Strontium Optical Clock Arrays for Precision Metrology

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Motivation

Our experiment uses ^{88}Sr to investigate methods for improving the fractional uncertainty of optical atomic clocks. We want to demonstrate spin-squeezing of the clock state using Rydberg atoms [1].

Strontium optical lattice clocks currently hold the record for lowest fractional uncertainty frequency measurements [2]. We will use arrays of magic wavelength tweezers to trap individual ^{88}Sr atoms. The excited clock state of these atoms will then be Rydberg-dressed to generate spin-squeezed states [1].

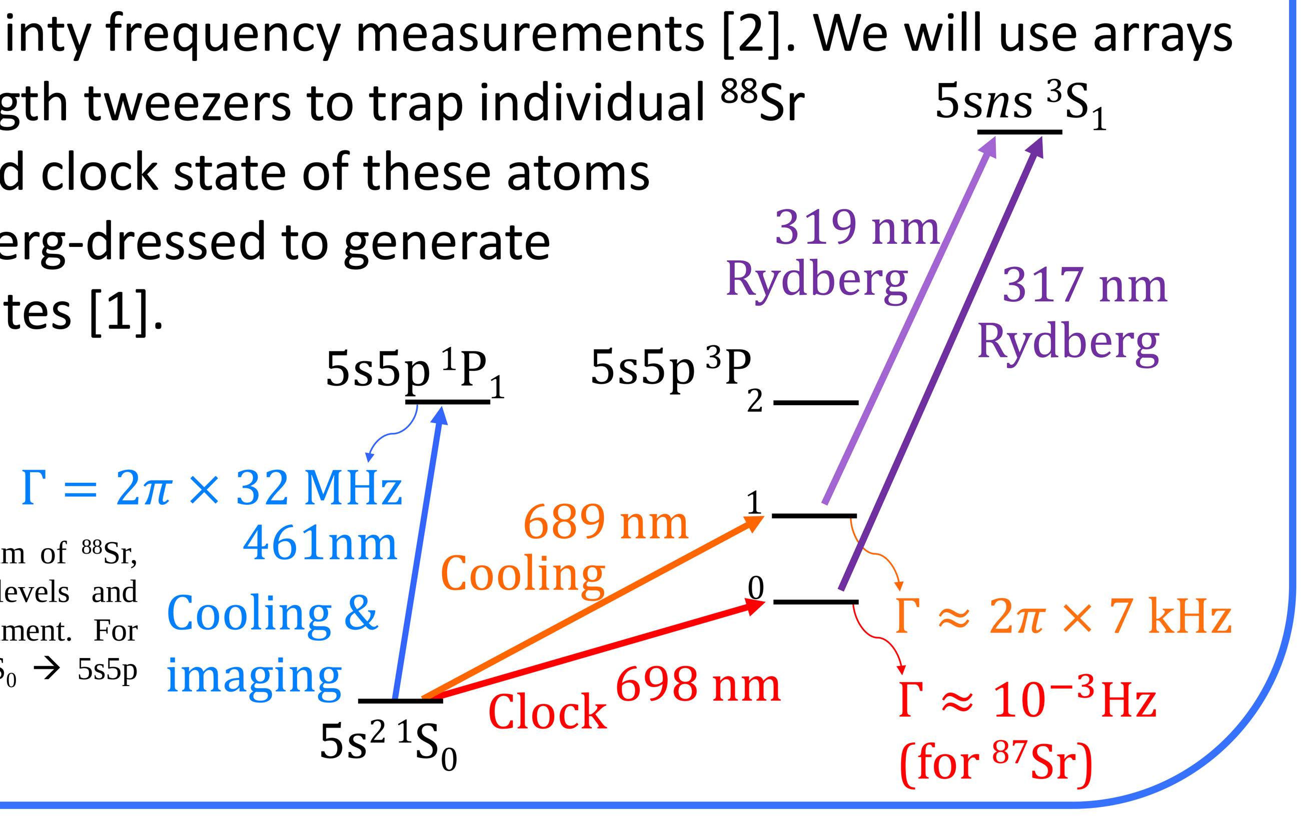


Fig. 1: An energy level diagram of ^{88}Sr, showing the various energy levels and transitions used in our experiment. For ^{88}Sr, the clock transition $5s_2\ ^1S_0 \rightarrow 5s5p\ ^3P_0$ has no linewidth.

Spin-Squeezed States

When making a measurement using individual, uncorrelated atoms there is an associated uncertainty: the quantum projection noise (QPN). This error can be reduced using spin-squeezed states, which uses entanglement to create correlations between atoms and suppress QPN [1].

