotation were controlled by stepping motors. This assembly, called the analyzer table, was mounted ~ 60 cm downstream from the interferometer on a movable arm, as indicated in Fig. 2. The analyzer was placed in the C3 beam, and its height and translation were optimized so that it was centered in the beam.

The neutrons were detected by $\frac{1}{2}$ -in.-diameter, cylindrical, 20-atm ^3He detectors, which are essentially black to thermal neutrons. The C2 detector was mounted vertically ~ 20 cm past the NI. It was surrounded by a casing made of B_4C powder suspended in epoxy, which absorbed any background neutrons. The beam was allowed to enter only through an opening, $\frac{1}{2}$ in. wide and 1 in. high, defined by a cadmium tube several inches long. The C3 detector was mounted on a rotatable arm attached to the analyzer table. Its position was also controlled by a stepping motor, so that it could be driven into the analyzed beam direction. At this distance (60 cm), the beam was too broad to be accepted by a $\frac{1}{2}$ -in.-wide vertical detector. For that reason, the C3 "detector" actually consisted of three ^3He detectors (all of which fed into the same electronic counting chain), mounted horizontally in a neutron-shielding B_4C -epoxy cassette with a 1×1 in. ^{2} collimated opening. This arrangement also had the advantage of making the detection probability constant in the horizontal plane. The wavelength of a neutron ray reflected by the monochromator depends on the reflection angle, and therefore varies in the horizontal plane. To detect all parts of the spectrum equally, the C3 detectors were mounted horizontally, so that all components saw the same detector thickness.

The vast majority of neutrons entering the interferometer fall outside the Darwin acceptance width and are not diffracted. This so-called "direct beam" also has a divergence to it, and would spill into the C3 detector and

TABLE I. Spectral widths expected in the direct and analyzed beams.

Beam	η_A (rad)	σ_λ (Å)	$\Delta\lambda/\lambda_0$
Direct		0.0120	1.20%
Analyzed, PR crystal, (111) parallel	0.0035	0.0106	1.06%
Analyzed, PR crystal, (111) antipar.	0.0035	0.0070	0.70%
Analyzed, NP crystal, (111) antipar.	0.00015	0.00030	0.03%

TABLE II. Mean signal and background counting rates per minute, and mean counting time per point.

Beam	Signal (min $^{-1}$)	Background (min $^{-1}$)	Time per point (min)
C2, all configs.	3430	207.5 $\pm$ 0.7	(same as C3)
Direct C3	1030	49.1 $\pm$ 1.2	5
C3, PR analyzer (111) parallel	400	37.6 $\pm$ 1.1	12
C3, PR analyzer (111) antipar.	230	58.2 $\pm$ 0.4	20
C3, NP analyzer (111) antipar.	32	61.2 $\pm$ 1.1	40

overwhelm the relatively weak C3 beam. To prevent this from happening, the direct beam was blocked with a B₄C-epoxy block directly after the NI.

B. Data collection and analysis

Even when there is no sample in the beam, a neutron interferometer operates at contrast C_0 that is less than 100%. The coherence loss due to the dephasing effect manifests itself in a *relative* drop in contrast from this starting value C_0 to a new value $C(D)$ when a sample was placed in the beam. It was therefore important to measure the “sample-out” contrast C_0 as well as the “sample-in” contrast $C(D)$ for each data set.

The basic procedure is described in detail in Ref. [1], and consists of taking simultaneous “sample-out” and “sample-in” interferograms. A sample is mounted on the translation bar, but driven to a position where it does not intercept the beam; we call this the “sample-out” position. With the phase rotator set to a certain position α_1 , we collect data until our monitor counter reaches a fixed preset number corresponding to a (nearly) constant detection time per point. This is the “sample-out” data. The sample is then driven into the beam on leg II of the interferometer, and we collect data again for a period approximately four times longer than the sample-out collection time. This is the “sample-in” data. The sample is then driven back out of the beam, the phase shifter is moved to a new position α_2 , and the counting process is repeated. After 30 or so data points, the result is a pair of interferograms, one with sample-out, and one with sample-in.

