Precision measurements

# Quantum engineering for optical clocks

## Progressive quantum technology enters the field of time keeping: Researchers demonstrate the operation of optical clocks with squeezed atomic samples[1] and single-atom tweezer arrays[2].

Today's most accurate clocks rely on the spectroscopy of narrow atomic transitions in the visible regime. The transition is regularly probed with an ultra-stable laser, enabling a long-term absolute stabilization of the laser frequency. In the case of optical lattice clocks, ensembles of atoms with two valence electrons are trapped in a lattice-like potential of an optical standing wave. The frequency of the optical lattice light is chosen to be 'magic' such that it does not perturb the optical transition frequency in first order. In the recent past, optical lattice clocks have undergone a tremendous rate of improvement, but challenges remain: The 'magic' trap causes slight perturbations, clock dead times degrade the clock stability, and the quantum projection noise poses a stability limit, which can only be surpassed by the creation of squeezing and entanglement between the atoms. Pedrozo-Peñafiel *et al.*[1] now report the transfer of squeezing in an ensemble of ytterbium-171 atoms from a nuclear spin transition in the electronic ground state to the electronic transition to which the atomic clock is referenced. How does this help the clock? Usually, atomic clocks use quantum superpositions of individual atoms between the lower and upper electronic state of the reference transition, in optical lattice clocks preparing many such atoms in parallel. If both states equally contribute to the superposition, the laser runs on the correct atomic frequency. In a clock measurement, each atomic superposition is randomly and individually projected on either the lower or upper state. These random outcomes add up to the quantum projection noise (QPN) and degrade the clock performance. If a squeezed state is used in the clock, the atoms do no longer act individually and the QPN is reduced.

Pedrozo-Peñafiel *et al.* have demonstrated a reduction of the QPN in a realistic clock sequence, albeit with a short coherent evolution time of the state. For high-performance clock operation, this evolution would have to be extended by a factor of 1000 to about one second, a long time to survive for a fragile system. However, the authors have shown that already now that their squeezed state can survive nearly as long. These measurements indicate that quantum correlations can indeed be combined with the second-long coherence times that are accessible in the electronic reference transitions of optical clocks. Before optical clocks can actually benefit from the demonstrated squeezing enhancement, further technical challenges must be overcome. Often, the frequency noise of the ultra-stable laser that excites the superposition state in combination with dead times for atomic preparation is a limiting factor for the clock stability.

Young *et al.*[2] present a new approach to mitigate this challenge. They split an ensemble of neutral clock atoms such that 150 single atoms are individually trapped in an array of magic-frequency laser traps called tweezers. The array is loaded extremely fast by a much stronger, additional optical potential. The central achievement of the presented work is the engineering of the tweezer array to enable a high-performance clock operation. Combined with very long coherence times of more than 20 s in their set-up, they minimize dead time. Making use of the possibility of individual readout of the tweezers, the authors perform two simultaneous clock measurements on two sub-ensembles. They observe a differential frequency instability between the two clock ensembles, which is close to the current lattice-clock record[3–5].

The geometry of the tweezer array can be chosen at will, such that increased distances suppress hopping and Doppler-like frequency shifts while operating the clock at much reduced intensities of the trapping laser. The tweezer geometry thus constitutes an alternative to high barriers or gravity-assisted inhibition in optical lattices[6]. In addition, this concept opens a path for a novel type of neutral atom clocks based on individually controlled atoms. While excellent clock stability has now been demonstrated, the characterization of the frequency uncertainty is the next step to realize a fully operational clock. For example, the present approach to form the tweezer array causes differential frequency shifts across the array that must be well controlled.

These publications impressively demonstrate how quantum-technological developments and precision metrology benefit each other. For optical clocks, sophisticated novel tools and platforms are now at hand and, in turn, entangled and single-particle resolved ensembles of clock atoms constitute an exciting system for further applications in the fields of quantum simulation and quantum information.

**References**


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