BACKGROUND

What Happens When Gravity Enters the World of the Very Small

Physics Gravity and quantum mechanics rarely interfere. But what if they do? For that, physicists need a new theory.

Dorine Schenk July 3, 2024 at 2:09 pm Reading time 7 minutes

Listen Reading list

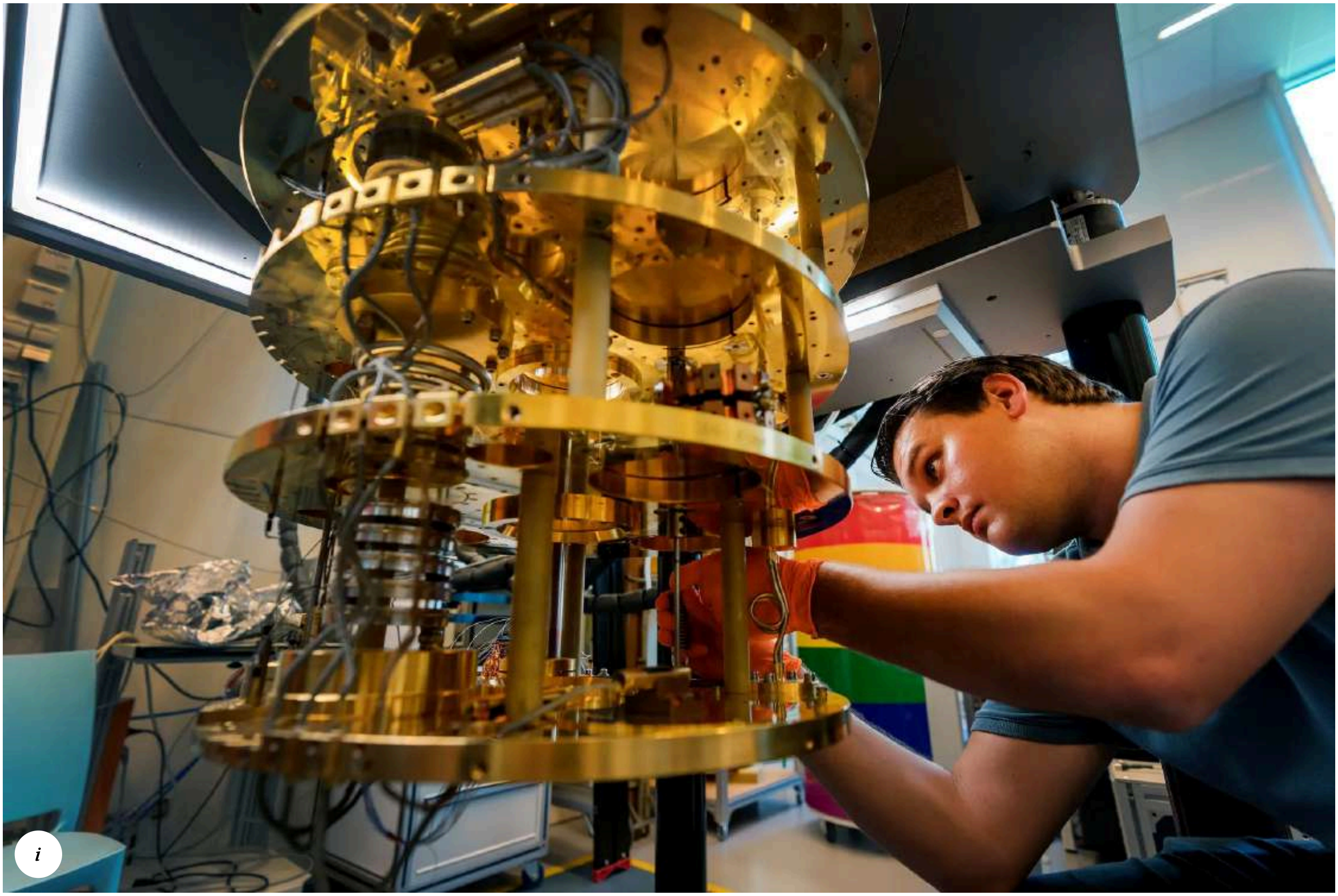


Photo Olivier Middendorp

Gravity is the most mundane, and at the same time the most mysterious force of nature. It makes the moon revolve around the earth and apples fall to the ground. The laws of gravity were already described by Newton and expanded (and refined) by Einstein. But unlike other forces of nature, it is not clear how gravity behaves on the smallest scale. In order to get a better grip on this, physicists want to examine the gravity between tiny objects in the coming years.

