Physicists Eye Quantum-Gravity Interface

By Natalie Wolchover

Gravity curves space and time around massive objects. What happens when such objects are put in quantum superpositions, causing space-time to curve in two different ways?

It starts like a textbook physics experiment, with a ball attached to a spring. If a photon strikes the ball, the impact sets it oscillating very gently. But there’s a catch. Before reaching the ball, the photon encounters a half-silvered mirror, which reflects half of the light that strikes it and allows the other half to pass through.

What happens next depends on which of two extremely well-tested but conflicting theories is correct: quantum mechanics or Einstein’s theory of general relativity; these describe the small- and large-scale properties of the universe, respectively.

In a strange quantum mechanical effect called “superposition,” the photon simultaneously passes through and reflects backward off the mirror; it then both strikes and doesn’t strike the ball. If quantum mechanics works at the macroscopic level, then the ball will both begin oscillating and stay still, entering a superposition of the two states. Because the ball has mass, its gravitational field will also split into a superposition.

But according to general relativity, gravity warps space and time around the ball. The theory cannot
tolerate space and time warping in two different ways, which could destabilize the superposition, forcing the ball to adopt one state or the other.

Knowing what happens to the ball could help physicists resolve the conflict between quantum mechanics and general relativity. But such experiments have long been considered infeasible: Only photon-size entities can be put in quantum superpositions, and only ball-size objects have detectable gravitational fields. Quantum mechanics and general relativity dominate in disparate domains, and they seem to converge only in enormously dense, quantum-size black holes. In the laboratory, as the physicist Freeman Dyson wrote in 2004, “any differences between their predictions are physically undetectable.”

In the past two years, that widely held view has begun to change. With the help of new precision instruments and clever approaches for indirectly probing imperceptible effects, experimentalists are now taking steps toward investigating the interface between quantum mechanics and general relativity in tests like the one with the photon and the ball. The new experimental possibilities are revitalizing the 80-year-old quest for a theory of quantum gravity.

“The biggest single problem of all of physics is how to reconcile gravity and quantum mechanics,” said Philip Stamp, a theoretical physicist at the University of British Columbia. “All of a sudden, it’s clear there is a target.”

Theorists are thinking through how the experiments might play out, and what each outcome would mean for a more complete theory merging quantum mechanics and general relativity. “Neither of them has ever failed,” Stamp said. “They’re incompatible. If experiments can get to grips with that conflict, that’s a big deal.”

Quantum Nature

At the quantum scale, rather than being “here” or “there” as balls tend to be, elementary particles have a certain probability of existing in each of the locations. These probabilities are like the peaks of a wave that often extends through space. When a photon encounters two adjacent slits on a screen, for example, it has a 50-50 chance of passing through either of them. The probability peaks associated with its two paths meet on the far side of the screen, creating interference fringes of light and dark. These fringes prove that the photon existed in a superposition of both trajectories.

But quantum superpositions are delicate. The moment a particle in a superposition interacts with the environment, it appears to collapse into a definite state of “here” or “there.” Modern theory and experiments suggest that this effect, called environmental decoherence, occurs because the superposition leaks out and envelops whatever the particle encountered. Once leaked, the superposition quickly expands to include the physicist trying to study it, or the engineer attempting to harness it to build a quantum computer. From the inside, only one of the many superimposed versions of reality is perceptible.

A single photon is easy to keep in a superposition. Massive objects like a ball on a spring, however, “become exponentially sensitive to environmental disturbances,” explained Gerard Milburn, director of the Center for Engineered Quantum Systems at the University of Queensland in Australia. “The chances of any one of their particles getting disturbed by a random kick from the environment is
Because of environmental decoherence, the idea of probing quantum superpositions of massive objects in tabletop experiments seemed for decades to be dead in the water. "The problem is getting the isolation, making sure no disturbances come along other than gravity," Milburn said. But the prospects have dramatically improved.

Dirk Bouwmeester, an experimental physicist who splits his time between the University of California, Santa Barbara, and Leiden University in the Netherlands, has developed a setup much like the photon-and-ball experiment, but replacing the ball on its spring with an object called an optomechanical oscillator — essentially a tiny mirror on a springboard. The goal is to put the oscillator in a quantum superposition of two vibration modes, and then see whether gravity destabilizes the superposition.

Ten years ago, the best optomechanical oscillators of the kind required for Bouwmeester’s experiment could wiggle back and forth 100,000 times without stopping. But that wasn’t long enough for the effects of gravity to kick in. Now, improved oscillators can wiggle one million times, which Bouwmeester calculates is close to what he needs in order to see, or rule out, decoherence caused by gravity. “Within three to five years, we will prove quantum superpositions of this mirror,” he said. After that, he and his team must reduce the environmental disturbances on the oscillator until it is sensitive to the impact of a single photon. “It’s going to work,” he insists.

Markus Aspelmeyer, a quantum physicist at the University of Vienna, is developing three experiments aimed at probing the interface between quantum mechanics and gravity.

