Physicists propose tabletop experiment to test gravity's quantumness

Scientists, including those associated with Kolkata's Bose Institute, have devised a new way to check whether gravity is quantum-mechanical using nanocrystals

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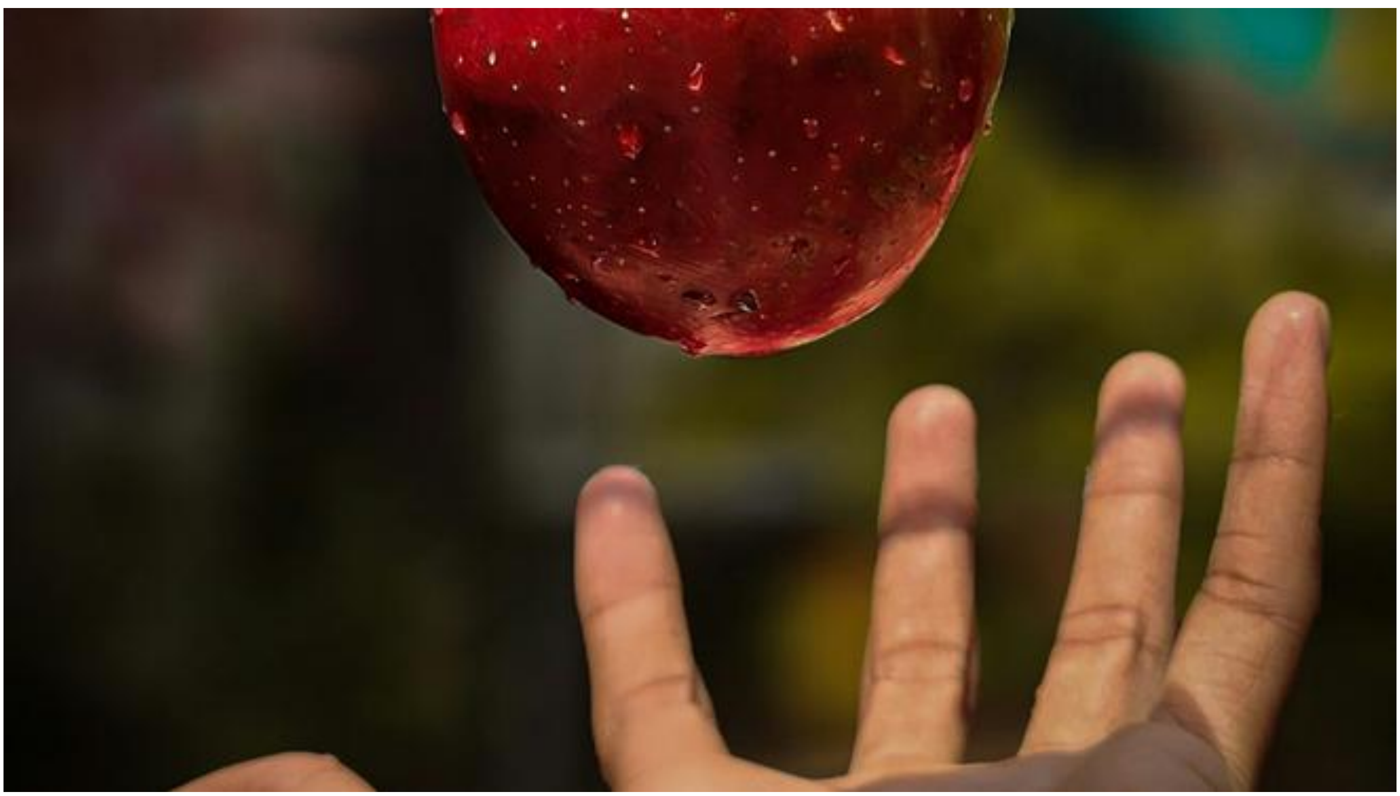

If a system undergoes measurement-induced collapse, it's said to live by the rules of quantum mechanics. Classical systems like falling apples or planets orbiting stars don't do this. | Photo Credit: Bithinraj MB

General relativity and quantum mechanics are two highly successful theories. The former explains gravity and the latter teams up with special relativity to describe the other three forces of nature: electromagnetic, strong nuclear, and weak nuclear forces.

However, scientists don't know how gravity fits into quantum mechanics. In fact, they have been proposing experiments that can test the quantumness of gravity. On October 29, 2024, one such proposal appeared in the journal *Physical Review Letters*.

With concepts like superposition, illustrated by the Schrödinger's cat thought experiment, and entanglement, quantum mechanics defies classical intuition. Quantum mechanics also allows seemingly absurd phenomena, e.g. the measurement of a quantum system (like a particle) can cause the system to instantaneously 'collapse' into one possible state that described the system before the measurement.

In fact, if a system undergoes measurement-induced collapse, it's said to live by the rules of quantum mechanics. Classical systems like planets orbiting stars, cricket balls flying in the air, and cars on the road don't do this.