In our experiment, we want to use Rydberg atoms to dress the excited clock state of the atoms and create spin-squeezing [1,3]. To achieve this we require three things:

- **Individual atoms** in magic wavelength **tweezer arrays**,
- The ability to excite atoms to **Rydberg states**,
- Measurements of the **clock transition** in ^{88}Sr.

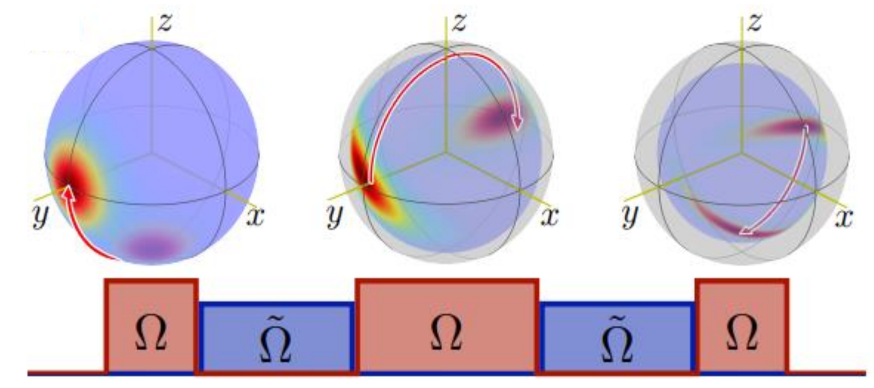
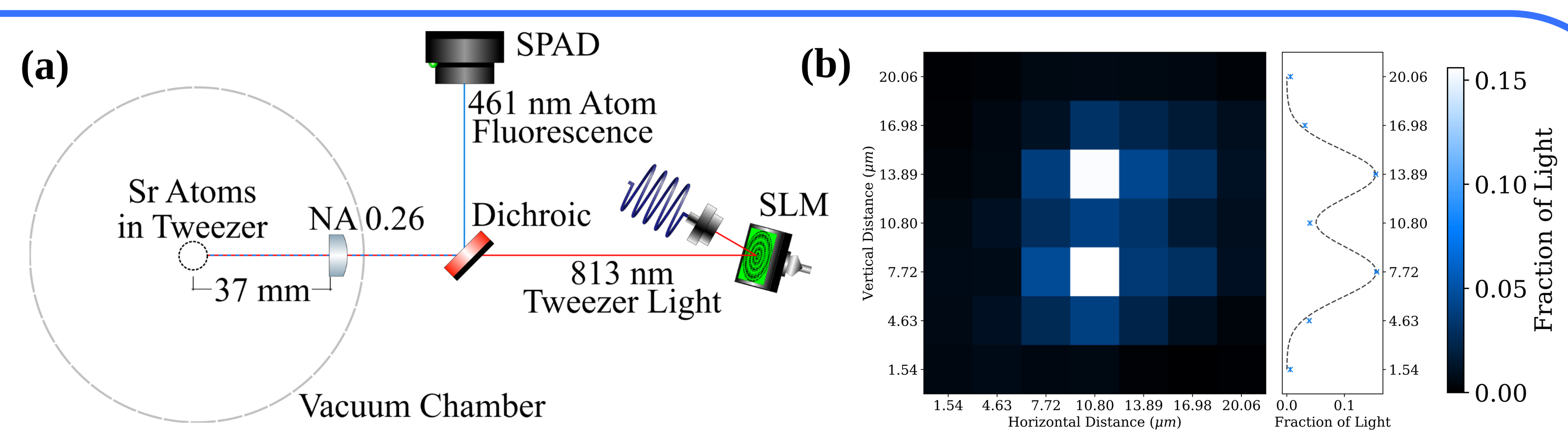


Fig. 2: A spin-squeezing protocol. $^{\pi}/_{2}$ and π pulses drive the atom between the clock ground and excited states with Rabi frequency Ω. Between these pulses, large-detuning Rydberg pulses with Rabi frequency $\tilde{\Omega}$ are applied, causing spin squeezing. This figure is taken from [1].

Tweezer Arrays

- For spin-squeezing, we require single atoms in individual tweezers separated by less than 10 μm (the Rydberg blockade radius) [3-6].
- We use a spatial light modulator (SLM) to generate arbitrary 3D arrays of tweezers with 2 μm waists.
- An aspheric in-vacuo lens is used to collect fluorescence from trapped atoms.
- The fluorescence is magnified 48.6 times by a double telescope lens setup.
- A single-photon avalanche diode (SPAD) array camera images the fluorescence.
- We are able to resolve fluorescence from individual tweezers separated by 6 μm.



