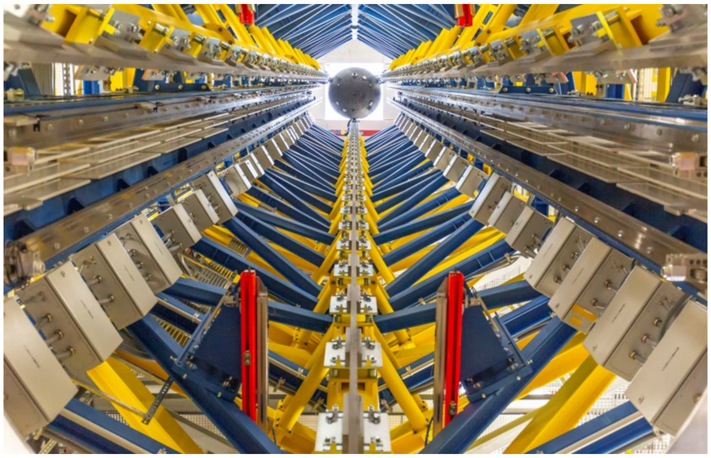
Entanglement Can Improve Precision of Gravity Measurements

The first measurement of gravity using quantum mechanically entangled atoms demonstrates the potential of the approach.

By **Philip Ball**

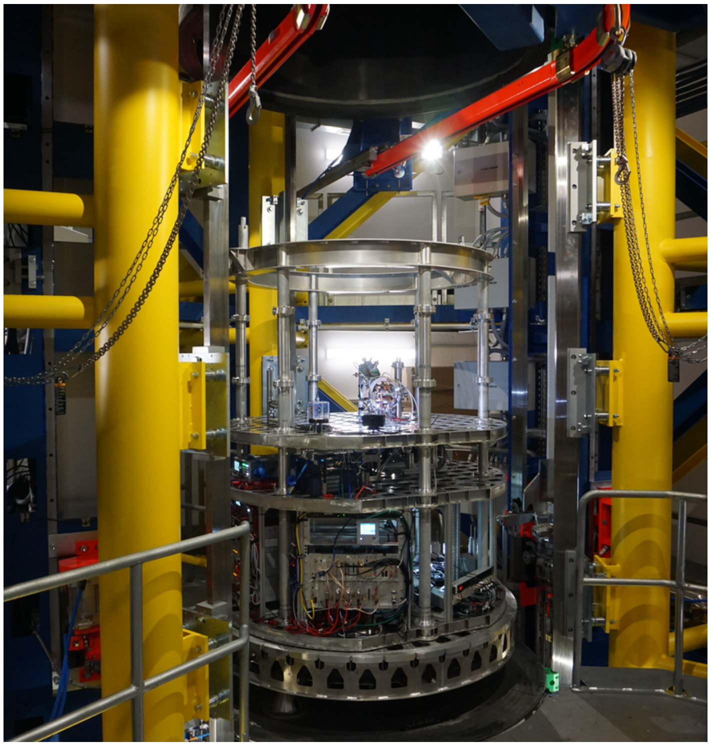
High-precision measurements of gravitational fields are needed for geophysical research and prospecting as well as for tests of general relativity and for detection of gravitational waves. One technique involves measuring the quantum interference of atoms undergoing freefall. A new experiment shows that the precision of this approach can potentially be increased if the atoms are quantum mechanically entangled [**1**]. Although the precision of this demonstration is still far from the state of the art, the developers say that a scaled-up version could eventually outperform other gravity-measuring techniques.



What goes up. The Einstein Elevator at Leibniz University Hannover, Germany, creates microgravity conditions by launching experiments upward into a 40-m-tall tower (upward-looking view shown here), providing 4 seconds of freefall during upward and downward motion (**video**).
Credit: M. Matthey/Leibniz University Hannover

To measure gravity, ultracold atoms can be prepared in quantum-mechanical states called wave packets, whose wavelength reflects their mass and energy. First, a cloud of these atoms is allowed to fall freely under gravity. Next, after falling a short distance, a microwave pulse separates the cloud into an equal mixture of two spin states (“up” and “down”). Laser pulses then accelerate and decelerate the two spin states in different ways so that they fall along different trajectories before being recombined. Then, another microwave pulse enables the spin states to interact, and because of their different trajectories, they have different quantum mechanical phases. Like any pair of out-of-phase waves, the two atomic clouds produce an interference pattern—a series of peaks and troughs in the atomic density. The amplitude of the interference pattern depends on the gravitational acceleration that the two clouds experienced and can be measured from the light absorption of the atoms.

The precision of this method depends on the statistical spread of positions and velocities of the atoms, which can be narrowed by preparing them as a Bose-Einstein condensate (BEC), in which all the atoms are in the same quantum state. However, the precision is also limited by random quantum fluctuations of the measured phase difference—an irreducible quantum “noise” due to the uncertainty principle governing their positions and momenta.



Freefall. The INTENTAS experiment (shown here being prepared for operations at the Einstein Elevator) will use the new entanglement-enhanced gravimeter to test the equivalence principle of general relativity.
Credit: J. S. Hasse/Leibniz University Hannover

The standard quantum limit (SQL) on precision imposed by these fluctuations can be surpassed by exploiting another quantum phenomenon: entanglement. The properties of entangled atoms are interdependent, so their fluctuations are not random but are correlated with one another. This correlation allows “squeezing” of the quantum fluctuations—reducing fluctuations of the property being measured at the expense of increasing them in some other parameter [**2**].

Carsten Klempt, a specialist in quantum metrology at the German Aerospace Center in Hannover and his co-workers have previously demonstrated that they can produce BECs of cold atoms that are entangled in their momentum states, permitting squeezing below the SQL [**3**]. The Hannover team has now carried out the first measurement of Earth’s gravitational acceleration by interferometry of entangled atoms.

The researchers created a BEC from about 6000 atoms of rubidium laser-cooled to an effective temperature of about 1.7 nanokelvin (the cloud was not strictly in thermal equilibrium). Next, they arranged for the atoms to become entangled via their quantum spins through collisional interactions. Klempt and colleagues then used laser pulses to transfer the spin entanglement to the momentum states of the atoms. After performing the usual separation and then recombination of the two clouds, the team was able to derive a measurement for the local gravitational acceleration that was within 0.01% of the established value.

Team member Christophe Cassens says the researchers are now developing the technology for space applications. They also plan to use it in a project called INTENTAS [**4**], where freefall in a drop tower called the Einstein Elevator at Leibniz University Hannover creates microgravity conditions. In such a situation, the entanglement-enhanced sensitivity might permit precise tests of the equivalence of gravitational and inertial mass, a central tenet of general relativity.

Optical physicist Mark Kasevich of Stanford University says that the work “exploits a clever squeezing protocol in a Bose-Einstein condensed sample.” He says that further improvements in precision should be possible by using larger numbers of atoms and longer measurement times.

The result “represents a stunning achievement,” says Stuart Szigeti, a specialist in quantum sensing at the Australian National University. But he notes that “state-of-the-art cold-atom gravimeters, which do not use entangled atoms, still achieve sensitivities orders of magnitude better than demonstrated here.”

Cassens says that the sensitivity depends on how long the atom clouds undergo freefall before being recombined. Conventional state-of-the-art devices can be up to 10 m tall, giving long measurement times, whereas the prototype developed by the Hannover team is much shorter. But Cassens says that “entanglement enhancement is fully compatible with the designs of large-scale atom interferometers.”

Philip Ball is a freelance science writer in London. His latest book is *How Life Works* (Picador, 2024).

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