 Cosmic conundrum

Can the cosmos test quantum entanglement?

Albert Einstein hated the idea he called “spooky actions at a distance,” but astronomers now are hoping to illuminate some of these tricky quantum puzzles. by Andrew Friedman

Quantum mechanics remains our best physical theory of nature at the smallest scales, describing the bizarre world of subatomic particles like photons and electrons. It is arguably the most successful theory of modern science, predicting the behavior of light and matter with amazing precision and enabling transformative technologies like lasers, computer chips, and iPads. Unfortunately, despite nearly a century since physicists laid the foundation of quantum theory, we don’t agree on its physical interpretation. While we know how to use quantum mechanics as a powerful practical tool, we still don’t understand what it actually means.

Most researchers simply apply quantum theory without considering what the equations imply about reality. But maybe our embarrassingly poor grasp of quantum foundations represents an opportunity. In this view, science isn’t just about making predictions and building useful gadgets — it’s about telling a story and explaining how the world works.

Perhaps a satisfying explanation of quantum reality consistently has eluded us because nature is subtly fooling us. Strange as it may sound, at the core of quantum mechanics lies an insidious possibility — a “loophole” — that might mean we lack complete freedom to set up our experiments. If the cosmos exploits this loophole, it might help explain some of the most perplexing aspects of quantum theory — but at the price of a conspiracy of cosmic proportions that could render the very concept of choice an illusion.

One path toward clarifying the quantum story is to leave the subatomic realm and instead look to the stars. By using connections between the quantum world and distant regions of the universe, we hope to illuminate some of the mysteries of quantum theory. To tell the cosmic story of how astronomy itself might help shore up quantum foundations, we must first explore “quantum entanglement.”

Inextricably entangled

Entangled particles are connected in a way that transcends space and time. Measuring some property of one particle seems to instantaneously “fix” the future measurement outcome for the other. This happens even if they were too far apart for any known signals (those that travel at light-speed or less) to have been exchanged during the measurements. This feature of entanglement, which Albert Einstein famously called “spooky actions at a distance,” holds no matter how far apart the particles are in the portion of the universe that we can observe.

Particles can become entangled either by interacting or being created together. Physicists routinely create them in laboratories, to create an entangled pair of photons, the wavy particles that make up light, experimenters send single photons through a special crystal that yields two photons each time. Entangled pairs also occur frequently in nature. How can such particles maintain coordination over vast distances and even? No one really knows. Despite many experiments verifying that entanglement is real, scientists remain baffled of its true nature. One way two photons can be entangled is with respect to the direction they vibrate, called “polarization.” Typically, the polarizations of entangled particles are aligned perpendicularly — one vertical and one horizontal. But which photon has which polarization?

Imagine that we measure the first photon: vertical polarization. Quantum theory says we don’t know because before we measure it, each photon is in an indefinite state with a 50-50 chance of horizontal or other) behaves both as a wave and a particle.

After two particles interact, they can become entangled — each one knows how the other acts no matter how far apart they are. Astronomers hope to use luminous distant galaxies called “quasars” to test this bizarre quantum mechanical behavior. STS: ROEN KELLY; ESA/NASA, THE HUBBLE HERITAGE TEAM; AND NASA/ESA/H. FERGUSON AND A. KOEKEMOER

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Light's preferred directions

Quantum theory is essentially the direction in which the radiation wiggles. In this illustration, light is linearly polarized. If a polarization filter is aligned (center) or misaligned (bottom) with light's polarization, radiation will either pass through or be absorbed, respectively. If a filter is misaligned at an intermediate angle, quantum theory predicts the probability that a vertically or horizontally polarized photon will pass or be absorbed. Before a measurement, however, two photons with entangled polarizations can each be in both “horizontal” and “vertical” states at the same time.

When a polarizing filter (like polarized sunglasses lenses) is in front of a polarized light source like a computer monitor, the screen brightens and dims, as seen through the lenses, based on how much the filter is aligned or misaligned with the average polarization of the photons. (images from Baer & Neff 2002)

First photon's outcome before we measure it, we can't use entanglement to transport information faster than light.) In modern laboratory setups, a source can send polarization-entangled photons to detectors dozens of miles away (although they could be on opposite ends of the cosmos). These detectors measure the photons' polarizations based on whether they pass through a special filter, similar to polarizing sunglasses lenses. The detectors' settings are the orientation angles of the polarizing filters, such as 30° or 105°. When the detectors align, they always produce polarization measurements with opposite outcomes. For varying angles of misalignment, quantum theory predicts how these measurements will be same or opposite results on each experimental run. Over many such runs, each detector measures what looks like a sequence of random outcomes. But when we compare the results, we see correlations that appear impossible to explain based on any shared history of the entangled particles. Quantum entanglement is an indisputable experimental fact, but we still cannot explain what it actually means! We do, however, have a few useful clues.