Ruling out alternatives

Multiple experiments have found that both quantum mechanics and general relativity are legitimate theories of nature — yet they remain incompatible with each other. This has encouraged physicists to try and come up with a larger theory that can accommodate both. One strong contender is string theory, another is loop quantum gravity. Both of them predict deviations from quantum mechanics and general relativity either at the beginning of the universe or inside black holes, meaning they're nearly impossible to test.

"So far, experimental tests are extremely difficult — the situation looks very bleak — it is not clear if it can be done at all," Dipankar Home of Bose Institute, Kolkata, and one of the authors of the new paper, said.

To check whether gravity is quantum mechanical, scientists need precise tests that rule out alternative possibilities.

Unlike the classical Newtonian mechanics, where measuring a system doesn't alter it, quantum mechanics dictates that observing a system forces it into a definite state. This isn't a matter of how carefully a physicist is making the measurement. The measurement will always collapse the state. So measuring the state versus not measuring it creates a way to test whether the system is behaving according to the laws of Newtonian mechanics or quantum mechanics.

As a first step, physicists said they needed an experiment where gravity helps an inherently quantum mechanical process happen. If gravity causes the state to collapse, it will be a sign that gravity behaves quantum mechanically.

The new study suggested the following design: a test mass is in a superposition of two possible paths it can take. A probe mass will interact with it gravitationally to force it to choose one of the paths. Here, both masses are in a superposition of which paths they take. These two paths come close, resulting in different distances between the two pairs of paths. That is, for each path of the test mass, there are two possible paths the probe mass can take.

"Such simple, yet novel proposals ... are very interesting to the community," said Sreenath K. Manikandan, a theoretical physicist at the Nordic Institute for Theoretical Physics, Sweden, who wasn't involved in the study.

Testing weak gravity

The idea is also interesting because it proposes to test weak gravity. Say you're performing an experiment where you're looking for light. If the light is bright, you can find it just by looking at it. But if it is very dim, you need sophisticated light-detecting cameras. Similarly, ideas to look for quantum gravity have so far involved strong gravity, like that near black holes, whereas the new test proposes looking for weak gravity, like the force near a small object.

"Our contention is that fundamental quantum gravity features can persist in this limit," Home said.

Igor Pikovski, a quantum gravity researcher at the Stevens Institute of Technology and Stockholm University, commended this: "The important lesson is that quantum gravity signatures might show themselves even ... in tabletop set-ups and not just in science-fiction scenarios."

But independent experts said the experiment is still challenging because the masses need to behave quantum mechanically.

Quantum properties usually show up in a measurable way in systems that exist at a smaller than microscopic scale, like inside atoms, whereas gravity is easier to measure around larger objects, like a building.

This is why Vivishek Sudhir of the Massachusetts Institute of Technology said, "Preparing a spatial quantum superposition of an object massive enough such that its gravitational force is also measurable is an enormous experimental challenge."

Creating a superposition

Bose et al. have proposed the use of masses weighing about one-trillionth of a gram while maintaining a separation of around one-tenth of a millimetre. Nanocrystals meet these criteria.

Yet the team still estimates a decade for their experiment to be conducted. Thus far, "the largest objects that have been placed in two places at once are macromolecules. We will have to place a nanocrystal, which is a billion times larger, in two places at once," Sougato Bose, one of the coauthors of the study, said.

"Creating this superposition is by far the main challenge," Debarshi Das, another coauthor, added.

To do so, the authors have proposed using a quantum property of the nanocrystals called spin. Simply speaking, the spin affects the nanocrystals' motion (and can be manipulated by an external magnetic field). The spin of each nanocrystal exists in a superposition of two states until it is measured. Since the state affects the nanocrystal's path, it also exists in a superposition of two paths until a measurement.

"Once prepared in such a state, the gravitational field produced by this configuration will need to be measured very rapidly," according to Sudhir. "This is because any spatial quantum superposition will be extremely fragile and will die quickly, [so] measurements have to be made before this happens."

Bose also said the nanocrystals can collide with gas atoms and other objects and forces in their environment, which could destroy the superposition. "This could include things like the gravitational forces from seismic activity in the earth or perhaps even those due to clouds moving in the sky," Sudhir said.

For these reasons, the experimental set-up will have to happen in a near-perfect vacuum and the masses' properties will have to be measured with extreme efficiency.

An open mind

Despite all these challenges, physicists are hopeful. The proposed test has a much shorter timeline than the centuries required for humankind to develop the technologies to test quantum gravity near black holes.

Pikovski agreed the future is bright: "Just a few years ago, it was considered impossible to experimentally test quantum gravity even in principle."

The experts also said that the test may reveal gravity isn't a classical force, and that overall they will have to keep an open mind: it may not necessarily mean gravity is quantum but that it could be a non-classical and non-quantum entity, something different altogether.

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