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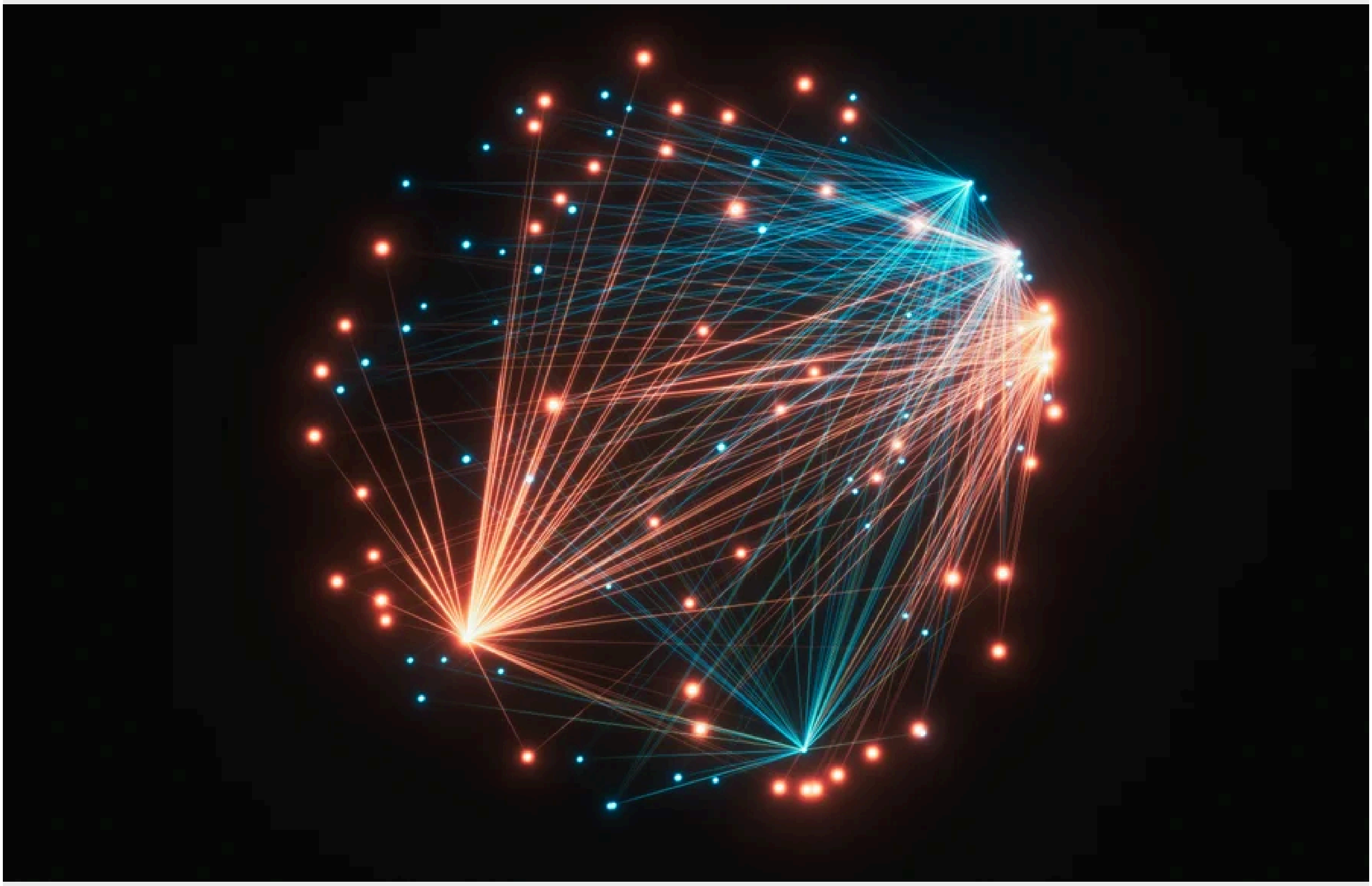
Physicists Achieve Best Ever Measurement of Fine-Structure Constant

Three times more precise than the previous record-holding determination, the result closely agrees with theoretical predictions but could still reveal pathways to new physics

BY DHANANJAY KHADILKAR



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The Sciences

Researchers at the Kastler Brossel Laboratory in Paris have made the most precise measurement of one of the fundamental constants, called the fine-structure constant, providing physicists with a vital tool to verify the consistency of their most cherished theoretical models.

