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Optical lattice clocks near the QPN limit: a tenfold improvement in optical clock stability

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Two classes of optical atomic clocks have surpassed microwave frequency standards: single-ion clocks and optical lattice clocks. Single-ion clocks hold the record for the lowest systematic uncertainty [1]; however, many-atom lattice clocks have the potential to outperform single-ion clocks because the standard quantum limit to atomic clock instability (known as quantum projection noise or QPN) scales as $1/\sqrt{N_{atoms}}$ [2]. For realistic atom numbers and coherence times, QPN-limited lattice clocks could average down to a given stability hundreds of times faster than the best ion clocks. Up to now lattice clocks with ~ 1000 atoms have not shown improvement over the stability of single-ion clocks. Lattice clock stability has been limited by laser noise (via the optical Dick effect). To address this problem, we constructed a new clock laser with a thermal noise floor of 1×10^{-16}—an order of magnitude improvement over our previous clock laser. With this laser, we compare two lattice clocks, reaching instability of 1×10^{-17} in 2000 s for a single clock. This instability is within a factor of 2 of the theoretical QPN limit for ~ 1000 atoms, representing the lowest reported instability for an independent clock [3]. The high stability of many-particle clocks can come at the price of larger systematic uncertainty due to a frequency shift from atomic interactions. To minimize this shift, we use a cavity-enhanced lattice [4] for our second clock. The high circulating power inside the cavity allows for a large trap volume, yielding a density at 2000 atoms that is 27 times smaller (than in our first clock) and permitting us to trap as many as 5×10^4 atoms. For 2000 atoms in our lattice, we measure a value for this shift (which is linear in density) of -3.11×10^{-17} with an uncertainty of 8.2×10^{-19} [3].

[1] Chou, et al., PRL 104, 070802 (2010)
[2] Ludlow, et al., Science 319 1805 (2008)
[3] Nicholson, et al., PRL 109, 230801 (2012)
[4] Westergaard, et al., PRL 106, 210801 (2011)