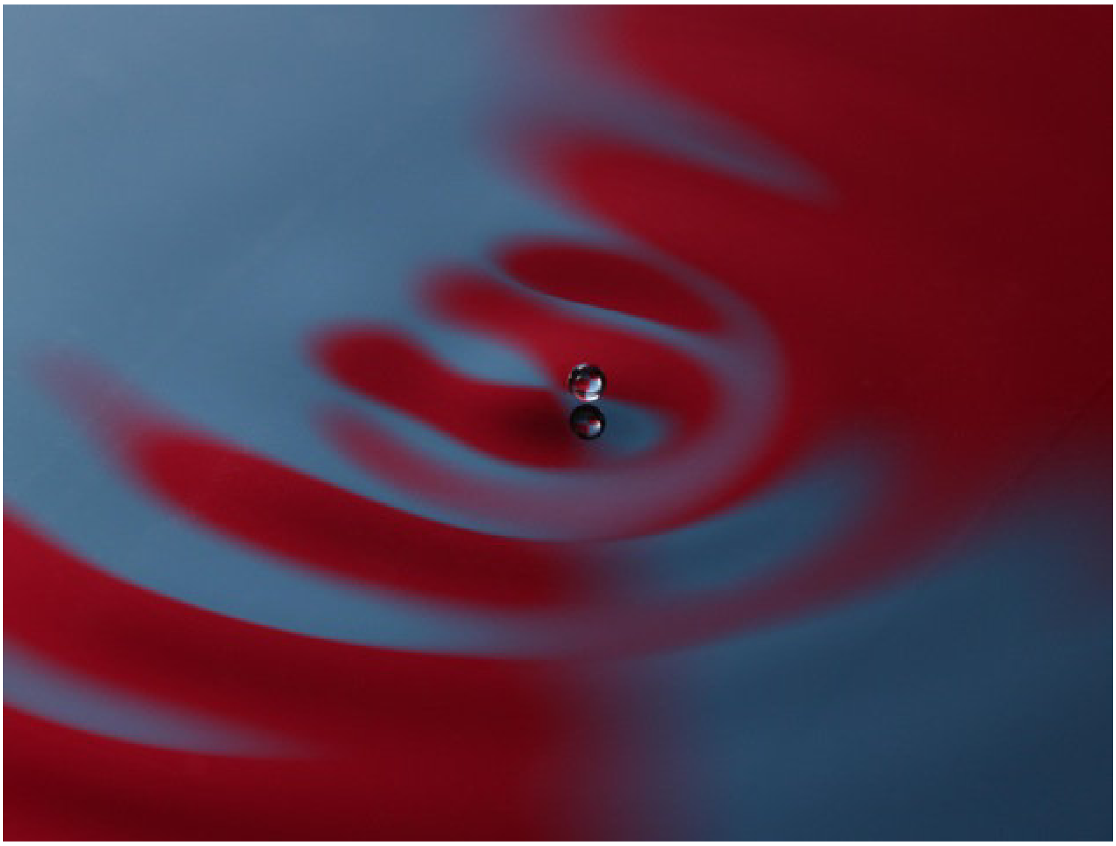
Fluid Tests Hint at Concrete Quantum Reality



Courtesy of John Bush

A droplet bouncing on the surface of a liquid has been found to exhibit many quantum-like properties, including double-slit interference, tunneling and energy quantization.

By: **Natalie Wolchover**

June 24, 2014

For nearly a century, "reality" has been a murky concept. The laws of quantum physics seem to suggest that particles spend much of their time in a ghostly state, lacking even basic properties such as a definite location and instead existing everywhere and nowhere at once. Only when a particle is measured does it suddenly materialize, appearing to pick its position as if by a roll of the dice.

This idea that nature is inherently probabilistic — that particles have no hard properties, only likelihoods, until they are observed — is directly implied by the standard equations of quantum mechanics. But now a set of surprising experiments with fluids has revived old skepticism about that worldview. The bizarre results are fueling interest in an almost forgotten version of quantum mechanics, one that never gave up the idea of a single, concrete reality.

