Observation of a motion-induced phase shift of neutron de Broglie waves passing through matter near a nuclear resonance

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We report the results of a neutron interferometry experiment where for the first time (to our knowledge) a phase shift of a neutron de Broglie wave induced by moving matter has been successfully measured. This experiment is the quantum-mechanical analog of the optical Fizeau effect. The observed phase shift is caused by the motion of matter itself, and not by the motion of its boundaries. The experimental results are found to be in good agreement with the theoretical predictions. Some unexpected and previously unreported neutron wave interference effects observed during the experiment are also reported.

I. INTRODUCTION

In recent years a number of theoretical and experimental investigations have been carried out to study the effect of the motion of matter on the phase of a neutron de Broglie wave through which it is propagating.[1–4] These studies have brought into focus important, but not so clearly obvious, differences in the interaction properties of photon and neutron waves with moving matter. In an excellent article, Horne *et al.* showed that for most materials the phase of a neutron wave can be affected only by the motion of the boundary of the moving matter and not by the motion of the bulk of the matter itself.[1] This is true when the neutron-nuclear interaction potential is velocity independent, which is the case for most materials in the thermal energy range. By contrast, the phase of the photon wave is influenced by motion of bulk material itself. This was first demonstrated by Fizeau in 1859 with the use of a Rayleigh-type optical interferometer.[5] With the advent of neutron interferometers within the last few years, a number of Fizeau-type experiments have been designed and successfully carried out.[2–4] These experiments have validated the theoretical prediction of no Fizeau-type phase shift for neutron waves interacting with materials having an energy-independent scattering length. The results of these experiments have also demonstrated the validity of Galilean transformation properties of $(\omega,\mathbf{k})$ four vectors for massive particles (neutrons) and have established an upper limit for the energy dependence of a neutron-nuclear Fermi pseudopotential.[2,3] Success of these experiments has led us to attempt an important experiment where the neutron passes through moving matter at a nuclear resonance. The neutrons then experience an energy-dependent potential and, as the theory suggests, a neutron wave phase shift truly analogous to the light-wave case should be observable. This represents a fundamentally different situation from earlier experiments in the sense that the observed phase shift results from the motion of the bulk of material and not from the motion of the boundaries of the moving matter.

We have carried out a neutron interferometric experiment where thermal neutrons pass through natural samarium with 13.9% isotopic abundance of ^{149}Sm, which has a nuclear resonance at 97.3 meV. In this paper the experiment is described in detail. An account of a preliminary version of this experiment has been given in the proceedings of a workshop.[6]

II. THEORY

A diagram of our perfect silicon crystal, Bonse-Hart interferometer[7] is shown in Fig. 1. An incident neutron beam is coherently split into two separate beams at point A. These two beams are simultaneously intercepted by a moving material slab with parallel sides of thickness T. If the motion of the slab induces any phase difference in the neutron waves travelling on path ABD relative to path ACD, then this would be made manifest in the phase of the recombined beams at point D. In the rest frame of the moving slab, the phase difference of the neutron waves traveling in these two paths is given by

$$\Delta\Phi=\Phi_{ABD}(\mathbf{k}_B)-\Phi_{ACB}(\mathbf{k}_C)\ , \tag{1}$$

where Φ_{ABD} and Φ_{ACD} are the neutron phases accumulated on paths ABD and ACD, respectively, and $\mathbf{k}_B$ and $\mathbf{k}_C$ are the incident wave vectors at points B and C in that frame. The magnitudes of k_B and k_C depend directly on the incident angle θ and slab velocity W. According to Fig. 1 the components of these wave vectors parallel and perpendicular to the slab sides are given by

$$k_{By}=k_0\sin\theta-\frac{mW}{\hbar},\quad k_{Bx}=k_0\cos\theta\ , \tag{2}$$

$$k_{Cy}=-k_0\sin\theta-\frac{mW}{\hbar},\quad k_{Cx}=k_0\cos\theta\ , \tag{3}$$

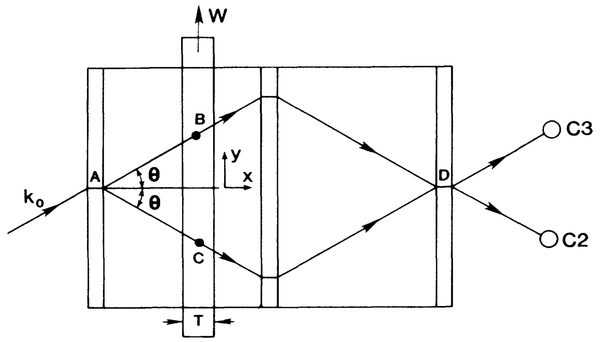


FIG. 1. Schematic of an LLL-type neutron interferometer showing the beam paths.

