

 OCTOBER 6, 2025 **FEATURE**

Strontium optical lattice clock exhibits record-high coherence time

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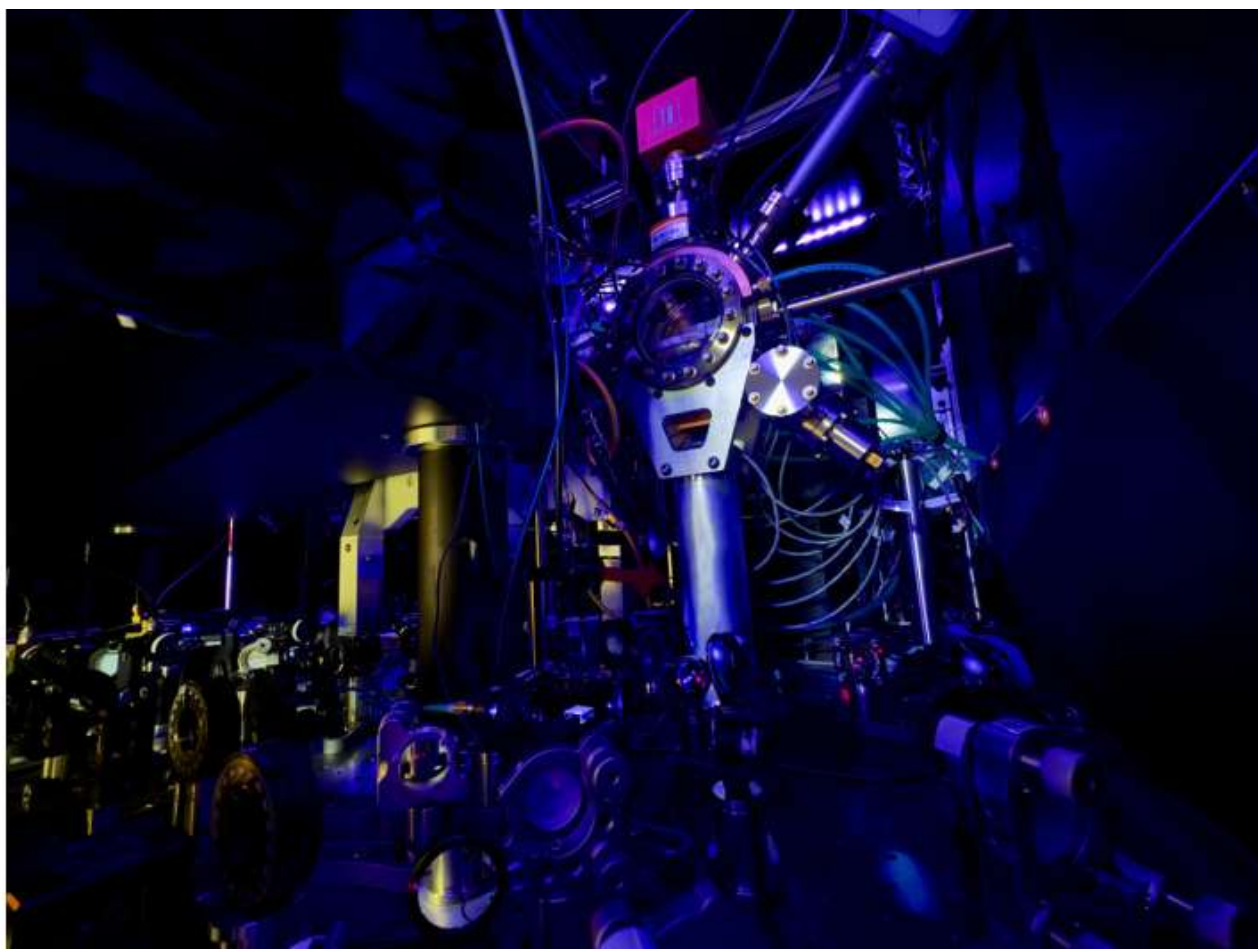


Photo of the strontium optical lattice clock in JILA. Credit: Kyungtae Kim.

Optical lattice clocks are emerging timekeeping devices based on tens of thousands of ultracold atoms trapped in an optical lattice (i.e., a grid of laser light). By oscillating between two distinct quantum states at a particular frequency, these atoms could help to measure time with much higher precision than existing clocks, which would be highly advantageous for the study of various fundamental physical processes and systems.