For example, the gravitational force exerted on each other by two golden balls, each weighing just 90 milligrams, was measured in Vienna in 2021. This is the smallest gravitational effect ever measured. The experiment showed that the two-millimeter balls neatly obey Einstein and Newton's laws of gravity. But this is just the beginning. Physicists are working on experiments that zoom in even further.

Will gravity continue to behave stubbornly according to the laws of Einstein and Newton or will it acquire a quantum mechanical character and will a new theory be needed to describe this quantum gravity?

It is clear that there is something special about gravity. Of the four known forces of nature, gravity is by far the weakest. That the electromagnetic force is stronger can easily be demonstrated by lifting your key ring with a magnet. That this works means that the force of a small magnet is greater than the gravity of the entire earth. The other two nuclear forces only work on the scale of atoms, but are at least a quadrillion times stronger than gravity.

Two theories

Yet gravity plays the main role on the large scale of the universe. It provides the attraction between stars, planets and other celestial bodies; and between an apple and the earth. This is because large objects almost always contain an equal amount of positive and negative charge, so that they exert no net electromagnetic force on each other, while the gravity of all particles adds up.

Gravity is the only force with its own theory. Albert Einstein's general theory of relativity describes gravity as a curvature of space – or actually of space and time – under the influence of matter or energy, which are interchangeable according to Einstein's $E=mc^{2.}$ The other three forces are not a property of spacetime. They exist in spacetime and are described by quantum mechanics, which deals with the behavior of small particles.

Both quantum mechanics and general relativity are remarkably successful and have been proven many times. But when physicists try to unify them, they run into problems. Mathematics then gets stuck and spits out nonsensical answers that have nothing to do with reality.

Usually, this is not a problem. Gravity has the upper hand on the large scale and quantum mechanics on the small scale. As a result, they rarely interfere with each other. Nevertheless, physicists are racking their brains about how to marry the two. There are situations in which they both play an essential role, such as just after the Big Bang and with black holes. These involve enormous amounts of matter that are compressed into a small space. Quantum mechanics and gravity are then forced to talk to each other. To understand these situations, physicists need a new theory that unites gravity and quantum mechanics.

> *You can't just simulate a black hole in a lab*

The vast majority of physicists working on this are looking for a quantum description of gravity. This would mean that spacetime on the smallest scale is made up of building blocks that behave according to the laws of quantum mechanics. Spacetime as we experience it and gravity would then arise from the behavior of these quantum building blocks. There are a number of candidates for this quantum gravity, such as string theory – which predicts that matter and spacetime arise from tiny, vibrating strings.

