Theorists to the Quantum Mechanical Wave: 'Get Real'

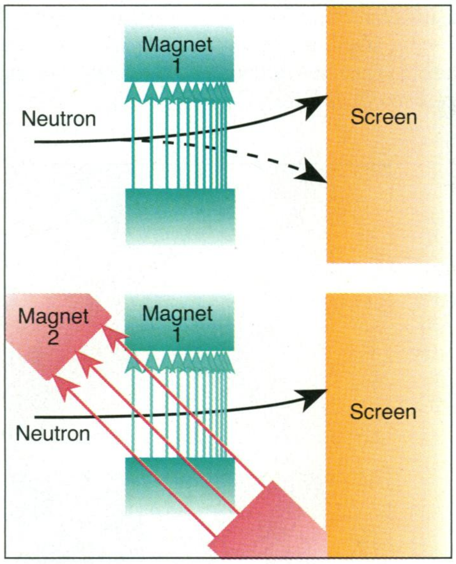
Quantum mechanics may soon be looking a little less mysterious. For five decades, most physicists have regarded the key phenomenon of quantum mechanics, the wave of probability corresponding to any particle, as off-limits—unmeasurable and in a sense unreal. Now two theorists may have devised a way to approach that inner sanctum and make a physical measurement of a quantum wave.

If Yakir Aharonov and Jeeva Anandan's idea holds up, it could force a sharp turnabout in the way physicists regard quantum mechanical reality. Says Harvard University theorist Sidney Coleman, "It may not affect the logical structure of quantum mechanics, but it addresses one of the points of maximum queerness." According to the conventional interpretation, which goes back to Niels Bohr, a particle is an unobservable wave—a purely mathematical entity representing all of the particle's possible states, including locations, energies, and spins—until it is observed. At that point the wave somehow "collapses" into an ordinary particle. As John Wheeler, a celebrated Princeton theorist, explains it, "The quantum wave has the same relationship to a particle as a weather prediction does to snow." By now, the notion of measuring the wave strikes most physicists as a little like the idea that you could get wet from reading a weather report.

If there is any living physicist qualified to turn the abstractions of quantum mechanics into tangible reality, though, it is Yakir Aharonov. In 1957, as a graduate student under physicist David Bohm of the University of London, Aharonov caught the physics world off-guard by proposing that a charged particle completely shielded from a magnetic field could be measurably affected by the field; until then the effect had been held to be as unmeasurable as the quantum wave, showing up in the mathematics but not in reality. The phenomenon has since been demonstrated in the laboratory, and many physicists now point to the Aharonov-Bohm effect as quantum mechanics' last great surprise; entire conferences are held on the subject.

Since then, Aharonov, who is now at the University of Tel Aviv, has been after bigger game: the strange unreality of the quantum wave itself. To do so, he had to come to grips with the phenomenon that is thought to keep a quantum wave off-limits. When a measuring device interacts with a quantum wave, say physicists, the device gets dragged into the particle's quantum mechanical confusion, a situation known as "entanglement." Both the particle and the device remain in this unreal mish-mash of multiple states until the device is observed, at which point the wave for both particle and device collapses, the particle jumps into a particular state, and the device is seen to present a definite reading. Quantum mechanics pioneer Erwin Schrödinger expressed the notion in a thought experiment: A cat is locked in a box along with a vial of poison whose release is triggered by the radioactive decay of an atom. Since the unobserved atom, in its quantum-mechanical ambiguity, will have both decayed and not decayed, the cat—an entangled measuring device—is both dead and alive until someone looks in the box and collapses the entangled wave. At that point the atom will either have decayed or not and the animal's fate is sealed.

Schrödinger squirmed at such "absurd" implications of entanglement as a cat that is at once dead and alive, but he saw no way around them. But a few years ago, after discussing the problem with University of Tel Aviv physicist Lev Vaidman, Aharonov thought he did. "The idea," says Anandan, "was to keep the wave function from collapsing by finding a way to avoid entanglement." If the multiple possible states represented by a particle's quantum wave could yield a single, uniform reading on a measuring device rather than dragging the device into quantum mechanical multiplicity, Aharonov reasoned, an observer wouldn't have to collapse the device's wave to read it. Then the particle's wave state, which normally collapses along with the device's, could remain uncollapsed, and the device could yield a direct measurement of the uncollapsed wave.



