Quantum acceleration

Clouds of cold atoms can be used to measure subtle variations in gravitational force

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Physicist Philippe Courteille and his colleagues at the São Carlos Physics Institute (IFSC) of the University of São Paulo (USP) are building an instrument to measure the effect of the gravitational force of the Earth on Bose-Einstein condensate, which are microscopic clouds of approximately 100,000 strontium atoms maintained at temperatures close to absolute zero (-273.15°C) with high precision. This device is an atomic gravimeter that should enable real-time calculation of the intensity of the gravitational force on a microscopic scale; this has not been well measured to date. There are similar instruments in the world with sufficient sensitivity to measure gravitational forces on this scale. However, the existing devices only reconstruct the motion of atoms afterwards and cannot follow them in real time, as the researchers in São Carlos promise to do. They believe that the new gravimeter will have practical and fundamental physics applications.

Other experiments with atomic gravimeters, some of which have been performed, and others are in progress, have measured the gravitational force on microscopic scales. Nonetheless, they have not achieved the degree of precision that has been obtained for the other fundamental physical forces. "There are theories that predict that Newton's law of gravity may not apply to distances under a few micrometers," says Courteille. The law of gravity states that the force of attraction between two bodies is inversely proportional to the square of the distance between them and explains observations in the macroscopic world notably well. "We may need to modify this law of attraction to explain what occurs at the microscopic level," says the physicist.

The practical applications of the new gravimeter will depend on its sensitivity. If the sensitivity is notably high, the device can be used to map oil and ore reserves. Courteille cannot yet establish the exact degree of sensitivity that his instrument will achieve, but he estimates that it should be able to surpass the best commercial high-precision gravimeters, which use laser beams to measure the acceleration of gravity that acts on a small free-falling mirror in vacuum. Geophysicists use this type of equipment to map underground reserves with economic value. Tiny variations in Earth's gravitational acceleration enable the detection of differences in subterranean rock densities, which indicates the presence of ore.

Courteille has finished developing the most important part of the gravimeter: the annular optical cavity. It consists of three small, special mirrors that are placed at the vertices of a triangle approximately 2 centimeters apart from each other. According to articles in the journals *Optics Express and Laser Physics Letters*, these carefully designed and arranged mirrors should ensure the success of the future device. Computer simulations, which were performed by Courteille and Romain Bachelard of IFSC in partnership with Marina Samoylova and Nicola Piovella of the University of Milan, Italy, and Gordon Robb of the University of Strathclyde in the UK, indicate that the optical cavity should improve the gravimeter operation for two reasons. First, the cavity should prevent the condensate destruction by the laser beam that interacts with it to measure its displacement. Second, the cavity should stabilize the oscillations of the condensate, making them more regular and predictable. The researchers submitted a patent application for the device to the Brazilian Industrial Property Institute (INPI) in 2015.

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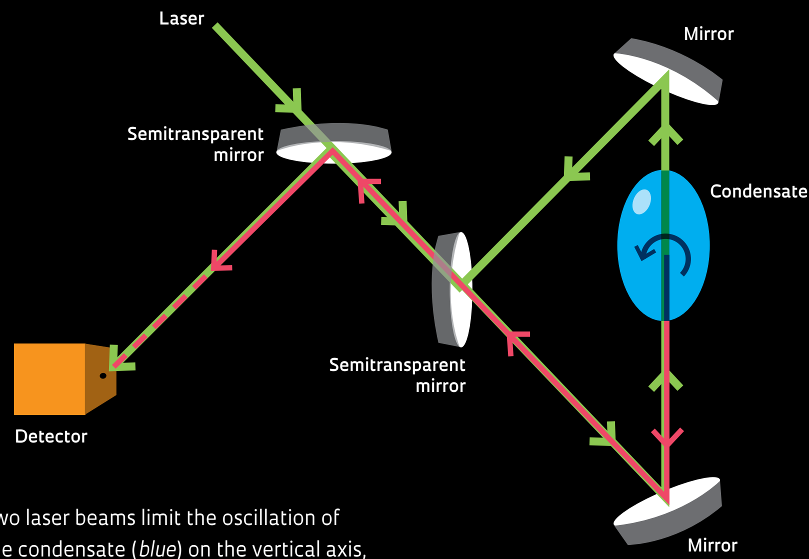
Physicists have performed experiments using cold atoms as gravimeters since the late 1990s. When cooled to temperatures close to absolute zero, some types of atoms can coalesce and form a so-called Bose-Einstein condensate. In the condensate, the atoms no longer act as individual particles and begin to move together, which forms a cloud of identical atoms; physicists say that the condensate behave like a single wave of matter. Several atomic gravimeters have been built to measure the changes in properties of this cloud of atoms when it moves exclusively under the effect of gravity. To analyze the action of only the gravitational force, physicists generate this cloud of atoms in a vacuum chamber and let it move vertically toward the ground. In this experiment, similar to an elevator in free fall, the cloud falls with nothing to slow it down; the only force acting is gravity.

However, Courteille's gravimeter works differently. It is similar to the device that the team of physicist Massimo Inguscio at the University of Florence, Italy, developed in 2005; in his experiment , the Bose-Einstein condensate falls freely to a certain point. When gravitational acceleration makes the condensate reach a certain speed, it interacts with a wave of light, which is created by the intersection of two laser beams. At that moment, the condensate is hit by an impulse from the light wave and starts moving upwards; this process is indefinitely repeated. "It's as if the wave of matter is jumping on a trampoline," explains Courteille. "The frequency of the jumps depends on Earth's gravitational acceleration."

Using three mirrors to create an optical cavity where the laser beams remain trapped and circulating almost indefinitely, Courteille could eliminate some drawbacks of the Italian experiment. Inguscio's gravimeter used a third laser to measure the displacement of the condensate, which destroyed it. In Courteille's set-up, the environment is controlled, and the light of the third laser does not disorder the condensate, even if it interacts with the condensate. Under Courteille's supervision, the physicist Raul Teixeira, who is a post-doctoral researcher at IFSC, is building the gravimeter's vacuum chamber and preparing the assembly of the lasers and optical cavity. "It's a huge technical challenge," says Courteille. "We won't have scientific results for at least two years." ■ **Igor Zolnerkevic**

The heart of the gravimeter

Three special mirrors trap the laser beams that control the movement of a condensate of atoms



Two laser beams limit the oscillation of the condensate (*blue*) on the vertical axis, and a third laser beam (*green*) monitors its displacement, which is affected by gravity. A detector reads the light (*in red*) that results from the interaction of the condensate with the green laser

SOURCE PHILIPPE COURTEILLE / IFSC-USP

Projects

1. *Development of quantum sensors based on ultracold atoms* (No. 2013/04162-5); **Grant Mechanism** Thematic Project; **Principal Investigator** Philippe Wilhelm Courteille (IFSC-USP); **Investment** R$1,988,250.00 (FAPESP – for the entire project).
2. *Continuous monitoring of Bloch oscillations of ultracold atoms for application in gravimetry* (No. 2014/12952-9); **Grant Mechanism** Fellowships in Brazil – Postdoctoral-; **Recipient** Raul Celestrino Teixeira; **Principal Investigator** Philippe Wilhelm Courteille (IFSC-USP); **Investment** R$177,860,00 (FAPESP).

Scientific Articles

SAMOYLOVA, M. *et al.* Synchronization of Bloch oscillations by a ring cavity. **Optics Express**. V. 23, No. 11. May 28, 2015.SAMOYLOVA, M. *et al.* Mode-locked Bloch oscillations in a ring cavity. **Laser Physics Letters**. V. 11, No. 12. Nov. 12, 2014.

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