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14. ABSTRACT
State-of-the-art atomic clocks are based on the precise detection of the energy difference between two atomic levels. The stability of the best atomic clocks is close to the so-called standard quantum limit (SQL). The generation of entanglement on an optical-clock transition and operation of an optical-lattice clock (OLC) beyond the SQL represent major goals in quantum metrology. We demonstrate for the first time the creation of a many-atom entangled state in an OLC with a metrological gain of 4.4 dB over the SQL using an ensemble consisting of a few hundred 171Yb atoms. This will enable further advances in timekeeping precision and accuracy, with many scientific and technological applications.

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Atomic clocks, entanglement, spin squeezing, standard quantum limit, timekeeping, atom interferometry

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Final report to ONR – Contract number N00014-17-1-2254

Optical-Transition Atomic Clock Beyond the Standard Quantum Limit

PI Vladan Vuletic, MIT

Major goals

A major goal was the first demonstration of operation below the standard quantum limit for a state-of-the-art atomic clock that uses an optical transition. This was to be accomplished by spin squeezing (entanglement) that is implemented in an ensemble of ytterbium atoms. The spin squeezing is first to be created between two magnetic sublevels in the electronic ground state, and then transferred onto the optical clock transition by means of a laser pulse.

A second goal was the demonstration of metrology with non-Gaussian states and quantum magnification of measurement sensitivity. Here an entangled state is to be created by the one-axis twisting Hamiltonian, followed by a sensing period. Subsequently, time reversal of the initial one-axis twisting Hamiltonian results in a magnification of the signal accumulated in the sensing period. This allows one to go beyond spin squeezing with Gaussian states and avoid limitations associated with the finite size of the system (curvature of the Bloch sphere) and finite measurement resolution.

Accomplishments

We have realized spin squeezing in an optical-transition clock atom, 171 Ytterbium. The squeezing is realized using light-atom interaction. We have achieved nearly 10dB of spin squeezing between the two nuclear sublevels of the ground electronic state. For the very first time in any spin squeezing experiment, the generated quantum state of the ensemble is nearly pure with an uncertainty area only twice that of an unentangled state. The corresponding paper has been published in PRL (Near-Unitary Spin Squeezing in 171Yb. B. Braverman, A. Kawasaki, E. Pedrozo, C. Shu, S. Colombo, Z. Li, L. Salvi, D. Akamatsu, Y. Xiao, and V. Vuletić, Phys. Rev. Lett. 122, 223203 (2019); http://doi:10.1103/PhysRevLett.122.223203)

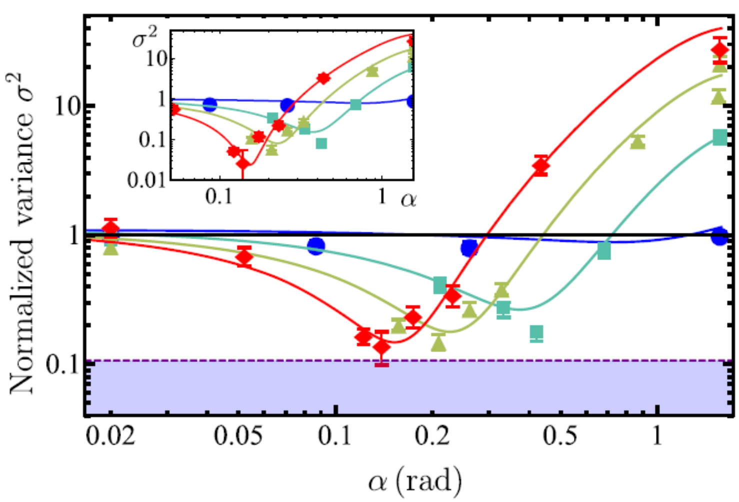

Figure 1. Measured normalized spin noise as a function of the state rotation angle α for different shearing strengths. The solid lines are theoretical fits. States in the violet region below the dashed line (detection limit) cannot be directly observed. Inset: normalized spin noise after subtracting measurement noise for the same parameters. (Adapted from Ref. 1.)