It is important to take these interferograms simultaneously, because the absolute contrast C_0 drifts a small amount with time due to environmental factors. Over the course of a day, the sample-out contrast C_0 might vary $\pm 3\%$ or so; however, the *relative* loss of contrast due to dephasing will *not* drift, as long as the sample-in and sample-out curves have the same “starting” contrast

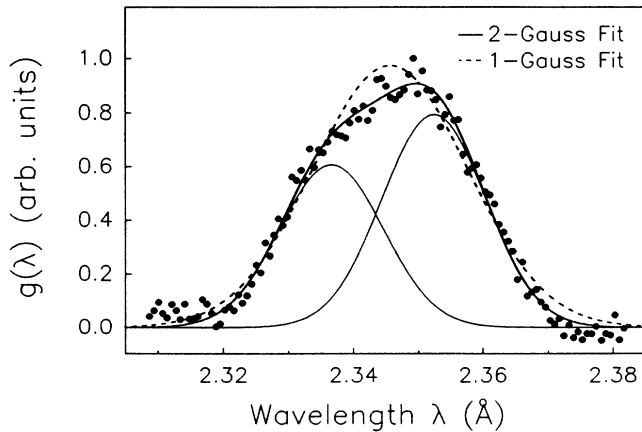


FIG. 7. The measured wavelength spectrum $g(\lambda)$ for the experiment. The single-Gaussian fit parameters to the data are $\lambda_0 = 2.3456 \text{ \AA}$, $\sigma_\lambda = 0.0120 \text{ \AA}$, $a = 0.974$. The double-Gaussian fit parameters to the data are $\lambda_1 = 2.3366 \text{ \AA}$, $\sigma_{\lambda 1} = 0.00798 \text{ \AA}$, $a_1 = 0.606$; $\lambda_2 = 2.3524 \text{ \AA}$, $\sigma_{\lambda 2} = 0.00800 \text{ \AA}$, $a_2 = 0.793$.

