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Twisting neutrons: Orbital angular momentum of neutron waves can be controlled

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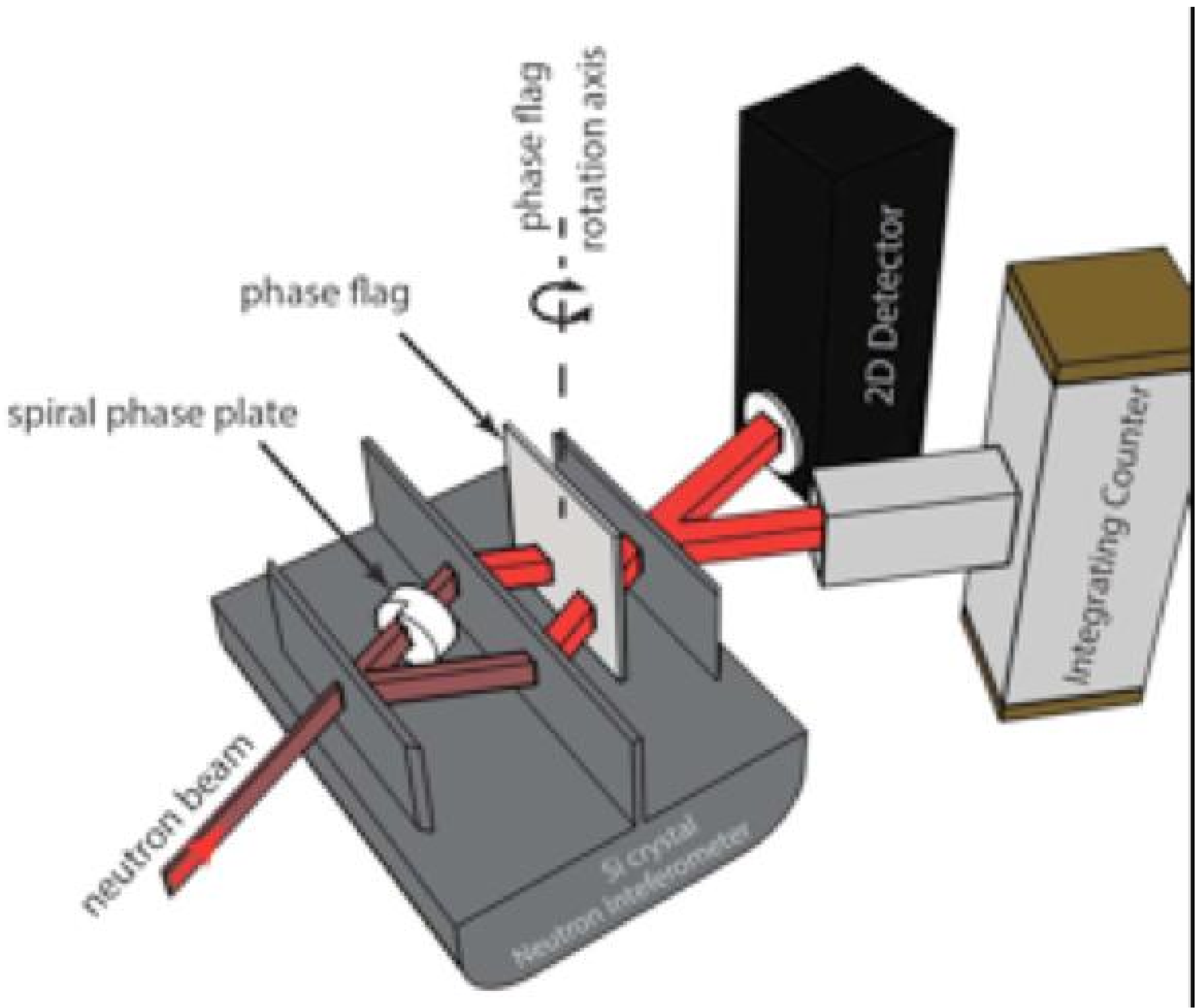


An experiment by a team of researchers led from the University of Waterloo's Institute for Quantum Computing shows, for the first time, that a wave property of neutrons, Orbital Angular Momentum, can be controlled.This newfound control of neutron OAM states means that researchers can now use neutron OAM beams to see inside materials that optical, x-ray or electron OAM beams can't penetrate. Pushin's experiment uses neutrons created by a nuclear reactor at the National Institute of Standards and Technology (NIST) and passes them through a Mach-Zehnder interferometer. Credit: University of Waterloo

