The tale of two clocks: Advancing the precision of timekeeping

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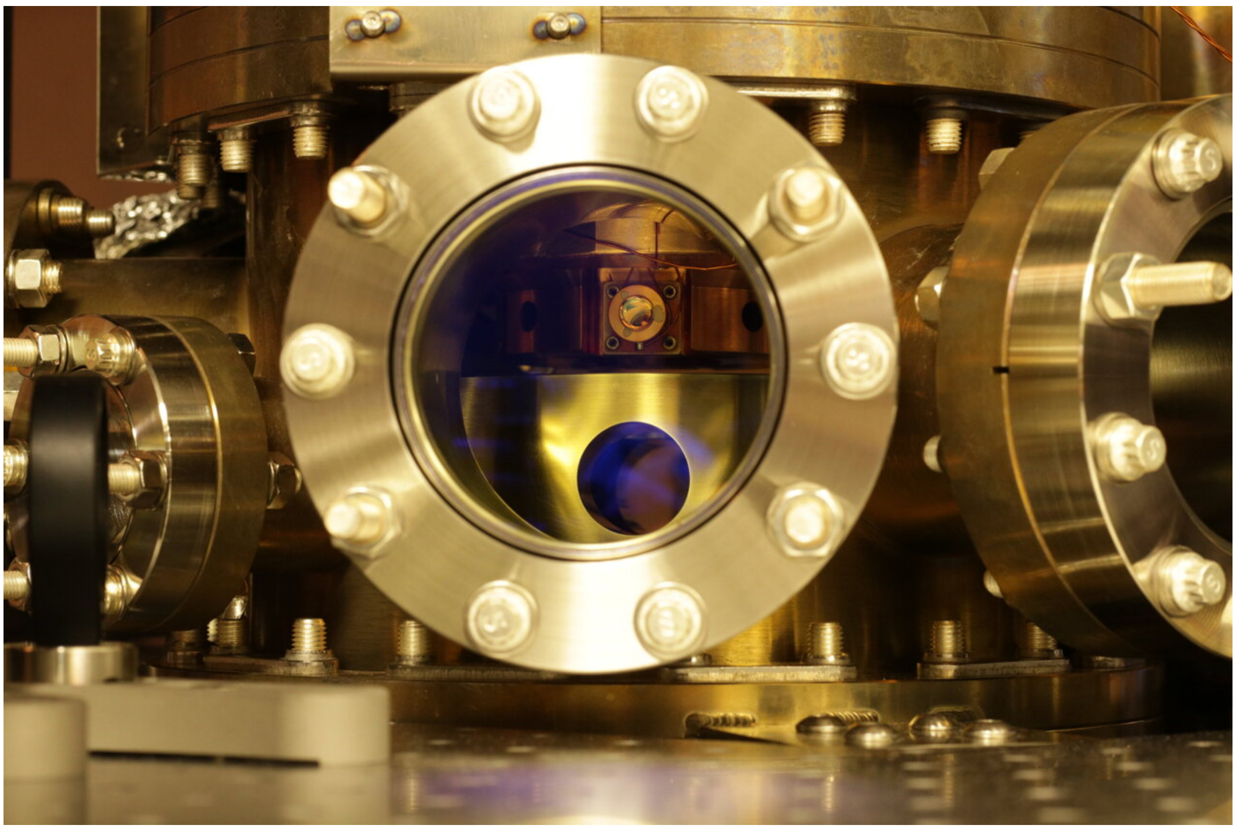

A photo of the atomic clock setup complete with the bisecting cavity. Credit: JILA/Ye Group

Historically, JILA (a joint institute established by the National Institute of Standards and Technology [NIST] and the University of Colorado

Boulder) has been a world leader in precision timekeeping using optical atomic clocks. These clocks harness the intrinsic properties of atoms to measure time with unparalleled precision and accuracy, representing a significant leap in our quest to quantify the most elusive of dimensions: time.

However, the precision of these clocks has fundamental limits, including the "noise floor," which is affected by the "quantum projection noise" (QPN). "This comes from the spin-statistics of the individual qubits, the truly quantum nature of the atoms being probed," elaborated JILA graduate student Maya Miklos.

State-of-the-art clock comparisons, like those directed by JILA and NIST Fellow Jun Ye, are pushing ever closer to this fundamental noise floor limit. However, this limit can be circumvented by generating quantum entanglement in the atomic samples, boosting their stability.

Now, Ye's team, in collaboration with JILA Fellow James K. Thompson, has used a specific process known as spin squeezing to generate quantum entanglement, resulting in an enhancement in clock performance operating at the 10^{-17} stability level. Their novel experimental setup, published in *Nature Physics*, also allowed the researchers to directly compare two independent spin-squeezed ensembles to understand this level of precision in time measurement, a level never before reached with a spin-squeezed optical lattice clock.

The development of these enhanced optical atomic clocks has far-reaching implications. Beyond the realm of timekeeping, they hold potential advantages for use in various scientific explorations, including testing fundamental physics principles, improving navigation technologies, and possibly contributing to the detection of gravitational waves.

"Advancing optical clock performance up to, and beyond, the fundamental limits imposed by nature is already an interesting scientific pursuit," explained JILA graduate student John Robinson, the paper's first author. "When one considers what physics you can uncover with the improved sensitivity, it paints a very exciting picture for the future."