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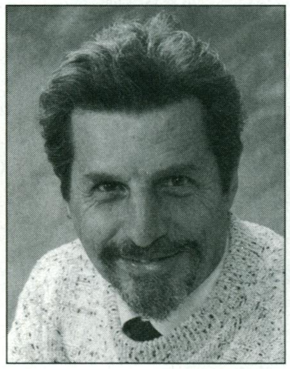

No choice. A varying magnetic field ordinarily splits a neutron's quantum wave, making it unobservable *(left, top)*. Yakir Aharonov *(above)* and Jeeva Anandan think adding a stronger, uniform field could pin the wave down for observation.

That was as far as Aharonov got until last year, when Anandan, who had been mulling over the quantum reality problem himself for more than a decade, heard of Aharonov's idea. The University of South Carolina physicist immediately joined forces with Aharonov in fleshing it out. Together, the two refined the concept and developed a proposal for an experiment, which will appear in the 1 June *Physical Review A*.

Their scheme relies on a device called a Stern-Gerlach apparatus, in which a neutron zips through a spatially varying magnetic field towards a screen that displays the point of impact. The neutron acts as a very weak magnet by virtue of its spin and thus feels a slight force proportional to the rate at which the field varies. The direction of the spin determines the direction of the force: A "spin-up" neutron is pulled upwards by the field, hitting the screen above center, while a "spin-down" neutron is pulled down below the center of the screen. But in the world of quantum mechanics, things are never cut-and-dried: Because any neutron's quantum mechanical wave combines spin-up and spin-down states, the wave ordinarily splits along two paths that create both high and low spots. In this way the Stern-Gerlach apparatus becomes entangled with the neutron, and according to the conventional interpretation it is only when the screen is observed that the wave collapses to produce a single spot either above or below center.

In Aharonov and Anandan's proposed "protected" version of the experiment, the spin-differentiating magnetic field is kept weak and a second, nonvarying field is added. Because this second field is spatially uniform, it doesn't deflect the neutron, regardless of spin direction, and so doesn't contribute to splitting the neutron's wave. But even so, the strong field does influence the wave: It swamps the effect of the weak, varying field so that it can't split the wave either. As a result, the wave impinges on the screen as a single spot. Thus the device doesn't get entangled in quantum mechanical multiplicity, and the screen can be observed without collapsing the wave.

But the wave's quantum mechanical nature should still show through, say Aharonov and Anandan. Even though the weak field is unable to split the neutron's wave, it still exerts a tug on it, so that the spot it forms on the screen is off-center. Just how far off-center the spot ends up reflects all the various potential states represented by the wave. In essence, the location of the spot provides a measurement of the uncollapsed wave itself—a measurement that physicists have long believed was impossible.

For the great majority of physicists, the observation of that single off-center spot will require a reassessment of what's real and what isn't. Though unfamiliar with the details of Aharonov and Anandan's new work, Wheeler concedes that such a measurement would be hard to reconcile with the conventional interpretation of quantum mechanics. "I find the idea hard to swallow," he says, "but the experiment Aharonov and Bohm proposed years ago also produced incredulity, so I wouldn't discount anything [Aharonov] says."

Even for the minority of physicists who are prepared to accept tangible quantum waves, the proposal is an eye-opener: "It's astonishingly clever," says Coleman. Adds Boston University physicist Abner Shimony, who has spent much of his career exploring the question of quantum mechanical reality, "They still have to tighten all the nuts and bolts, but sometimes you don't have to wait for all the details to know that an idea sounds right. This idea is ingenious and plausible."

As always, though, experiment will have the final word. Anandan says he is discussing the prospects with experimental physicists and is convinced the task will be challenging but feasible. "The hard part will be performing the measurement on a single neutron or atom," he says. "But experimentalists always seem to have a way of surprising me."

Aharonov, meanwhile, has already set his sights on yet another puzzle deemed unsolvable by virtually all physicists: what happens when a wave actually *does* collapse into a particle. As for his work on measuring the quantum wave, he notes that it merely confirms what one of quantum mechanics' pioneers asserted from the beginning. "In a sense, Schrödinger has been vindicated," he says. "He believed in the reality of the wave." Perhaps the cat didn't half-die in vain after all.

