Quantum Manipulation Using Light-Atom Interaction

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1. Squeezed atomic clock operating below the standard quantum limit

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A two-level quantum system in vacuum—in the absence of any perturbing fields—constitutes an ideal clock whose oscillation frequency $\omega = E/\hbar$ is given by the energy difference E between the two levels $|1\rangle$, $|2\rangle$. In a single measurement of duration T performed on a single particle this frequency can be determined with an uncertainty $\Delta\omega = 1/T$. If the measurement is performed simultaneously on N independent identical particles, and this measurement is repeated with a cycle time $T_c > T$ for a total averaging time $\tau > T_c$, the fundamental quantum uncertainty of the frequency determination is given by the standard quantum limit [1,2]

$$\frac{\Delta\omega}{\omega} = \frac{1}{\omega T}\sqrt{\frac{T_c}{N\tau}} \tag{1}$$

The $N^{-1/2}$ scaling arises because the quantities to be measured are the nonzero probabilities to find a particle in either of the clock states $|1\rangle$, $|2\rangle$; when the independent particles in the ensemble are read out, the observed populations of the two clock states are binomially distributed, leading to so-called projection noise on the estimation of those probabilities [3,4]. The $\sqrt{T_c/\tau}$ scaling arises because the sequential measurement repeated τ/T_c times using N particles each is equivalent to a single measurement using $N\tau/T_c$ atoms. For a given total measurement time τ the stability improves as the duration T of the single measurement is increased. The latter is limited by the coherence time of the transition. While the absolute stability does not depend on the transition frequency ω, the fractional stability improves with higher transition frequency.

The standard quantum limit, Eq. (1), can be overcome by entanglement between the particles such that the readout quantum noise is reduced by quantum correlations while the signal is (almost) not affected. This approach is referred to as "spin squeezing" [5], and has recently been demonstrated experimentally [6-12]. While in principle the precision of an atomic clock as given by Eq. (1) can be increased simply by increasing the atom number, even at the maximum available atom number spin squeezing can improve the signal-to-noise ratio further. In addition, there may be other limitations on the maximum allowed atom number N such as density shifts of the clock transition due to atom-atom collisions [13-18].

We have recently demonstrated a spin-squeezed atomic clock using the hyperfine transition in ^{87}Rb and measured its Allan deviation spectrum (see Fig. 1) [12]. For averaging times up to 50 s the squeezed clock achieves a given precision 2.8(3) times faster than a clock operating at the standard quantum limit, Eq. (1).

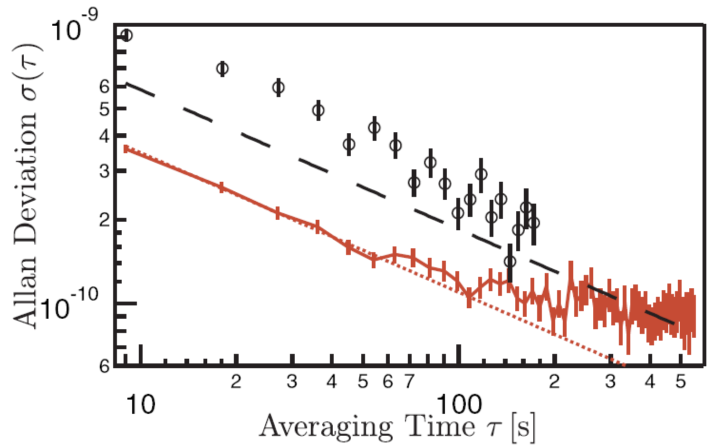

Fig. 1. Allan deviation of a squeezed ^{87}Rb hyperfine clock operating below the standard quantum limit. The solid red line with error bars was measured using a squeezed input state. The dotted red line indicates $\sigma(\tau)=1.1 \times 10^{-9}\ s^{1/2}/\tau^{1/2}$. The open black circles were measured with a traditional clock using an uncorrelated input state. The dashed black line at $1.85 \times 10^{-9}\ s^{1/2}/\tau^{1/2}$ indicates the standard quantum limit. For integration times shorter than 50 s, the squeezed clock achieves a given precision 2.8(3) times faster than a clock operating at the standard quantum limit (for the same atom number and perfect Ramsey contrast). For longer integration times magnetic noise dominates. (From Ref. [12].)