where k_0 is the incident-beam wave vector in the rest frame. It is important to note that the components of the slab velocity perpendicular to the beam paths do not induce any phase shifts. This can be understood simply by noting that a neutron-nuclear potential for a slab moving perpendicular to the beam paths is indistinguishable from a potential for a slab at rest. Since phase shifts are relativistically invariant quantities, $\Delta\Phi$ must also be the phase shift in the laboratory frame. The expression for $\Delta\Phi$ has been rigorously deduced previously;[8] the result is

$$\Delta\Phi = 4\pi\hbar NTW \tan\theta \frac{db}{dE} , \tag{4}$$

where N is the atom density of the slab material, W is the slab velocity, T is the slab thickness, $\hbar$ is the Planck's constant/2π, θ is the angle of incidence, b is the real part

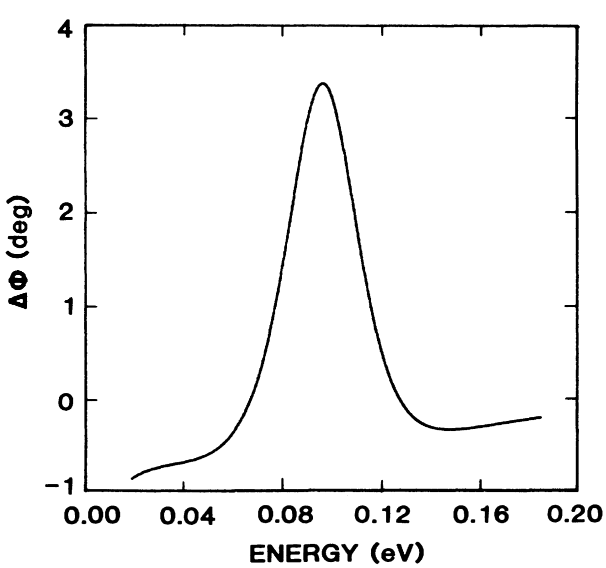


FIG. 2. Calculated phase shift of a neutron wave passing through moving natural Sm foil. In this case the foil thickness is 33 μm and the foil velocity (W) is approximately 87 m/sec. [See Eq. (9)].

of the coherent nuclear scattering length per atom of the slab material, and E is the incident neutron energy. It is seen from Eq. (4) that a nonvanishing motion-induced phase change occurs only if db/dE is nonzero, and the magnitude of phase change depends linearly upon the slab velocity W. With currently available neutron interferometer dimensions and experimentally feasible material thickness and velocity, a motion-induced phase shift of only a few degrees can be expected. Figure 2 shows the theoretical phase shift obtained for a typical set of parameter values for our experiment.

III. EXPERIMENT

The experiment was carried out with the use of a symmetric LLL-type perfect silicon crystal interferometer at the University of Missouri Research Reactor Facility. As shown in Figs. 1 and 3, an interferometer of this type consists of three identical Si single-crystal blades joined to a common base. It uses Bragg reflection in the Laue geometry to coherently split, redirect, and recombine an incident neutron beam. The beam paths inside such an interferometer are shown in Figs. 1 and 2. The energy of the neutron beam is 95.8 meV (wavelength 0.924 Å, velocity 4280 m/s), which is very close to the resonance energy of 97.3 meV in ^{149}Sm.

