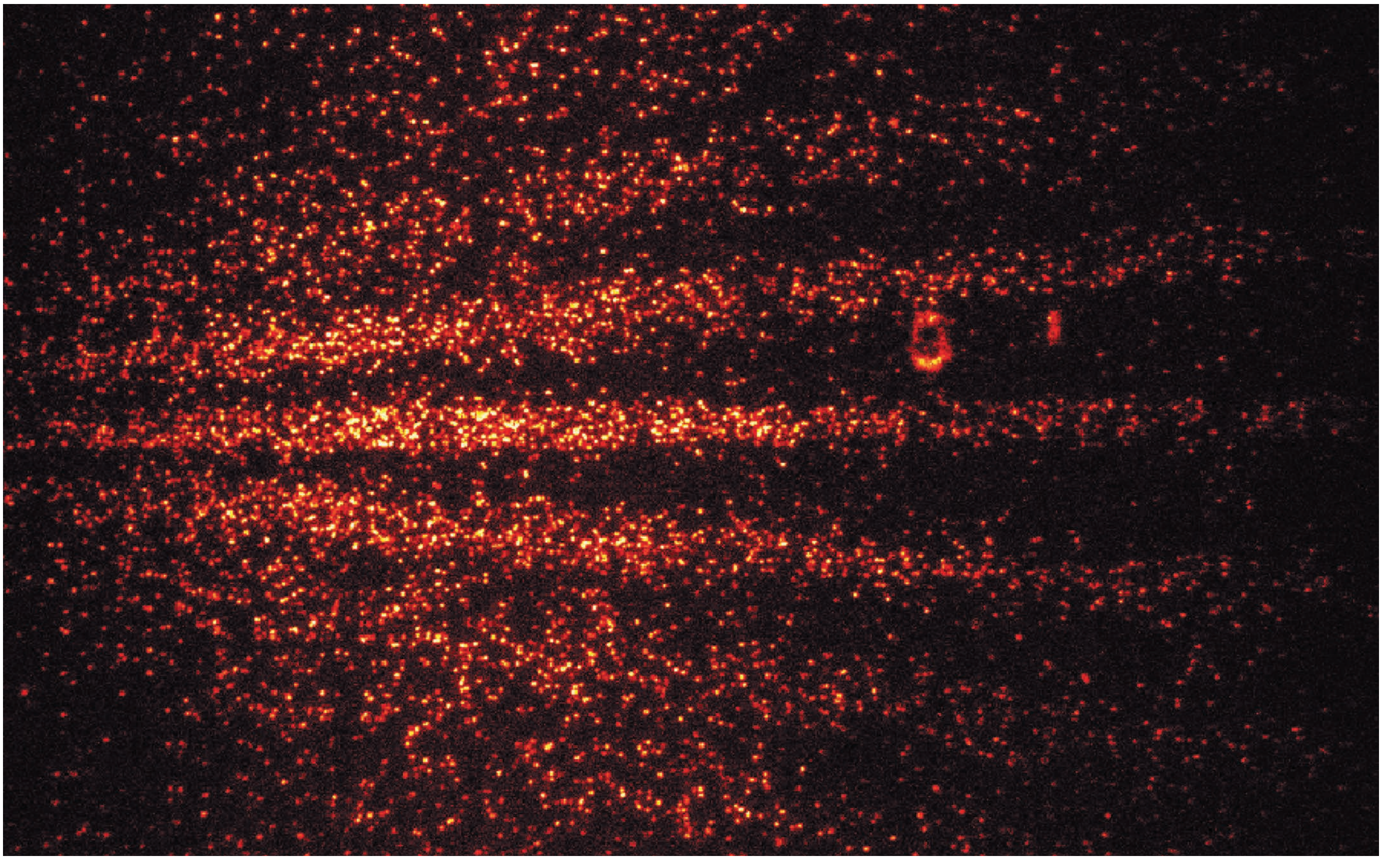
COMMENT


MARKUS ARNDT ET AL

Interference patterns in double-slit experiments have demonstrated the quantum nature of large molecules.

Witness gravity's quantum side in the lab

Physicists should rethink interference experiments to reveal whether or not general relativity follows classical theory, argue **Chiara Marletto** and **Vlatko Vedral**.

Sixty years ago, physicists congregated to discuss gravity in a seminal conference at the University of North Carolina in Chapel Hill. Richard Feynman proposed a thought experiment to analyse a deep problem: the incompatibility of quantum theory and general relativity[1]. We think that his argument needs revisiting.