Operation below the standard quantum limit is achieved by using a squeezed spin state as an input state to the Ramsey clock sequence (Fig. 2). A phase-squeezed input state then translates into reduced readout noise at the end of the Ramsey sequence (Fig. 2 bottom bar). The squeezed spin state is generated using cavity feedback squeezing [10,23], a new technique that we have developed that deterministically produces entangled states of distant atoms by means of their collective interaction with a driven optical resonator.

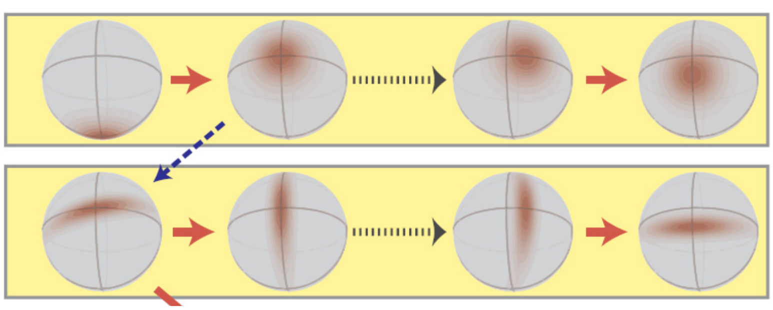

Fig. 2. Regular and squeezed-clock operation. A standard Ramsey protocol (top bar) consists of preparing a spin-down coherent spin state, rotation about the *y* axis into the equatorial plane using a microwave pulse (solid red arrow), free precession time (dotted black arrow), and conversion of the accrued phase into a measurable population difference along ***z*** by a rotation about *x*. The fuzzy area indicates the uncertainty of the coherent spin state, or equivalently, the projection noise upon final state readout. We can shear the coherent spin state into a squeezed state using cavity feedback (dashed blue arrow) [10,23], then orient the narrow axis of the squeezed state in the phase direction (bottom bar) to start the clock sequence. The final readout of the phase (bottom right) has lower quantum noise than the standard clock (top right).

Cavity feedback squeezing relies on the repeated interaction of the atomic ensemble with the light circulating in the optical resonator. It generates spin dynamics similar to those of the one-axis twisting Hamiltonian $H \propto S_z^2$ in the original proposal of Kitagawa and Ueda [5], i.e., it produces an S_z-dependent rotation of the spin state about the *z* axis, which results in shearing of the originally circular uncertainty region of the unentangled coherent spin state (see Fig. 3d). (As usual, we identify the two levels $|1\rangle$, $|2\rangle$ with a spin ½ system, and **S** is the sum of the individual spins.) The coupling of the atoms to the resonator manifests itself both as a differential light shift of the hyperfine clock states, which causes the spin to precess about the *z* axis, and as a modified index of refraction which shifts the cavity resonance frequency. If a resonator mode is tuned halfway between the optical transition frequencies for the two hyperfine clock states (Fig. 3c), the atomic index of refraction produces opposite frequency shifts of the mode for atoms in each of the states, yielding a net shift proportional to the population difference S_z.

The resonator is driven by a probe laser with fixed incident power detuned from the cavity resonance by half a linewidth (Fig. 3b). As the intracavity power is S_z-dependent, so is the light shift, which generates a spin precession through an angle proportional to S_z. The state of each atom now depends, through S_z, on that of all other atoms in the ensemble. In particular, a coherent spin state prepared on the equator of the Bloch sphere has its circular uncertainty region sheared into an ellipse with a shortened minor axis (Fig. 3d).