The natural Sm foil used in the experiment was nominally 33 μm thick and was sealed inside the two halves of a specially constructed aluminum disk. Because of the high absorption of neutrons by the Sm foil near the nuclear resonance, this choice of thickness allowed an acceptable data collection rate, while still inducing a measurable motion-induced phase shift at the experimentally feasible foil velocity. The overall thickness of the disk was 5 mm and was 10 cm in diameter. The foil was sealed in such a fashion that the disk was partitioned into four alternating Al and Al-Sm sectors. Figure 3 shows the placement of the disk with faces parallel to the interferometer blades in the first section of the interferometer. In the actual situation, the disk was housed in an ambient thermally controlled enclosure [Figs. 4(a) and 4(b)] and

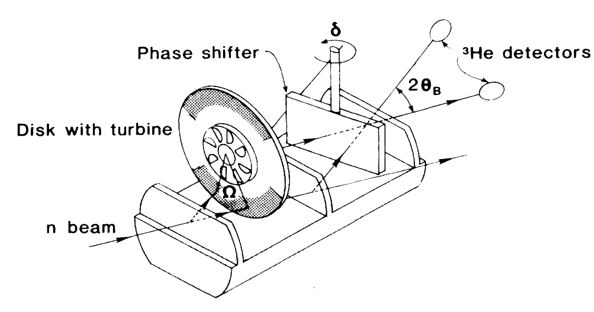
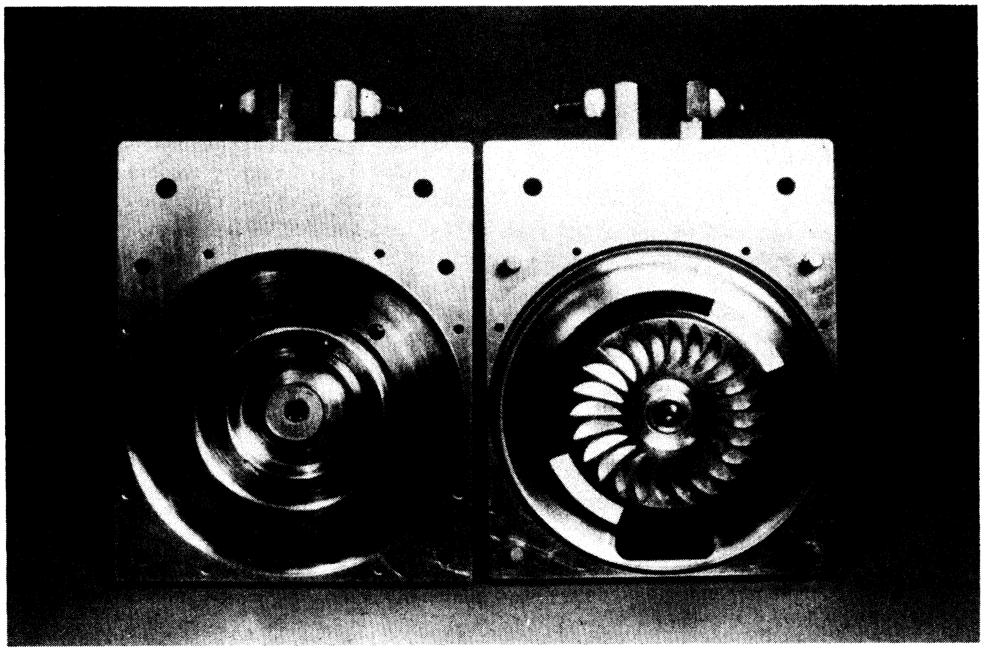
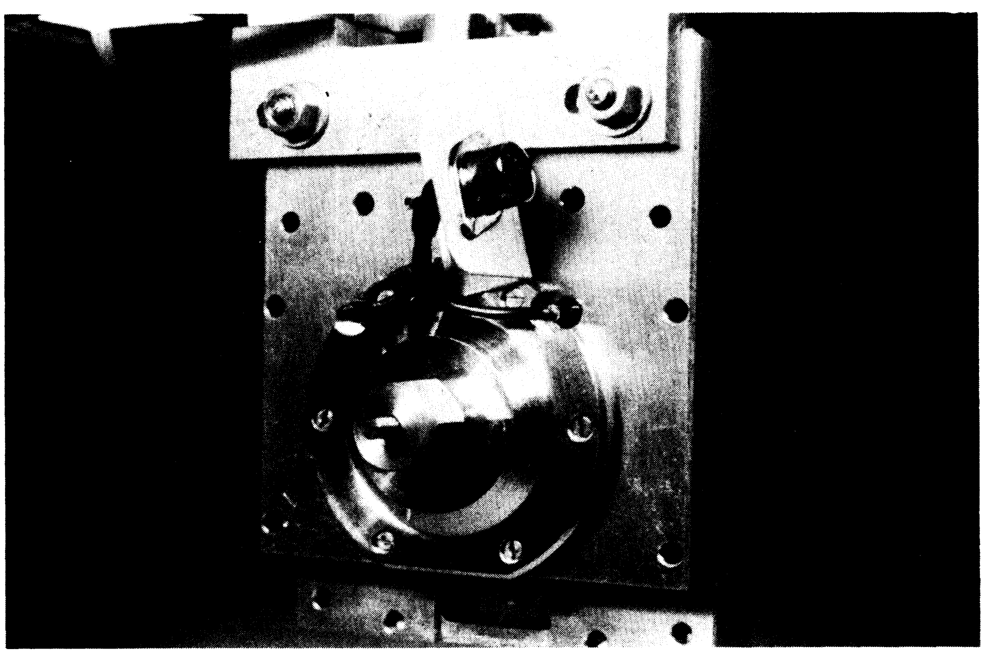