General relativity is a 'classical' theory, in that any quantity that can be observed — such as the gravitational field — has a definite value that can be represented by real numbers. In quantum theory, by contrast, observables such as position or velocity cannot both have definite values at the same time. A particle may exist in a 'superposition' of states — being in two places at once, for example. When you measure its location you get a certain value, but you cannot predict ahead of the measurement what it will be. Hence the notorious story of Schrödinger's cat. According to quantum theory, one can set up an experiment where a cat hidden in a box with deadly poison is in a superposition of being alive or dead until someone opens the box and reveals its fate.

Feynman's imagined experiment goes to the heart of this clash. First, he considers a mass in a quantum superposition of two locations, A and B. General relativity describes how the mass interacts with the gravitational field: the mass falls according to the strength of gravity locally and also changes the field's value slightly at A and B by its presence. This brings us to a curious situation, Feynman reasoned. Applying both theories implies that, like Schrödinger's cat, the gravitational field must also assume two configurations at once: corresponding to the mass being at either A or B. Gravity, in other words, takes on a quantum nature when it interacts with a mass that is also behaving in a quantum way.

Feynman identifies two ways to solve this contradiction. Either quantum theory prevails and gravity too is 'quantized'; or general relativity prevails and quantum theory applies only at certain scales. Some principle yet to be discovered determines what those scales are[2,3]. Feynman then poses the central question: is it possible to design an experiment that rules out either possibility? So far, no one has proposed one.

The reason is that most physicists think that the intersection between quantum theory and general relativity is too difficult to access through laboratory experiments. And they assume that firm predictions are impossible without a fully fledged theory of 'quantum gravity', which combines quantum theory and general relativity in a new set of laws that can be compared against observations. We beg to differ. As Feynman realized, the main question we want to test is whether gravity is classical or not. And we can do that by developing theoretical and experimental tools we already have.

We call on the physics community to explore indirect tests of gravity's quantum behaviour. Such tests need not assume any particular theory of quantum gravity or manipulate the gravitational field itself in a quantum way. They will, however, require a profound change in mindset. The benefit is that the harder problem of describing a full theory of quantum gravity can be separated from Feynman's simpler challenge of witnessing experimentally gravity's 'quantumness'.

