Testing Superposition in Quantum Mechanics

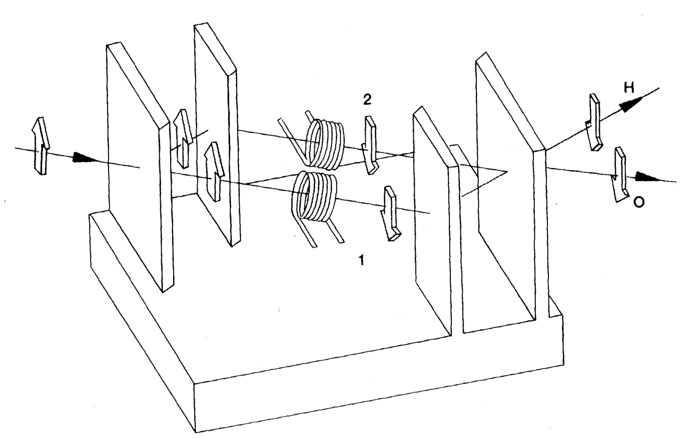
Several recent experiments explore the range of validity of the linear superposition principle in quantum mechanics; not yet answered is whether it applies to macroscopic objects

DESPITE 60 years of successfully explaining the properties of submicroscopic physical systems, quantum mechanics remains disturbing to some physicists with a philosophical bent. Much of the difficulty derives in one way or another from the linear superposition principle, which applies to the ghostly wave functions that describe the behavior of matter in the microworld. Stimulated by recent experimental advances, the New York Academy of Sciences held a conference in January on the unusual subject of quantum measurement theory, where two types of experiments explored the limits of linear superposition.*

Consider an atom with many energy states. Linear superposition comes into play when a researcher has to construct a wave function for the atom before making a measurement to determine what energy the atom actually has. In this case, the wave function is a linear combination of the wave functions for each value of the energy, that is, a linear superposition. When the energy is measured, the wave function instantaneously reduces to the one appropriate for the observed value. The same principle holds for any property of any physical system to which quantum mechanics applies.

Neutron interferometry, the first of the two types of experiments, focuses on an aspect of the linear superposition of wave functions—interference—that occurs before a measurement and the concomitant wave-function reduction. Interference is a distinctly wavelike phenomenon, and it gives matter the particle-wave duality for which quantum mechanics is renowned.

Macroscopic quantum tunneling, the second type of experiment, although it does not directly demonstrate interference, paves the way toward such a test of whether quantum mechanics applies to the macroworld or whether there is some more fundamental difference between submicroscopic and macroscopic physical systems than their sizes. Because of interference, for example, quantum mechanics is at odds with the commonsense or classical notion of realism—that is, the idea that an object exists and has specific properties whether they are measured or not. While merely disturbing in the microworld, the demise of realism in the macroworld would be highly upsetting, to say the least.



Neutron interferometer

A neutron enters from the left, passes through the interferometer along path 1 or 2, and exits in direction O *or* H. *Radio-frequency coils in one or both paths can reverse the spin (arrow) of a spin-polarized neutron.*

Neutron interferometry was reviewed by Helmut Rauch of the Atomic Institute of the Austrian Universities in Vienna. In 1974, Rauch's group inaugurated what it called perfect-crystal interferometry. The neutron analog of a Mach-Zehnder optical interferometer is carved out of a 10-centimeter-long block of nearly perfect crystalline silicon that is precisely oriented (see drawing). The vertical vanes are thin, so they act as partially reflecting mirrors, where the reflection is by means of neutron diffraction from crystal lattice planes running from front to rear through the vanes.

To get a feeling for what is involved, let one neutron at a time make its way through the interferometer. For the ideal case, in which the vanes are 50 percent reflecting (ignore the neutrons lost through the sides of the interferometer), one expects that half the time a neutron follows path 1 and half the time path 2. At the output, a neutron taking either path has an equal chance of being transmitted or reflected. Hence, it should emerge in direction O and in direction H with equal probability independent of the path.