FIG. 3. Sketch of an LLL-type interferometer showing the placement of the aluminum disk containing the Sm foils in between the splitter and the mirror blades. The shaded segments on the disk correspond to the positions of the Sm foils. The positions of the detectors and the aluminum phase shifter are also shown.

the whole assembly was placed in between the blades without coming into any contact with the interferometer. There were two air-driven turbines mounted on the opposite faces of the disk. Supported by high-speed bearings, the disk could be rotated in either clockwise or counterclockwise senses by directing jets of air onto these turbines through built-in nozzles in the enclosure. As the disk rotated about an axis perpendicular to the interferometer blades, the Al and Al-Sm sectors of the disk intercepted the two coherent neutron beams in a cyclic



(a)



(b)

FIG. 4. (a) View of the unassembled enclosure showing the disk inside. (b) Photograph of the assembled enclosure. The window which allows the neutrons to pass through the disk is seen at the bottom.

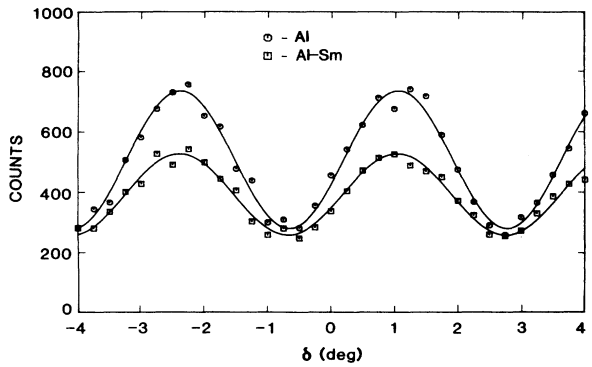


FIG. 5. Neutron interferograms of a typical run at 303 Hz rotation frequency of the disk. Data collection times for the Al and Al-Sm sectors were 2 and 6 min per point, respectively.

manner. At the same time, a very flat rectangular aluminum phase shifter was turned in steps about a vertical axis in the other section of the interferometer in order to vary the optical path difference of the two beams. As a result, the neutron counts of the resultant interfering beams varied sinusoidally as a function of this path difference and were recorded in detectors $C2$ and $C3$. The counts corresponding to the passage of neutrons through the Al and Al-Sm sectors were gated electronically and were recorded in separate channels. Figure 5 shows two typical intensity patterns (interferograms) recorded in detector $C3$. The difference of the initial phases of such a pair of interferograms gives a measure of the effect of Sm foil motion on the phase of the neutron wave. The experiment was carried out at ± 3, ± 170, and ± 303 Hz disk rotation frequencies. The plus and minus signs corresponded to clockwise and counterclockwise senses of disk rotation.