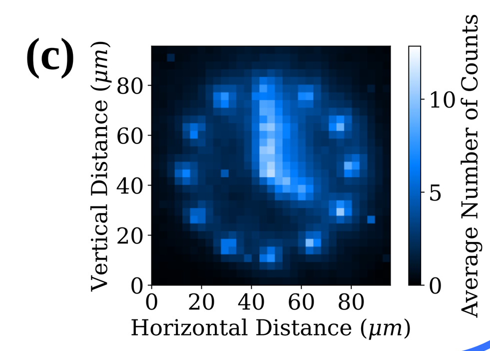


Fig. 3: (a) A simplified diagram of the experimental setup used to generate tweezer arrays and collect fluorescence from trapped atoms. **(b)** A normalised false-colour image of fluorescence from two individual tweezers containing many atoms each. The tweezers are separated by around 6 μm in the vacuum chamber. Each SPAD pixel corresponds to 3×3 μm in the vacuum chamber. **(c)** An example of a larger arbitrary array imaged with our experiment. This image is comprised of atomic fluorescence from 18 tweezers.

Single Atoms

- We want single atoms for the ability to read out individual states.
- We have demonstrated detection of single ^{88}Sr atoms in individual 532 nm tweezers [7].
- Multiple atoms can lead to collisional broadening and reduced lifetimes.
- We intend to use light-assisted collisions to achieve single atoms in a tweezer [4,5].

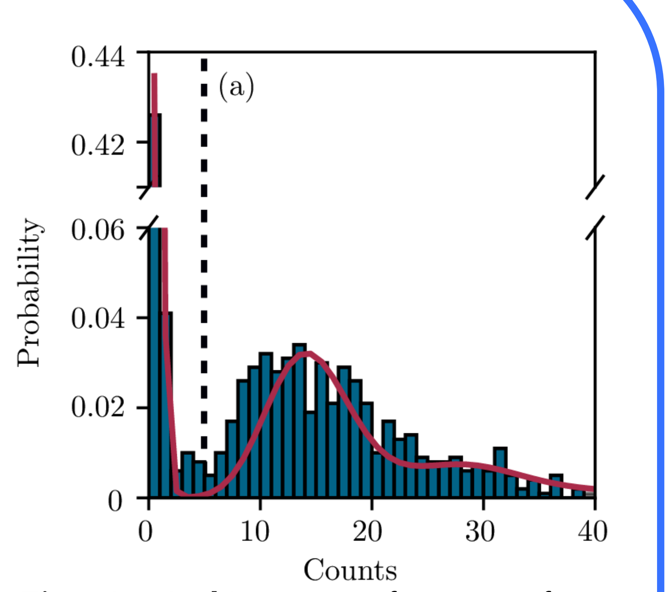
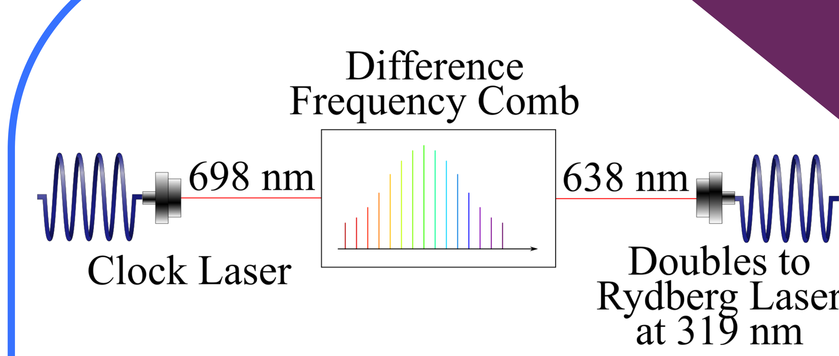
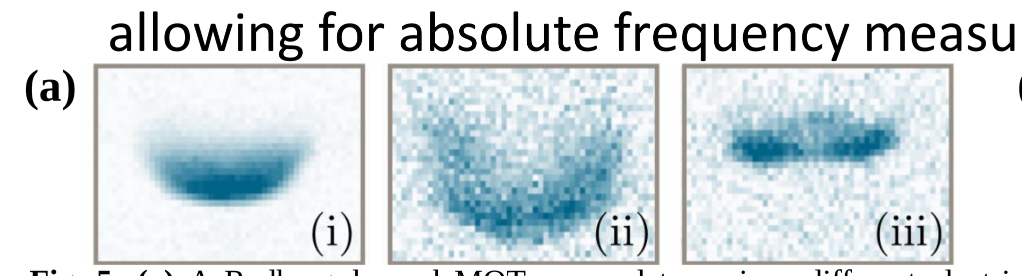


Fig. 4: A histogram of counts for an experimental run (blue bars), with a sub-Poissonian model fitted (red line). Distinct peaks can be resolved for counts associated with 0 and 1 atoms. This figure is taken from [7].

