Observation of Gravitationally Induced Quantum Interference*

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We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

In most phenomena of interest in terrestrial physics, gravity and quantum mechanics do not *simultaneously* play an important role. Such an experiment, for which the outcome necessarily depends upon both the gravitational constant and Planck's constant, has recently been proposed by two of us.[1]

A neutron beam is split into two beams by an interferometer of the type first developed by Bonse and Hart[2] for x rays. The relative phase of the two beams where they recombine and interfere, at point D of Fig. 1, is varied by rotating the interferometer about the line AB of the incident beam. The dependence of the relative phase β on the rotation angle φ is

$$\beta = q_{\text{grav}} \sin\varphi, \tag{1}$$

where

$$q_{\text{grav}} = 4\pi\lambda g h^{-2} M^2 d(d + a\cos\theta)\tan\theta. \tag{2}$$

The neutron wavelength is $\lambda = 1.445$ Å, g is the acceleration of gravity, h is Planck's constant, M is the neutron mass, and θ is the Bragg angle, 22.1°. The dimensions $a = 0.2$ cm and $d = 3.5$ cm are shown in Fig. 1. $q_{\text{grav}}/\pi = (\Delta N)_{180}$, the number of fringes which will occur during a 180° rotation. Except for the term $a\cos\theta$, which accounts for the thickness of the interferometer slabs, Eq. (2) is equivalent to Eq. (8) of Ref. 1. For our experiment $(\Delta N)_{180} \approx 19$ fringes.

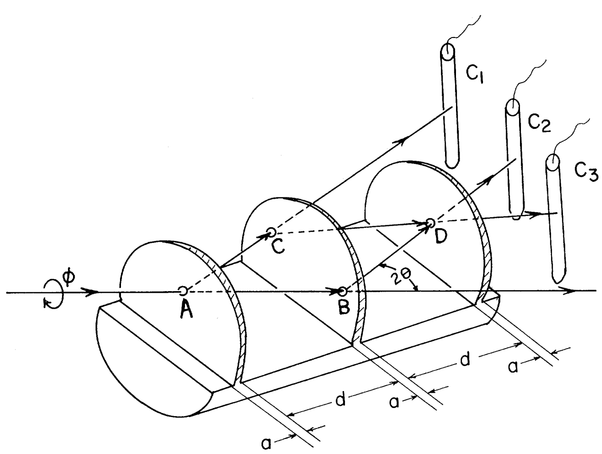

FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.

The interferometer was cut from a dislocation-free silicon crystal approximately 2 in. in diameter and 3 in. long. Our particular design was chosen so that the experiment could also be carried out with 0.71-Å x rays. This is extremely important because the bending of the interferometer under its own weight varies with φ and introduces a contribution q_{bend} to β:

$$\beta = (q_{\text{grav}} + q_{\text{bend}}) \sin\varphi. \tag{3}$$

The major problem was finding[3] a method for mounting the crystal so that the relative phase β is constant across the transverse dimensions (3 mm× 6 mm) of the interfering beams at D. The best results were obtained with the crystal freely resting on two felt strips (3 mm wide and perpendicular to the axis of the cylindrical crystal). These strips were located 15 mm from either end of a V block equal in length to the crystal. This arrangement limited rotations to $-30° < \varphi < 30°$.

Three small, high-pressure He^3 detectors were used to monitor one noninterfering beam (C_1) and the two interfering beams (C_2 and C_3) as shown in Fig. 1. These detectors, the interferometer, and an entrance slit were rigidly mounted in a metal box which could be rotated about the incident beam. This entire assembly was placed inside an auxiliary neutron shield.

The counting rates at C_2 and C_3 are expected to

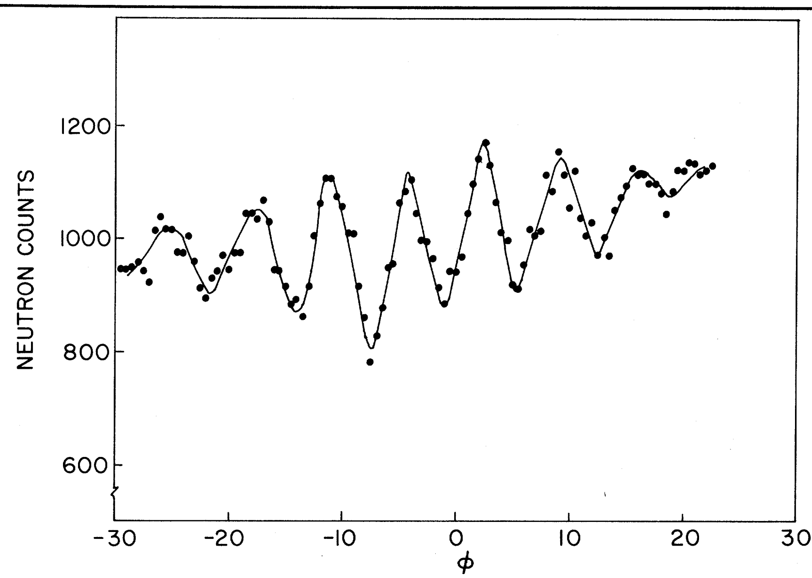

FIG. 2. The difference count, $I_2 - I_3$, as a function of interferometer rotation angle φ. Approximate counting time per point was 80 min. The fringe contrast is less than that predicted by Eqs. (4).

be[4]

$$I_2 = \gamma - \alpha\cos\beta, \tag{4a}$$

$$I_3 = \alpha(1 + \cos\beta), \tag{4b}$$

where $\gamma/\alpha = 2.6$, an average intensity ratio which we confirmed experimentally. Note that the sum $I_2 + I_3$ is independent of rotation angle φ. Consequently the interference effect is most conveniently displayed by plotting the difference $I_2 - I_3$. Our first results are shown in Fig. 2. The oscillation frequency was determined by Fourier transforming the data. We find

$$q_{\text{grav}} + q_{\text{bend}} = 54.3. \tag{5}$$

For our interferometer, Eq. (2) predicts

$$q_{\text{grav}} = 59.6. \tag{6}$$

We ascribe the difference between (5) and (6) to q_{bend}, fringes caused by bending of the interferometer base during rotation. We have determined this effect by rotation experiments using x rays, as shown in Fig. 3. The abscissa of Fig. 3 is the distance s of the felt supporting strips from either end of the crystal.