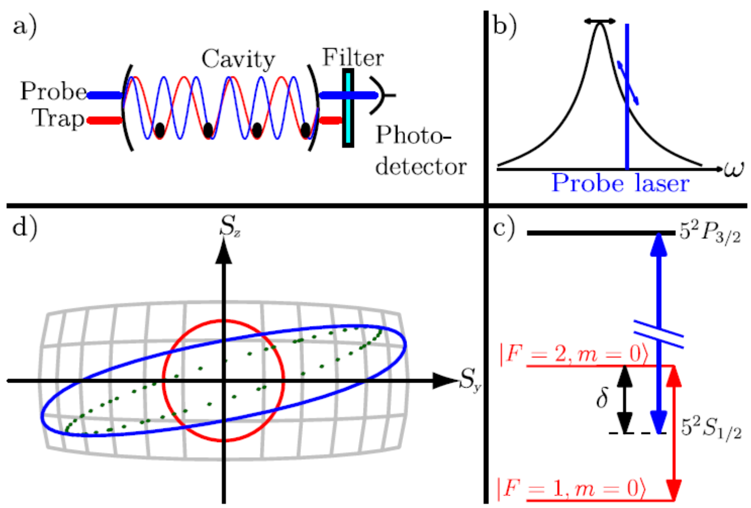

Fig. 3. Cavity squeezing. (a) The ^{87}Rb atoms are trapped in a standing-wave dipole trap inside an optical resonator. (b) The probe laser is detuned from cavity resonance by half a linewidth, so that atom-induced shifts of the cavity frequency change the intracavity power. (c) The cavity is tuned halfway between the optical transition frequencies for the two hyperfine clock states. (d) The S_z-dependent light shift shears the circular uncertainty region of the initial coherent spin state (red circle) into an ellipse (dotted). Photon shot noise causes phase broadening that increases the ellipse area (solid blue).

As reported in Ref. [10], we have implemented cavity squeezing for the canonical $|F=1,m_F=0\rangle \rightarrow |F=2,m_F=0\rangle$ hyperfine clock transition in ^{87}Rb atoms, achieving a 5.6(6) dB improvement in signal-to-noise ratio. To our knowledge, this is the largest such improvement to date. Moreover, the shape and orientation of the uncertainty regions we observe agree with a straightforward analytical model [23], without free parameters, over 2 orders of magnitude in effective interaction strength. The observed squeezing was limited by our technical-noise-limited ability to read out of the final state. By subtracting the independently measured technical noise, we infer that the lowest intrinsic spin variance is a full 10 dB below the projection noise limit. It should be possible to reach this value of spin squeezing with straightforward technical improvements in state detection. (10dB of spin squeezing would shorten the integration time to reach a certain precision by a factor 10 compared to a perfect unentangled clock.)

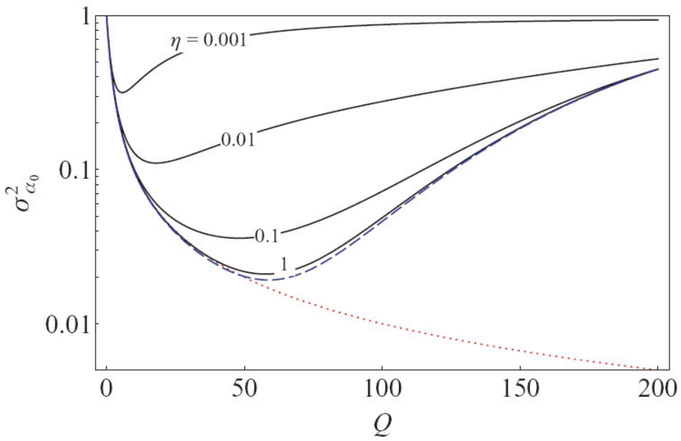

Fig. 4. Calculated cavity spin squeezing. (From Ref. [23].) The calculation includes the broadening effects of photon shot noise, and Raman scattering of photons by the atoms into free space. The plot shows the normalized spin variance (spin squeezing) as a function of shearing strength Q for $N=2\times10^4$ atoms [23]. (Q is proportional to the product of photon and atom number.) The various curves correspond to different resonator finesse (various single-atom cooperativities η = 0.001, 0.01, 0.1, 1 (solid lines)). The dashed line shows the limit due to the curvature of the Bloch sphere when free-space scattering is ignored, i.e. for a resonator with strong coupling to a single atom ($\eta \gg 1$). The dotted line shows the variance neglecting both free-space scattering and curvature, scaling as 1/Q for $Q \gg 1$.

The obtainable spin squeezing improves with the quality of the resonator and the number of atoms. Fig. 4 shows the calculated spin squeezing for a typical atom number ($N=2\times10^4$) and varying finesse of the resonator. Note that we obtain excellent agreement between the calculation [23] and the experiment [10] when we include the observed technical noise without any free parameters. We estimate that 12-15 dB of squeezing should be obtainable in the existing setup or one equivalent to it, and even higher values if the atom number or the cavity finesse are increased. Also, the cavity spin squeezing is limited by photon shot noise [10,23] that is in principle removable in a modified setup corresponding to a one-sided cavity [24], which would further improve the squeezing. We note that compared to the squeezing of light that is typically limited by optical loss, the lifetime of the atomic states (T_1 relaxation time) is very long (several seconds), and not a limiting factor.

