Neutrons as Waves

An interferometer for de Broglie waves demonstrates the wave nature of neutrons

BY DIETRICK E. THOMSEN

A basic principle of modern physics says that every material object is both a particle and a wave. The statement leads to both experimental and ideological paradoxes since the behavior of waves and particles often seems to be irreconcilable. Philosophical attempts to resolve the difficulty (the most well known being Niels Bohr's complementarity principle) have not been universally satisfying, but physicists have to accept the duality because it has been well proven experimentally, especially with light and electrons.

The duality was one of the great physical insights of Louis de Broglie, who provided a simple mathematical formula to connect particle and wave: The length of a body's matter wave (often called de Broglie wave after him) is equal to Planck's constant divided by its momentum (in symbolism: $\lambda = h/p$).

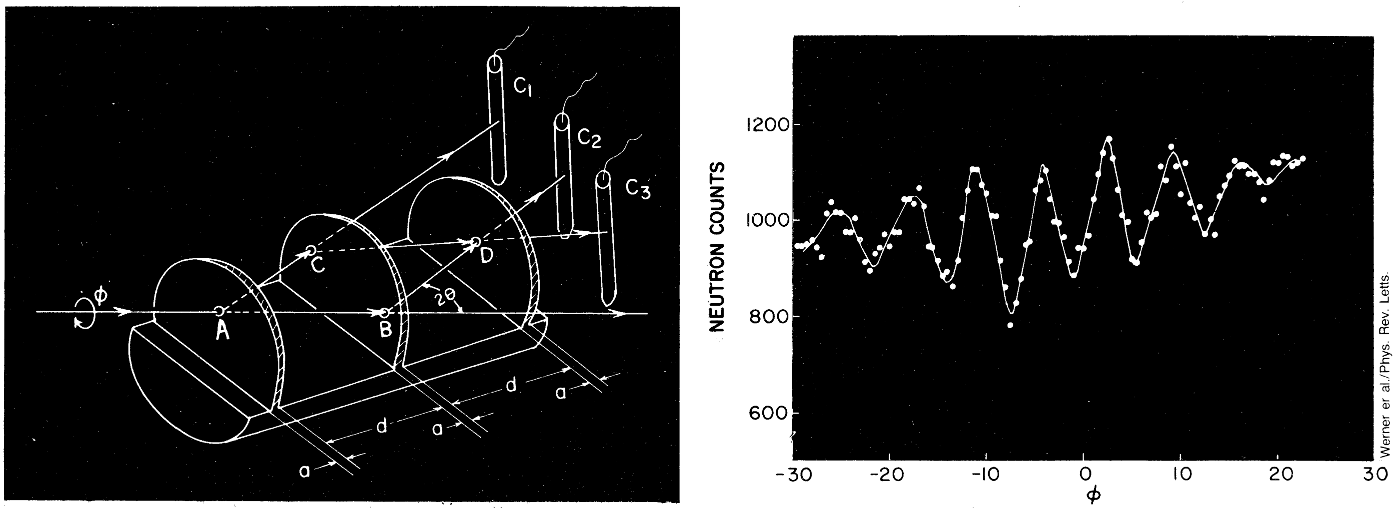
The heavier a particle is, the more difficult it is to imagine or set up experiments to demonstrate its wave nature. The photon, or light particle, is so massless that the wave nature of light is easier to show than its particulate nature. Electrons work with fair facility either way. The wave nature of neutrons, though difficult, is susceptible to exhibition.

Over the last two years a group of physicists from various institutions in the middlewestern United States, Samuel A. Werner of the University of Missouri at Columbia, R. A. Colella and A. W. Overhauser of Purdue University and C. F. Eagen of the Ford Motor Co., have constructed an apparatus that exhibits the interference of neutron waves. With it they have proved for the first time two important propositions of matter-wave physics: that gravity affects the phase of matter waves and that changing the orientation of a neutron's spin makes its physical (wave) behavior different. Both these propositions separate quantum physics importantly from classical physics, and both had been generally believed though never before proved. In the future, Werner and co-workers plan a further tour de force, an experiment that will do for neutron waves what Michelson and others did in 1926 for light: It will look for the effect of the rotation of the earth on the propagation of neutron waves.