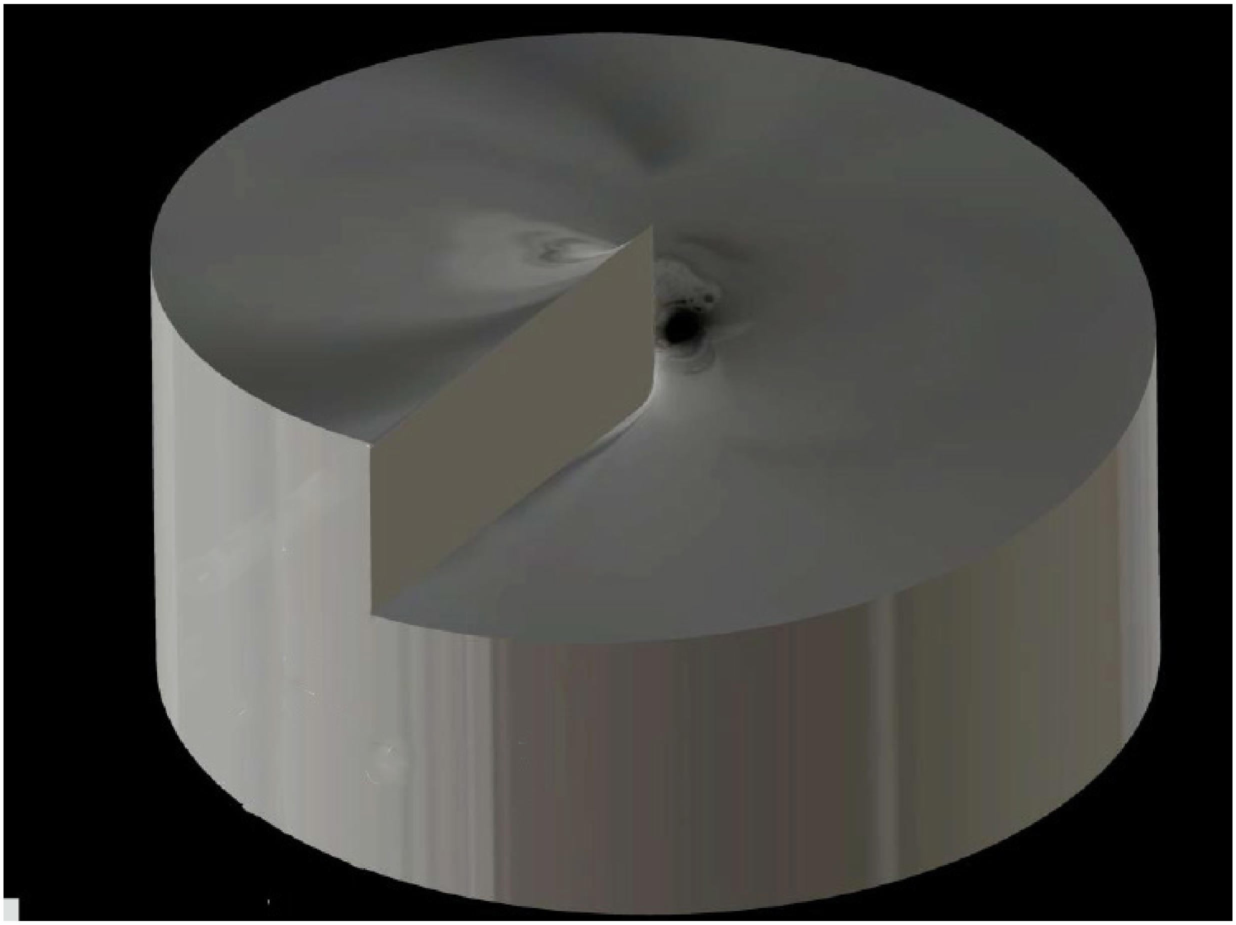
It's easy to contemplate the wave nature of light in common experience. White light passing through a prism spreads out into constituent colors; it diffracts from atmospheric moisture into a rainbow; light passing across a sharp edge or a diffraction grating creates an interference pattern. It's harder to fathom the wave behavior of things usually thought of as particles, such as electrons and atoms. And yet these matter waves play a role in physics and in technology. For example, electron beams, manifested as waves, provide an important form of microscopy.

Neutrons, a basic constituent of atomic nuclei, have wave properties which are employed in a variety of research areas such as determining the structure of materials. A recent experiment provides a new handle for control of neutrons by demonstrating that a quantum variable called orbital angular momentum is accessible in beams of neutron waves, and that it can be manipulated for use in neutron imaging and quantum information processing.

This work was performed by a collaboration of scientists from the Institute of Quantum Computing (IQC: University of Waterloo, Canada), the Joint Quantum Institute (JQI), the National Institute of Standards and Technology (NIST), Boston University and the Perimeter Institute. The results are summarized in an article published in the 24 September 2015 issue of journal *Nature*. A News & Views essay, written by an independent scientist, accompanies the article.