An important general note is that any entanglement generation (such as spin squeezing) requires an interaction between the atoms in order to create quantum correlations between their internal states. Direct interaction, such as the collisional interaction used to create spin squeezing in a Bose-Einstein condensate [8,9], is incompatible with a precision application such as a clock unless the interaction can be completely switched off. Here we induce an effective interaction between distant atoms via the light field inside the resonator – when the light field is switched off, the atoms do not interact. Furthermore, note that it is only necessary to supply an entangled input state to the Ramsey clock sequence, and no further entangling interaction, that could potentially affect clock precision or accuracy, is required during clock operation.

2. Ion ensemble in trap array coupled to an optical resonator

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Trapped ions provide a system where two-qubit quantum gates with very high fidelity have been implemented using the strong Coulomb interaction between ions [25]. However, since Coulomb gates can be implemented only between adjacent ions, transport of the ions is required for implementing interactions in a larger system [26]. It would be advantageous to transport the information optically, rather than through motion of massive particles. Mapping of quantum states between ions and light would also allow one to connect remotely to other ions or atoms for long-distance entanglement [27].

In order to achieve coherent mapping between atomic internal states and photons with near-unity efficiency, the ion must be strongly coupled to the cavity, i.e. the Rabi frequency for coherent exchange of a single excitation between the ion and the cavity mode (single-photon Rabi frequency) must exceed both the decay rate of the photon from the cavity (i.e. the cavity linewidth), and the linewidth of the excited state. In the UV region, where ions have strong transitions, the necessary high cavity finesse cannot be achieved with currently available mirror coatings. However, it is possible to make up for cavity finesse by coupling to an ensemble of ions, as demonstrated with atomic ensembles [28,29]. In the latter case, the quantum state is not stored in any particular ion, but as a collective excitation of the ensemble that due to interference between contributions from different atoms (Dicke states) displays collectively enhanced coupling to the cavity mode [28].

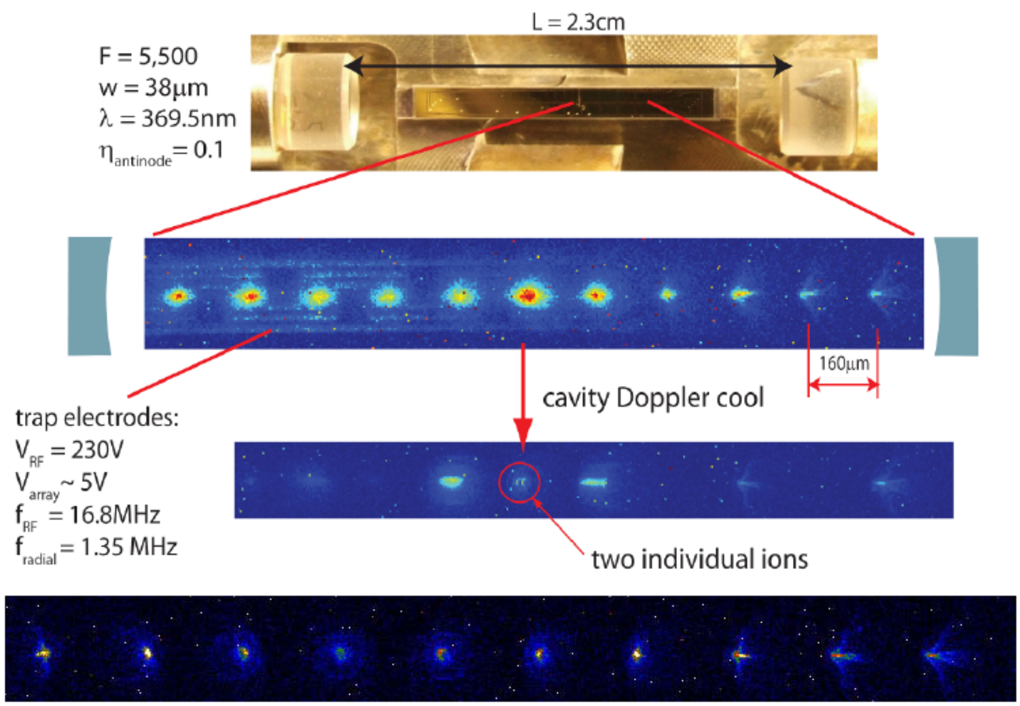

Fig. 5. Microfabricated ion trap with optical resonator and image of ions trapped in array of Paul traps. The top bar shows the microfabricated chip mounted inside a Fabry-Perot resonator of 2.3 cm length. The lower bars show pictures of trapped $^{174}Yb^{+}$ ions excited by light circulating inside the optical resonator before and after Doppler cooling. The individual traps in the array are spaced by 160 μm, and located 140 μm above the chip surface.