The work began with the gravitational interaction. To begin with, it should be pointed out that the *classical* effect of gravity on subatomic particles is so small and difficult to detect that it is usually completely ignored in the machines, such as accelerators, that operate with them. Because a particle like a neutron or a proton possesses mass, the attraction of the earth's gravity on that mass should make a flying neutron or proton describe a parabolic path just as a flying baseball or artillery shell does. But the particle flies so fast that its parabola is extremely shallow, and it takes a very delicate experiment to distinguish it from a straight line. That was accomplished for neutrons 25 years ago by Andrew W. McReynolds of Brookhaven National Laboratory.

McReynolds's experiment showed that neutrons (and so presumably other subatomic particles) are subject to Newton's laws of gravity. Everything in it can be explained by classical physics. What Werner and co-workers were after was a quantum mechanical effect of gravity not covered by classical physics, an alteration of the phase of the de Broglie waves of a neutron beam due to the action of gravity. This is predicted by an equation that unites gravity and quantum mechanics by including both the term for the acceleration induced by gravity and the basic measuring term of quantum physics, Planck's constant. The equation predicts that two neutron beams that start out with their de Broglie waves in phase with each other and proceed through regions where the gravitational potential is different will have their phases changed by different amounts and will be out of phase and interfere destructively if they are later brought together.

The apparatus that does the experiment is a neutron interferometer. The possibility of making it was pointed out by Colella and Overhauser. Werner joined them in construction and experimentation. The apparatus closely follows the design of a similar instrument for X-rays. (In fact, certain compromises were made in the design so that this one could also be used with X-rays for purposes of checking instrumental effects that might alter the expected behavior of the neutrons.) The wavelength of the neutrons used (they came from the Ford reactor at the University of Michigan) was 1.445 angstroms. A slight amount of fudging of the characteristics of the reflectors and beam splitters in the interferometer allows it to be used for 0.71-angstrom X-rays as well.



Werner et al./Phys. Rev. Letts.

Neutron interferometer from a single silicon crystal (l) produced interference fringes due to gravitational phase shift (r).

The first thing such an instrument has to do is produce two beams of neutrons that start out in phase with each other and go in different directions. Since there is no such thing as a laser for neutron waves, the best way to ensure phase coherence at the beginning is to split a single beam. The instrument is built of a single silicon crystal with pieces cut out so that it forms three slabs. The first slab passes part of the beam straight through and deviates part of it at an angle, called the Bragg angle, that depends on the wavelength and the spacing of atoms in the crystal. In this case the Bragg angle is 22.1°.

Further on, both beams strike the second slab, which again passes part of each and deviates the other part. The two deviated parts are bent back toward each other this time so that they meet at the third slab forming in all a parallelogram. Geometrically, the two halves of the parallelogram perimeter are the same length so that if the two waves that traverse them are unaffected by any other considerations, they will be in phase when they are rejoined. If there are other effects, such as the gravitational influence being tested for, the waves are likely to be out of phase.

The final part of the apparatus, which tells the phase relation, is a trio of neutron counters that record both of the interfering beams after they cross each other in the last slab and, as a kind of reference check, one of the undeviated beams. With light or X-rays one might use photographic film to record, but that is not effective for neutrons, so cylinders of helium 3 are used.

One of the standard interpretations of de Broglie waves is that they are probability functions that give the instantaneous probability of finding a neutron in a given volume. Where two waves interfere constructively, there is an enhanced probability of finding neutrons; where they interfere destructively, a lessened probability. Any changes in the phase relation between the two waves will show up as a varying difference in the counts of the two beams of neutrons after they have crossed and interfered with each other.

The interferometer was designed so that it could be rotated around the direction of the original unsplit neutron beam. This has the effect of moving the paths of the two interfering beams through different levels in the earth's gravitational field in a cyclic way: At the top of the swing one path is above the other; after a 90° rotation, both are at the same level; at the bottom of the swing positions are reversed, and so forth. Rotating around like this should produce a cyclic change in the phase relations of the interfering beams, and the difference in the neutron counts of the two beams should change according to the pattern known as interference fringes.

The experiment showed the expected fringes, but the result deviated slightly from the theoretical expectation. Checking through the apparatus with X-rays (which are not subject to the effect) shows that the discrepancy is caused by bending of the apparatus under its own weight as it rotates.