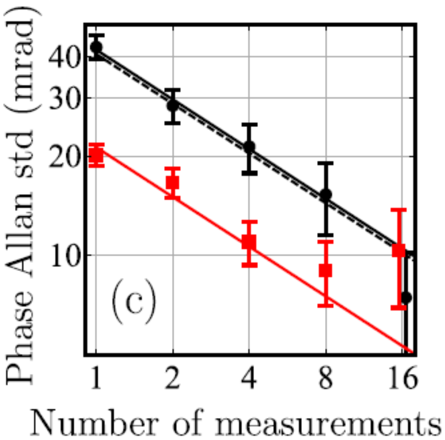

Figure 2. Allan deviation of a phase measurement for an unentangled coherent spin state (black squares) with Standard Quantum Limit (dashed line) and for a spin squeezed state (red data). The red solid line is fit to the first three data points. The reduction in the measurement time over the Standard Quantum Limit is a factor of 3.7(2), (Adapted from Ref. 1.)

We have also shown theoretically that such nearly unitary spin squeezing is important for clock performance. The corresponding paper has been published. (Impact of Non-Unitary Spin Squeezing on Atomic Clock Performance. B. Braverman, A. Kawasaki, and V. Vuletić, New J. of Phys. 20, 103019 (2018).)

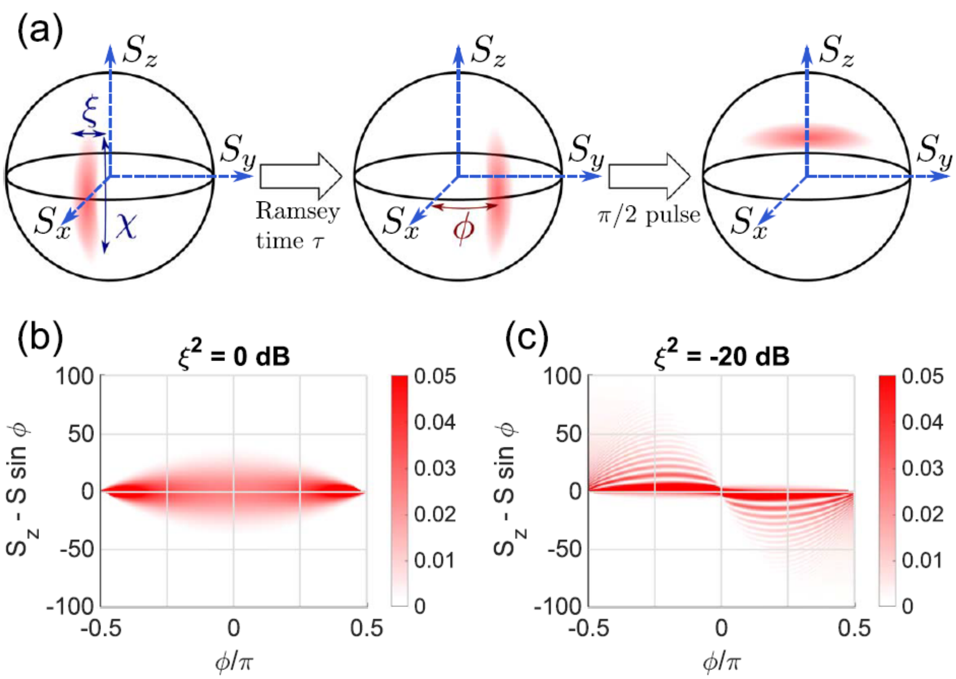

Figure 3. (a) Illustration of a Ramsey sequence using a spin squeezed state. A collective spin state pointing along x is prepared with a quadrature reduced variance in the phase direction, and an increased variance in the S_z direction. If the phase deviation f is non-zero, the final readout of S_z becomes sensitive to the antisqueezing. (b) and (c) S_z distributions, as a function of accumulated phase for a clock with 10^3 atoms, using a coherent state and a pure spin squeezed state with 20 dB of spin squeezing, respectively. The S_z distribution is narrowed by squeezing only when the magnitude of the phase deviation is small. (From Ref. 2.)