Researchers at JILA, National Institute of Standards and Technology and University of Chicago recently developed an optical lattice clock based on strontium atoms that was keeping time with remarkable precision and accuracy. The new strontium optical clock, introduced in a paper [published](#) in *Physical Review Letters*, could open new possibilities for research aimed at testing variations in fundamental physics constants and the timing of specific physical phenomena.

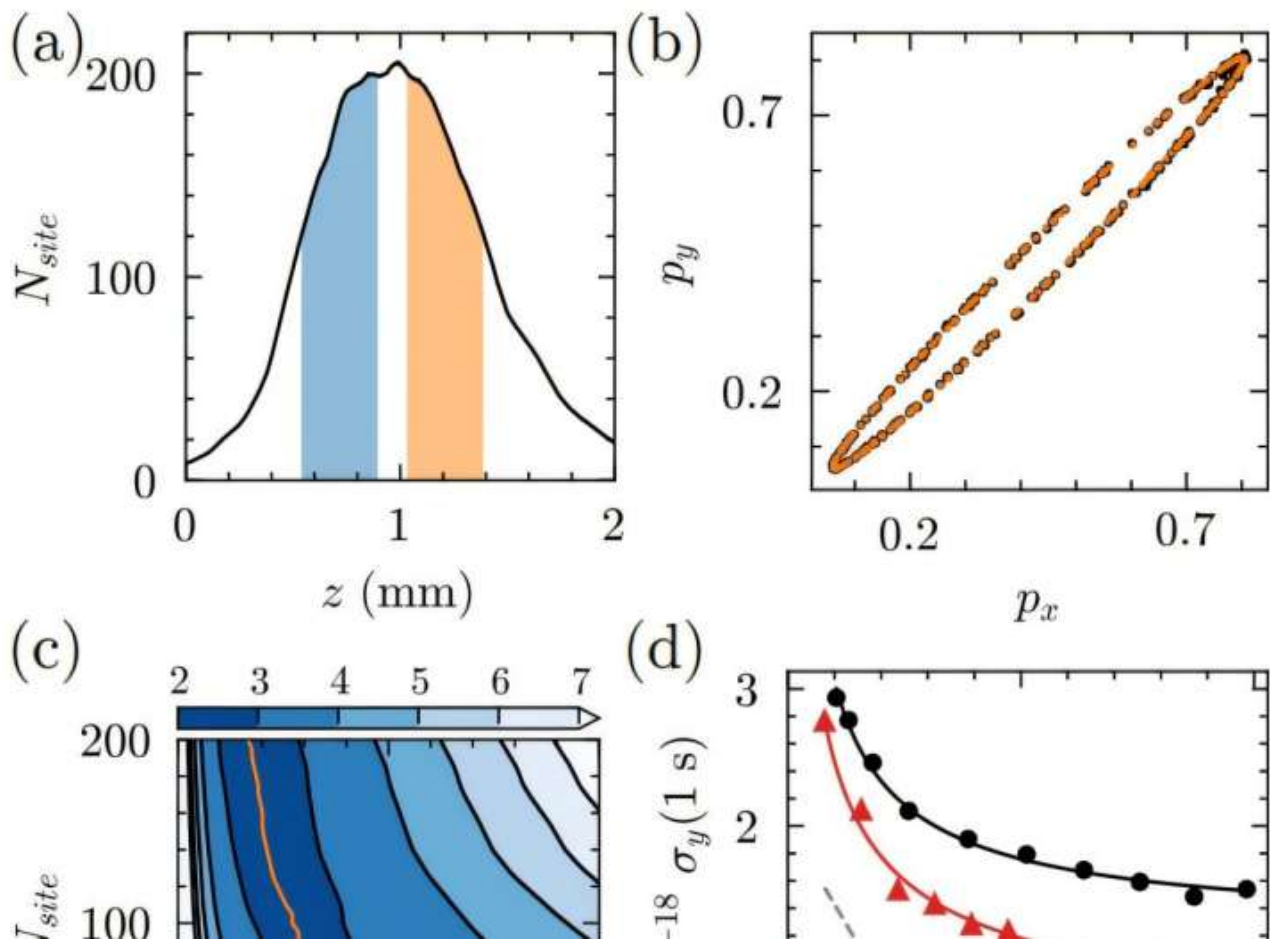
"We have been pushing the performance of the optical lattice clock," Kyungtae Kim, first author of the paper, told Phys.org. "Thanks to a major upgrade from 2019 to 2021, we demonstrated record differential frequency measurement capability, reaching [a resolution of gravitational redshift below the 1-mm scale](#), as well as [record accuracy \(until this July\) as a frequency standard](#). To push the performance further, one needs to understand and model the current system. This work provides a detailed snapshot of the clock's current operation."