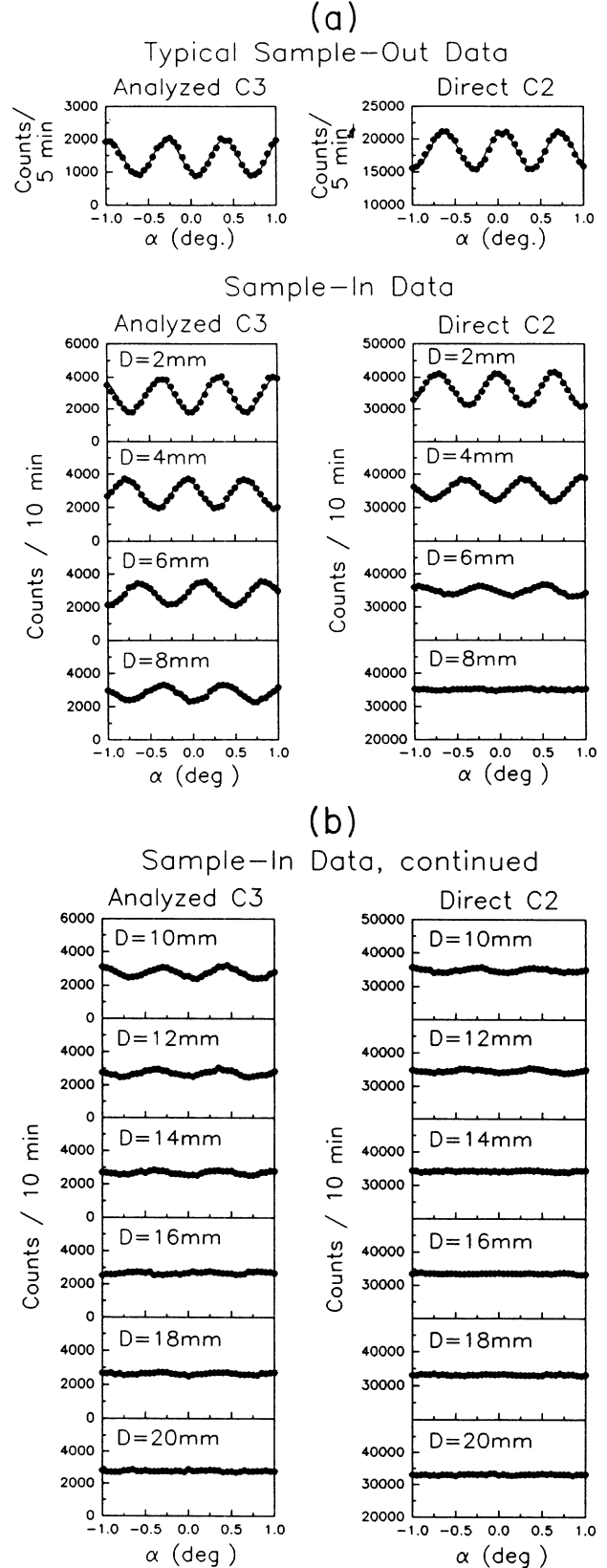


FIG. 8. Interferograms in the C2 and analyzed C3 beams vs phase rotator angle α (see Fig. 1) normalized to the same counting time per point (10 min) for the PR analyzer crystal in the (111) antiparallel configuration, with various sample thicknesses D .

TABLE III. Relative contrast results in the direct C3 beam.

Bi Sample No.	D (mm)	Δl (Å)	$\Delta\phi$ (rad)	C_{out} (%)	C_{in} (%)	C_R (%)
$\frac{1}{2}$	2.09	-44.2	-118	46.3 ± 0.5	40.8 ± 0.4	88.1 ± 1.3
1	4.01	-84.7	-227	46.9 ± 0.5	26.8 ± 0.4	57.3 ± 1.0
$1\frac{1}{2}$	6.10	-128.9	-345	43.5 ± 0.5	7.7 ± 0.4	17.8 ± 0.9
2	7.99	-168.8	-452	48.0 ± 0.5	1.3 ± 0.4	2.2 ± 0.8
$2\frac{1}{2}$	10.08	-213.0	-571	47.8 ± 0.5	4.2 ± 0.4	8.7 ± 0.8
3	12.26	-259.1	-694	45.2 ± 0.5	3.6 ± 0.4	8.0 ± 0.8
$3\frac{1}{2}$	14.35	-303.2	-812	45.0 ± 0.5	1.8 ± 0.4	3.9 ± 0.9
4	16.15	-341.2	-914	41.5 ± 0.5	0.7 ± 0.3	1.8 ± 0.8
$4\frac{1}{2}$	18.24	-385.4	-1032	46.6 ± 0.5	1.3 ± 0.3	2.8 ± 0.7
5	20.08	-424.3	-1135	48.4 ± 0.5	1.4 ± 0.3	2.9 ± 0.6

C_0 . To insure that this is the case, we have to take the two data sets at the same time.

Collecting two such interferograms for a given sample constituted one data "run." The process was repeated for all Bi samples individually (including the paired " $\frac{1}{2}$ " samples). The counting time per point depended on the analyzer crystal and configuration being used; see Table II. In selecting out a small portion ($\sigma_\lambda/\sigma_\lambda^0$) of the wavelength spectrum, we also selected out only a fraction of the available neutron intensity, which led to long counting times and greater statistical error. The counting times listed below are average values; for high contrast runs with thin samples, we used shorter counting times; with thicker samples we increased the counting time to more accurately measure the expected small contrast. The direct beam scans took about 6 h apiece; the PR analyzer scans lasted about 13 h; and the NP analyzer scans required over 36 h to complete.