When $s < 15$ mm the interferometer sags in the middle and $q_{\text{bend}} > 0$. When $s > 15$ mm the ends sag and $q_{\text{bend}} < 0$. This behavior was established by inserting a $\frac{1}{4}\lambda$ plate (~ 0.0005 in. Mylar) in one of the x-ray beams and observing the phase shift of the rotation fringes. Our placement of the felt strips for the neutron experiment was estimated from the data of Fig. 3. A misplacement of these strips by 1.5 mm accounts for the difference between (5) and (6). We are presently setting up an x-ray facility on the reactor floor so that we can measure $q_{\text{grav}} + q_{\text{bend}}$ and q_{bend} simultaneously. We expect that q_{grav} can then be determined to 1%. By inserting a $\frac{1}{4}\lambda$ plate (~ 0.002 in. Al) in one of

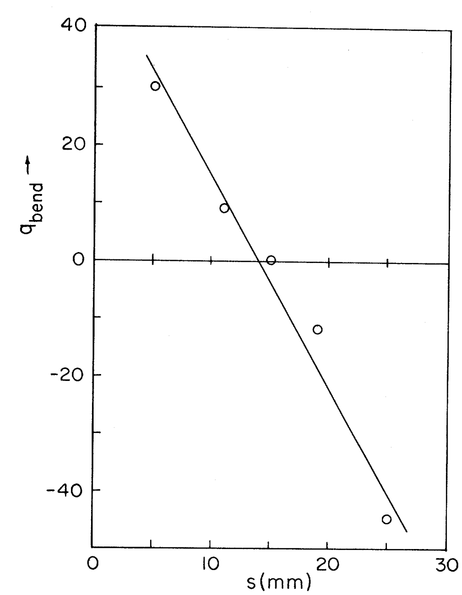

FIG. 3. Rotation fringe rate q_{bend}, see Eq. (3), caused by bending of the interferometer base under its own weight, as a function of the position s of the felt strips from either end of the crystal.

the neutron beams and observing the phase shift of the fringes shown in Fig. 2 we have verified that the sign of our result, Eq. (5), corresponds to the Newtonian potential $+Mgy$ in Schrödinger's equation (rather than $-Mgy$).

We wish to emphasize again that this is an interference experiment which demonstrates that a gravitational potential coherently changes the *phase* of a neutron wave function. Other experiments employing *single* beams, e.g., free-fall[5] or double-crystal experiments that could detect a change in λ with vertical position y, depend on Planck's constant only if Bragg reflection is used as a technique for velocity selection. If Fermi choppers were used instead, Planck's constant would not enter, so the influence of gravity in such experiments is purely classical.

Furthermore we remark that since Eq. (2) can be derived[6] when no gravitational field is present, provided the neutron source, beam collimators, and the interferometer have a uniform acceleration g, this experiment provides the first verification of the principle of equivalence in the quantum limit.

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[1]A. W. Overhauser and R. Colella, Phys. Rev. Lett. 33, 1237 (1974).

[2]U. Bonse and M. Hart, Appl. Phys. Lett. 6, 155 (1965).

[3]All attempts to mount the crystal with glue, wax, etc. failed.

[4]R. Colella, A. W. Overhauser, and S. A. Werner, to be published.

[5]A. W. McReynolds, Phys. Rev. 83, 172 (1951); J. W. T. Dobbs, J. A. Harvey, D. Paya, and H. Horstmann, Phys. Rev. 139, B756 (1965).

[6]We take it for granted that quantum mechanics correctly predicts experimental results in a Newtonian frame of reference and in zero gravitational field. Therefore it suffices to predict the outcome of a *gedanken* experiment where the apparatus is accelerating with respect to a Newtonian frame. This can be done in two ways. The first way is to take account of the Doppler shift of the Schrödinger waves as they diffract off the moving Bragg planes. This has been verified experimentally: C. G. Shull and N. S. Gingrich, J. Appl. Phys. 35, 678 (1964). The phase difference between the two interferometer beams at the point where they interfere can then be shown to agree with Eq. (2). The second way is to transform the time-dependent Schrödinger equation (in the Newtonian frame) to an accelerating coordinate system (with acceleration equal to g). The new equation then contains a term involving $\partial\psi/\partial y$, which can be eliminated; one lets $\psi \equiv \varphi \exp(iS)$, where $S \equiv (Mgty/\hbar) + (Mg^2t^3/6\hbar)$. φ then obeys the standard Schrödinger equation with a Newtonian potential Mgy added. Since the two interferometer beams have the same S at the space-time points where they interfere, the predicted fringe pattern will be the same as that derived for a stationary apparatus in the presence of gravity. We are grateful to Michael Nauenberg for this second derivation. Details of this discussion will be submitted in a longer article.