The experiments involve an oil droplet that bounces along the surface of a liquid. The droplet gently sloshes the liquid with every bounce. At the same time, ripples from past bounces affect its course. The droplet's interaction with its own ripples, which form what's known as a pilot wave, causes it to exhibit behaviors previously thought to be peculiar to elementary particles — including behaviors seen as evidence that these particles are spread through space like waves, without any specific location, until they are measured.

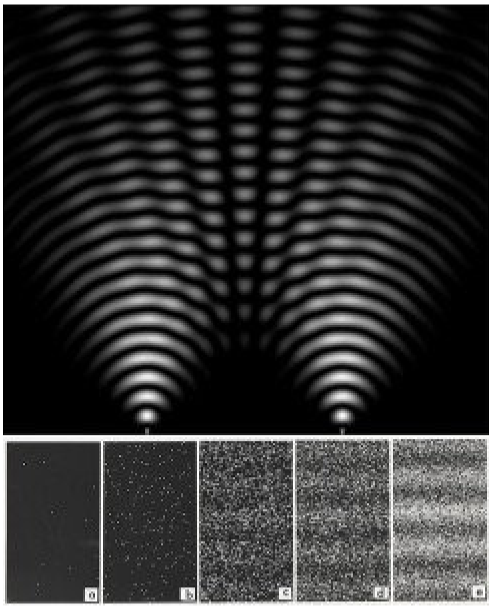
Particles at the quantum scale seem to do things that human-scale objects do not do. They can tunnel through barriers, spontaneously arise or annihilate, and occupy discrete energy levels. This new body of research reveals that oil droplets, when guided by pilot waves, also exhibit these quantum-like features.

To some researchers, the experiments suggest that quantum objects are as definite as droplets, and that they too are guided by pilot waves — in this case, fluid-like undulations in space and time. These arguments have injected new life into a deterministic (as opposed to probabilistic) theory of the microscopic world first proposed, and rejected, at the birth of quantum mechanics.

"This is a classical system that exhibits behavior that people previously thought was exclusive to the quantum realm, and we can say why," said John Bush, a professor of applied mathematics at the Massachusetts Institute of Technology who has led several recent bouncing-droplet experiments. "The more things we understand and can provide a physical rationale for, the more difficult it will be to defend the 'quantum mechanics is magic' perspective."

Magical Measurements

The orthodox view of quantum mechanics, known as the "Copenhagen interpretation" after the home city of Danish physicist Niels Bohr, one of its architects, holds that particles play out all possible realities simultaneously. Each particle is represented by a "probability wave" weighting these various possibilities, and the wave collapses to a definite state only when the particle is measured. The equations of quantum mechanics do not address how a particle's properties solidify at the moment of measurement, or how, at such moments, reality picks which form to take. But the calculations work. As Seth Lloyd, a quantum physicist at MIT, put it, "Quantum mechanics is just counterintuitive and we just have to suck it up."



Bottom: Akira Tonomura/Creative Commons

When light illuminates a pair of slits in a screen (top), the two overlapping wavefronts cooperate in some places and cancel out in between, producing an interference pattern. The pattern appears even when particles are shot toward the screen one by one (bottom), as if each particle passes through both slits at once, like a wave.

A classic experiment in quantum mechanics that seems to demonstrate the probabilistic nature of reality involves a beam of particles (such as electrons) propelled one by one toward a pair of slits in a screen. When no one keeps track of each electron's trajectory, it seems to pass through both slits simultaneously. In time, the electron beam creates a wavelike interference pattern of bright and dark stripes on the other side of the screen. But when a detector is placed in front of one of the slits, its measurement causes the particles to lose their wavelike omnipresence, collapse into definite states, and travel through one slit or the other. The interference pattern vanishes. The great 20th-century physicist Richard Feynman said that this double-slit experiment "has in it the heart of quantum mechanics," and "is impossible, absolutely impossible, to explain in any classical way."

Some physicists now disagree. "Quantum mechanics is very successful; nobody's claiming that it's wrong," said Paul Milewski, a professor of mathematics at the University of Bath in England who has devised computer models of bouncing-droplet dynamics. "What we believe is that there may be, in fact, some more fundamental reason why [quantum mechanics] looks the way it does."