–David H. Freedman

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EXTINCTIONS

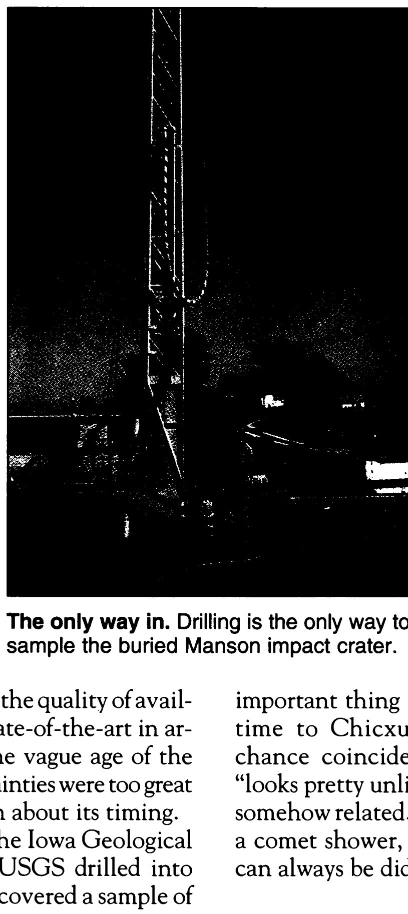
Second Crater Points to Killer Comets

There are no doubts about the cause of the catastrophe that struck at the end of the age of dinosaurs 65 million years ago. Whatever blasted out the Yucatan's Chicxulub crater—the largest known crater on the planet—was surely to blame for the environmental havoc that caused at least some of the massive extinctions occurring then (*Science*, 14 August 1992, p. 878). But still uncertain is the identity of the culprit that produced the crater. It might have been a single asteroid, or, as preliminary analyses suggested in 1989, Earth may have been pelted by debris from one or more comets. New data to be presented next week in two talks at the Lunar and Planetary Science Conference in Houston now provide further support for the comet theory.

Geochronologists Peter Zeitler of Lehigh University in Bethlehem, Pennsylvania, and Michael Kunk of the U.S. Geological Survey (USGS) in Reston, Virginia, will report that the latest dating of Iowa's 35-kilometer Manson impact crater confirms that its age is indistinguishable from that of the killer Chicxulub impact. The finding suggests that Earth was struck simultaneously or nearly so by two large objects, something that rarely happens with asteroids.

Comets, on the other hand, at times come in bunches. One possible scenario, for example, has a large comet breaking up—as 20 modern comets have done—and two or more of the resulting pieces hitting Earth within minutes or years of each other. Or, in another scheme, the gravitational pull of a passing star could have shaken a swarm of comets out of the Oort cloud that lies far beyond Pluto (*Science*, 22 March 1985, p. 1451), with at least two striking Earth. Such comet showers are thought to occur every 100 million years or so on average and last roughly a million years.

The new evidence implicating multiple comet hits comes from argon-argon dating, a technique for reading the clock that ticks in many rocks as the radioactive potassium-40 they contain decays steadily into argon-40. Kunk had previously used the method in 1989 to determine when the shock of the Manson impact reset the clock to zero by driving off argon-40 from certain feldspar minerals found beneath the crater. The figure he came up with —65.7 million years ± 1.0 million years—was intriguing because, at the time, the age of the massive impact that had been linked to the extinctions occurring at the boundary between the Cretaceous and Tertiary periods (the K-T boundary) was estimated to be somewhere around 65 million to 66 million years, give or take a million years. Although the Manson impact itself would have released too little energy to have been the putative killer impact, it did seem to have hit at close to the same time. But, given the quality of available samples, the then state-of-the-art in argon-argon dating, and the vague age of the K-T boundary, the uncertainties were too great to draw a firm conclusion about its timing.



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The only way in. Drilling is the only way to sample the buried Manson impact crater.

But just last summer the Iowa Geological Survey Bureau and the USGS drilled into the Manson crater and recovered a sample of rock actually melted by the impact. That's a much more desirable sample for dating because melting drives off all the argon, not just part of it as shocking does. Argon-argon dating of the melt rock shows, says Kunk, that the impact can't be older than 65.4 ± 0.4 million years, though a continuing search for more pristine samples may still turn up slightly younger melt rock. A sample of Chicxulub debris from the K-T boundary in Haiti analyzed in the same run gave an age of 65.0 ± 0.2 million years, indistinguishable from Manson's. And in cooperation with Kunk, Zeitler has dated new samples of shocked feldspar at 65.3 ± 0.5 million years.

"It's a work in progress...but within the stated errors, [Manson and Chicxulub] are the same age," says Kunk, who nonetheless cautions that the uncertainties are still hundreds of thousands of years. Argon-argon dating will never prove that the two impacts were simultaneous, agrees impact geologist Eugene Shoemaker of the USGS in Flagstaff. But he adds, "The important thing is that Manson is close" in time to Chicxulub. To Shoemaker, the chance coincidence of two such impacts "looks pretty unlikely," suggesting they were somehow related. They were probably part of a comet shower, he says, but "of course, we can always be diddled by statistical flukes."

–Richard A. Kerr