After completion, each interferogram was fit to a cosine function by a nonlinear least-squares-fit routine. We used the fit parameters to calculate the contrast C_{meas} of the interferogram (see Ref. [1]). This was done separately for the data in both detector channels C2 and C3 for both the sample-out and sample-in conditions. The sample-in contrast had to be corrected for attenuation

due to the sample, as discussed in Sec. I. The fit program also computed a statistical error for each fit parameter. Using standard statistical methods, we calculated error bars for our results. If the sample-out contrast is $C_0 \pm \sigma_0$, and the sample-in contrast is $C_{in} \pm \sigma_{in}$, then the relative contrast $C_R \pm \sigma_R$ is given by

$$C_R = \frac{C_{in}}{C_0}, \quad (27)$$

where

$$\sigma_R = C_R \left[\left(\frac{\sigma_0}{C_0} \right)^2 + \left(\frac{\sigma_{in}}{C_{in}} \right)^2 \right]^{1/2}. \quad (28)$$

C. Results

Since the contrast results depend on the shape of $g(\lambda)$, we first need to know the spectrum to be able to predict the outcome of the experiment. The measurement technique is described in Ref. [1], and consists of using a (nearly) perfect silicon crystal to do a θ - 2θ scan in the C3 beam, and converting this to a wavelength spectrum. The resulting spectrum, arbitrarily normalized to 1, is shown in Fig. 7, along with the one- and two-Gaussian

TABLE IV. Relative contrast results in the analyzed C3 beam, PR analyzer crystal, (111) antiparallel configuration.

Bi Sample No.	D (mm)	C_{out} (%)	C_{in} (%)	C_R (%)
$\frac{1}{2}$	2.09	47.9 ± 0.8	47.8 ± 0.6	99.8 ± 2.0
1	4.01	49.9 ± 0.8	38.8 ± 0.6	77.8 ± 1.7
$1\frac{1}{2}$	6.10	50.1 ± 0.8	31.6 ± 0.5	61.1 ± 1.5
2	7.99	51.3 ± 0.8	21.9 ± 0.5	42.6 ± 1.1
$2\frac{1}{2}$	10.08	50.9 ± 0.8	15.6 ± 0.4	30.6 ± 1.0
3	12.26	51.2 ± 0.8	9.9 ± 0.4	19.2 ± 0.9
$3\frac{1}{2}$	14.35	51.8 ± 0.8	6.3 ± 0.4	12.2 ± 0.8
4	16.15	50.7 ± 0.8	3.9 ± 0.4	7.7 ± 0.7
$4\frac{1}{2}$	18.24	53.0 ± 0.8	3.8 ± 0.4	7.0 ± 0.7
5	20.08	49.6 ± 0.8	1.4 ± 0.3	2.8 ± 0.6

TABLE V. Relative contrast results in the analyzed C3 beam, PR analyzer crystal, (111) parallel configuration.

Bi Sample No.	D (mm)	C_{out} (%)	C_{in} (%)	C_R (%)
$\frac{1}{2}$	2.09	48.2 ± 0.7	44.3 ± 0.5	91.8 ± 1.7
1	4.01	49.5 ± 0.7	33.6 ± 0.5	67.9 ± 1.4
$1\frac{1}{2}$	6.10	48.3 ± 0.7	22.2 ± 0.4	45.9 ± 1.1
2	7.99	49.0 ± 0.7	7.4 ± 0.4	15.1 ± 0.8
$2\frac{1}{2}$	10.08	48.6 ± 0.7	1.0 ± 0.3	2.0 ± 0.7
3	12.26	49.7 ± 0.7	2.9 ± 0.3	5.9 ± 0.7
$3\frac{1}{2}$	14.35	48.0 ± 0.7	1.8 ± 0.3	3.8 ± 0.6
4	16.15	46.8 ± 0.7	0.5 ± 0.3	1.1 ± 0.7
$4\frac{1}{2}$	10.24	47.4 ± 0.7	0.5 ± 0.3	1.1 ± 0.6
5	20.08	49.3 ± 0.7	1.0 ± 0.3	1.9 ± 0.6

fits to the data. Note that the two-Gaussian fit gives two peaks that are nearly equivalent in width and amplitude; thus, our approximation in Sec. IIC was a fairly good one.

