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FUNDAMENTAL CONSTANTS

A cool way to measure big *G*

Published results of the gravitational constant, a measure of the strength of gravity, have failed to converge. An approach that uses cold atoms provides a new data point in the quest to determine this fundamental constant.

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In our daily lives, we can see the effect of the gravitational force between Earth and an object, say an apple. However, the gravitational attraction between two apples cannot be observed without using a sensitive apparatus such as a torsion balance — it is just too small. In a paper published on *Nature*'s website today, Rosi *et al.*[1] describe an amazing measurement: the gravitational force between a rubidium atom and a 516-kilogram mass, with a relative uncertainty of just 0.015%. Their experiment was aimed at a precise determination of the gravitational constant, which describes the strength of the gravitational pull that bodies exert on each other, and was based on the technique of atom interferometry — a method that takes advantage of the wave nature of cold atoms to precisely measure gravitational acceleration.

In the atom interferometer described by Rosi and colleagues, a cloud of rubidium atoms at a temperature close to absolute zero is repeatedly tossed up vertically. To understand how this cloud in free fall probes gravity, quantum mechanics is needed. For simplicity, consider that the atoms in the cloud can be in two different atomic states, A and B. At the beginning, all atoms are in state A. By exposing an atom to an appropriately shaped light pulse, the atom can transition from A to B with a certain probability, let's say 50%. While the atom is not being observed, it is simultaneously in both states (50% in A and 50% in B), a concept known as superposition. In addition to inducing the transition from A to B, the light pulse transfers vertical momentum such that the B state has a larger vertical velocity than the A state.

The relative fraction of the two different states in this superposition varies with time, and its rate of change depends on the difference of the products of the momentum and the travelled vertical distance for each state. Owing to its larger momentum, state B travels higher than state A in the presence of the local gravitational acceleration, g, caused mostly by Earth and any masses in the vicinity of the cloud. Hence, the rate of change is a function of g. After the atomic cloud descends, close to the launch point, the ratio of the number of atoms in state A to state B is measured, from which g can be calculated[2].

To measure the gravitational constant G, an external mass, referred to as a field mass, is required. To understand the principle of the experiment we make two simplifications: we assume the field mass is a point with mass M, and that the atom interferometer measures g at one fixed point. In reality, the atom interferometer measured along a trajectory and cylindrical field masses were used. In this case, the idea is the same, although the maths is more complicated. The point mass is first located a distance z above the interferometer and the acceleration $g_{\text{above}} = -g + G(M/z^2)$ is measured. Next, the point mass is moved to a distance z below and $g_{\text{below}} = -g - G(M/z^2)$ is obtained. As long as g remains the same between the two measurements, G can be obtained from the difference between the measurements, $G = (g_{\text{above}} - g_{\text{below}})\, z^2/(2M)$. Unfortunately, g changes with time owing to tidal accelerations produced by the Sun and the Moon, air-pressure variations, and the movement of masses in the vicinity of the experiment.

To solve this problem, Rosi and co-workers measured g_{above} and g_{below} simultaneously by stacking two atom interferometers on top of each other. Two field masses were used and were at first in between the interferometers. The measured difference between g_{above} and g_{below} (the signal) is mostly independent of the temporal variation of g, but is dependent on its spatial variation, because the measurements were taken at different locations. The field masses were then moved such that one was above the upper interferometer and the other was below the lower interferometer, and the measurement was repeated. The difference between the signals in the latter field-mass configuration and the former one is independent of the spatial variation of g, and G was obtained by averaging about 100 such signal differences. The result is $G = (6.67191 \pm 0.00099) \times 10^{-11}$ cubic metres per kilogram per square second. The relative uncertainty of the measurement is 0.015%.

The experiment is exciting because it uses modern tools to solve an old problem. Using

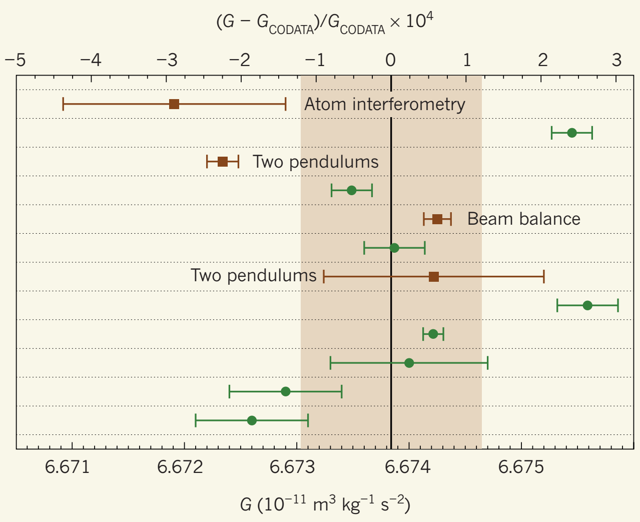

Figure 1 | The big picture for big *G*. Published results of measurements of the gravitational constant, G, over the past 32 years. The solid circles denote measurements that employed torsion balances. The three lower solid squares show results that were obtained using a beam balance or two pendulums. The upper solid square is the result obtained by Rosi and colleagues[1] using the technique of atom interferometry. The shaded area denotes the one-standard-deviation confidence interval of the value from the 2010 CODATA compilation of physical constants[18].

atoms to sense gravity instead of conventional mechanical devices, such as torsion balances, has several advantages. For example, the atom does not require a physical connection to the laboratory and is hence not biased by stray forces that such a connection would introduce to the measurement.

Naively, one would think that torsion balances are much better tools to precisely determine *G* than other devices. The torsion balances are much simpler in design and measure in a direction perpendicular to *g*, avoiding systematic effects caused by temporal variations of *g*. However, measurements performed over the past two centuries, mostly using torsion balances, have failed to converge on a trustworthy value of *G*. Figure 1 shows the results obtained in the past three decades. Out of the 11 results[3–13] shown, only three were measured with devices other than a torsion balance. One measurement was performed with a beam balance, a device that is typically used to measure mass, and two with pairs of pendulums. The relative difference between the largest and the smallest number is 0.055% — or about 40 times the size of the error bars of the experiment with the smallest uncertainty.

The various measurements of *G* seem not to converge on a value; it seems that the convergence gets worse with each additional data point. This is especially disconcerting because it is thought that *G* is a fundamental constant of nature. Although we cannot rule out for certain that the spread of the obtained values is caused by so far undiscovered properties of gravitation, this hypothesis seems unlikely because most plausible modifications to our theory of gravitation are excluded by other experimental tests. Adding more data points from isolated experiments has not been the best strategy to improve the situation. Instead, forming an international consortium[14] to coordinate these demanding experiments has been suggested.

Under the auspices of such a consortium, one or more apparatus can be sent to different institutions for measuring *G*. The different results and uncertainties could be compared. Such a procedure would provide insight into underestimation of uncertainties, the propensity to overlook bias in the experiment, and 'intellectual phase locking'[15], which is the tendency of an experimenter to stop looking for systematic effects once the measurement agrees with previously published results. By enhancing our understanding of these three human sources of error, which could be responsible for the spread shown in Figure 1, a more credible value of *G* can be obtained.

Rosi and colleagues' experiment provides an important data point in our quest to measure *G* (ref. 16). The experiment is vastly different from all other measurements, and the size of the achieved uncertainty, although still somewhat large, is approaching those obtained using torsion balances. Over the past 6 years, this team has reduced the uncertainty of their experiment by a factor of 10 compared with a preliminary result published in 2008 (ref. 17). Stay tuned, as they continue to push this technique to smaller uncertainties. ■

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