Optical strontium atomic clock sets new stability record

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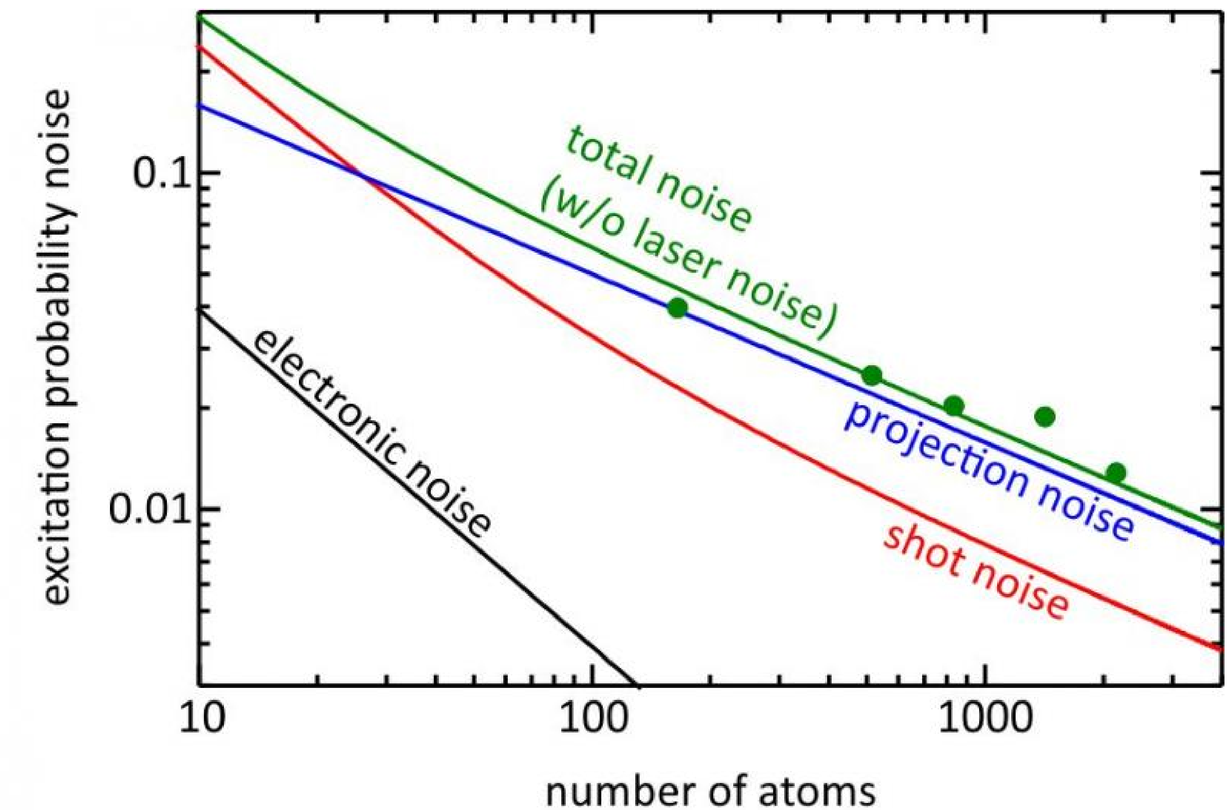

Noise contributions of the strontium lattice clock as a function of the number of atoms. The predicted total noise at suppressed frequency noise of the interrogation laser (green line) is confirmed by experimental data (green circles). The quantum projection noise (blue line) already dominates with few atoms. Credit: PTB

Researchers from the Physikalisch-Technische Bundesanstalt (PTB) have thoroughly analyzed the noise processes in their optical lattice clock with neutral strontium atoms. This analysis proves that their optical atomic clock has reached the best stability worldwide thanks to a newly developed laser system whose frequency is extremely stable. This allows high-precision measurements in a short time and considerably facilitates the future reduction of the total measurement uncertainty down to a few parts in 10^{18}.

In the research community, optical clocks have been attracting increasing interest. They could allow the SI base unit of time, the second, to be realized with even greater accuracy in future and thus replace the current definition which is based on the interaction between microwave radiation and cesium atoms. The most highly precise clocks, however, cover a wide range of applications which range from geodesy (where they allow the direct and more accurate measurement of the gravitational potential of the Earth), to the investigation of the "great questions" of modern physics (such as a unified theory of the fundamental interactions) by searching for possible variations in fundamental constants (e.g. the fine-structure constant) by comparing diverse clocks with each other.

The accuracy and the stability of optical clocks are mainly based on the fact that the frequency of the optical radiation used is higher (by several orders of magnitude) than that of the microwave radiation which is used in cesium atomic clocks, which makes optical clocks much more precise than cesium clocks. In a strontium clock, laser cooling is used to slow an atomic gas down to temperatures near absolute zero. Then, an extremely narrow transition between long-lived eigenstates of the atoms is excited in order to stabilize the frequency of the excitation laser to that of the atoms. The simultaneous interrogation of numerous atoms leads to a particularly high signal-to-noise ratio and, thus, to high stability.

However, since an atomic cloud must be prepared after each interrogation, interruptions in the observation of the laser frequency occur. The laser itself hence serves as a "flywheel" and is commonly pre-stabilized to an optical resonator which keeps the laser frequency stable over short periods of time. The scientists from PTB have therefore developed a resonator whose frequency is among the most stable worldwide: with a length of 48 cm and ingenious thermal and mechanical isolation from its environment, it reaches a fractional frequency instability of $8\ 10^{-17}$.

The scientists analyzed the individual contributions to noise of the detected excitation probabilities of their clock. Based on their analysis, PTB's strontium clock attains the quantum projection noise limit, which is due to the laws of physics, with as few as 130 atoms. This noise results from the state measurement itself, since after excitation, each atom is first in a superposition of the two eigenstates and is randomly projected into one of the two states only when the measurement is performed.

To analyze the clock's instability, the model derived from this was supplemented by the known influence of the laser frequency noise, and its prediction was experimentally verified by a self-comparison of the clock. From this, the scientists at PTB derived a fractional instability in normal operation amounting to $1.6\ 10^{-16}/\tau 1/2$ as a function of the averaging time τ in seconds. This is the best published value for an atomic clock so far. It is expected to considerably facilitate the further reduction of the total uncertainty of the strontium clock down to a few parts in 10^{18}.

More information: Ali Al-Masoudi et al. Noise and instability of an optical lattice clock, *Physical Review A* (2015). DOI: 10.1103/PhysRevA.92.063814

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