Riding Waves

The idea that pilot waves might explain the peculiarities of particles dates back to the early days of quantum mechanics. The French physicist Louis de Broglie presented the earliest version of pilot-wave theory at the 1927 Solvay Conference in Brussels, a famous gathering of the founders of the field. As de Broglie explained that day to Bohr, Albert Einstein, Erwin Schrödinger, Werner Heisenberg and two dozen other celebrated physicists, pilot-wave theory made all the same predictions as the probabilistic formulation of quantum mechanics (which wouldn't be referred to as the

“Copenhagen” interpretation until the 1950s), but without the ghostliness or mysterious collapse.

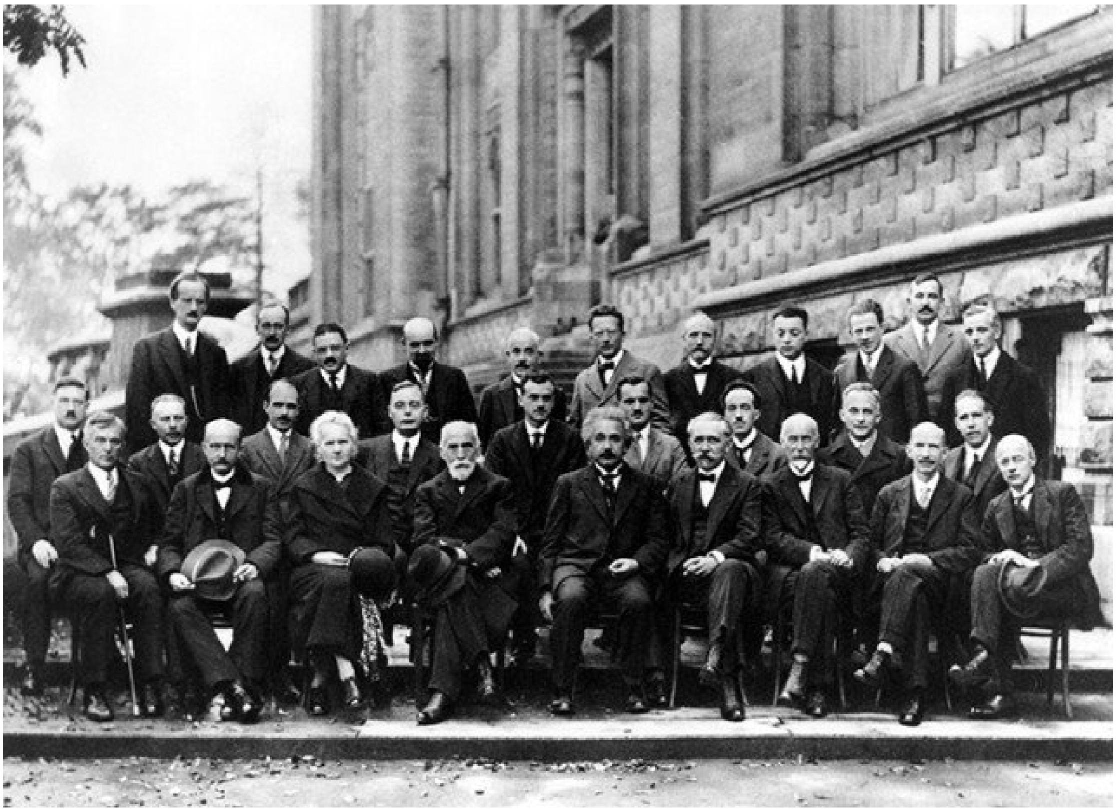
The probabilistic version, championed by Bohr, involves a single equation that represents likely and unlikely locations of particles as peaks and troughs of a wave. Bohr interpreted this probability-wave equation as a complete definition of the particle. **But de Broglie urged his colleagues to use two equations: one describing a real, physical wave, and another tying the trajectory of an actual, concrete particle to the variables in that wave equation, as if the particle interacts with and is propelled by the wave rather than being defined by it.**

For example, consider the double-slit experiment. In de Broglie’s pilot-wave picture, each electron passes through just one of the two slits, but is influenced by a pilot wave that splits and travels through both slits. Like flotsam in a current, the particle is drawn to the places where the two wavefronts cooperate, and does not go where they cancel out.

