

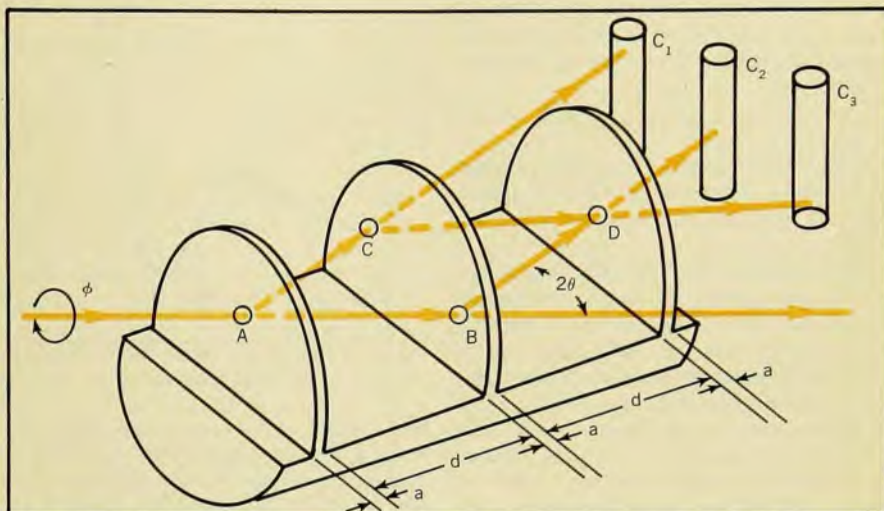
search & discovery

Go and catch a falling neutron . . .

A team of experimenters has used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with the Earth's gravitational field. The experiment is one of the first (if not *the* first) observations of the principle of equivalence for a quantum-mechanical system. The experimenters, who reported their work in *Phys. Rev. Letters* on 9 June, are Roberto Colella and Albert W. Overhauser (Purdue University) and Samuel A. Werner (Ford Motor Company).

An x-ray interferometer became feasible about ten years ago, once the electronics industry was able to produce large single crystals of silicon without dislocations. One needs every atomic plane in the silicon to be on the average in the right position within 10^{-8} cm. Such an x-ray interferometer was reported in 1966 by Ulrich Bonse and Michael Hart (then at Cornell University). Then last year H. Rauch and W. Treimer (Atom Institut der Österreichischen Hochschulen, Vienna) and Bonse (now at Institut für Physik, Universität Dortmund) successfully constructed a neutron interferometer.

In the experiment done by Colella, Overhauser and Werner, neutrons from the Ford Nuclear Reactor at the University of Michigan strike a single crystal of silicon that has been cut to form three connected slabs (see figure on this page). The original crystal was a cylin-



Neutron interferometer used to measure gravity-induced quantum interference. The high-pressure He^3 detectors monitor one noninterfering beam (C_1) and two noninterfering beams (C_2).

der 2 inches in diameter and 3 inches long; after cutting it with a diamond saw the experimenters were left with three slabs on a base that is essentially half of the original cylinder.

The velocity-selected neutron beam is split into two partial beams, one moving uphill in the gravitational field. The neutrons are freely falling; they hit a Bragg-reflecting plane and again fall freely along the next path. After going through a sequence of three Bragg reflections, the two beams interfere.

(The free fall of neutrons had been measured, earlier, first by Andrew W. McReynolds at Brookhaven National Laboratory in 1951, and then with much greater precision by John W. T. Dabbs, J. A. Harvey, D. Paya and H. Horstmann at Oak Ridge National Laboratory in 1965.)

The relative phase β of the two beams where they recombine and interfere, at point D of the figure, is varied by rotating the interferometer about the line AB of the incident beam. The phase is

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Man-made square wells offer insight and applications

Thanks to teams at two laboratories, that textbook abstraction of quantum mechanics, the one-dimensional square well, has become realized in a physical object. Known as a "heterostructure," this object consists of accurately deposited thin layers of two different semiconductors of matching lattice constants. When these man-made square wells are built up into stacks of 10–100 periods, they constitute essentially an infinite configuration (because of the finite mean free path of the carriers) known as a "superlattice" (PHYSICS TODAY, August 1973, page 20). These structures open the possibility of creating quantum states with predetermined energy levels and bandwidths.

Because of the unique characteristics of heterostructures and their related superlattices, including their unusual dimensions and negative-resistance regions, important devices are expected to result from this work, including terahertz oscillators, amplifiers, waveguides and greatly improved injection lasers. Laser oscillations from optically pumped multilayer structures of this type have already been reported.¹

Considered as important as the potential applications, however, are the physical insights the study of these structures affords. These were explored in papers by Raphael Tsu, Leroy Chang, George Sai-Halasz and Leo Esaki² at the IBM Research Center,

who investigated their transport properties, and by Raymond Dingle, Arthur Gossard and William Wiegmann³ of Bell Laboratories (Murray Hill), who carried out a systematic determination of their energy levels by an optical-transmission method. Although much of this work was done at low temperatures (2–10 K), the IBM group studied photocurrents up to room temperature (300 K). Dingle told PHYSICS TODAY that the laser oscillations mentioned have also been observed at room temperature.

The techniques used by the two labs were similar in many respects: Both used gallium arsenide as the "well" material and gallium aluminum arsenide,

omers at the McGraw-Hill Observatory. This will allow accurate optical observations of x-ray sources during periods of unusual activity.

Falling neutron

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given by $\beta = q_{\text{grav}} \sin \phi$ where ϕ is the rotation angle and

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

The neutron wavelength λ used was 1.445 Å, g is the acceleration due to gravity, h is Planck's constant, M is the neutron mass, and θ is the Bragg angle, 22.1 deg.