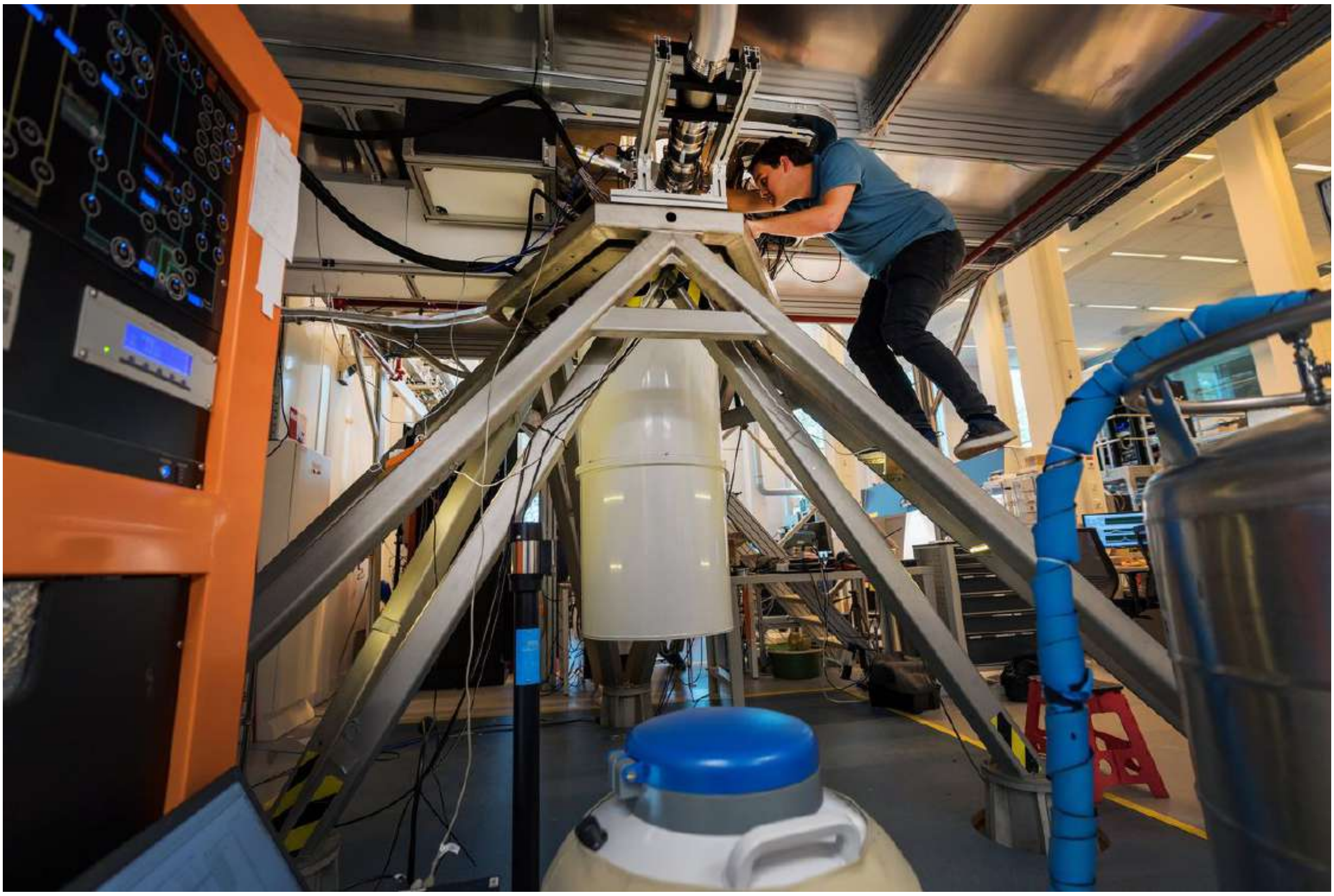
To determine which theory is on the right track, experiments are needed that map out the possible quantum nature of gravity. That is not easy. You cannot simply simulate a black hole in a lab. “For that, you need energies that are much higher than what is achievable with current particle accelerators,” says Tjerk Oosterkamp, professor of experimental physics at Leiden University.

That’s why physicists are taking a different approach. They are developing experiments that zoom in on the unknown territory where the large scale on which gravity rules transitions into the small scale that is the domain of quantum mechanics. Somewhere in that territory, gravity and quantum mechanics could meet. Physicists hope to catch gravity interfering with quantum effects or exhibiting quantum behavior there, for example.

White spot

"That area is still a blank spot on the map," says Oosterkamp. "We are trying to color it in by measuring gravity in increasingly smaller objects and observing quantum properties in increasingly larger objects."

One of those quantum properties is superposition, where a quantum particle is in two or more places at the same time. Physicists have become adept at bringing electrons, atoms and molecules into superposition in a controlled manner. And in the last ten years, this has sometimes been possible with larger objects, such as a kind of quantum drum skin of a few micrometers. But these quantum superpositions are fragile and can easily disappear due to disturbances, such as vibrations. Then the particle is no longer in two places at the same time, but just in one.



Dennis Uitenbroek in the lab in Leiden.

Photo Olivier Middendorp

Research groups like Oosterkamp's and the one in Vienna are trying to fill in the spot from the other side by measuring increasingly smaller gravitational effects. After the record in Vienna with the two-millimeter golden balls, the Leiden research group is trying to measure the gravity between particles of one millimeter and eventually 100 micrometers in size, says Oosterkamp.

They do this by floating a magnet in a high-tech refrigerator at -273 degrees Celsius. This low temperature ensures as few disturbances as possible. They let a wheel with three blocks on it rotate under the floating magnet. Every time a block is at the top, its gravity pulls the magnet down a little, says Leiden PhD candidate Dennis Uitenbroek. When the block is gone, the magnet springs back up. By measuring this movement, they can determine the gravity between the block and the magnet. "The first successful experiments were with blocks of 2.4 kilograms on a wheel that was outside the refrigerator," says Uitenbroek. "Now we want to move to blocks of a few milligrams on a smaller wheel that will be placed in the refrigerator."