The fine-structure constant determines the strength of the electromagnetic force, and is central in explaining a number of phenomena including the interactions between light and charged elementary particles such as electrons. It is an important part of the equations of the Standard Model, a theory that predicts and describes all the known fundamental forces other than gravity—namely electromagnetism as well as the weak and strong nuclear forces. The team in Paris measured the value of the fine-structure constant as 1/137.035999206, to an accuracy of 11 digits. The result appears in a study published in *Nature*.

"I am amazed by the level of precision achieved," says Massimo Passera of the Italy-based National Institute for Nuclear Physics, who was not a part of the experiment.

Using the fine-structure constant in the Standard Model equations, one can calculate the magnetic moment of the electron, a property exhibited by the negatively charged particle under the influence of a magnetic field. The electron's magnetic moment makes for an excellent candidate to test the Standard Model, as it has been repeatedly measured in the lab and theoretically predicted to a very high degree of precision.

"With the new determination of the fine-structure constant, these predicted and experimental values agree at better than one part per billion, thereby providing an outstanding consistency check of the Standard Model of particle physics—in particular of its electromagnetic sector," Passera says. "Moreover, the closeness of the two values sets a strong limit on the possible internal structure of the electron."

Performed using rubidium atoms in a technique called atom interferometry, the new measurement is more accurate by a factor of three from the previous record-holding determination, which was achieved by a team from the University of California, Berkeley, in an experiment using cesium atoms.

According to Pierre Cladé, who co-authored the *Nature* paper, the improvement was the result of "continuous work of small steps." In addition to a major upgrade in the apparatus and new laser sources, he says, the team's success arose from efforts to reduce noise and systemic effects. "We did a lot of modeling to deeply understand the physics of our experiment. Three years ago, we reached a better understanding of the interaction between a photon and the rubidium atom." That enhanced understanding allowed the team to determine a more precise value for a rubidium atom's mass.

"Once the mass of the rubidium atom is measured, we use it with the relative mass of an electron to calculate the fine-structure constant. The more precise the mass of the rubidium atom, the more accurate the value of the fine-structure constant," says Saïda Guellati-Khelifa, the paper's lead author.

The experiment employed multiple standard approaches to reach its stunning precision, starting with the laser cooling of a cloud of rubidium atoms. Six laser beams exert force on the atoms in such a way that they drastically reduce the atoms' velocities. Because such atomic kinetic motions are the basis of macroscale manifestations of heat, the end result of reducing the rubidium atoms' velocities is to lower their temperature to a mind-bogglingly frigid four microkelvins—slightly above absolute zero, or –273.15 degrees Celsius. "At such temperatures, an atom behaves like a particle and a wave," Cladé says.

This wavelike behavior of atoms is quite different from the waves of water that we are more familiar with. In this case, the wave in question concerns the probability of finding a rubidium atom in a certain position. Using lasers, the team prepared the atoms in both the ground state and excited state (in the latter the atom moves with a slightly greater velocity). “This produces two trajectories that are separated and later recombined to create an interference pattern,” Cladé says. “The interference depends on the velocity acquired by the atoms after they absorb photons from a laser source. Once this recoil velocity is measured from the interference, the rubidium atomic mass can be derived.”

As a first step, the team began an almost yearlong run of the experiment in December 2018, collecting data to ensure their equipment was working properly.

“While performing such experiments, there are different physical processes that underlie what is being measured. Each process can potentially affect the accuracy of the measurement by inducing errors. We need to understand and evaluate errors in order to make corrections,” says Guellati-Khelifa, who has been taking measurements of the fine-structure constant for more than 20 years.

After making the corrections, the team derived final measurements during a monthlong run, finally determining the fine-structure constant’s value to a precision of 81 parts per trillion.

According to Passera, efforts to find the precise values of fundamental constants are complementary to the particle accelerator–based experiments that exploit huge energies in order to create new, never-before-seen particles.

“The ‘tabletop’ experiments such as the ones in the Kastler Brossel or Berkeley laboratories, are done at very low energies. And yet, their extremely precise measurements can indirectly reveal the existence or even the nature of a particle that may not yet be directly seen at high energies. Even the very last digits of a precise measurement have a story to tell,” Passera says.

Consider, for instance, the muon—a cousin of the electron that is two hundred times heavier. Just like the electron, the muon also exhibits a magnetic moment when subjected to a magnetic field. Moreover, similar to the electron, there is a difference between the theoretical and experimental values of the muon's magnetic moment.

Discrepancies in this context are determined in terms of standard deviation, which is a combination of the difference in the two values and the uncertainties associated with the theoretical calculation and experimental measurement of each value.

