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Null Fizeau effect for thermal neutrons in moving matter

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We have carried out an interferometer experiment to determine the phase shift of slow neutrons caused by the motion of a material medium. Within experimental error, we confirm the theoretical prediction of a null result for the case when the medium moves inside stationary boundaries. Upper limits on the energy dependence of neutron-nucleus potential and on the wavelength dependence of s-wave neutron scattering lengths are deduced.

I. INTRODUCTION

The effect of a moving medium on the phase shift observed in a neutron interferometer was discussed extensively in a recent theoretical paper[1] which draws the distinction between two different situations. In the first case the boundaries of the medium are in motion and the results depend on the correct transformation of the $(\omega, \mathbf{k})$ four vector of the neutrons into, and out of, the medium. This was the subject of an earlier experiment[2] whose results showed good agreement with theoretical predictions. In the second case where the boundaries of the moving medium are at rest, which is more closely analogous to the classic work of Fizeau,[3] on the phase shift of light waves induced by the motion of water flowing in stationary tubes, or to the later work of Macek, Schneider, and Salamon,[4] who used a rotating transparent disk inside an optical interferometer. In contrast to the results with light, the corresponding experiment with neutrons traversing a moving medium contained inside stationary boundaries is predicted to give a null result.[1,5] This somewhat surprising conclusion, discussed from several points of view in Ref. 1, depends on the specific form of the dispersion relation for neutrons in material media and, ultimately, on the velocity independence of the nuclear scattering lengths and of the neutron-nucleus potentials.

In this Rapid Communication we report on the results of such an experiment which tests the prediction of a null result and allows us to place an upper limit on the velocity dependence mentioned above.

II. THEORY

In traversing a stationary, parallel-sided slab of thickness D and refractive index n upon which they are incident at an angle θ, neutrons with wave number $\mathbf{k}$ experience a phase shift[1]

$$\phi(\mathbf{k}) = \{[k^2 n^2(k) - k^2 \sin^2\theta]^{1/2} - k \cos\theta\} D \quad . \tag{1}$$

In the present experiment we are concerned with any additional phase shift induced by motion of the slab parallel to its sides.

When the slab is set into motion the phase shift in the rest frame of the slab will be $\phi(\mathbf{k}')$ where $\mathbf{k}'$ is the incident wave vector in that frame. Since phase shifts are relativistically invariant, $\phi(\mathbf{k}')$ must be the phase shift in every frame including the laboratory frame. Therefore the extra phase shift introduced by the motion of the slab is

$$\delta\phi = \phi(\mathbf{k}') - \phi(\mathbf{k}) \quad , \tag{2}$$

which depends on the relation of $\mathbf{k}'$ to $\mathbf{k}$ and the k dependence of the refractive index.

In our experiment both neutrons and slab are moving slowly enough for a Galilean transformation to the slab rest frame to be sufficient. If w is the slab velocity in the laboratory frame we have in the frame of the slab (primed) moving parallel to its boundaries:

$$k' \sin\theta' = k \sin\theta - \frac{mw}{h}; \;\; k' \cos\theta' = k \cos\theta \tag{3}$$

and

$$k'^2 = k^2 \left[1 - 2 \sin\theta \frac{mw}{\hbar k} + \left(\frac{mw}{\hbar k} \right)^2 \right] \quad . \tag{4}$$

If $|n^2 - 1| << 1$, as is usually the case with neutrons in matter, Eq. (1) is well approximated by

$$\phi(\mathbf{k}) = \frac{k^2(n^2-1)D}{2k \cos\theta} \quad . \tag{5}$$

Using Eqs. (2)–(5) we find

$$\delta\phi = -\left\{ (n^2-1) + k^2 \frac{\partial n^2}{\partial k^2} \right\} (mw/\hbar) D \tan\theta \quad . \tag{6}$$

In forming Eq. (6) we have dropped the w^2 term in Eq. (4). This is valid, for in our experiment the slab velocity is of the order of 1% of the neutron velocity.

Within the large parentheses in Eq. (6) are two terms. The first (n^2-1) is given by the kinematics of change of frame alone, whereas the second term involving $\partial n^2/\partial k^2$ depends on the dispersion of the medium. In the case of light in water, the dispersion term is only a small correction. In the case of neutrons in matter, this term is as large as the first term and opposite in sign, as we shall now see.

