A new and so far the most precise determination of the gravitational constant $G$ has been made by Jun Luo and colleagues at the Huazhong University of Science and Technology (HUST) [1].

The combination of $G$ with two other most fundamental physical constants, the speed of light $c$ and Planck’s constant $\hbar$, can together construct the natural units (a.k.a. Planck units) of time, length and mass. These relationships inform us that, among the aforementioned three constants and three units, a total of six physical quantities, three and only three quantities should have their values defined.

In the SI system, just updated in 2019, the following were chosen to have defined values: the second as the unit of time, $c$ and $\hbar$. Today, $G$ remains to be measured.

$G$ lags far behind $c$ and $\hbar$ in measurement precision due to the extreme weakness of gravity. Within a hydrogen atom, the gravitational force between the proton and the electron is weaker than the Coulomb force by 39 orders of magnitude. Measuring $G$ in the quantum world is exceedingly difficult due to interference of any residue electromagnetic interaction. So far, the most precise measurements of $G$ were made on macroscopic objects using the torsion balance method pioneered by John Michell and Henry Cavendish in the late eighteenth century. For sure, the implementation of the method has been vastly improved with modern ingenuity.

But all was not well in recent years. A sense of confusion hung over the field as over 10 independent measurements of $G$ made in the past two decades exhibited discrepancies, in some cases as large as 10 times the quoted uncertainties. The situation cast doubt on the physicist’s ability to measure weak forces on the laboratory scale. Two international meetings were organized in 2014 to examine possible biases in these measurements and to encourage new measurements that might resolve the impasse [2]. The paper of Li et al. [1] was just what the community had been waiting for.

Building upon the experience of a continual quest at HUST for over three decades, Jun Luo and colleagues conducted two types of torsion balance experiments. In one experiment (Fig. 1), the center plate was hung on a thin fiber twisting back and forth. Its oscillation period ($\sim$7 min) was precisely measured to reveal the gravitational pull from the two stationary balls. In another experiment, the balance and the balls revolved around a common center axis, with their rotation speeds varied in a controlled way so that the fiber was maintained in its natural position without any twist. Ideally, these two methods, possessing two different sets of systematic effects, should converge into a consistent value of $G$.

A brilliant example of precision measurement, this work combined both insight and patience in many details. The balance was so close to lossless that a free oscillation could go on for several months on its own, yet its minute deviation from an ideal spring needed to be examined and understood. Each stainless steel ball, with a diameter of 57 mm, was hand polished to guarantee its exact spherical shape allowing deviation of at most 0.25 $\mu$m. The measurements were conducted inside a cave laboratory 100 m away from any human presence.

Both methods in this work reached a relative accuracy of 12 ppm, 1000 times more accurate than the original Cavendish value. However, the two methods differ from each other by 45 ppm, suggesting biases yet to be uncovered.

While determining $G$ is of fundamental interest in physics, the capability in small force measurements leads to useful technologies. Gravimetry has a wide range of applications including navigation, oil and gas exploration, and water resource management.
ACKNOWLEDGEMENTS
The author thanks Shanqing Yang and Yifu Cai for helpful discussions.

FUNDING
This work was supported by the National Natural Science Foundation of China (91636215).

Conflict of interest statement. None declared.

REFERENCES
1. Li Q, Xue C and Liu JP et al. Nature 2018; 560: 582–8.
2. NIST. Newtonian Constant of Gravitation International Consortium. National Institute of Standards and Technology. 2014. https://www.nist.gov/programs-projects/newtonian-constant-gravitation-international-consortium (25 January 2020, date last accessed).

Atomic physics determination of the fine structure constant
Zong-Chao Yan

The fine structure constant \( \alpha \) is a fundamental physical constant that describes the electromagnetic interaction between charged particles and serves as the coupling constant of quantum electrodynamics (QED). It is dimensionless and thus remains the same under all systems of units. It is worth noting that \( \alpha \) cannot be calculated by QED itself; it must be determined experimentally, often with the help of QED directly or indirectly. Determinations of \( \alpha \) from different sources can be used to test QED and other sectors of the Standard Model of particle physics, provided both theory and experiment can reach a sufficiently high precision. However, one cannot both test QED and measure \( \alpha \) simultaneously, and so at least two independent measurements are required. One of the two most precise determinations of \( \alpha \) so far is from the anomalous magnetic moment or \( g_e - 2 \) of the electron, which yields \( \alpha \) to an accuracy of 0.24 ppb (parts per billion) [1]. The other one comes from the cesium recoil experiment that gives rise to \( \alpha \) at 0.20 ppb [2]. The \( g_e - 2 \) determination of \( \alpha \) involves a monumental QED calculation, whereas the Cs recoil one relies on QED only in an indirect way, because the Rydberg constant \( R_\infty \) used in the Cs recoil determination was already established to very high precision by hydrogen and deuterium transition frequencies together with their corresponding QED calculations. However, these two determinations of \( \alpha \) have a 2.5\( \sigma \) discrepancy that may have some implications for new physics beyond the Standard Model [2]. From a metrology viewpoint, with the adoption of the 2019 re-definition of the SI base units, a more precise value of \( \alpha \) would mean a more precise value of the electron mass \( m_e \) according to \( R_\infty = \alpha^2 m_e (c/4\pi\hbar) \).

The helium \( 2^3P \) \( (f = 0, 1, 2) \) fine structure is another venue to derive a precise value of \( \alpha \), as was first proposed by Schwartz [3] in 1964 aiming at a ppm (parts per million) determination. It differs from either the \( g_e - 2 \) or the Cs recoil determination in that it is a bound-state QED problem. Compared to the electron \( g_e - 2 \) problem, a splitting between two fine structure levels in \( 2^3P \) is more sensitive to \( \alpha \) by a factor of \( \sim 137 \). Helium is also more appealing to experimentalists than hydrogen since the \( 2^3P \) energy levels in helium are more widely spaced than \( 2^3P \) in hydrogen, and the lifetime of \( 2^3P \) is a factor of 100 longer than \( 2^2P \). Historically, the first breakthrough for realizing the Schwartz proposal was the derivation of order \( m_e\alpha^6 \) relativistic and QED corrections by Douglas and Kroll [4] in 1974. In 1995, Yan and Drake [5] evaluated these corrections to a very high precision and thus laid a foundation for pursuing a ppb level determination of \( \alpha \), instead of the original ppm. Other milestones in theory include the work by Zhang, Yan and Drake [6] in 1996 for the QED corrections of order \( m_e\alpha^7 \) in \( \alpha \), the work by Pachucki [7] in 2006 for \( m_e\alpha^7 \) and the extension of \( m_e\alpha^7 \) to helium-like ions by Pachucki and Yerokhin [8] in 2010.

Since Schwartz’s proposal was published, significant progress has been made on the experimental frontier using various measurement techniques. The interplay between theory and experiment has stimulated measurements with ever-increasing accuracy. Some systematic effects, long considered negligible, are now becoming important, such as quantum interference. Recently, the group at University of Science and Technology of China (USTC) led by Shui-Ming Hu [9] has measured the fine structure splittings \( \nu_02 \) and \( \nu_{12} \) in the \( 2^3P \) manifold of helium by laser spectroscopy and achieved an accuracy of 4 and 80 ppb, respectively. Their results are in good agreement with the QED calculations of Pachucki and Yerokhin [8] up to order \( m_e\alpha^7 \).