As the experimenters rotate the interferometer in the gravitational field, the potential Mgy (where y is the vertical height) in the Schrödinger equation, effectively changes the index of refraction of Schrödinger waves as a function of y . The neutron beam going uphill has its index of refraction increased. This changes the optical path. So as the interferometer is rotated, if the intensity at D moves up and down, one is presumably seeing the effect of gravity on the index of refraction of the neutrons.

The experimenters were delighted that the interference effect is big enough to see. Using their experimental parameters, the Purdue-Ford group calculated that they would see 19 fringes for a 180-deg. rotation, just about right for a convenient experiment. There wasn't much latitude in varying the parameters. If the neutron wavelength is increased, one no longer gets any Bragg reflection because the wavelength exceeds the lattice constant of the crystal. If the size of the interferometer is increased, the neutrons, as they fall in their parabolic path, will fail to Bragg reflect from the second slab because their angle of attack on the crystal will have changed. So in fact the experiment is limited to wavelengths less than 4 Å and crystals no larger than say 100 cm, Overhauser says.

To verify that the fringes they see are in fact due to quantum interference, the Purdue-Ford team first did their experiment with 0.71-Å x rays, which of course have no rest mass and therefore are practically not affected by the gravitational potential of the earth. Hence one would expect no change in the interference fringes as the crystal is rotated. In fact, however, the experimenters did see intensity variations because the interferometer itself was warping under its own weight and changing its orientation. Building an interferometer that will hold its shape rigid to 1 Å, Overhauser remarks, is "sort of like building an ordinary optical interferometer out of a blob of Jello. If you tried to ro-

tate that, you can imagine what would happen."

The group had to find a method to mount the crystal so that the relative phase β is constant across the transverse dimensions (3 mm × 6 mm) of the interfering beams at D. Finally, after many months of effort, the experimenters found that they could get the best results with the crystal freely resting on two felt strips (3 mm wide and perpendicular to the axis of the cylindrical crystal). These strips were placed 15 mm from either end of a V block equal in length to the crystal. The rotation of the crystal was restricted to ± 30 deg.

Significance. Observation of the fringes, Overhauser notes, proves that one needs a Newtonian gravitational potential in Schrödinger's equation. In other words, the gravitational potential coherently modifies the phase of the quantum-mechanical wave function. Furthermore, in their paper Colella, Overhauser and Werner say their experiment "provides the first verification of the principle of equivalence in the quantum limit." Elaborating on this point, Overhauser told us that he means they have tested the principle in a situation where the quantity being measured depends on Planck's constant in a way that cannot be eliminated.

The principle of equivalence says that one cannot tell the difference between doing an experiment in a gravitational field and doing it in a uniformly accelerating elevator. This implies that inertial mass is equivalent to gravitational mass. From the experiments of Galileo Galilei at Pisa to the more modern experiments by Roland von Eötvös and more recently by Robert Dicke and by Vladimir Braginski, the equivalence of gravitational and inertial mass has been well established.

In more recent times, the experiment done by Robert Pound (Harvard University) first with Glen Rebka (now at the University of Wyoming) and later with Joseph Snider (now at Oberlin College) verified the principle of equivalence for photons, the effect often called the gravitational redshift. That experiment verified that gravity affects matter of zero rest mass in the manner required by the principle of equivalence, Pound explains. In the Pound-Rebka-Snider experiment, the effect of gravity is made measurable by observing the change in a Mössbauer resonance when the source initially at the top of a building is moved to the bottom and the absorber at the bottom is moved to the top. In the process of falling in the gravitational field, the photons undergo a slight increase in frequency, Pound says. Overhauser argues that the Pound-Rebka-Snider result can be derived purely as a classical Doppler shift, and the derivation

doesn't even involve Planck's constant.

The experiment done by Paul L. Richards (now at the University of California at Berkeley) and Philip Anderson (Bell Labs) ten years ago attempted to measure the quantum interference effect in superfluid helium (that is, the ac Josephson effect), in which the gravitational potential difference was provided by the difference in height between two reservoirs of liquid helium. In 1972 D. L. Musinski and David H. Douglass (University of Rochester) repeated the experiment and attributed the effect obtained by Richards and Anderson to something other than the Josephson effect. They and Isadore Rudnick (UCLA) argued that Richards and Anderson were observing an acoustic resonance. Richards and Anderson, on the other hand, believe that although subsequent experiments are all subject to this flaw, because they were done with a closed apparatus and fixed helium levels, their first attempt was not necessarily flawed, because the level was continuously changing. So they believe that their experiment might have been the first done on quantum interference due to a gravitational potential.

Anderson remarks that the Purdue-Ford experiment is analogous to the thought experiment proposed by David Bohm and Yakir Aharonov in the 1950's, which demonstrated the significance of the vector and scalar potentials. Both experiments involve the quantum interference of two beams. In the Bohm-Aharonov experiment, magnetic flux produces an electron phase shift. In the Colella-Overhauser-Werner experiment, the gravitational potential produces a neutron phase shift.

Other fundamental experiments in quantum mechanics are possible with the new neutron-interferometer technique. Werner, Overhauser and Colella, for example, are putting one neutron beam into a region with a magnetic field, which causes the spins to precess. If the precession is 360 deg, because the neutron is a spin- $\frac{1}{2}$ particle, the wave function changes sign. They hope to verify this theoretical property of spinors.

Other possible experiments were described to us by Clifford Shull, who together with Joseph Callerane, is currently building a neutron interferometer at MIT. One can polarize the two coherent components in the interferometer system. Then the polarization of one of the beams can be changed, and the two beams allowed to recombine with a change of polarization. Another possible experiment is to investigate how neutral the neutron is to greater precision than previously. Or, in the same vein, one can refine the limits on the electric dipole moment of the neutron. —GBL