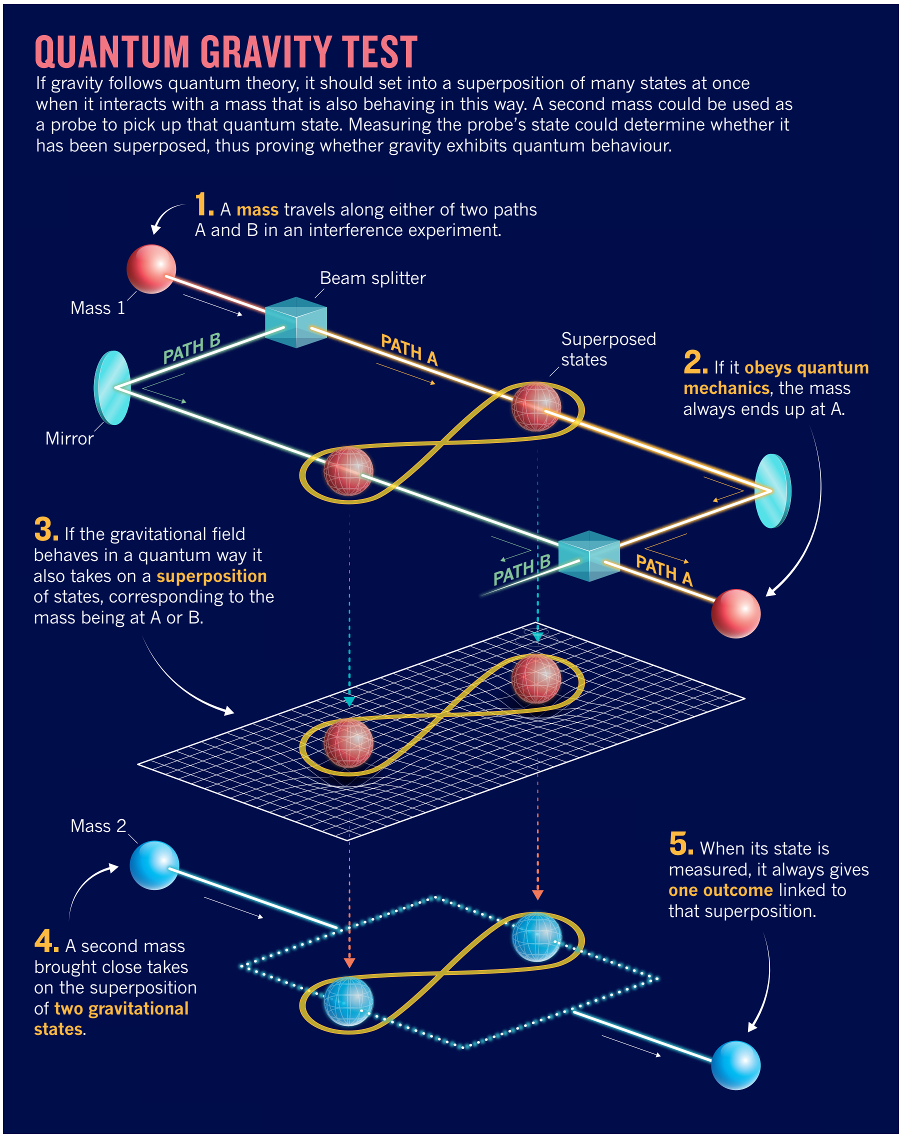
TESTING PREDICTIONS

Theories of quantum gravity are too underdeveloped to test explicitly. There are many proposals. Most redefine, or 'quantize', the gravitational field so that it can assume different values at the same time. Some proposals split it into small units or 'quanta' called gravitons — particles that carry gravitational energy, just as photons carry electromagnetic energy. Each theory makes different predictions.

But all such predictions have a fundamental problem. In the lab, quantum gravitational effects such as gravitons are impossible to see directly[4]. This is because gravity couples only very weakly to matter[5,6] — around 10^{43} times less than the equivalent coupling of an electromagnetic field to a charged particle. So, for instance, although it takes around 1 nanosecond for an energized atom to emit a photon, it would take much longer than the age of the Universe for a graviton to appear spontaneously. No one has ever seen one.

Other ways to gather experimental evidence have been suggested. But these also rely on testing particular theories. For example, quantum gravity might have left marks in the very young Universe. Just after the Big Bang, when the Universe was much smaller than an atom, quantum effects may have distorted how energy is spread around the cosmos[7]. These irregularities could have been amplified by 'inflation', a mechanism that made space expand in a flash. If so, signatures of quantum gravity might linger today as patterns in the cosmic microwave background — the relic radiation of the Big Bang. No such imprints have been detected yet. And even if they were, cosmic tests are inconclusive. They rely on a chain of theories and assumptions, like inflation[8].

Happily to answer Feynman's question we do not need a full theory of quantum gravity. All we need is to witness quantum behaviour in the gravitational field.



TEST NON-CLASSICALITY

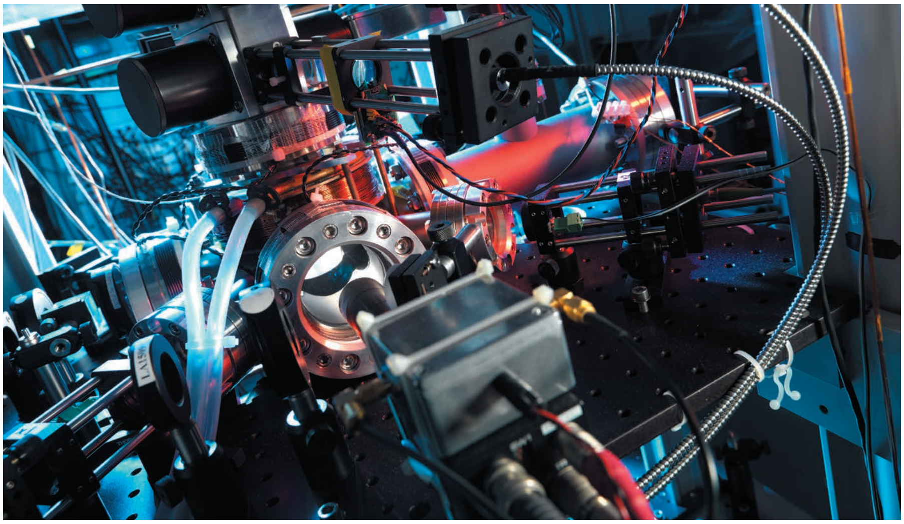
The standard tool for witnessing quantum behaviour is an interference experiment. This puts the system into a superposition of states and converts it back again to its original state. Symmetries in quantum theory mean that applying the same transformation twice brings you back to the state you started with.

For example, sending a photon along path A through a beam splitter (similar to a partially reflecting mirror) either allows it to continue or be diverted to a perpendicular route B. The photon is now in a superposition of the two paths, A and B. It is then sent through another beam splitter, reversing the experiment, and its path is measured. If it has obeyed quantum physics, the photon will always be on the original path, A.

It is possible to vary this scheme. For example, inserting a thin piece of glass across one path makes it asymmetric with respect to the other. Depending on the thickness of the glass, the output of the experiment changes according to a characteristic pattern — to the point that the photon can be swayed to emerge always on path B. Observing this pattern implies that the particle must behave according to quantum theory.