Building on the unitary spin squeezing work, we have created spin squeezing on the optical transition in ^{171}Yb. The spin squeezing is generated between the nuclear sublevels in the electronic ground state, and then transferred onto the optical transition by means of a high-fidelity π pulse of the local oscillator (LO) clock laser. We have demonstrated an optical transition clock (Ramsey sequence) that operates 4 dB below the standard quantum limit, as shown in Figures 4 and 5. This is the first time that any optical clock with many atoms has been entangled.

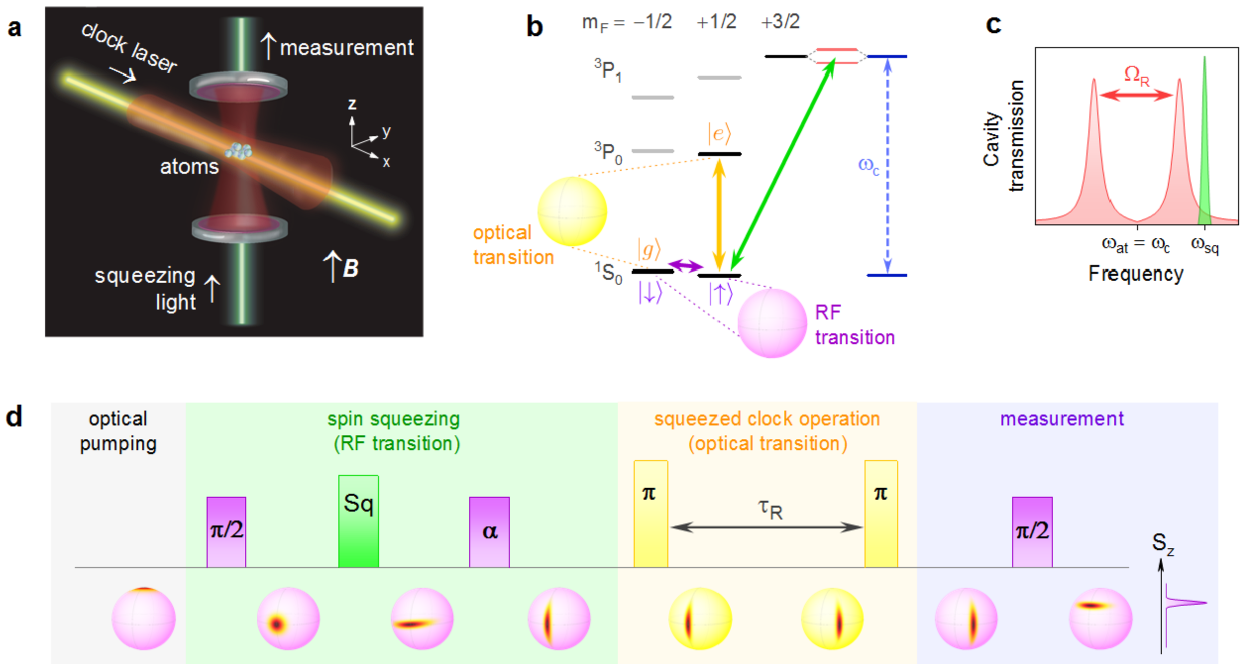

Figure 4. Setup and squeezed-clock sequence. a, ^{171}Yb atoms are trapped inside an optical cavity in a two-dimensional magic-wavelength optical lattice along the x and z directions (red beams). Light for optical pumping and spin squeezing (green) is applied along the cavity axis z, while the clock laser (yellow) propagates along x. b, Energy levels and transitions. Purple, green, and yellow pulses indicate the ground-state radiofrequency (RF) transition, squeezing transition, and optical-clock transition, respectively. The system evolves either in the ground-state manifold (purple Bloch sphere), or in the clock-state manifold (yellow Bloch sphere). The cavity frequency is tuned in resonance with the squeezing transition. c, Spin squeezing. Strong coupling of the atoms to the cavity results in vacuum Rabi splitting of the cavity resonance (red peaks). A laser is applied detuned from the Rabi peak (green peak) to produce a spin squeezed state via cavity feedback [1]. d, Squeezed-clock sequence. A spin squeezed state is prepared in the ground-state manifold, transferred to the clock manifold, evolved in a Ramsey sequence, and mapped back onto the ground-state manifold, where a state measurement is performed. The evolution of the quantum state is depicted on the Bloch spheres for the RF (purple) and optical (yellow) transitions. (From. Ref.3.)