We have built a system where an optical resonator is mounted on a microfabricated ion trap chip. The near-confocal resonator is mounted such that its TEM_{00} mode is aligned with the trap axis at a height of 140 μm above the chip surface. The linear Paul trap consists of three electrodes, where the outer two are driven together at 15 MHz relative to the middle electrode. The middle electrode is split into three parts in order to produce a periodic modulation of the trap potential along the trap axis (Fig. 6, middle bar). The resulting linear trap array with a period of 160 μm can trap ions over a substantial length (~1cm), with a portion of the trapping region shown in Fig. 5.

The different bars show pictures before and after Doppler cooling of the ions. Individual ions can be spatially resolved at each trapping site.

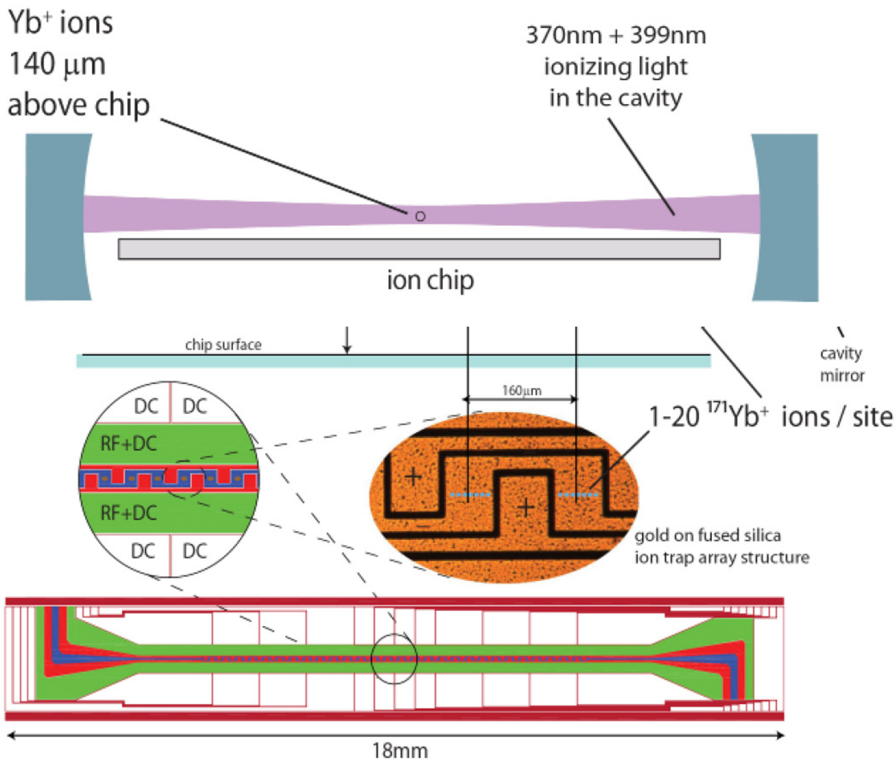

Fig. 6. Details of the microfabricated ion trap. The linear RF Paul trap is formed by three electrodes, where the outer two electrodes are driven at ~15 MHz with respect to the middle electrode. The middle electrode is split into three parts to which different dc potentials can be applied (inset right), creating a periodic dc potential along the trap axis. A number of outer electrodes provide dc compensation along the trap.

In the future, we plan to use the system to implement a quantum gate between two photons. Two incident photons can be stored in adjacent regions of an ion crystal using techniques akin to stimulated rapid adiabatic passage [30] and related to "stopping light" techniques via adiabatic reduction of the light group velocity to zero [31]. Then each stored photon can be mapped onto a single ion using the Coulomb interaction between the ions, and it can be arranged that neighboring ions in the linear crystal contain the two photons. Then a standard quantum gate can be induced between those two ions using again the Coulomb interaction [25], and finally, the stored photons can be mapped back into collective (delocalized) excitations that couple strongly to the optical resonator for optical readout of the photons.

Other possibilities include all-optical trapping of the ions in the strong light field circulating inside the optical resonator [34], and phase transitions between a Coulomb crystal in a single trap and an order as determined by the external periodic potential.

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