We then began our data collection, beginning with the contrast scans in the direct C3 beam. The analyzer crystal was rotated to a position perpendicular to the beam, so that there would be no Bragg reflection and minimal absorption. The detector cassette was moved into the direct C3 beam and its position was optimized with a rocking curve. We then took a series of contrast scans using different sample thicknesses. The relative contrast results of these scans are given in Table III.

We next mounted the pressed silicon (PR) analyzer crystal in the C3 beam, and rotated it and the detector arm until we found the (111) antiparallel reflection ($\theta_A = -22.0^\circ$). The positions of the analyzer and detector were optimized with a series of rocking curves. Once maximized, the analyzer and detector remained fixed. We then took a second set of contrast scans with different bismuth samples. The contrast results of these scans are given in Table IV.

Plots of the PR antiparallel interferograms are shown in Fig. 8, along with the fits to the data. The sample-out curves did not vary much from run to run, so only one representative set is shown. The plots show that the contrast does fall off more slowly in the analyzed beam than in the direct beam as anticipated. The relative contrast curve in the C2 beam is identical to that in the direct C3

beam because both have the same spectral width σ_λ^0 . Comparing the graphs, we see that the overall C2 contrast decayed quickly, reaching (nearly) zero by a sample thickness of $D = 8$ mm; the analyzed C3 beam, on the other hand, had visible contrast up to a thickness of $D = 14$ mm or so.

We next rotated the PR analyzer and detector arm into the (111) parallel direction ($\theta_A = +22.0^\circ$), and optimized their positions with a series of rocking curves. This arrangement was used to take the third set of contrast scans for various sample thicknesses D . The contrast results of the PR (111) parallel scans are given in Table V. For the fourth and final data set, we replace the PR analyzer with the nearly perfect (NP) silicon crystal. The analyzer and detector positions were optimized in the (111) antiparallel configuration ($\theta_A = -22.0^\circ$), and another set of contrast scans using various sample thicknesses was performed with this arrangement. The contrast results calculated for the NP (111) antiparallel runs are given in Table VI. Due to the long collection time, there were fewer data runs taken in this configuration.

The relative contrast results of all four data sets are shown in Fig. 9. Also shown are the curves predicted by our model using Eq. (10) and the fit parameters listed in the caption to Fig. 7. As Fig. 9 shows, there was an increase in contrast in the analyzed beam compared to the direct beam. The contrast in the direct C3 beam fell rather rapidly to a minimum of $C_R = 2.2\%$ at $D = 8$ mm, improved a bit, fell to another minimum at $D = 16$ mm,

TABLE VI. Relative contrast results in the analyzed C3 beam, NP analyzer crystal, (111) antiparallel configuration.

Bi Sample No.	D (mm)	C_{out} (%)	C_{in} (%)	C_R (%)
1	4.01	37.2 ± 1.4	36.1 ± 1.3	97.1 ± 5.1
2	2.77	41.7 ± 1.4	41.2 ± 1.3	99.0 ± 4.8
3	12.26	43.1 ± 1.5	38.7 ± 1.4	89.6 ± 4.4
4	16.15	42.2 ± 1.8	36.3 ± 1.3	86.0 ± 4.8
5	20.08	39.1 ± 1.6	37.3 ± 1.3	95.2 ± 5.2

TABLE VII. Phase difference between the direct C2 and analyzed C3 interferograms for the PR (111) antiparallel analyzer contrast runs.