In the standard theory of refraction of neutrons

$$n^2 \equiv 1 - V/E = 1 - 2mV/\hbar^2 k^2 \ , \tag{7}$$

where V is an effective average neutron potential. In this case Eq. (6) yields

$$\delta\phi = \frac{dV}{dE}(mw/\hbar)D \tan\theta \ . \tag{8}$$

In the standard theory V is given in terms of the mean coherent scattering length b, and the nuclear number density N by

$$V = 2\pi\hbar^2 Nb/m \ . \tag{9}$$

In this case V is energy independent and the resulting phase change $\delta\phi$ is predicted to be zero.

III. EXPERIMENT

The experiment was performed at the University of Missouri Research Reactor, using a Bonse-Hart perfect-crystal neutron interferometer. Topologically analogous to the Mach-Zehnder interferometer in classical optics, this device consists of three parallel slabs of silicon, joined in one monolithic perfect cyrstal, in which dynamical diffraction is responsible for coherently splitting, reflecting, and recombining a neutron beam. A detailed description of the neutron interferometer may be found in a recent review article.[6] Here we simply note that when a slab of material is inserted into the interferometer, as shown in Fig. 1, a phase shift of the beam on one of the paths, relative to the beam on the other path, is induced by virtue of the difference in effective thicknesses of material traversed by the beams.

In order to measure any additional phase shifts induced by the differential motion of such a slab, a 5-cm-radius disk of 1-cm-thick fused quartz was rotated at variable speed, intercepting the coherent beams inside the interferometer.

The rotor, supported on gyrocompass bearings, was enclosed in a partially evacuated box and was driven by integrally mounted turbines supplied with jets of air from the ambient, thermally controlled enclosure. In an attempt to minimize systematic effects, the fused quartz disk was sawn off to the shape shown in the diagram. In this way, sectors of quartz alternated with empty sectors and the neutron counts were synchronously gated into separate channels, with suitable guard intervals in between. Thus two interleaved sets of data points were obtained when an aluminum phase shifting slab was scanned in angular position inside the interferometer, thereby obtaining two neutron interferogram for such rotational speed.

IV. DATA ANALYSIS

Runs were made at rotor frequencies of 25, 40, 55, 70, 85, and 100 Hz, in both directions of rotation. Near 60 Hz, fringe visibility was significantly reduced as a result a minor mechanical resonance vibration of the rotor support. A typical run is shown in Fig. 2. Interference fringe phase shifts were determined from a least squares polynomial fit to the cross-correlation function between the data points for beams traversing the quartz and empty sectors. This analysis was performed on the summed data for the five runs at each frequency and individually on each run to obtain an estimate of error limits. The difference of these relative phase shifts from the average for all the runs is shown in Fig. 3. In all cases these relative additional phase shifts are within 0.2 rad of the average. Considering an average phase shift of ~ 500 rad for the given thickness of our rotor, our measurement accuracy is about 4 parts in 10 000.

From these measurements we may put an upper limit on the energy dependence of the effective average neutron potential V for neutrons in quartz, which have a wavelength of $\lambda = 1.268$ Å. Using Eq. (8) the motion-induced phase shift between the two coherent beams incident upon the rotor at $\pm\theta_B$, the Bragg reflection angle of the interferometer (19.3° for $\lambda = 1.268$ Å) is

$$\Delta\phi = \delta\phi|_{\theta_B} - \delta\phi|_{-\theta_B}$$

$$= 2\frac{dV}{dE}(mw/\hbar)D \tan\theta_B \ , \tag{10}$$

where w is the velocity of the rotor parallel to its boundaries at the radius at which it is traversed by the beams (4.6 cm

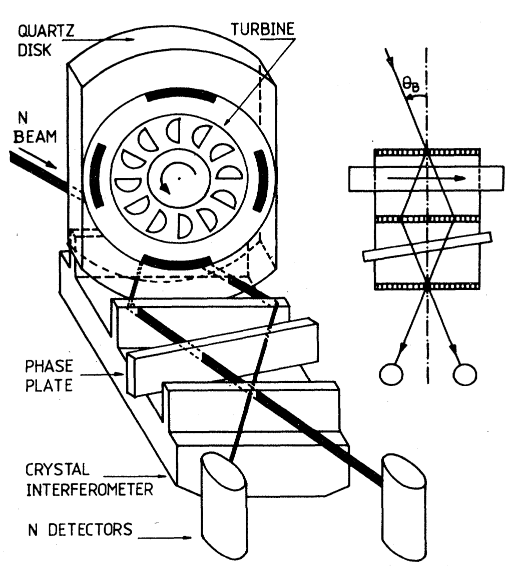

FIG. 1. Overall layout of neutron interferometer showing rotating quartz disk. Inset: schematic of neutron interferometer.