IV. ANALYSIS AND RESULTS

The interferograms were fitted to a function of the form

$$I(\delta)=A+B\cos[Cx(\delta)+P] \ . \tag{5}$$

Here, $I(\delta)$ is the neutron counting rate at the phase-shifter position δ, and $x(\delta)$ is the optical path difference between the two beams. A, B, and P are the mean, amplitude, and initial phase of the interferograms and C is a fit parameter. The fringe visibility or contrast $[(B/A)100]$ was typically 50%, indicating a wobble-free motion of the disk and excellent isolation of the interferometer from vibration induced by the motion of the disk. This was crucial to ensure the collection of good quality data needed to measure the small expected phase shift. The initial phase P of the interferograms can be written as

$$P=P_0+\Phi(f) \ . \tag{6}$$

P_0 is the motion-independent phase, and $\Phi(f)$ is an additional motion-induced phase at the disk rotation frequency f. The difference of the initial phases of the interferograms corresponding to passage of the neutron beams through the Al and Al-Sm sectors is then given by

$$\Delta P=\Delta P_0+\Delta\Phi(f) \ . \tag{7}$$

ΔP_0 is a constant and represents the phase difference of the neutron wave passing through the disk at rest. Since the neutron-nucleus potential is velocity-independent for aluminum, there is no motion-induced phase shift by the Al sector. For the Al-Sm sector the motion-dependent phase is induced only by the ^{149}Sm present in the natural Sm foil. For each rotation frequency of the disk at least ten independent runs were made and a set of ΔP values was obtained by analyzing the data for each run separately. From this set of ΔP values, a mean $\overline{\Delta P}$ and appropriate error limit were obtained. The technique of synchronous data collection for the Al and Al-Sm sectors provided a reference initial phase $P_{\rm Al}$ for each run and minimized any effect of possible phase drift in the determination of ΔP for individual runs. As shown in Fig. 6, a linear regression fit of these $\overline{\Delta P}$ values was made against rotation frequency f of the disk. The intercept of fitted line on the ordinate then yielded a value of ΔP_0. Using this value of ΔP_0 and experimentally obtained ΔP values in Eq. (7), the values of the frequency-dependent $\Delta\Phi$ were obtained.

In terms of the rotation of frequency f of the disk, the velocity of the Sm foils in the plane of the beams is given by

$$W=2\pi r f\cos\frac{\Omega}{2} \ , \tag{8}$$

where r is the mean distance of the beams from the disk rotation axis and Ω is the angular separation of the

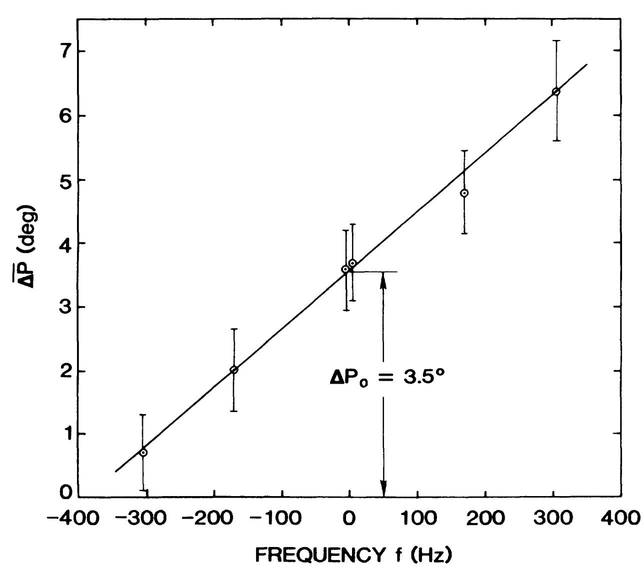


FIG. 6. A linear regression fit of the experimentally determined $\overline{\Delta P}$ values against the disk rotation frequency f. Intercept of the linear fit on the ordinate yields ΔP_0.

TABLE I. Measured and calculated values of $\Delta\phi$.

	f (Hz) (deg)					
$\Delta\phi$	-303	-170	-3	3	170	303
Expt.	-2.7 ± 0.57	-1.5 ± 0.65	0.1 ± 0.65	0.2 ± 0.60	1.3 ± 0.65	2.9 ± 0.78
Theory	-3.3 ± 0.2	-1.9 ± 0.1	-0.03 ± 0.002	0.03 ± 0.002	1.9 ± 0.1	3.3 ± 0.2

beams in the plane of the disk. For our experiment the magnitude of W ranged from 0 to 87.2 m/sec. Taking into consideration the isotopic abundance fraction a of ^{149}Sm and the above expression of foil velocity W, the motion-dependent phase shift in Eq. (1) can be rewritten as

$$\Delta\Phi = 8\pi^2 \hbar a N T r f \cos\frac{\Omega}{2} \tan\theta \frac{db}{dE} \ . \tag{9}$$