We have also developed some new methods for loading small magic-wavelength optical traps inside the cavity as documented in Ref. 4. Furthermore we have developed a new laser-system for the optical-clock laser (LO) that uses optical narrowing by feedback to substantially reduce the linewidth of a distributed Bragg reflector diode laser (Ref. 5). This laser is then locked to a high-stability optical reference cavity.

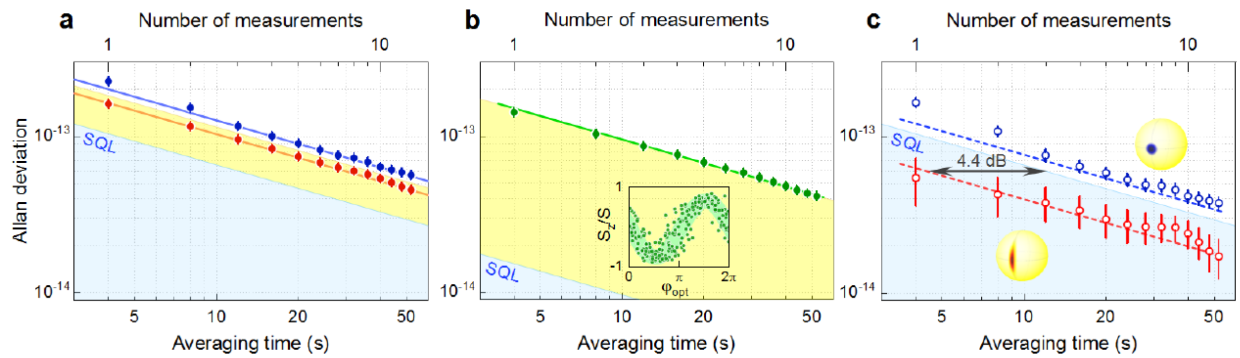

Figure 5. Stability improvement with the squeezed clock. In all three subfigures, the blue shaded area represents the region below the Standard Quantum Limit, while the yellow shaded area in a, b, represents the additional contribution from LO phase noise. a, Inferred single-clock cycle stability (self-comparison Allan deviation) for an unentangled coherent spin state (sequence C1, blue) and a squeezed spin state (S1, red) with Ramsey time of 0.17 ms. The squeezed clock operates within the yellow region set by the Standard Quantum Limit and LO phase noise because the quantum projection noise is reduced below the Standard Quantum Limit. b, Allan deviation for a squeezed spin state (sequence S2, green) with longer Ramsey time of 1.16 ms, where the total noise is dominated by the LO noise. Inset: Ramsey fringes vs. LO phase 'opt of the second Ramsey π-pulse for S2. c, Data for C1 and S1 after subtraction of the LO phase noise, where the latter has been calculated from the data for S2. The dashed lines indicate the expected performance estimated from the separately measured Wineland parameter. The spin squeezing reduces the measurement time by 4.4 dB.

Training

Several graduate students (Enrique Mendez, Chi Shu, Zeyang Li) and postdocs (Edwin Pedrozo, Simone Colombo), and one undergraduate student (Megan Yamoah) have been trained on this experiment.

Honors and Awards

Megan Yamoah won a 2019-20 Barry M. Goldwater Scholarship.

Technology Transfer

We are collaborating with a group in the ARL lab in Adelphi (PI Vladimir Malinovski) on spin squeezing. They have successfully applied for a LUCI proposal to analyze theoretically improved methods to achieve spin squeezing in a clock system.

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