The ultimate goal is to combine the gravity measurements and the superposition measurements in an experiment that measures the effect of gravity on an object in a quantum superposition. If gravity affects this quantum state, for example by making the superposition disappear, then that indicates that gravity has quantum features. It will certainly take decades before the gravity measurements are sensitive enough and the quantum objects large enough.

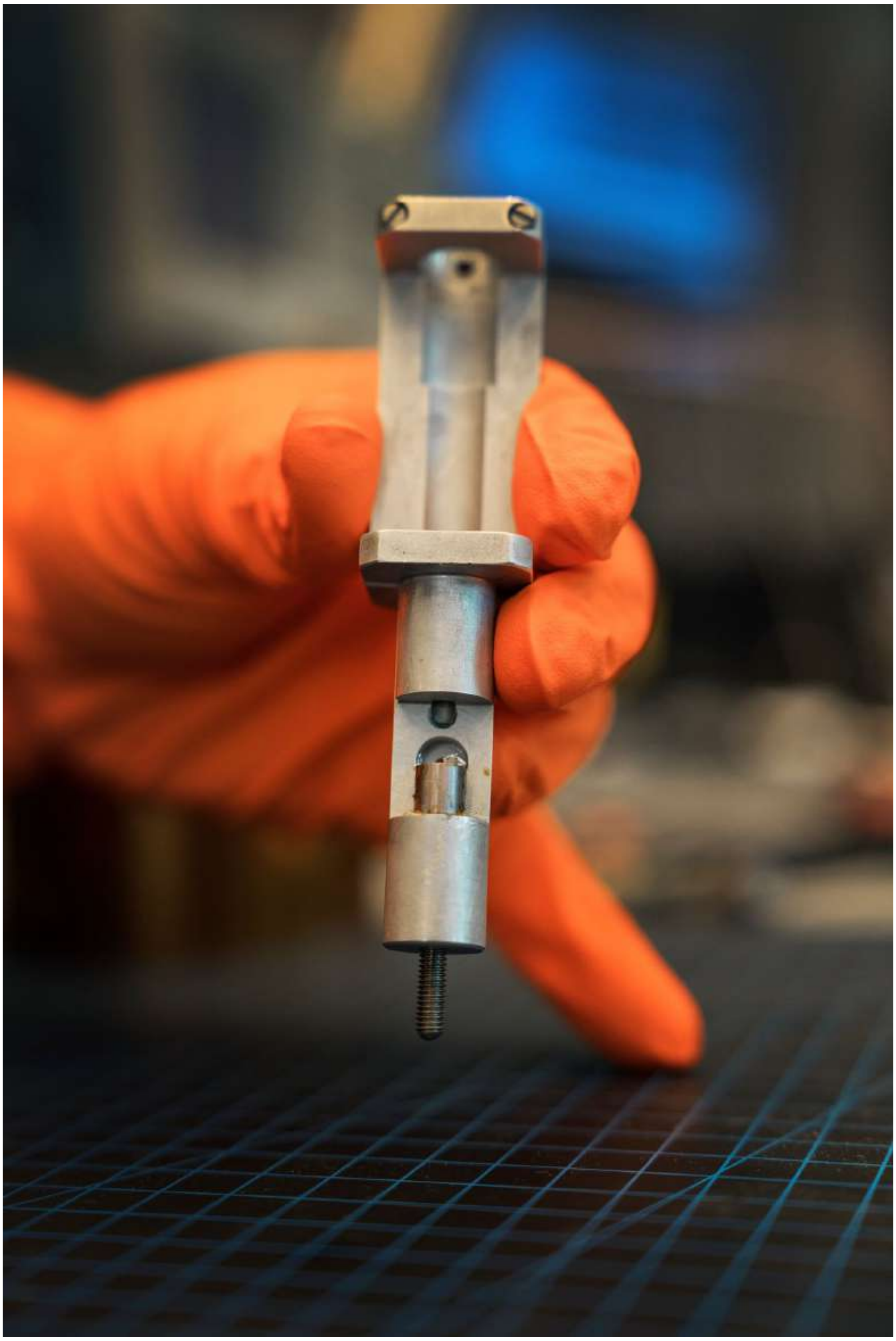


Photo Olivier Middendorp

Entangled diamonds

There are more ways to search for evidence of quantum gravity in experiments. For example, Anupam Mazumdar, professor of physics at the University of Groningen, is working with an international group of colleagues on a promising experiment based on quantum entanglement, another quantum effect. When two quantum particles are entangled, they have a special bond that means measurements of the particles are no longer independent of each other. This works as follows: if Alice and Bob are quantum entangled and both toss a coin and Alice sees that she gets heads, she immediately knows that Bob got tails, without looking at his coin. The same goes the other way around.

Mazumdar's experimental design consists of two diamonds of a billionth of a milligram. In the diamond lattices of both, there is a special spot, the so-called NV center. This can be brought into superposition. The NV centers of two diamonds can become entangled with each other. In the experiment, the diamonds are placed with the NV centers at a distance of about 50 to 60 micrometers from each other. If gravity has quantum properties, then it can entangle the NV centers in the diamonds. If you measure that entanglement has occurred, then that is a strong indication of quantum gravity.

“Gravity is not the only way that entanglement can occur,” Mazumdar says. It can also happen under the influence of an electromagnetic force, generated by electrical charge in the environment. “The beauty of it is that we have ways to block those electromagnetic forces, but we can’t block gravity; so if gravity is truly quantum, then the two masses are bound to become entangled.”

With that, the experiment could convincingly demonstrate that gravity is a quantum force. However, this is still a pipe dream for the time being. Mazumdar: "It is a marathon experiment; it will take at least 20 to 25 years to build the experiment. We are currently in the early stages."

It will therefore take a few decades before experiments are able to measure the effects of quantum gravity. Oosterkamp does not think he will experience this before his retirement. Nevertheless, he is enthusiastic about the developments. “I think it is great that there are now hundreds of researchers working on experiments at the boundary between quantum mechanics and gravity. Twenty years ago, it was still seen as philosophical thought experiments. Doing it meant that you were done with your physics career. It was something for after your retirement. Fifteen years ago, we therefore kept quiet about the fact that we were working on it when we wrote project proposals. Now, the experiments seem feasible and we can admit it without losing research funding.”

