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Cosmic Test For Quantum Physics' Last Major Loophole

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What does light from the most distant objects in the universe and quantum mechanics have in common?

More than most would imagine — potentially including answers to whether quantum encryption technology is hackable to whether physics on the smallest scales allows for complete philosophical "free will."

A recent paper published in the journal *Physical Review Letters* details National Science Foundation-funded research that proposes a real-time experiment that would use incoming light from ancient quasars — literally on opposite ends of the universe — to close one of the last major theoretical loopholes in quantum mechanics.

"We wanted to come up with a potential test that could close one of the last major remaining quantum physics loopholes that could still allow entangled particle experiments to be interpreted according to classical physics," said Andrew Friedman, an MIT postdoctoral fellow and the paper's second author.

This artist's impression of one of the most distant, oldest, brightest quasars ever seen is hidden behind dust. The quasar dates back to less than one billion years after the big bang. The dust is also hiding the view of the underlying galaxy of stars that the quasar is presumably embedded in. (Credit: NASA/ESA/G.Bacon, STScI)

As Friedman explains, when pairs of particles are in an "entangled" quantum state, measuring one particle seems to affect the outcome of a measurement conducted on the other, even if the particles are so far apart that no known signals could have traveled between them during the measurements. Fifty years ago, physicist John Bell quantified the maximum amount that such measurements could be correlated, assuming both particles behaved independently.

No one would expect to find the roll of the dice to be the same across those two separate craps tables more often than chance, says David Kaiser, an MIT theoretical physicist and one of the paper's co-authors. Bell's Theorem, explains Kaiser, puts a mathematical limit on how often these measurements could line up and agree if the particles were independent.

However, Einstein, says Kaiser, called "quantum entanglement," the concept that subatomic particles can be connected across space and time and, as a result, affect each other instantly —"spooky action at a distance."

Einstein thought that the theory must be wrong, says Kaiser, who says he would expect their own proposed experiment's measurements to look like the predictions of quantum mechanics.

The concept, says Friedman, is to focus on whether the settings of the detectors that measure the entangled particles could have been correlated with any "hidden" information in their shared pasts. That is, correlations not accounted for by quantum mechanics. By selecting cosmic sources that have never been in causal contact with each other, or anything else in their shared past, he explains, the experiment would place the most stringent limit possible on this important, but often overlooked, loophole.

But as Friedman explains, "no matter how strange it sounds," it is a logical possibility that some shared events could have somehow influenced both detector settings to make them correlated and thus not as completely free and independent as one would expect. If so, the physicists might not have complete free will to choose the settings of their detectors.

"We ultimately hope to collaborate with our experimentalist colleagues who have expressed sincere interest in performing the experiment," said Friedman. "Our role would be mainly to help choose which cosmic sources to observe, help design an observational program, and potentially help interpret the results of the experiment from the theoretical side."

To that end, the paper's authors have been discussing their proposed experiment with an experimental physics group at the University of Vienna which has already performed similar experiments in the Canary Islands.

"They've been able to send entangled optical photons 144km through the open air between the islands of La Palma and Tenerife," said Friedman.

The Vienna group, headed by longtime quantum physicist Anton Zeilinger, found that the outcomes of measurements using detector settings chosen with quantum random number generators were "correlated" and thus obeyed the laws of quantum mechanics.

Our "Cosmic Bell" setup, says Friedman, would replace these number generators with real-time observations of quasars, using existing Canary Islands telescopes. These telescopes would be connected to a different set of detectors to measure some property of the arriving cosmic photons, such as their arrival time, to electronically switch the entangled photon detector settings — all while the entangled photons are in flight.

"This requires very fast detector responses and switching electronics so that a given experimental run is completed on the order of a few hundred microseconds," said Friedman.

In principle, it could all be done with existing off-the-shelf technology.

The experiment would need a source of entangled photon pairs, each of which would be shot in an opposite direction to receiver stations 50-100 miles away, says Jason Gallicchio, the paper's lead author and an experimental physicist at the University of Chicago.

These entangled photons, Gallicchio says, could travel to the receiving stations via fiber-optics or free-space; the latter involving small aperture telescopes for transmitting and receiving. He notes that each of the two receiving stations would not only measure one of the entangled photons, but do so based on a quasar photon that just entered a telescope in the same building.

Thus, the experiment's detector settings would, in part, be based on properties such as whether the quasar photon arrived on an even or odd microsecond, or if it were redder or bluer than average.

"There are tens of thousands of candidate quasar pairs that could be used for our experiment," said Friedman. "But the brighter the quasar, the better. And the more distant the quasars, the easier it is to be pretty sure the detector settings are chosen freely and independently of each other and anything else quantum mechanics might neglect."

In theory, however, events capable of affecting both quasars and in turn the experiment's detector settings would have to have been in place near the dawn of time some 13.8 billion years ago. And while such profundities are intellectually interesting, one of the experiment's practical goals would be to ultimately prove that quantum encryptions are unhackable.

"If any sort of classical theory is viable, then quantum encryption schemes of the future would not be as secure as researchers think," said Friedman. "So, there is a huge practical motivation to close these loopholes and rule out these alternative theories once and for all."

And, in the process, it would prove the reliability of quantum encryption. Although the researchers say that while they could obtain a result with only a night's observations, they would need to double-check their data with several different pairs of quasars. They are also quick to point out that the experiment is still in the "design feasibility" stage.

"If we were to get the result that we expect from quantum mechanics," said Gallicchio, "somebody who still insists on clinging to a classical physics explanation would have to concede that our earth-based entangled particle sources and detectors are somehow conspiring with these ancient, distant quasars."

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