Novel Particle Beam Could Challenge Einstein’s Theory of Gravity

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Researchers at the Paul Scherrer Institute PSI and ETH Zurich have produced an intense, cold beam of exotic atoms. They aim to use this to test a fundamental principle of Einstein’s theory of gravity – the universality of free fall.

- Alongside the elementary particles that make us up, there is a second and third generation of matter.
- Muonium is an exotic atom containing a second-generation antiparticle.
- Using an intense, cold beam of muonium, researchers aim to measure for the first time whether the Earth’s gravitational pull acts on the exotic atom in the same way as it does on ordinary matter.
- A difference in the gravitational effect on normal and exotic matter could point to the existence of a further, as yet unknown, fundamental force.

Does gravity act equally on all particles in the universe, or are there differences between ordinary and exotic matter? Anna Soter and her team at ETH Zurich and the Paul Scherrer Institute PSI are investigating this question. “We have taken an important step towards carrying out an exciting experiment on this topic,” says the professor of physics: “We want to measure the gravitational interaction of the muon.”

To do this, the research team use an exotic atom called muonium. It resembles a hydrogen atom, but its nucleus does not contain a proton, but an antimuon.

All matter surrounding us – including ourselves – consists of protons, neutrons and electrons. Physicists refer to this as the first generation of particles. There are also two further generations comprising heavier particles. The muon, for example, is the heavier sibling of the electron and belongs to the second generation.

At PSI, researchers artificially produce muons and their antiparticles using a large particle accelerator. When a positively charged antimuon combines with a negatively charged electron, a neutral muonium atom is formed.

The standard model of particle physics describes the generational structure of matter. “But we physicists do not yet understand why these additional generations exist at all in the first place,” says Soter: “And why are there three in total?” Another particularly fascinating question is whether the increasing masses of the second- and third-generation particles behave in exactly the same way within terms of gravity as the lighter particles of the first generation.

The enigmatic principle of equivalence

In ordinary matter, all bodies fall at the same rate at a given point within a gravitational field. This universality of free fall was recognised as early as the time of Galileo Galilei and Isaac Newton, and, as the equivalence principle between gravitational mass and inertial mass, it is a cornerstone of Albert Einstein’s theory of gravitation.

This puzzling principle, however, has so far only been demonstrated with ordinary matter or first-generation antimatter. By measuring the gravitational behaviour of muonium, the researchers would, for the first time, investigate how a second-generation particle falls. “The exotic muonium is very well suited to this because it is a neutral atom,” explains Soter: “After all, to make something fall, you need something neutral.” In the case of a charged particle, the weak effect of gravity would be masked by stray electromagnetic fields.

However, there are also major difficulties: muons decay very quickly, after just 2.2 microseconds. And previous sources of muonium produced atoms that flew off in many directions at different speeds and were therefore unsuitable for precise experiments.

At PSI, at a facility known as the Swiss research infrastructure for particle physics CHRISP, researchers have now achieved a breakthrough. “We have managed to produce the muonium atoms in a ‘cold’ state, which is what makes the gravity experiment possible in the first place,” says Soter: “In this case, ‘cold’ means that the atoms propagate at similar speeds, almost parallel to one another.”

This new muonium beam is also exceptionally bright – a feature that is essential for a precise measurement. To measure gravity, scientists watch how atoms fall. Yet the effect of gravity is tiny, so the longer the atoms can fall for, the more precise measurement. “As muonium atoms have such a short lifetime, we need to start with a large number so that enough survive long enough to be measured after falling for a few microseconds,” explains Soter.

Quantum fluid providing the decisive boost

This was achieved by way of a new method for generating muonium atoms, as the researchers report in the journal *Nature Physics*. “In order to achieve this, we used superfluid helium that had been cooled close to absolute zero at minus 273 degrees Celsius,” explains Jesse Zhang, lead author of the study: “Superfluid helium is what is known as a quantum fluid, in which the individual helium atoms lose their identity, and which does not tolerate any impurities within it.”

The method: the antimuons produced in the PSI accelerator are fired into a thin layer of superfluid helium, where they are slowed down. When an antimuon encounters a free electron in the helium, a muonium atom with a positive chemical potential is formed and is, as it were, forced out of the liquid. When the muon reaches the surface, the chemical potential is converted into kinetic energy. The atom receives a boost and shoots vertically out of the liquid. “So we’re using the chemical potential as an atomic cannon,” explains Zhang.

It is crucial that the muonium atoms can move unhindered through the quantum liquid at a specific speed and without collisions; otherwise, given their extremely short lifetime, they would never reach the surface at all. “For our experiments, we also rely on PSI’s particle accelerator, which generates the world’s most intense, continuous muon beams,” says Soter: “Thanks to this high-quality source, a great many muonium atoms can be produced.”

Gravity shifts interference patterns

As a next step, the researchers are now developing the apparatus they intend to use to measure the effect of gravity on the muonium beam – a so-called interferometer. It utilises the wave properties of the atoms to generate an interference pattern. The tiny shift in this pattern caused by Earth’s gravitational pull makes it possible to determine the gravitational effect on muons.“We hope to be able to test the method for the first time with the atomic beam this year, and if all goes well, the actual gravity experiment should follow in two or three years’ time,” as Soter relates.

The new muonium beam is also expected to enable new experiments in laser spectroscopy. This would allow muonium to be measured much more precisely than previously was the case. This would provide insights into the mass of the muon and fundamental physical constants, which is also a future goal of the research group.

The new muonium beam is set to become even brighter in the future. With the new High Intensity Muon Beams (HIMB), part of PSI's IMPACT upgrade, the researchers will be able to create a beam with one hundred times more muonium atoms. This will allow Soter and her team to increase the sensitivity of the gravity experiment. "This is a very exciting prospect for precision measurements, since our measurement is statistically limited," says Soter.

But what if gravity acts differently on this exotic atom than it does on ordinary matter? "That would indeed be surprising, and, in addition to other theories, it could point to the existence of a fifth force," as Soter outlines. To date, physics has assumed there are four fundamental interactions: gravity, electromagnetism, the strong interaction and the weak interaction. Although a fifth force has been proposed time and again, it has never been proven.

However, such proof is not Soter's primary aim: "I am completely open-minded," she says: "I simply want to measure, for the first time, whether the equivalence between gravitational and inertial mass also applies to the second generation of particles – this alone is quite an inspiring piece of work."

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About PSI

The Paul Scherrer Institute PSI develops, builds and operates large, complex research facilities and makes them available to the national and international research community. The institute's own key research priorities are in the fields of future technologies, energy and climate, health innovation and fundamentals of nature. PSI is committed to the training of future generations. Therefore about one quarter of our staff are post-docs, post-graduates or apprentices. Altogether PSI employs 2300 people, thus being the largest research institute in Switzerland. The annual budget amounts to approximately CHF 450 million. PSI is part of the ETH Domain, with the other members being the two Swiss Federal Institutes of Technology, ETH Zurich and EPFL Lausanne, as well as Eawag (Swiss Federal Institute of Aquatic Science and Technology), Empa (Swiss Federal Laboratories for Materials Science and Technology) and WSL (Swiss Federal Institute for Forest, Snow and Landscape Research). *(Last updated in June 2026)*

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Synthesis of a high intensity, superthermal muonium beam for gravity and laser spectroscopy experiments.
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https://www.psi.ch/en/news/media-releases/novel-particle-beam-could-challenge-einstein-s-theory-of-gravity