To compare with theory, db/dE in the above equation was obtained by differentiating the expression for b given by the Breit-Wigner formalism.[9] The theoretical values were calculated for $\theta = 13.92°$, $\Omega = 11°$, $r = 4.6$ cm, and foil thickness of 33 ± 2 μm. The experimentally determined phase shift $\Delta\Phi$ and the calculated values from Eq. (9) are summarized in Table I. Within the limit of uncertainty the experimental values agree with the theoretical prediction. Plots of the results are also shown in Fig. 7. The error bars shown in Figs. 6 and 7 appear to be larger than the straight-line fit to the data might suggest. We believe that this is fortuitous.

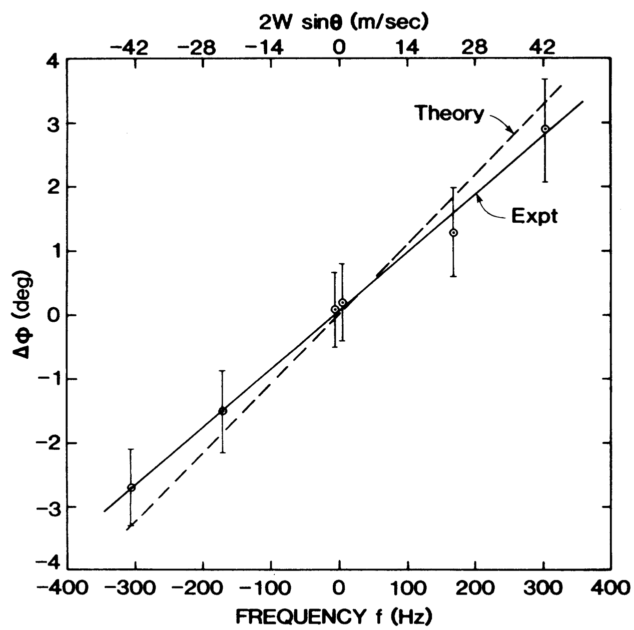


FIG. 7. Plot of experimental and calculated motion induced phase shifts $\Delta\Phi$ against disk rotation frequency f. The velocity components of the disk motion along the beam directions, which caused these phase shifts, are listed along the top x axis.

V. DISCUSSION

The result of this experiment demonstrates that the phase of a neutron de Broglie wave can be affected by the motion of the bulk of matter through which the neutron propagates. For the first time we have been able to observe and measure a shift in the phase of a neutron wave which is induced by matter motion. In this respect it is correct to call this experiment a true neutron analog of the historic Fizeau experiment, where a shift in the phase of the light wave due to matter motion was observed. This experiment also distinguished itself from a number of previous neutron Fizeau-type experiments, where a phase shift was induced by the motion of the boundary of the moving matter.

Within the limits of uncertainty, the experimentally observed phase shifts were consistent with the theoretical predictions. However, the calculated phase shifts were consistently higher than those experimentally obtained by up to 20%. This indicates a systematic error in our measurement or in the calculations of the phase shift $\Delta\Phi$. The calculated and measured db/dE values are 2.39×10^{-10} cm/eV and $(1.90\pm 0.34)\times 10^{-10}$ cm/eV, respectively. The theoretical values were calculated by using the currently accepted literature values of the ^{149}Sm resonance parameters. The thickness of the commercially purchased foil was independently verified through neutron transmission measurements and also through direct measurements by a comparator device. These are the most obvious and likely parameters capable of causing the discrepancy. However, at this point we are unable to explain the exact cause of the observed discrepancy with certainty.