Bi Sample No.	D (mm)	ϕ_{C2} (deg)	ϕ_{C3} (deg)	$\phi_{C2} - \phi_{C3}$ (deg)
$\frac{1}{2}$	2.09	19 ± 0.5	202 ± 0.6	177 ± 0.8
1	4.01	216 ± 0.7	39 ± 0.8	177 ± 1.1
$1\frac{1}{2}$	6.10	110 ± 1.5	306 ± 0.9	164 ± 1.7
2	7.99	186 ± 9.8	182 ± 1.1	4 ± 9.8
$2\frac{1}{2}$	10.08	141 ± 2.8	148 ± 1.5	-7 ± 3.2
3	12.26	174 ± 3.2	183 ± 2.4	-9 ± 4.0
$3\frac{1}{2}$	14.35	207 ± 9.8	192 ± 3.5	15 ± 10
4	16.15	40 ± 17	294 ± 5.7	106 ± 18
$4\frac{1}{2}$	18.24	28 ± 9.3	180 ± 5.4	208 ± 11
5	20.08	120 ± 13	287 ± 14	193 ± 18

and then tailed off. When the PR analyzer was used in the (111) parallel configuration, the contrast fell a bit more slowly than in the direct C3 beam, but not substantially so. This is to be expected, since this reflection only reduced the spectral width by $\sim 12\%$. In the antiparallel configuration, the PR analyzed contrast falls off much more slowly than in the direct C3 beam. While the direct beam curve goes through a contrast minimum at $D = 8$ mm, the antiparallel PR data still have 48% relative con-

trast. When the nearly perfect analyzer is used, the contrast hardly declines at all; even with 20 mm of Bi, the relative contrast remains near 90%. Very good contrast can thus be extracted from an apparently incoherent beam. The measured data also agree fairly well with the predicted curves.

The second goal of the experiment was to calculate the phase difference between the interferograms in the C2 beam and in the analyzed C3 beam. We used the data from the PR (111) antiparallel scans to make the phase comparison. The C2 and analyzed C3 relative contrast curves are plotted jointly in Fig. 10(a). The C2 curve goes through contrast minima at $D = 8$ and 16 mm, at which points we expect a 180° shift in the phase of the interferogram. The PR analyzed curve does not go through a contrast minimum (Fig. 9), so it should not ex-

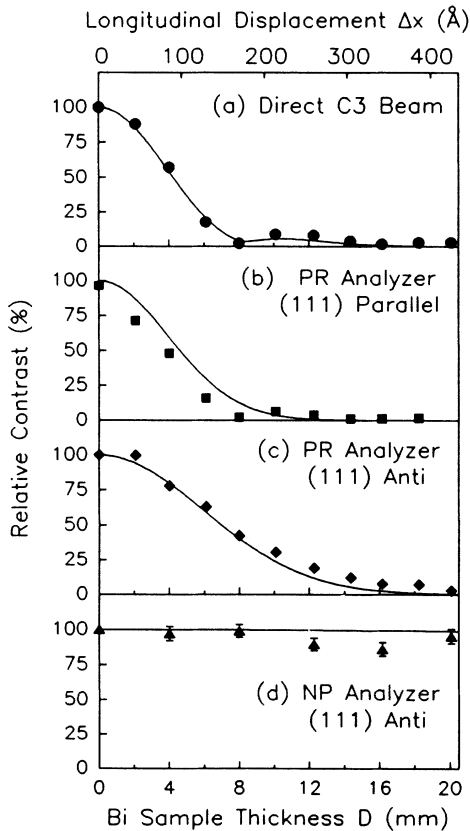


FIG. 9. The relative contrast results vs sample thickness for the different analyzer configurations used in the experiment. The solid lines represent the theoretical curves based on our model and spectral measurements.