Colella, Overhauser and Werner thus conclude that they have proved the existence of the effect of gravity on the phase of neutron waves. Furthermore, the nature of the experiment is such that it is also a test of the principle of equivalence in quantum physics. The principle of equivalence states that the source of a body's gravitational forces and the source of its resistance to the action of all forces are one and the same property called mass. This principle has been widely debated by theorists. (The charge that is the source of other kinds of force, electrical ones for instance, is not the same as mass, so why should gravity's charge be?) For centuries the principle of equivalence has been tested in macroscopic physics (SN: 3/20/76, p. 181). This is its first test in the quantum domain: ". . . this experiment provides the first verification of the principle of equivalence in the quantum limit," the three experimenters conclude.

Having the neutron interferometer, Werner, Colella and Overhauser, now joined by Eagen, decided to test another curious prediction of quantum mechanics, that a neutron changes its behavior if its spin axis is rotated 360°. From a classical physics point of view, such a statement is nonsense. Rotate the spin axis of a top 360° and nothing is changed. But in quantum mechanics, where a particle has an associated de Broglie wave, there are instances where such a rotation produces a radical change.

A neutron has half a unit of spin, and the relation between spin and the characteristics of the de Broglie wave predicts that rotating the spin axis full circle shifts the phase of the wave by 180°. Shifting the phase of a wave 180° makes a big difference. It changes plus into minus, darkness to light. A wave that has been shifted 180° will interfere completely destructively with one that has not.

In classical physics, unless one observes the action taking place, there is no way to know whether something has been rotated 360° or any multiple number of full rotations. In quantum mechanics, for particles with half-integral amounts of spin (the neutron is only one of a class of these, called collectively fermions), one can tell the difference between an odd number of rotations and an even number. An odd number of rotations shifts the phase of the wave 180°, an even number results in no net change. The difference should show up in an interferometric experiment, and proving that it does is not just an exercise because much of the difference in theoretical treatment between fermions and bosons (particles with integral amounts of spin) is based on the belief that fermions show this rotation effect and bosons do not.

To turn over the spin of a neutron, one uses a magnet. Although a neutron is electrically neutral over all, it contains within itself a distribution of positive and negative charge that makes it susceptible to magnetic forces. In the interferometer experiment one arm of the parallelogram path is put through a magnetic field calculated to rotate the neutron spins, and the other is not. Destructive interference should be the result, and so it turned out.

The four physicists now hope to increase the sensitivity of the interferometer and to repeat the gravitational experiment with higher precision. Then they intend to go on to check the effect of the earth's rotation on the phase of neutron waves.

The forthcoming experiment, which Werner expects to be set up in a few months, will test for the effect of Coriolis force on the phase of neutron waves. Coriolis force, like centrifugal force, belongs to a class that physicists call "fictitious forces." They are effects of geometry that can be treated as if they were forces.

Coriolis force comes about because the linear speed of the surface of the rotating earth changes with latitude. At the poles, as at the hub of a wheel, the rotation produces no linear motion. As one moves toward the equator, the surface gets farther and farther from the axis, and the linear speed of surface features increase continually, reaching a maximum at the equator. Artillerymen, naval gunners and lately rocket engineers have always had to allow for this difference in linear speed in calculating the aim of their projectiles. It turns out by a theory as old as long-range gunnery that this gradual change can be treated as if it were a steady force deviating the path of the projectile. It is named Coriolis force after a French physicist of the mid-19th century.

It turns out that Coriolis force should cause a change in the phase relations of wave trains in an interferometer as their paths are oriented differently with respect to the rotating earth's surface. Werner says the expected Coriolis effect on phase relations of neutron waves is about 2 percent of that of the gravitational effect he and his colleagues previously tested for. So they have had to increase the precision of the apparatus and go to a reactor with a much higher neutron flux than the one they used before. The new set-up is at the University of Missouri at Columbia, and the experimenters expect to begin taking data by about June.

The analogous experiment for light waves (which can also be regarded as de Broglie waves) was done 50 years ago by Albert A. Michelson, H. G. Gale and F. Pearson. Proving that the effect exists for neutron waves will provide yet another underpinning for the theory that treats them as real physical waves rather than as some kind of convenient imaginative or calculational construction. ☐