It is not feasible to do this with a graviton. But gravity might be brought into such an experiment by other means. For example, a particle with mass can be split among two locations and interact with Earth's gravitational field. Carrying out an interference experiment on that mass could demonstrate that the particle exhibits quantum behaviour. By Feynman's logic, if the gravitational field obeys quantum laws, it should also be set simultaneously to two different values — corresponding to the mass being on paths A or B. To answer Feynman's question, one has to resolve an extra issue. How can you tell that the gravitational field too is in a superposition of states?

Some physicists have considered whether clocks might be the key. According to general relativity, the rate at which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The apparatus around atomic clocks makes them too big to use in experiments on quantum gravity.

a clock ticks changes with the strength of the gravitational field in which it sits — an effect called gravitational time dilation. So a clock on top of Mont Blanc runs slower than one at sea level. Atomic clocks are sensitive enough to detect a change in altitude of 0.5 metres (a time dilation of about one part in 10^{-16}). If an atomic clock could be superposed in two locations — one high, one low — the different ticking rates might be exploited in an interference experiment, the thinking goes[9].

The effect of the gravitational field on the ticking rates would be different on the two paths; the clock on the higher path would be faster than that on the lower path. This would introduce an asymmetry in the paths that affects the interference output, just like inserting glass does for a photon. It could even cause the clock to end up on path B at the end of the experiment. A simulation of an analogous experiment has been proposed, using a magnetic field instead of gravity[7]. But an atomic clock has never been put into a superposition of states. It is too big — the apparatus that stabilizes the clock is the size of a ping-pong table.

In any case, an experiment such as this would not address Feynman's core question. What it shows is that the gravitational field can interact with a quantum object without spoiling its quantum behaviour. But it does not provide evidence that the field itself is quantum. In other words, it doesn't take into account the extra influence of the clock's mass on the gravitational field at A and B: it assumes that there is one ticking rate per height.

If the gravitational field has quantum qualities, we would need to witness a superposition of two ticking rates — corresponding to the gravitational field being in a superposition of two values. The clock experiment, as proposed, does not go far enough.

INDIRECT TESTS

The good news is that, in principle, quantum superpositions of the gravitational field can be probed — indirectly — through a second mass.

We can see how this works by looking at an analogous experiment involving the electromagnetic field. A quantum superposition of two values of the electric field — another example of a Schrödinger-cat state — can be set up by using an electron superposed in two different locations in an atom[10]. A second atom, used as a quantum probe, can be brought into that field. As a result of the interaction, the probe is set to a particular quantum state, depending on the exact superposition the field is in. Repeating the experiment and measuring the probe at the end always gives the same quantum state. Without quantum superposition, there would be a range of outcomes, with some probability. Thus the quantum behaviour of the electric field is confirmed without manipulating the field, or photons, directly.

> **"All we need is to witness quantum behaviour in the gravitational field."**

Likewise, one could envisage an experiment that uses two quantum masses. These would need to be massive enough to be detectable, perhaps nanomechanical oscillators or Bose–Einstein condensates (ultracold matter that behaves as a single super-atom with quantum properties). The first mass is set in a superposition of two locations and, through gravitational interaction, generates Schrödinger-cat states on the gravitational field. The second mass (the quantum probe) then witnesses the 'gravitational cat states' brought about by the first. Observing that the probe mass always ends up in that state would confirm the existence of quantum features in gravity, without having any direct quantum control over it (see 'Quantum gravity test').

Such an experiment requires an extra step than in Feynman's original suggestion. The first mass sets the fields into the quantum superposition; the second mass then interacts with the field and is measured to reveal the field's quantum features.

BROADER THINKING

Feynman's conundrum is so familiar to physicists that they have neglected seeking possible extensions. We argue that, with more rigorous attention, an experiment could be designed to perform the test. Physicists need to consider which experimental and theoretical tools could be used to explore the quantization of the gravitational field using quantum probes.

Which features should a suitable quantum probe have, and which observables should be measured? Would a simple mass do or would some form of atomic clock be better? What size of probe would be appropriate? How would one eliminate the actions of other fields, such as the electromagnetic field, and distinguish the quantum effect of gravity from other forces?

There might be fundamental limitations caused by the weakness of the gravitational interaction. Alternatively, macroscopic effects could cancel out or disrupt quantum signals, leading to some kind of 'gravitational decoherence'[8]. Nonetheless, assessing whether such tests are feasible is the first step towards progress.

A starting point would be a focused meeting bringing together the quantum- and gravity-physics communities, as well as theorists and experimentalists. Perhaps it is time for a second Chapel Hill conference. ■

Chiara Marletto *is a junior research fellow at Wolfson College, Oxford, and* **Vlatko Vedral** *is professor of quantum information science in the Department of Physics, University of Oxford, Clarendon Laboratory, Oxford OX1 3PU, UK.*
e-mails: chiara.marletto@physics.ox.ac.uk; vlatko.vedral@qubit.org

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