A hidden quantum reality

Fifty years ago, physicist John S. Bell gave us perhaps the most helpful clue. He quantified the maximum amount that entangled particle measurements could be correlated assuming that both particles behave independently, which is what they would do if information could travel no faster than light-speed and these particles follow classical physics — and not quantum — rules. This is now known as “Bell’s theorem.” Quantum mechanics predicts correlation values greater than the maximum from Bell’s theorem, and every published experimental test has strongly favored quantum theory. The usual conclusion is that quantum mechanics must be non-local, meaning that measuring properties of entangled particle sets can be performed without using any information about the composite system of two particles. For those of us in the business of explanation, this seems quite unsatisfactory.

Is our theory of quantum mechanics complete, or is it missing key hidden information and therefore a fundamentally incomplete description of reality? This mystery formed the crux of the long-standing debate between Einstein and physicist Niels Bohr that began in 1927. In the 1960s, and still remains one of the greatest controversies of science today. Einstein desperately wanted physics to be about reality and argued that quantum theory must be fundamentally incomplete, while Bohr declared that quantum mechanics was the whole story and it was meaningless to ask what was really going on in the quantum realm. Einstein’s and Bohr’s positions seemed fundamentally irreconcilable until Bell’s theorem entered the fray in 1964.

Closing quantum loopholes

Like any theorem, Bell’s proof requires certain assumptions. By altering any of them, one can introduce loopholes that could allow different explanations of entangled particle tests that would make sense without quantum mechanics — where the world is locally real, and comprehensible, after all, just as in classical physics. We dub these quantum competitors “local hidden variable” theories to denote that information is missing from quantum theory. If such alternative theories are true, there might be a sensible story about the real, intrinsic, local properties of particles before, during, and after measurements.

Scientists who believe quantum theory is complete — and therefore doesn’t require any local hidden variables — have gone to great lengths to test it by designing experiments that ensure the universe can’t exploit certain loopholes. For example, to rule out a loophole that results from potential hidden communication between parts of the experiment — the so-called “locality” loophole — one can choose detector settings at the last instant while the entangled photons are still in flight. To close another loophole that could give biased results from inefficient detectors — the so-called “fair sampling” loophole — one can use extremely efficient new detectors.

While physicists have been performing locality and fair sampling experiments over the past four decades, they’ve only recently begun testing a third loophole. This is the so-called “setting independence” or “freedom of choice” loophole, which questions if the detector settings themselves were correlated with hidden information in their shared pasts. For example, if some hidden variables sent signals that influence the detectors before the measurement, then the experimenters might be unable to freely choose detector settings. This could constrain one’s choices in a way that previous tests could not have ruled out, leaving no quantum explanation visible. We sometimes fancifully call this the “free will” loophole (see “Testing possible loopholes in Bell’s theorem,” on p. 32).

Recent theoretical work shows that only a minuscule amount of information shared between the detectors and any hidden variables could conspire to mimic quantum predictions. Even if the experimenters retain most of their freedom to choose detector settings, tiny constraints in their choices could explain entanglement experiments while preserving locality.

Anton Zeilinger of the Vienna Center for Quantum Science and Technology and his colleagues were the first to tackle this loophole in a 2008 experiment, which they published in 2010. They performed a groundbreaking Bell test by sending polarization-entangled photons an unprecedented 89 miles (144 kilometers) through open air between detectors at two observatories in the Canary Islands — one on La Palma and the other on Tenerife. The long distance gave the scientists enough time to use quantum random-number generators to rapidly change the orientations of the polarizing filters. This detail ensured that the entangled photons were still in flight. This sophisticated setup did not close the fair sampling loophole, but it did close the locality loophole and narrowed the free will one, firmly ruling out any conspiratorial correlations set during the experiment.

Because Zeilinger’s study did not fully close the free will loophole, he left open the possibility of a conspiracy beginning a few milliseconds before the test. It takes only tens of milliseconds for light to cross Earth, so there is a chance that any terrestrial process we use to select detector settings could fall prey to this loophole. Furthermore, no experiment has closed all three major loopholes simultaneously. Now, my colleagues and I have proposed an experiment that we think can do so by relegating any conspiracy to the most distant epochs of cosmic history — all the way back to the universe’s beginning 13.8 billion years ago.