Markus Aspelmeyer, a professor of physics at the University of Vienna, is equally optimistic. His group is developing three separate experiments at the quantum-gravity interface — two for the lab and one for an orbiting satellite. In the space-based experiment, a nanosphere will be cooled to its lowest energy state of motion, and a laser pulse will put the nanosphere in a quantum superposition of two locations, setting up a situation much like a double-slit experiment. The nanosphere will behave like a wave with two interfering peaks as it moves toward a detector. Each nanosphere can be detected in only a single location, but after multiple repetitions of the experiment, interference fringes will appear in the distribution of the nanospheres’ locations. If gravity destroys superpositions, the fringes won’t appear for nanospheres that are too massive.
The group is designing a similar experiment for Earth’s surface, but it will have to wait. At present, the nanospheres cannot be cooled enough, and they fall too quickly under Earth’s gravity, for the test to work. But “it turns out that optical platforms on satellites actually already meet the requirements that we need for our experiments,” said Aspelmeyer, who is collaborating with the European Aeronautic Defense and Space Company in Germany. His team recently demonstrated a key technical step required for the experiment. If it gets off the ground and goes as planned, it will reveal the relationship between the mass of the nanospheres and decoherence, pitting gravity against quantum mechanics.

The researchers laid out another terrestrial experiment last spring in Nature Physics. Many proposed quantum gravity theories involve modifications to Heisenberg’s uncertainty principle, a cornerstone of quantum mechanics that says it isn’t possible to precisely measure both the position and momentum of an object at the same time. Any deviations to Heisenberg’s formula should show up in the position-momentum uncertainty of an optomechanical oscillator, because it is affected by gravity. The uncertainty itself is immeasurably small — a blurriness just 100-million-trillionth the width of a proton — but Igor Pikovski, a theorist in Aspelmeyer’s group, has discovered a backdoor route to detecting it. When a light pulse strikes the oscillator, Pikovski claims that its phase (the position of its peaks and troughs) will undergo a discernible shift that depends on the uncertainty. Deviations from the predictions of traditional quantum mechanics could be experimental evidence of quantum gravity.

Aspelmeyer’s group has started to realize the first experimental steps. Pikovski’s idea “provides us with a quite, I have to admit, unexpected improvement in performance,” Aspelmeyer said. “We are all a little surprised, actually.”

**The Showdown**

Many physicists expect quantum theory to prevail. They believe the ball on a spring should, in principle, be able to exist in two places at once, just as a photon can. The ball’s gravitational field should be able to interfere with itself in a quantum superposition, just as the photon’s electromagnetic field does. “I don’t see why these concepts of quantum theory that have proven to be right for the case of light should fail for the case of gravity,” Aspelmeyer said.

But the incompatibility of general relativity and quantum mechanics itself suggests that gravity might behave differently. One compelling idea is that gravity could act as a sort of inescapable background noise that collapses superpositions.

“While you can get rid of air molecules and electromagnetic radiation, you can’t screen out gravity,” said Miles Blencowe, a professor of physics at Dartmouth College. “My view is that gravity is sort of like the fundamental, unavoidable, last-resort environment.”
In an optomechanical oscillator, the light confined between two mirrors causes one of the mirrors to oscillate on a spring. Experimentalists plan to use such devices to pit quantum mechanics against general relativity.

The background-noise idea was conceived in the 1980s and 1990s by Lajos Diósi of the Wigner Research Center for Physics in Hungary and, separately, by Roger Penrose of Oxford University. According to Penrose’s model, a discrepancy in the curvature of space and time could accumulate during a superposition, eventually destroying it. The more massive or energetic the object involved and, thus, the larger its gravitational field, the more quickly “gravitational decoherence” would happen. The space-time discrepancy ultimately results in an irreducible level of noise in the position and momentum of particles, consistent with the uncertainty principle.

“That would be a wonderful result if the ultimate reason for the uncertainty principle and the puzzling features of quantum physics are due to some quantum effects of space and time,” Milburn said.

Inspired by the possibility of experimental tests, Milburn and other theorists are expanding on Diósi and Penrose’s basic idea. In a July paper in Physical Review Letters, Blencowe derived an equation for the rate of gravitational decoherence by modeling gravity as a kind of ambient radiation. His equation contains a quantity called the Planck energy, which equals the mass of the smallest possible black hole. “When we see the Planck energy we think quantum gravity,” he said. “So it may be that this calculation is touching on elements of this undiscovered theory of quantum gravity, and if we had one, it would show us that gravity is fundamentally different than other forms of decoherence.”

Stamp is developing what he calls a “correlated path theory” of quantum gravity that pinpoints a possible mathematical mechanism for gravitational decoherence. In traditional quantum mechanics, probabilities of future outcomes are calculated by independently summing the various paths a particle can take, such as its simultaneous trajectories through both slits on a screen. Stamp found that when gravity is included in the calculations, the paths connect. “Gravity basically is the interaction that allows communication between the different paths,” he said. The correlation between paths results once more in decoherence. “No adjustable parameters,” he said. “No wiggle room. These predictions are absolutely definite.”

At meetings and workshops, theorists and experimentalists are working closely to coordinate the various proposals and plans for testing them. They say it’s a mutually motivating situation.

“In the final showdown between quantum mechanics and gravity, our understanding of space and
time will be completely changed,” Milburn said. “We’re hoping these experiments will lead the way.”

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