So far there has been no measurement to verify which path the neutron took, so, according to the linear superposition principle of quantum mechanics, the neutron wave function once it enters the interferometer is proportional to the sum of the wave functions for each path. Although classically the neutron cannot be split so that one part follows path 1 and one part path 2, in the absence of any specific path information, linear superposition requires this nonrealistic wavelike behavior. Because of constructive and destructive interference of the "waves" in paths 1 and 2 on the vane at the output of the interferometer, the probability of a neutron emerging in direction O varies sinusoidally with the relative phase of the waves, which can be varied experimentally.†

Rauch's group, including Gerald Badurek and J. Summhammer, reported in 1983 more refined demonstrations of interference that used spin-polarized thermal neutrons from a reactor, a realization of a *gedanken* or thought experiment originally discussed in terms of electrons by one of the doyens of quantum measurement theory, Eugene Wigner of Princeton University, in 1963. In this case, not only the intensity but also the polarization of the output neutrons must be monitored.

For starters, the investigators generated an interference pattern by inserting an aluminum plate in the interferometer to adjust the phase of the neutron wave function in one path relative to that in the other and by recording the outcomes as many spin-polarized neutrons passed one at a time through the interferometer. As the condition for constructive and destructive interference changed with the phase adjustment, both outputs O and H recorded sinusoidal varia-

*New York Academy of Sciences, "New Techniques and Ideas in Quantum Measurement Theory," New York, 21 to 24 January 1986. Proceedings to be published in *Ann. N.Y. Acad. Sci.*

†The equivalent experiment with single photons was also reported at the conference (*Science*, 14 February, p.671).

tions in intensity, with one output being 90° out of phase with the other and the neutrons retaining the initial spin orientation.

But the use of spin-polarized neutrons makes additional tests of linear superposition possible because the quantum mechanics of spin is well worked out. For example, if the input electrons are all "spin up," what happens to the interference when the spin of a neutron taking path 1 but not path 2 is reversed or flipped to "spin down"? Upon working out the consequences of the linear superposition of wave functions for neutrons in the two paths, Anton Zeilinger of the Vienna Atomic Institute had previously found that both outputs O and H receive half the neutrons, but they are all polarized in the x-y plane perpendicular to the original spin direction z!

For the particular case where the spin flip is accomplished by means of a radio-frequency coil tuned to a resonance frequency that excites the neutron from the lower energy "spin up" to the higher energy "spin down" orientation, there are two effects. One is a rotation in the x-y plane of the polarization vector as the phase difference between the paths is adjusted. The second, which occurs for a fixed phase difference between the two paths, is that the polarization also rotates with time at a frequency equal to that of the resonance. In sum, despite the spin flip, the phase information in the neutron wave function is retained and manifests iteself in these interference effects, as the Vienna group's experiments clearly demonstrated.

Finally, there is the matter of what happens when radio-frequency coils are in both paths through the interferometer, so that the spin of neutrons in both paths are flipped. Badurek, Rauch, and D. Tuppinger of the Vienna group recently completed a series of experiments of this type. In brief, the investigators found the predicted interference behavior with the output neutrons polarized "spin down" under three conditions: the two resonant spin flippers operated in phase, at a fixed phase difference, and in phase but at a fixed, small frequency difference.

Since interference under this wide variety of conditions is in accord with quantum mechanics, as are other neutron interference results described at the meeting by Samuel Werner of the University of Missouri and by Zeilinger, its observation is not surprising. Nonetheless, to see individual neutrons maintain the phase coherence necessary for interference after passing through a substantial volume of silicon and traveling a macroscopic distance is gratifying to quantum physicists. "We knew the interference effects were there, but it's marvelous to see them. You get an elevated feeling," waxed Abner Shimony of Boston University in his conference summary, quoting a phrase of Wigner.

In the orthodox view, quantum mechanics is valid for all physical systems—large systems just have more complicated wave functions than small ones do. However, interactions between a macroscopic physical system and its environment quickly disrupt any phase coherence of the type needed to maintain the system's wave function in a linear superposition. While the experimenter may not watch the system, nature in effect does. Hence, the wave function of a macroscopic physical system is always reduced; that is, the system behaves according to classical mechanics.‡

‡Even apart from enviromental interactions, interference would not be seen in many macroscopic systems. The quantum mechanical wavelength of a physical system is inversely proportional to its momentum. For any conceivable velocity, the system's wavelength would be far smaller than its size. Hence, any interference effects would be washed out.