De Broglie could not predict the exact place where an individual particle would end up — just like Bohr’s version of events, pilot-wave theory predicts only the statistical distribution of outcomes, or the bright and dark stripes — but the two men interpreted this shortcoming differently. Bohr claimed that particles don’t have definite trajectories; de Broglie argued that they do, but that we can’t measure each particle’s initial position well enough to deduce its exact path.

In principle, however, the pilot-wave theory is deterministic: The future evolves dynamically from the past, so that, if the exact state of all the particles in the universe were known at a given instant, their states at all future times could be calculated.

At the Solvay conference, Einstein objected to a probabilistic universe, quipping, “God does not play dice,” but he seemed ambivalent about de Broglie’s alternative. Bohr told Einstein to “stop telling God what to do,” and (for reasons that remain in dispute) he won the day. By 1932, when the Hungarian-American mathematician John von Neumann claimed to have proven that the probabilistic wave equation in quantum mechanics could have no “hidden variables” (that is, missing components, such as de Broglie’s particle with its well-defined trajectory), pilot-wave theory was so poorly regarded that most physicists believed von Neumann’s proof without even reading a translation.



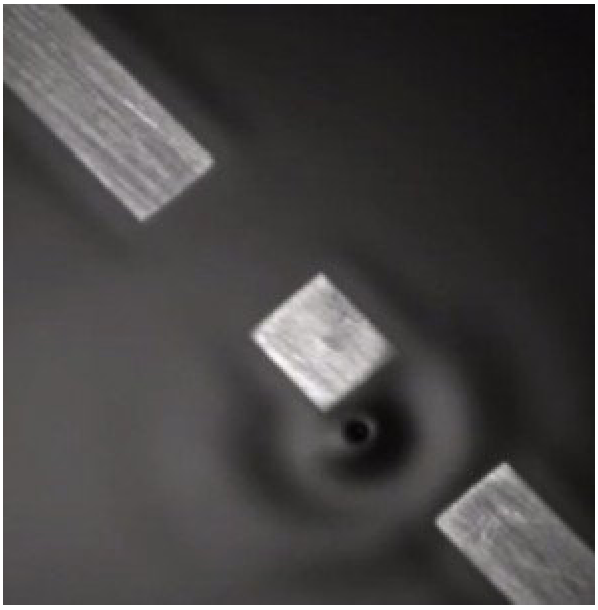
At the fifth Solvay Conference, a 1927 meeting of the founders of quantum mechanics, Louis de Broglie (middle row, third from right) argued for a deterministic formulation of quantum mechanics called pilot-wave theory. But a probabilistic version of the theory championed by Niels Bohr (middle row, far right) won the day.

More than 30 years would pass before von Neumann's proof was shown to be false, but by then the damage was done. The physicist David Bohm resurrected pilot-wave theory in a modified form in 1952, with Einstein's encouragement, and made clear that it did work, but it never caught on. (The theory is also known as de Broglie-Bohm theory, or Bohmian mechanics.)

Later, the Northern Irish physicist John Stewart Bell went on to prove a seminal theorem that many physicists today misinterpret as rendering hidden variables impossible. But Bell supported pilot-wave theory. He was the one who pointed out the flaws in von Neumann's original proof. And in 1986 he wrote that pilot-wave theory "seems to me so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored."

The neglect continues. A century down the line, the standard, probabilistic formulation of quantum mechanics has been combined with Einstein's theory of special relativity and developed into the Standard Model, an elaborate and precise description of most of the particles and forces in the universe. Acclimating to the weirdness of quantum mechanics has become a physicists' rite of passage. The old, deterministic alternative is not mentioned in most textbooks; most people in the field haven't heard of it. Sheldon Goldstein, a professor of mathematics, physics and philosophy at Rutgers University and a supporter of pilot-wave theory, blames the "preposterous" neglect of the theory on "decades of indoctrination." At this stage, Goldstein and several others noted, researchers risk their careers by questioning quantum orthodoxy.

A Quantum Drop



Yves Couder et al.

When a droplet bounces along the surface of a liquid toward a pair of openings in a barrier, it passes randomly through one opening or the other while its "pilot wave," or the ripples on the liquid's surface, passes through both. After many repeat runs, a quantum-like interference pattern appears in the distribution of droplet trajectories.