Cosmic light to the rescue

Jason Gallicchio of the University of Chicago, David Kaiser of the Massachusetts Institute of Technology in Cambridge, and I
envision closing the free will loophole with the help of some of the oldest light in the universe. Our approach adds a new wrinkle to standard Bell tests by taking ourselves out of the equation and essentially letting the universe decide how to set the detectors on each run of the experiment.

In collaboration with the Zeilinger group, our test would first use a standard laboratory source to send entangled photons to two detectors 89 miles (144km) apart in the Canary Islands. Meanwhile, we would point telescopes on each island at astronomical sources on opposite sides of the sky and use the random arrival times of the photons from those objects to set the polarization angles of both detectors while the earthbound entangled photons are still in flight. We would use real-time fluctuations in the signals from ancient objects such as quasars (active galaxies that lived billions of years ago) or patches of the cosmic microwave background (CMB, the Big Bang's residual light). Our so-called "cosmic Bell test" would thus effectively turn the night sky into a special kind of random-number generator, where — most crucially — the astronomical signals are effectively guaranteed to be uncorrelated with one another and any past hidden variables, in principle. While laboratory photons are specifically prepared in an entangled state, the quasar's (or CMB's) photons are entangled as well with anything or anything in their shared past — by design.

By picking pairs of quasars that are sufficiently distant from each other and Earth, we can be as sure as possible that no local hidden variables could have sent signals to both quasars in the finite amount of time since the Big Bang. The quasars themselves would have had no causal contact or mutual influence from anywhere else in the known universe (see "Two Bell tests, and how they differ," on p. 33). Unentangled cosmic light from the night sky can therefore help disentangle some of the trickiest parts of quantum entanglement here on Earth. How distant must these quasars be? Sources on opposite sides of the sky that emitted their light 12.1 billion years ago are now at redshifts greater than 3.63, nothing else could have jointly communicated with both quasars in the past 3.8 billion years. We could incorporate these quasars in a cosmic Bell test from space — say, using the International Space Station (ISS) as a distant satellite. For a ground-based experiment, we would need objects whose light was emitted 12.3 billion years ago (corresponding to a redshift of at least 4.13) to simultaneously observe both quasars above the horizon. Many such quasars exist that are bright enough to observe with 1- to 3-meter telescopes.

Loopholes all the way down?

Despite how careful our experimental work will be to use distant light sources, even a cosmic Bell test is susceptible to another key loophole. It stems from a phase of hyperaccelerated expansion called inflation that occurred during the first instant of cosmic history. A recent claim observed a pattern in the polarization of cosmic microwave background (CMB) — thought to result from primordial gravitational waves produced during inflation — that gave us even more confidence that inflation occurred. However, if the infant universe underwent inflation, all events in our observable universe — including light emitted from distant quasar pairs — would have a shared past during the inflationary epoch and thus could have communicated with one another in those first moments of cosmic history.

Because hidden variables during inflation could still exploit the free will loophole, this might seem to fundamentally undercut our argument. If inflation actually occurred, however, our proposed test is arguably the best anyone can do with 1- to 3-meter telescopes. In such an unlikely scenario, the degree to which the universe’s shared past states would be accessible was left to the imagination.

If the cosmos underwent inflation in the past, then a second, any pair of distant cosmic sources could have communicated during inflation.

Cosmic Bell in the real world?

So what might a cosmic Bell experiment like ours reveal? While I wouldn't bet we would see correlations that violate Bell’s result, as quantum theory predicts, no matter which cosmic sources we use, other outcomes are possible. That is the beauty of science. We can't be sure what we'll see until we actually perform the experiments! For instance, if Bell’s result is somehow not violated for any quasar pairs, or if the experiment displays a dependence on which quasar we use, then the role of inflation could turn from a bug into a feature. In such an unlikely scenario, the degree to which these objects shared pasts during inflation might relate to why the experiment shows deviations from quantum predictions. Thus, we could use a cosmic Bell test to experimentally falsify some of the key theories of the early universe, and possibly even quantum gravity. Even if our cosmic Bell test yields the expected outcome, the experiment would still test quantum entanglement, non-locality, and further close the free will loophole — while increasing our confidence in quantum theory.

This seems to us like a clear win-win situation, either result will reveal important information about our universe. And while I wouldn't be seeing anything surprising, experiments that leverage the astronomical distances and timescales of cosmology to explore fundamental physics are exactly the types of tests that could reveal something even weirder than quantum mechanics.