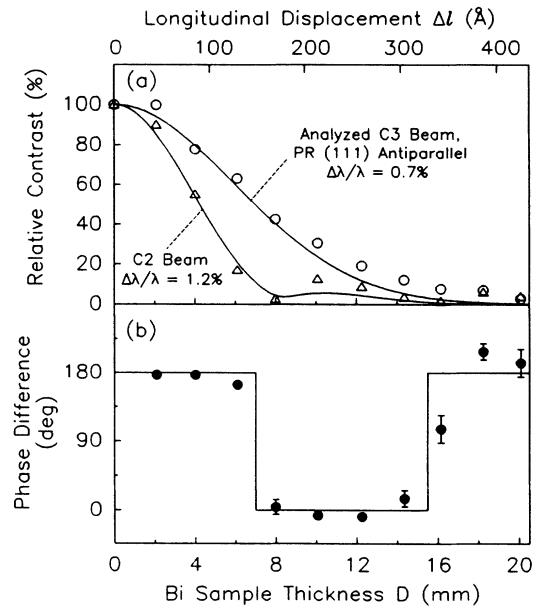


FIG. 10. (a) The relative contrast vs sample thickness in the C2 beam and the analyzed C3 beam, using the PR analyzer in the (111) antiparallel configurations. (b) The phase difference between the C2 and analyzed C3 beam in this configuration.

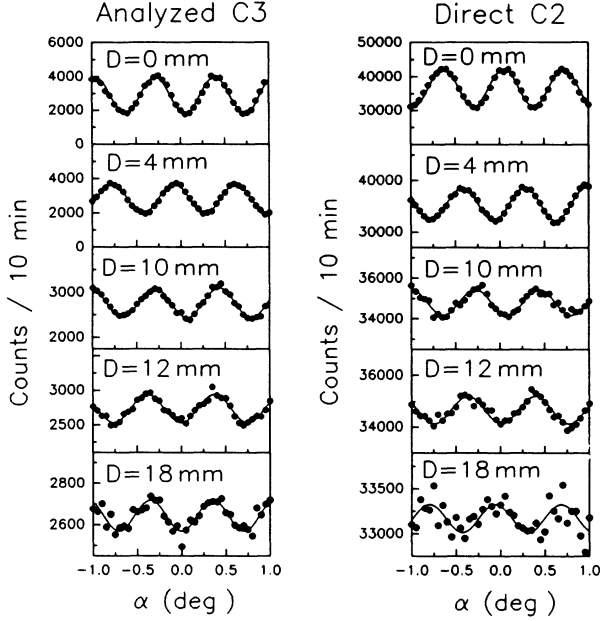


FIG. 11. Several interferograms replotted from Fig. 8, with the vertical axes scaled so that the phasing is readily apparent. In the first two panels ($D=0$ and 4 mm), the C2 and analyzed C3 curves are clearly 180° out of phase; for $D=10$ and 12 mm, in the next two panels, the curves are in phases; and in the final panel, with $D=18$ mm, the curves are again out of phase.

perience a 180° phase shift at any point.

Table VII gives the initial phases ϕ_{C2} and ϕ_{C3} and the difference $\phi_{C2} - \phi_{C3}$ of the C2 and analyzed C3 interferograms, sample-in condition, for each sample thickness in the PR (111) antiparallel data set. If necessary, 360° were added to ϕ_{C2} to make it greater than ϕ_{C3} . The $\phi_{C2} - \phi_{C3}$ data in Table VII are plotted in Fig. 10(b), and show that the 180° phase shift does occur. Up to a thickness of 6 mm of Bi, C2 and the analyzed C3 beam are 180° out of phase. Between 6 and 8 mm of Bi, C2 goes through a contrast minimum, so that from 8 to 14 mm of Bi, the C2 and analyzed C3 beams are in phase. At about 16 mm of Bi, C2 goes through another contrast minimum, so that from 18 to 20 mm of Bi, the two beams are again 180° out of phase. This effect can be seen directly from the interferograms shown in Fig. 11.

It should be mentioned once again that this 180° phase shift only occurs when we compare the *analyzed* C3 beam with the overall C2 beam. The overall C2 and C3 beams are always 180° out of phase. With the analyzer, however, we can pull out of the beam a certain range of components whose mean phase is different from that of the overall beam. This is only possible due to the non-Gaussian shape of the wavelength distribution.