Now at last, pilot-wave theory may be experiencing a minor comeback — at least, among fluid dynamicists. "I wish that the people who were developing quantum mechanics at the beginning of last century had access to these experiments," Milewski said. "Because then the whole history of quantum mechanics might be different."

The experiments began a decade ago, when Yves Couder and colleagues at Paris Diderot University discovered that vibrating a silicon oil bath up and down at a particular frequency can induce a droplet to bounce along the surface. The droplet's path, they found, was guided by the slanted contours of the liquid's surface generated from the droplet's own bounces — a mutual particle-wave interaction analogous to de Broglie's pilot-wave concept.

In a groundbreaking experiment, the Paris researchers used the droplet setup to demonstrate single- and double-slit interference. They discovered that when a droplet bounces toward a pair of openings in a damlike barrier, it passes through only one slit or the other, while the pilot wave passes through both. Repeated trials show that the overlapping wavefronts of the pilot wave steer the droplets to certain places and never to locations in between — an apparent replication of the interference pattern in the quantum double-slit experiment that Feynman described as "impossible … to explain in any classical way." And just as measuring the trajectories of particles seems to "collapse" their simultaneous realities, disturbing the pilot wave in the bouncing-droplet experiment destroys the interference pattern.

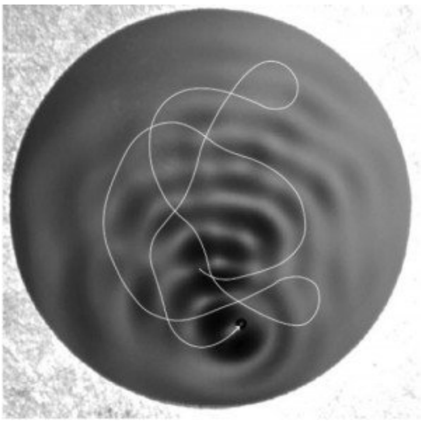
Droplets can also seem to "tunnel" through barriers, orbit each other in stable "bound states," and exhibit properties analogous to quantum spin and electromagnetic attraction. When confined to circular areas called corrals, they form concentric rings analogous to the standing waves generated by electrons in quantum corrals. They even annihilate with subsurface bubbles, an effect reminiscent of the mutual destruction of matter and antimatter particles.

Daniel Harris and John Bush

Video: The pilot-wave dynamics of walking droplets.

In each test, the droplet wends a chaotic path that, over time, builds up the same statistical distribution in the fluid system as that expected of particles at the quantum scale. But rather than resulting from indefiniteness or a lack of reality, these quantum-like effects are driven, according to the researchers, by "path memory." Every bounce of the droplet leaves a mark in the form of ripples, and these ripples chaotically but deterministically influence the droplet's future bounces and lead to quantum-like statistical outcomes. The more path memory a given fluid exhibits — that is, the less its ripples dissipate — the crisper and more quantum-like the statistics become. "Memory generates chaos, which we need to get the right probabilities," Couder explained. "We see path memory clearly in our system. It doesn't necessarily mean it exists in quantum objects, it just suggests it would be possible."

The quantum statistics are apparent even when the droplets are subjected to external forces. In one recent test, Couder and his colleagues placed a magnet at the center of their oil bath and observed a magnetic ferrofluid droplet. Like an electron occupying fixed energy levels around a nucleus, the bouncing droplet adopted a discrete set of stable orbits around the magnet, each characterized by a set energy level and angular momentum. The "quantization" of these properties into discrete packets is usually understood as a defining feature of the quantum realm.



Harris et al., PRL (2013)

As a droplet wends a chaotic path around the liquid's surface, it gradually builds up quantum-like statistics.

If space and time behave like a superfluid, or a fluid that experiences no dissipation at all, then path memory could conceivably give rise to the strange quantum phenomenon of entanglement — what Einstein referred to as "spooky action at a distance." When two particles become entangled, a measurement of the state of one instantly affects that of the other. The entanglement holds even if the two particles are light-years apart.

In standard quantum mechanics, the effect is rationalized as the instantaneous collapse of the particles' joint probability wave. But in the pilot-wave version of events, an interaction between two particles in a superfluid universe sets them on paths that stay correlated forever because the interaction permanently affects the contours of the superfluid. "As the particles move along, they feel the wave field generated by them in the past and all other particles in the past," Bush explained. In other words, the ubiquity of the pilot wave "provides a mechanism for accounting for these nonlocal correlations." Yet an experimental test of droplet entanglement remains a distant goal.