Successful completion of this experiment required very precise mechanical tolerances in our apparatus and excellent vibration isolation of the interferometer to maintain good contrast and phase stability. Some difficulty in measuring the phase shifts was associated with the lower neutron flux at 95.8 meV and high-absorption cross section of ^{149}Sm. This resulted in long data collection time which made the task of maintaining a very strict phase stability during the counting period somewhat difficult. During early attempts of this experiment, transmission of vibration to the interferometer by mechanical means and by microphonics caused loss of contrast in the interference pattern, particularly at or near a mechanical resonance of the rotating disk assembly. This was accompanied by a relative change of the initial phase of the interferograms by either zero or π radians, with a sharp transition occurring between these two values near a

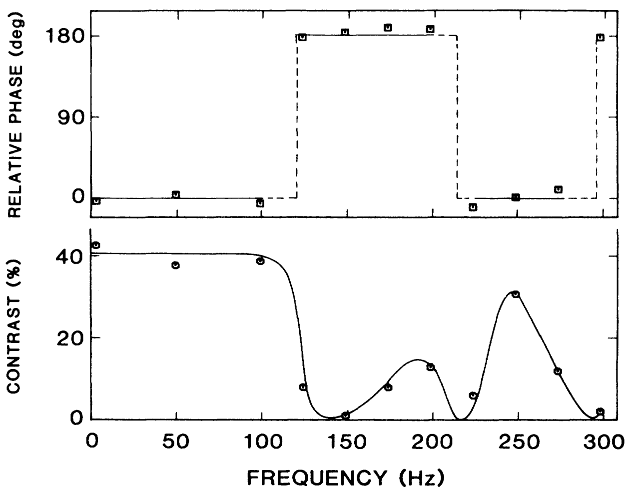


FIG. 8. Effects of transmitted vibration on the phase and contrast of interference pattern in the early version of this experiment. The magnitude of the transmitted vibration depended on the rotation frequency of the disk.

minima of contrast. This is shown in Fig. 8. This effect was puzzling, and to our knowledge has never been observed before. However, by a simple model which takes into account vibrations of the disk coupled to the interferometer, we were able to understand this effect qualitatively. This model is described in the Appendix. An understanding of this anomalous effect was very important in making proper modification to the apparatus for the successful completion of the experiment.

ACKNOWLEDGMENTS

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APPENDIX

Suppose that vibrations of the rotating disk couple to the interferometer and induce a time-dependent phase shift

$$\Delta(t)=\Delta_0\cos(\omega t) \ . \tag{A1}$$

The time-dependent intensity of the interference pattern can then be written as

$$I(t)=A+B\cos[\beta+\Delta(t)] \ . \tag{A2}$$

In the above equations, ω is the angular speed of the rotating disk, A is the mean, B is the amplitude of the time-dependent intensity, and β is the phase associated with the phase shifter. The time-averaged intensity for one complete revolution of the disk is then given by

$$I=\frac{1}{T}\int_0^T I(t)dt=\frac{1}{2\pi}\int_{-\pi}^{\pi} I(\omega t)d(\omega t) \ , \tag{A3}$$

where

$$\omega T=2\pi f T=2\pi \ .$$

Using the expression for $I(t)$ from Eq. (A2) in Eq. (A3) and carrying out the integration, the average intensity is then found to be

$$I=A+BJ_0(\Delta_0)\cos\beta \ , \tag{A4}$$

and the contrast C is

$$C=\frac{B}{A}\,|J_0(\Delta_0)| \ . \tag{A5}$$

Here J_0 is the zeroth-order Bessel function. The phase-locked coupling of the rotating disk to the interferometer may be through vibrational forces or torques giving rise to a periodic Sagnac effect.[10] According to this model, as Δ_0 goes through the zeros of the Bessel function, Eq. (A4) predicts that the initial phase changes by 180°, and the contrast vanishes in accord with the observed behavior shown in Fig. 8. To obtain quantitative predictions of this model, the frequency dependence of $\Delta_0(\omega)$ would be needed. It is important to note from this analysis that there is no vibration-induced phase shift, except the abrupt 180° phase reversals. In subsequent experiments the experimental setup was modified to mechanically isolate the rotating disk assembly from the interferometer, thus assuring minimum transmission of vibration and loss of contrast.