IV. CONCLUSIONS

In this experiment, we were able to restore coherence to an apparently incoherent beam by filtering out of that beam those neutrons whose wavelengths lie in a narrow band σ_λ . Indeed, with the nearly-perfect-silicon analyzer, we extracted essentially 100% relative contrast

TABLE VIII. Calculated longitudinal coherence lengths Δx of the neutrons in the different analyzer configurations.

Beam	Δx (Å)
Direct C3 (and C2)	86.2
PR analyzer, (111) parallel	97.5
PR analyzer, (111) antiparallel	148
NP analyzer, (111) antiparallel	3450

from a “contrastless” beam, even with 20 mm of bismuth dephasing the beam. We were also able to show that the mean phase of the neutrons in this wavelength band may not be the same as that of the beam as a whole, but may instead differ by 180° .

Although the results make perfect sense from a wave-component viewpoint, it brings into question the connection between particles and localized wave packets. When we say there is a neutron wave packet of coherence length Δx , we often think semiclassically that the wave packet somehow “is” the localized neutron particle. If the two wave packets traversing paths I and II in the interferometer overlap within a distance Δx in the region of recombination, we picture the neutron overlapping with itself, giving rise to interference.

But consider what this conceptual picture means in light of this experiment. By reducing the wavelength spread, we increase the longitudinal coherence length of the packet, according to the uncertainty principle:

$$\Delta x (\text{FWHM}) = \sqrt{8 \ln 2} \sigma_x = \frac{1.034 \text{ Å}^2}{\sigma_\lambda}, \quad (29)$$

for $\lambda = 2.35 \text{ Å}$. The calculated coherence lengths are given in Table VIII. The thing to keep in mind is that we determine the coherence length *after* the interference has taken place, far downstream from the interferometer; Δx can be 86, 149, or 3450 Å, or any other value for that matter. If the wave packets “were” the neutron particle, we could not vary their physical extent, at will, after the fact, as we have apparently done in this experiment.

The conclusion to be drawn is a familiar one in quantum mechanics: matters waves are not particles, and we have no right to think of them as such, even in a semiclassical way. The neutron wave-packet formalism is merely the mathematical description of Wheeler’s quantum-mechanical “great smoky dragon” [12]. We know the neutron is a particle when it is emitted, and again when it is detected, but between these two times, the physical connection between the neutron particle and the wave packet remains hidden, no matter how diligently we try to analyze the quantum questions with our classical tools.

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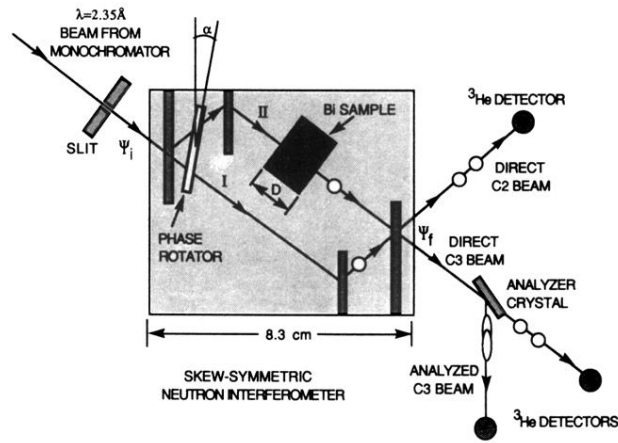


FIG. 1. Schematic diagram of a perfect Si crystal skew-symmetric neutron interferometer. The beam from the monochromator, of nominal wavelength $\lambda = 2.35 \text{ \AA}$, passes through a $8 \times 6 \text{ mm}^2$ slit immediately in front of the NI. The circles represent the coherence length of the wave packets resulting from one neutron entering the NI and traversing the two beam paths. The beam on path II passes through one or two bismuth slabs, which spatially delay the wave packet due to the positive optical potential of Bi. The packets recombine, interfere, and are detected by one of the ^3He detectors. The C3 beam is detected after reflection by a Si analyzer crystal. The interference contrast is measured by rotating the aluminum phase shifter in steps α about a vertical axis.