Orbital angular momentum

Angular momentum in physics is defined as the momentum of an object times its distance away from a center (a point or axis) around which the momentum operates. For example, the orbital angular momentum (OAM) of a planet going around the sun is the planet's momentum times its distance from the sun. Orbital angular momentum is also encountered in wave motions. In addition to their familiar motion as parallel wavefronts along one direction, waves can also corkscrew around their direction of propagation. The corkscrew or vortex orbital angular momentum (OAM) has been demonstrated previously for beams of light, x-rays, and electrons. The use of such beams is expected to be applied in the study of optical and x-ray microscopy, astronomy, the micromanipulation of particles, multiplexing/ de-multiplexing of waves with different OAM in a common communication channel, lithography, and the manipulation of quantum states.



A schematic phase plate for imparting extra quantum units of orbital angular momentum. Neutron waves fall on the face of this plate, made by milling a dowel of aluminum into a ramp-shaped spiral. The steeper the pitch of the milled phase plate, the more orbital angular momentum will be imparted to the neutron beam. Credit: Ivar Taminiau

Experimental setup

To test these ideas with neutron waves, the researcher team performed interference experiments on neutrons produced by the nuclear reactor at the NIST Center for Neutron Research.

The number of neutrons produced per second by the reactor (the neutron flux) is comparable to the number of light particles (photons) emitted per second by the display panel of a smartphone. This neutron flux is distributed among a dozen or so experiments outside the reactor. Only about 10 neutrons per second out of the total flux of the reactor pass through the neutron interferometer used in the experiment. Since each neutron takes only about 50 microseconds to pass through the interferometer, there is almost never more then one neutron present in it. Indeed, when one neutron is in the interferometer, its successor has usually not even been born in the nuclear reactor. Neutrons thus interfere in just the way that Paul Dirac described interference of light: "Each photon then interferes only with itself. Interference between two different photons never occurs."

As a quantum particle, the neutron behaves much like a wave, with a wavelength (the deBroglie wavelength) which in this experiment is about 0.3 nm, comparable to the diameter of the hydrogen atom. The neutron interferometer works in the following way. When the neutron beam encounters the first blade of the interferometer, it is split into two paths. Each of the paths encounters a second blade, which acts like a mirror. The two paths merge and interfere at a third blade. The resultant interference is observed using two neutron detectors. The neutron interferometer is about 10 centimeters long, so the neutron wave function is spread out over an apparatus that is 300 million times the size of its deBroglie wavelength. An optical interferometer that had the same ratio of path length to wavelength would have to be the size of two football fields.

The orbital angular momentum of a neutron is expressed in the phase of its wavefunction. Thus, the value of the OAM can be changed by twisting the phase of the neutron wavefunction. This is accomplished using a counterintuitive property of neutrons: they travel faster through some materials than they do through a vacuum.

"That's a crazy consequence of quantum mechanics," says co-author Charles Clark (JQI), "which was first understood by Enrico Fermi in the 1930s." On one of the two paths of the interferometer, neutrons pass through a "spiral phase plate" of aluminum, a miniature, dime-sized, spiral staircase. In classical terms, the time it takes a neutron to travel through the plate from the top of the staircase is 200 femtoseconds less than the time to travel through from the bottom stair. "It's not a big effect," adds Clark, "but it's good enough for Government work." This classical difference in transit times corresponds to the "twist" of the wavefunction.

The twist in the neutron wavefunction is revealed in the pattern of interference of the two neutron paths, which are recombined at the third blade and sent towards two detectors. The neutron wave can be thought of as being spread out across the whole apparatus, until it enters the detectors. Then, the neutron is detected - in one detector or the other - by a destructive and violent process: it is absorbed by a nucleus, which splits into fragments whose energies are converted into optical and electrical signals. It is one of the remarkable features of quantum reality that even though neutron arrivals are recorded one by one, the looked-for characteristic pattern corresponding to neutron-wave interference within the apparatus should emerge by integrating the detected locations of many individual neutrons arriving over the week-long course of an experimental run. This position information is obtained by a two-dimensional (2D) detector. The observed pattern shows the characteristic shape one would expect for neutron waves with exactly the orbital angular momentum imposed by the phase plate.

"We've exploited a quantum variable - orbital angular momentum - that was not previously available for use in neutron-based quantum information processing and imaging," says Dmitry Pushin (IQC), the lead investigator on the project. "By using neutron interferometry, we have demonstrated the addition and conservation of quantum angular momenta, and have entangled the quantum paths and orbital angular momenta of neutrons, which are uniquely massive and penetrating quantum particles."

More information: Controlling neutron orbital angular momentum, *Nature*, DOI: 10.1038/nature15265

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