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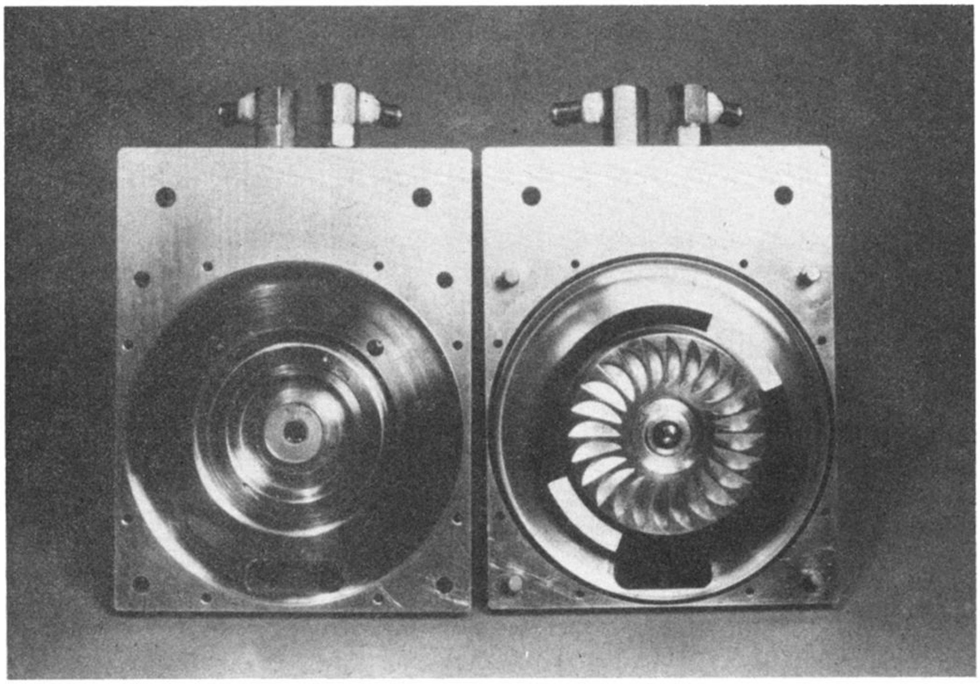

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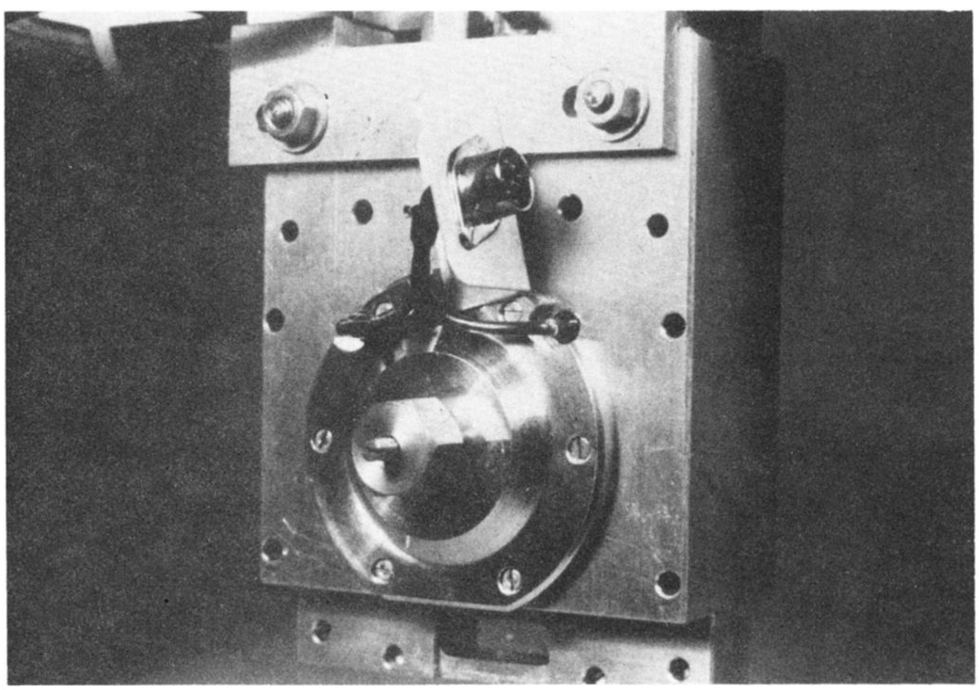

(b)

FIG. 4. (a) View of the unassembled enclosure showing the disk inside. (b) Photograph of the assembled enclosure. The window which allows the neutrons to pass through the disk is seen at the bottom.