The performance of optical lattice clocks greatly depends on the coherence of their underlying atoms, also known as atomic coherence. This is essentially the time for which atoms can retain their quantum oscillations, without being disturbed by noise.

A key objective of the recent work by Kim and his colleagues was to identify the mechanisms and physical processes that limit the atomic coherence of optical lattice clocks. This would in turn allow them to improve the atomic coherence and stability of their clocks.

"To improve frequency measurement stability, we want many atoms to reduce quantum projection noise (similar to reducing statistical uncertainty in coin-tossing)," explained Kim.

"Increasing the number of atoms, however, also enhances collisional frequency shifts and phase diffusion, which in turn limit coherence time and precision. A key design feature of our clock is its large trapping volume, achieved with an optical cavity, which reduces the atomic density."



Estimation of atomic contribution to the clock stability. Credit: Kyungtae Kim et al

Kim and his colleagues aligned the optical lattice in their clock along the direction of gravity, as this created a tilted lattice potential (i.e., a tilted "staircase" of trapping sites). Due to an effect known as Wannier–Stark localization, this tilted lattice potential makes it harder for atoms to move around, even when they are trapped in more shallow trapping sites. This shallow depth lattice clock uses an optical trapping potential about one fifth to one tenth of a traditional lattice clock.

The researchers then set out to explore how long different numbers of atoms trapped in the optical lattice stayed synchronized (i.e., their coherence time) and how quickly they decayed out of the "clock state" (i.e., their population decay rates). To do this, they employed a technique known as imaging spectroscopy, which can be used to study how physical systems respond to light and capture their underlying configuration or spatial features in a microscopic map.

"Atoms within the same lattice site behave as identical fermions and interact only via p-wave interactions," said Kim. "However, atoms can still interact through s-wave collisions from two sources: interactions between different sites since atoms in different sites experience different laser phases; and interactions with spectator atoms created when lattice photons scatter atoms into other nuclear spin states."

The strontium optical lattice clock developed by this team of researchers was found to achieve a record-high atomic coherence time (T_2^*) of 118(9) seconds and an atomic instability of 1.5×10^{-18} at

1 second. This time-keeping system could be used to conduct future fundamental physics studies, while also potentially informing the realization of other highly precise and stable optical lattice clocks.

"We also identified the atomic interactions that limit performance," said Kim. "At shallow lattice depths, inter-site s-wave interactions are dominant, whereas at deep lattice depths, s-wave interactions with spectator atoms generated by lattice photon scattering become the primary limitation. Recognizing these distinct regimes clarifies exactly which mechanisms must be addressed to further extend coherence time."

In their paper, Kim and his colleagues also uncovered physical processes that can limit the coherence time of optical lattice clocks, one of which is the interaction between adjacent lattice sites. They are now developing a strategy that can suppress these effects and thus enable even longer coherence times in clocks with high atomic densities.

"More importantly, we are now excited about the prospect of combining atom interferometry (for gravimetry) with atomic clocks (for redshift measurements) within the same experimental platform," added Kim. "The methods demonstrated here have already been applied in this direction and are providing valuable guidance for future developments."

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More information: Kyungtae Kim et al, Atomic coherence of 2 minutes and instability of 1.5×10^{-18} at 1 s in a Wannier-Stark lattice clock. *Physical Review Letters* (2025). DOI: [10.1103/3wtv-sty2](https://doi.org/10.1103/3wtv-sty2). On *arXiv*: DOI: [10.48550/arxiv.2505.06444](https://arxiv.org/abs/10.48550/arxiv.2505.06444)

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