A noisy ensemble of atoms

Optical atomic clocks function not through gears and pendulums but through the orchestrated rhythms between atoms and excitation laser.

QPN poses a fundamental obstacle to the precision of these clocks. This phenomenon arises from the inherent uncertainty present in quantum systems. In the context of optical atomic clocks, QPN manifests as a subtle but pervasive disturbance akin to a background noise that can obscure the clarity of time measurement.

"Because each time you measure a quantum state, it gets projected into a discrete energy level, the noise associated with these measurements looks like flipping a bunch of coins and counting if they show up as heads or tails," said Miklos.

"So, you get this law-of-large-number scaling where the precision of your measurement increases with the square root of N, your atom number. The more atoms you add, the better the stability of your clock is. However, there are limits to that because, past certain densities, you can have density-dependent interaction shifts, which degrade your clock stability."

There are also practical limits on the achievable number of atoms in a clock. However, entanglement can be utilized as a quantum resource to circumvent this projection noise. Miklos added, "That square root of N scaling holds if those particles are uncorrelated. If you can generate entanglement in your sample, you can reach an optimal scaling that increases with N instead."

To address the challenge posed by QPN, the researchers employed a technique known as spin squeezing. In this process, the quantum states of atoms are delicately adjusted. While the uncertainties of a quantum measurement always obey the Heisenberg uncertainty principle, these spins are "squeezed" through precise interventions, reducing uncertainty in one direction while increasing it in another.

Realizing spin squeezing in optical clocks is a relatively new achievement, but similarly entangled resources like squeezed light have been used in other fields. "LIGO [The Laser Interferometer Gravitational-Wave Observatory] already employed the squeezing of vacuum states to improve their measurements of interferometer lengths for gravitational wave detection," explained JILA graduate student Yee Ming Tso.

Creating a quantum 'elevator'

To achieve the spin-squeezing, the team created a novel laboratory setup comprising a vertical, 1D moving lattice intersecting with an optical cavity (a resonator composed of two mirrors) along the horizontal direction. The researchers used the laser beams of the lattice to move the atomic ensembles up and down the entire lattice like an elevator, with some groups of atoms, or sub-ensembles, entering the cavity.

This project was inspired by a recent collaboration between the Ye research group and JILA Fellow Adam Kaufman, who had also explored spin-squeezing in other laboratory setups.

"Until this point, spin-squeezing in optical clocks had only been implemented in proof-of-principle experiments, where the noise from the clock laser obscured the signal," Robinson said.

"We wanted to observe the positive impact of spin-squeezing directly, and so we turned the optical lattice into this elevator such that we could independently spin-squeeze and compare multiple sub-ensembles and, in this way, remove the negative impact of the clock laser."

This setup also allowed the researchers to show that the quantum entanglement survived during the transportation of these atomic sub-ensembles.

Using the optical cavity, the researchers manipulated the atoms to form spin-squeezed, entangled states. This was achieved by measuring the collective properties of the atoms in a so-called "quantum non-demolition" (QND) fashion.

QND takes a measure of a quantum system's property so that the measurement doesn't disturb that property. Two repeated QND measurements exhibit the same quantum noise, and by taking the difference, one can enjoy the cancellation of the quantum noise.

In an atom-cavity coupled system, the interaction between the light probing the optical cavity and the atoms located in the cavity allowed the researchers to project the atoms into a spin-squeezed state with reduced impact of QPN uncertainty. The researchers then used the elevator-like lattice to shuffle an independent group of atoms into the cavity, forming a second spin-squeezed ensemble within the same experimental apparatus.

Comparing clock to clock

A key innovation in this study was directly comparing the two atomic sub-ensembles. Thanks to the vertical lattice, the researchers could switch which atomic sub-ensembles were in the cavity, directly comparing their performances by alternately measuring the time as indicated by each spin-squeezed sub-ensemble.

"At first, we performed a classical clock comparison of two atomic sub-ensembles without spin squeezing," Tso explained. "Then we spin-squeezed both sub-ensembles and compared the performance of the two spin-squeezed clocks. In the end, we concluded that the pair of spin-squeezed clocks performed better than the pair of classical clocks in terms of stability by an improvement of about 1.9 dB [~25% improvement]. This is pretty decent as the first result of our experimental setup."

This stability enhancement persisted even as the clocks' performance averaged down to the level of 10^{-17} fractional frequency stability, a new benchmark for spin-squeezed optical lattice clock performance. "In one generation of this experiment, we've roughly halfway closed the gap between the stability of the best spin-squeezed clocks and the best classical clocks for precision measurement," elaborated Miklos, who, with the rest of the team, hopes to improve this value even further.

An exploration beyond timekeeping

With its dual-ensemble comparison, this experimental setup marks a significant step toward harnessing quantum mechanics for practical and theoretical advancements, including in fields as varied as navigation to fundamental physics, enabling tests of gravitational theories, and contributing to the search for new physics.

Miklos, Tso, and the rest of the team are hopeful that their new setup will allow them to dive deeper into the fundamentals of gravity.

"The precise measurements of the gravitational redshift, which was recently done in our lab, is something that we'd like to look into further using this experimental design," Miklos added. "Hopefully, it can tell us more about the universe we live in."

More information: John M. Robinson et al, Direct comparison of two spin-squeezed optical clock ensembles at the 10^{-17} level, *Nature Physics* (2024). DOI: 10.1038/s41567-023-02310-1

Provided by JILA

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