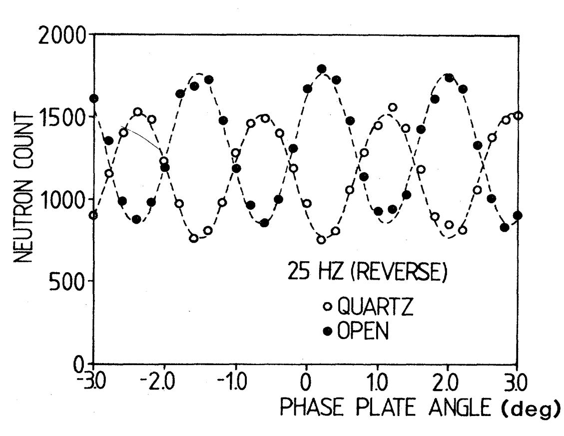

FIG. 2. Neutron interferogram for a typical run.

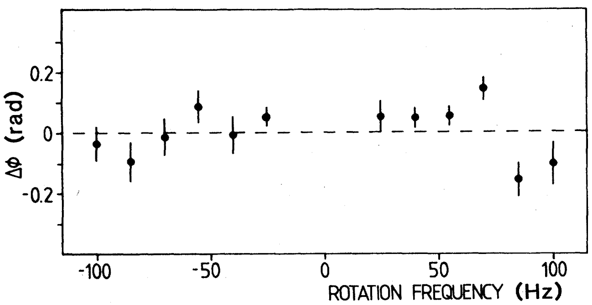

FIG. 3. Neutron phase shift due to motion. (Departure from average.)

from the axis). The data of Fig. 3 were straight-line fitted with an allowance for a phase offset between forward and reverse rotations due to any tilt of the rotor axis caused by asymmetry of the forward and reverse drive jets. (In Fig. 3 we have arbitrarily set the mean phase shift to zero.) This fit indicated a variation of $\Delta\phi$ with rotation frequency of $(0.8 \pm 5.9) \times 10^{-4}$ rad Hz^{-1}, which within experimental error agrees with the theoretical prediction of a null variation of $\Delta\phi$ with rotation frequency. From Eq. (10), this places an upper limit on the energy dependence of V for neutrons in quartz, which have a wavelength of $\lambda = 1.268$ Å,

$$\left|\frac{dV}{dE}\right| \leq 2.1 \times 10^{-8} \ . \tag{11}$$

In terms of proportional changes

$$\left|\frac{dV/V}{dE/E}\right| \leq 0.012 \ . \tag{12}$$

The corresponding limits on the wavelength dependence of the mean coherent scattering length are

$$\left|\frac{db}{d\lambda}\right| \leq 3.0 \times 10^{-6} \ , \qquad \frac{db/b}{d\lambda/\lambda} \leq 0.02 \ . \tag{13}$$

While comparable limits may have been inferred from existing neutron scattering data, the present results represent a direct interferometric verification of the energy (and wavelength) independence of s-wave neutron scattering lengths. The main contribution to the uncertainty in our measurements comes from very minute wobbling of the rotor, resulting in vibration being transmitted to the interferometer. This can be particularly pronounced at certain frequencies where resonances occur. There is also the possibility of microscopic oscillation of the interferometer plates as a result of the periodic disturbance of the air mass between plates, caused by the wobbling rotor assembly. This can be especially true at higher frequencies. Each rotation frequency was maintained within $\pm 0.5\%$, which also introduces certain uncertainty in the analysis of the experimental data.

In any future experiment, uncertainty in the results could be reduced further through even better isolation of the interferometer from vibration, improved frequency control, and design of a "wobble-free" rotor. At higher rotor frequencies it might also be helpful to operate the rotor and interferometer assembly in vacuum.

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