IceCube Measurements at the South Pole

Ultra-sensitive experiments in the lab are not the only way to discover the possible existence of quantum gravity. This can also be done with the IceCube detector in the South Pole ice, which searches for neutrinos, superlight, chargeless particles that are created, among other things, when energetic cosmic rays collide with the atmosphere and during powerful cosmic events, such as stellar explosions.

“Neutrinos are suitable for quantum gravity research because they are almost exclusively influenced by gravity – or quantum gravity – during their journey through the atmosphere or the universe,” says Tom Stuttard of the University of Copenhagen. And they have another special property: neutrinos can come in three different flavors and they are almost always in a quantum superposition of these three. So they are three flavors at the same time, as long as nobody interferes.

“IceCube detected the flavours of about 300,000 neutrinos that were created in the atmosphere,” says Stuttard. “We know how the probabilities of the flavours are distributed when they are created, and therefore know what to expect in the detector. If the flavours do not match expectations, then that could mean that quantum gravity has interfered.”

The results, published in March in the journal *Nature Physics,* showed no deviations from expectations. “We saw no evidence for quantum gravity,” says Stuttard. “That’s a bit disappointing, but it also means that we can rule out theories that predicted quantum gravity would be so strong that we would measure something.”

The next step is to look at neutrinos from the distant universe. They have travelled longer and could therefore pick up weaker quantum gravity effects. "These cosmic neutrinos are rarer and it is more difficult to determine exactly where and how they originated. That information is needed to determine which flavours we can expect." Moreover, all kinds of effects can occur along the way that influence the superposition. It will take at least ten years before these measurements are possible.

Already a subscriber? Log in

About NRC
About us
Work at
Copyright
Privacy
Terms of delivery
NRC Code
Our app
Archive
To advertise

My NRC
Subscribe
login
create an account
Digital newspaper
My subscriptions
Service & Delivery
Newsletters

Contact
Editorial
Opinion editorial
The Ombudsman
Colophon
AdSales
Customer service
Family announcements

NRC websites
Media house NRC
NRC Career
NRC Webshop
NRC Readers Fund