In the case of the electron, the experimental measurement of the magnetic moment is 1.6 standard deviations above the theoretical prediction based on the fine-structure constant measured by the Paris group. Whereas the muon's experimental value, announced and refined in a trio of papers published between 2002 and 2006, is 3.7 standard deviations above the figure predicted by the Standard Model theory.

Physicists are now eagerly awaiting the first results of the "Muon g-2" experiment at Fermilab that is expected to provide the most precise experimental measurement of the muon's magnetic moment. If this value goes beyond five standard deviations from the theory—the gold standard for discovery in particle physics—it would be convincing evidence of new physics beyond the Standard Model.

Generally, when it comes to the theoretical prediction of the magnetic moment using the Standard Model, the muon discrepancy is not as sensitive to the precise value of the fine-structure constant as the electron. However, according to Alex Keshavarzi, who is managing operations and leading analysis efforts for the Muon g-2 experiment, "the new fine-structure constant measurement is interesting for the muon discrepancy."

Keshavarzi, who is not part of the Paris research group, says if new physics emerges from the Muon g-2 results of the muon measurement, the positive discrepancies for both the electron and the muon would make it simpler to develop models and explanations than if the discrepancies were in the opposite directions.

However, he adds that even aside from its potential connection to the muon, the Paris group's electron-based measurement of the fine-structure experiment has introduced other mysteries—namely, why it produced a *positive* standard deviation of 1.6 whereas the 2018 experiment at Berkeley produced a *negative* deviation of 2.5.

According to Cladé, both the Paris and Berkeley experiments are based on the same physics, making the divergence all the stranger. "I don't think the discrepancy is due to the use of cesium or rubidium. There is probably something in one of the two experiments that may not have been accounted for. That is something we should now try to understand," he says.

DHANANJAY KHADILKAR is a Paris-based journalist who mostly covers science and technology. He also writes on chess.

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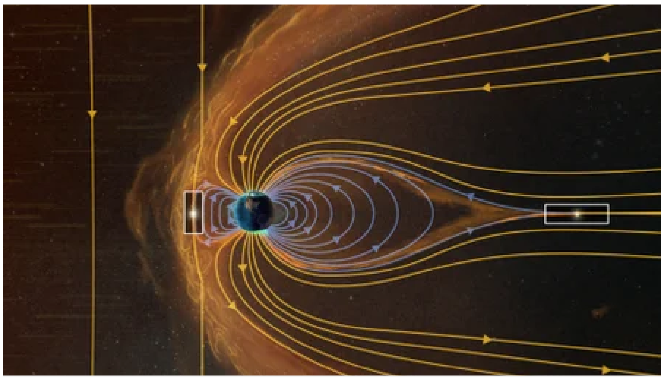

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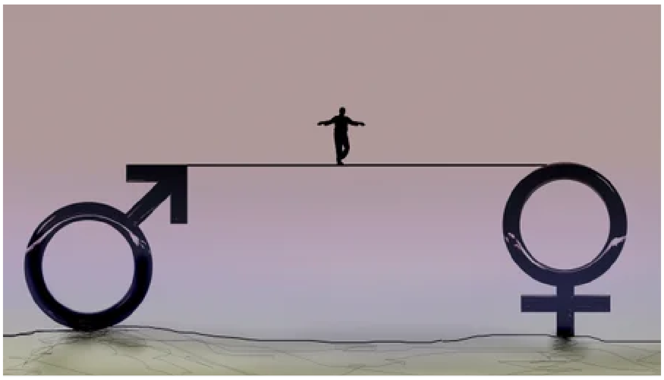

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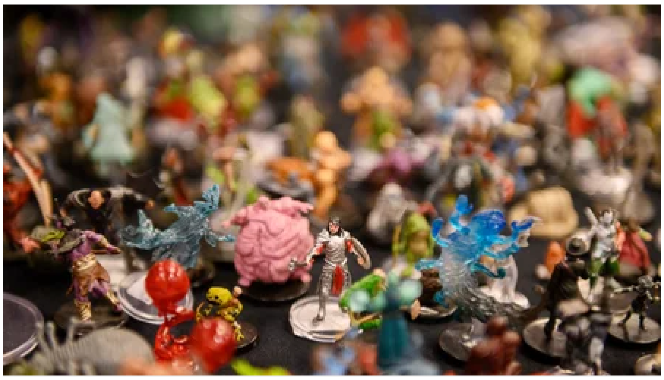

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