Subatomic Realities

Many of the fluid dynamicists involved in or familiar with the new research have become convinced that there is a classical, fluid explanation of quantum mechanics. "I think it's all too much of a coincidence," said Bush, who led a June workshop on the topic in Rio de Janeiro and is writing a review paper on the experiments for the Annual Review of Fluid Mechanics.

Quantum physicists tend to consider the findings less significant. After all, the fluid research does not provide direct evidence that pilot waves propel particles at the quantum scale. And a surprising analogy between electrons and oil droplets does not yield new and better calculations. "Personally, I think it has little to do with quantum mechanics," said Gerard 't Hooft, a Nobel Prize-winning particle physicist at Utrecht University in the Netherlands. He believes quantum theory is incomplete but dislikes pilot-wave theory.

Many working quantum physicists question the value of rebuilding their highly successful Standard Model from scratch. "I think the experiments are very clever and mind-expanding," said Frank Wilczek, a professor of physics at MIT and a Nobel laureate, "but they take you only a few steps along what would have to be a very long road, going from a hypothetical classical underlying theory to the successful use of quantum mechanics as we know it."

"This really is a very striking and visible manifestation of the pilot-wave phenomenon," Lloyd said. "It's mind-blowing — but it's not going to replace actual quantum mechanics anytime soon."

In its current, immature state, the pilot-wave formulation of quantum mechanics only describes simple interactions between matter and electromagnetic fields, according to David Wallace, a philosopher of physics at the University of Oxford in England, and cannot even capture the physics of an ordinary light bulb. "It is not by itself capable of representing very much physics," Wallace said. "In my own view, this is the most severe problem for the theory, though, to be fair, it remains an active research area."

Pilot-wave theory has the reputation of being more cumbersome than standard quantum mechanics. Some researchers said that the theory has trouble dealing with identical particles, and that it becomes unwieldy when describing multiparticle interactions. They also claimed that it combines less elegantly with special relativity. But other specialists in quantum mechanics disagreed or said the approach is simply under-researched. It may just be a matter of effort to recast the predictions of quantum mechanics in the pilot-wave language, said Anthony Leggett, a professor of physics at the University of Illinois, Urbana-Champaign, and a Nobel laureate. "Whether one thinks this is worth a lot of time and effort is a matter of personal taste," he added. "Personally, I don't."

Courtesy of John Bush

Attendees of Hydrodynamic Quantum Analogs IV, a meeting held June 2-6 in Rio de Janeiro. The conference organizer, John Bush, a professor of applied mathematics at MIT, is pictured at left.

On the other hand, as Bohm argued in his 1952 paper, an alternative formulation of quantum mechanics might make the same predictions as the standard version at the quantum scale, but differ when it comes to smaller scales of nature. In the search for a unified theory of physics at all scales, "we could easily be kept on the wrong track for a long time by restricting ourselves to the usual interpretation of quantum theory," Bohm wrote.

Some enthusiasts think the fluid approach could indeed be the key to resolving the long-standing conflict between quantum mechanics and Einstein's theory of gravity, which clash at infinitesimal scales.

"The possibility exists that we can look for a unified theory of the Standard Model and gravity in terms of an underlying, superfluid substrate of reality," said Ross Anderson, a computer scientist and mathematician at the University of Cambridge in England, and the co-author of a recent paper on the fluid-quantum analogy. In the future, Anderson and his collaborators plan to study the behavior of "rotons" (particle-like excitations) in superfluid helium as an even closer analog of this possible "superfluid model of reality."

But at present, these connections with quantum gravity are speculative, and for young researchers, risky ideas. Bush, Couder and the other fluid dynamicists hope that their demonstrations of a growing number of quantum-like phenomena will make a deterministic, fluid picture of quantum mechanics increasingly convincing.

"With physicists it's such a controversial thing, and people are pretty noncommittal at this stage," Bush said. "We're just forging ahead, and time will tell. The truth wins out in the end."

http://www.quantamagazine.org/20140624-fluid-tests-hint-at-concrete-quantum-reality/