Delayed Choice Supports Quantum Theory

The disturbing incompatibility of quantum mechanics with our commonsense or classical notion of realism has been pushed to its limit by John Wheeler of the University of Texas at Austin, who some years back discussed what he called a delayed-choice experiment. Wheeler's idea involved photons passing one at a time through a special type of Mach-Zehnder optical interferometer. The geometry is the same as that of a neutron interferometer experiment, with optical beam splitters at the input and output of the interferometer and two photodetectors to record photons coming out (see main story). With the output beam splitter in place, interference is observed, just as in the neutron experiments. With the beam splitter removed there is no interference and each photodetector has a 50 percent chance of recording a photon.

Delayed choice means deciding whether to remove the beam splitter at the last moment after the photon has already entered the interferometer, thereby dramatizing that the photon can have no way of knowing at the time it reaches the input of the interferometer whether it is supposed to manifest its particle or its wave nature. The orthodox interpretation is that one cannot ascribe specific properties to a physical system until they are measured. Or, as Wheeler put it, "No elementary phenomenon is a phenomenon until it is a recorded phenomenon."

In any case, modern electrooptical technology has made delayed-choice experiments very similar to Wheeler's feasible. Two of these were reported at the quantum measurement conference in New York. The first experiment, reported by Carroll Alley of the University of Maryland, College Park, was completed in 1984, and the second was discussed by Arthur Zajonc of Amherst College, who worked with Herbert Walther at the Max Planck Institute for Quantum Optics in Garching, West Germany, on an updated version of the Maryland experiment. Both groups found that the expectations of orthodox quantum mechanics were upheld. For example, the same interference behavior was seen in the delayed-choice experiment as in the normal interference experiment.

Walther's group also implemented a quite different version of a delayed-choice experiment. A single barium atom in an atomic beam that passes through a weak magnetic field is excited by linearly polarized laser radiation to a higher energy quantum state. However, the Zeeman effect due to the magnetic field splits the excited state into several states with slightly different energies, two of which quantum mechanical selection rules allow to be filled by optical excitation from the ground state. According to linear superposition, the excited state wave function is therefore a linear combination of these two energy states. Interference shows up as a "quantum beat" traceable to the slightly different frequencies of radiation emitted as fluorescence when the barium decays back to the ground state.

Specifically, after measuring the times at which the photon was emitted for many events, one would build up a decay curve in which the normal exponential drop-off in intensity is modulated sinusoidally. The period of the oscillation corresponds to the frequency difference between the photons. However, by measuring the polarization of the emitted photons, one can distinguish which of the two excited states the barium was in, and the interference disappears. The delayed choice comes in by the use of a polarizer that can, in effect, be inserted in front of the photodetector after the photon has been emitted by the barium. ■ **A.L.R.**

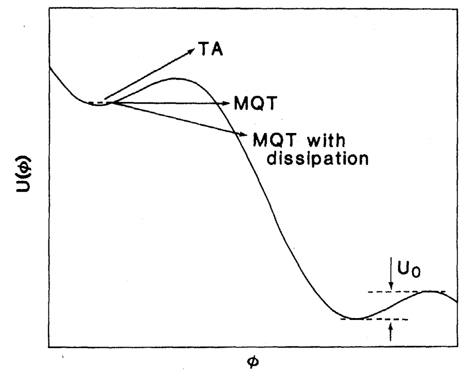
The environment affects microscopic systems, too, but the loss of phase coherence usually takes much longer because the small size does not present much for the environment to couple to. An exception is the aforesaid measurement process, where the deliberate coupling to the macroscopic measuring system instantaneously causes loss of coherence in the form of wave-function reduction.

At the meeting, Anthony Leggett of the University of Illinois questioned whether it is universally true that environmental interactions or, in his words, dissipation wipes out phase coherence in macroscopic physical systems. If one chooses the macroscopic system carefully, then there might be a chance to observe the phase relationships. In particular, he contended, modern cryogenic, microfabrication, and noise control technologies in fact might make it just possible to observe macroscopic coherence in a superconducting quantum interference device (SQUID). Claudia Tesche of the IBM Yorktown Heights Laboratory described preparations there for such an experiment, although it may be some time yet before results are in hand.

Sean Washburn, who is also at IBM, summarized the quite convincing evidence for the related macroscopic quantum tunneling effect in superconducting Josephson junctions and in SQUID's. Macroscopic quantum tunneling does not directly test coherence, but it does show that the superconducting devices, which are macroscopic compared to elementary particles if not to baseballs, behave as quantum mechanical and not classical systems in that they can in a certain sense tunnel.

It is important not to be confused about what it is that tunnels. A Josephson junction comprises two segments of superconducting material that meet. At the junction there is a thin layer of insulator only a few atomic layers thick. Electrons in one superconductor can tunnel through the insulator into the other, a microscopic tunneling process in which electrons physically move from one location to another. If the current flowing through the Josephson junction is below a certain critical value, there is no voltage drop and the junction is in a superconducting state. Above the critical current, a voltage drop appears and the junction is in a normal state.

Consider the case where the current is somewhat below the critical value. All the electrons on a given side of the junction have the same phase, so the difference between the phases on each side is a macroscopic variable associated with the junction. One can think of a fictitious one-dimensional "particle" representing the Josephson junction. It turns out that the particle moves on a potential energy curve characterized by a series of potential energy wells on a sloping background as the phase difference changes (see drawing). A particle in a well represents the Josephson junction in the superconducting state. A particle excited out of a well cascades down the slope and represents the Josephson junction in the normal state.



Macroscopic tunneling

The potential energy (U) of the fictitious macroscopic particle representing the Josephson junction has periodic minima as the phase difference (ϕ) changes. The particle can escape from a minimum by thermal activation (TA), macroscopic quantum tunneling (MQT), or tunneling with dissipation.

In analogy with microscopic particles in potential wells, the fictitious particle can be thermally excited out of the potential energy well, driving the transition from the superconducting to the normal state. Alternatively, if the temperature is too low for thermal excitation, the particle can tunnel through the energy barrier between the well and the sloping background, which also causes the transition to the normal state. Although it is somewhat abstract, this is macroscopic quantum tunneling because there are two macroscopically distinct states, as marked by the phase difference.

Dissipation also plays an important role in macroscopic quantum tunneling, as discussed originally by Amir Caldeira (now at the State University of Campinas in Brazil) and Leggett. As the particle tunnels through the potential barrier, the interaction with its environment can be thought of as a frictional effect by which the particle loses energy to its surroundings. Experiments reported in 1981 by Richard Voss and Richard Webb of IBM and by Lawrence Jackel and several co-workers at AT&T Bell Laboratories verified the theoretically predicted suppression of tunneling due to dissipation.

Since then several theorists have made much more detailed calculations of macroscopic quantum tunneling as a function of temperature in the presence of dissipation. The 1985 experiments discussed by Washburn were all aimed at verifying the newer model. Two of these (by Washburn, Webb, Voss, and Sadeg Faris at IBM and by Michel Devoret, John Martinis, and John Clarke at the Lawrence Berkeley Laboratory) did just this for Josephson junctions. The third (by Daniel Schwartz, Bidyut Sen, Charles Archie, and James Lukens at the State University of New York, Stony Brook) did the same for SQUID's, which have a similar physical model.

For the observation of macroscopic quantum coherence, the SQUID is a more suitable physical system than the Josephson junction. A SQUID comprises a ring of superconductor with one Josephson junction in it. The salient feature of a SQUID is that the flux of any magnetic field passing through the ring must be quantized in units of $h/2e$, where h is Planck's constant and e is the electronic charge. One can again consider a fictitious particle representing the system, but this time, for a constant magnetic field, there are two symmetric potential energy wells corresponding to the two nearest numbers of flux quanta.

In the absence of any measurement, the wave function for the SQUID must be a linear superposition of wave functions for the particle in each of the potential wells. According to quantum mechanics, the linear superposition is a dynamic one, so that the particle oscillates coherently by tunneling between the two potential wells. The proposed experiment is to measure which state the SQUID is in at intervals over a long time, all the while not disturbing the oscillations. If linear superposition is valid, a certain correlation function deduced from the data will oscillate with the same frequency.

According to Leggett, the experiment could have three outcomes. The first is that the environmental dissipation is stronger than expected and disrupts the coherence of the oscillations, so that quantum and classical mechanics give the same results. This would be a disappointment but would not be unexpected. The second possible result is that the coherent oscillations are seen and are in accordance with quantum theory. This would scale up the problem of the incompatibility of quantum mechanics and commonsense realism to the macroscopic level. Finally, the third outcome is that the experiment finds an observable effect that is different from what quantum theory predicts. This would be truly revolutionary because it would mean that the physics of complex macroscopic objects could not be entirely deduced from that of the constituents. Complexity adds a new ingredient. ■

ARTHUR L. ROBINSON