Rydberg Atoms



- We have previously demonstrated Rydberg dressing in a MOT [8]; we now aim to demonstrate this in a tweezer array.
- We want to study properties of Rydberg states, such as the C_6 coefficient [9].
- Our clock and Rydberg laser are referenced to a frequency comb, allowing for absolute frequency measurements [10].



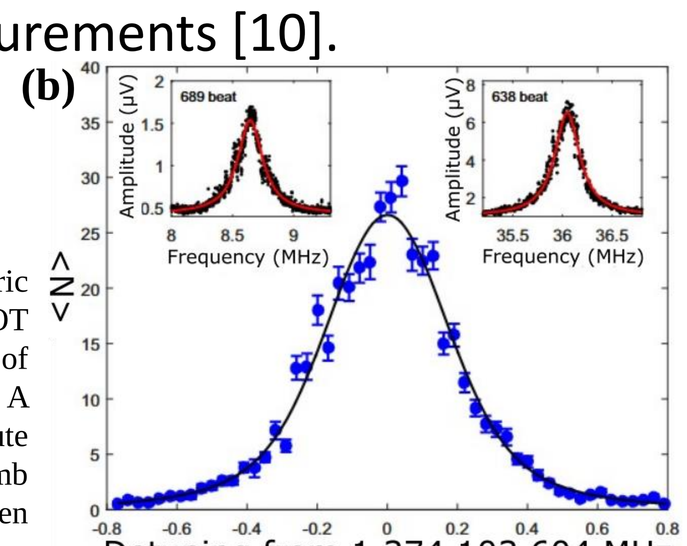


Fig. 5: (a) A Rydberg-dressed MOT exposed to various different electric field strengths: (i) 1.1 V cm^{-1}, (ii) 1.6 V cm^{-1}, and (iii) 2.1 V cm^{-1}. The MOT deforms further as the field strength increases due to the sensitivity of Rydberg atoms to the electric field. This subfigure is taken from [8]. **(b)** A precision Rydberg spectroscopy measurement taken against absolute frequency. The insets show beat frequencies between the frequency comb and the clock (left) and Rydberg (right) lasers. This subfigure is taken from [10].

Clock Physics

- We are about to begin searching for the clock transition.
- The clock transition in ^{88}Sr is $5s^2\ ^1S_0 \leftrightarrow 5s5p\ ^3P_0$.
- The clock transition is forbidden in ^{88}Sr, so a large B field on the order of 10 G is required to magnetically induce the transition.

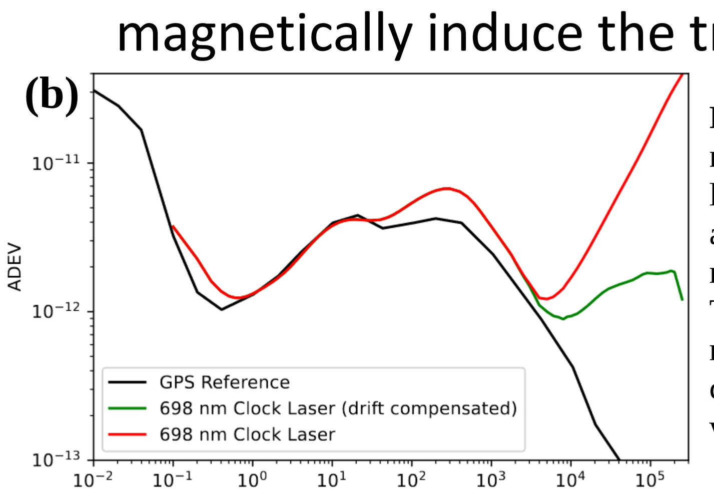


Fig. 6: (a) A photograph of our 698 nm clock laser. This laser has a linewidth of 1 Hz. **(b)** An example of an Allan deviation for our clock laser measured using our frequency comb. The black line is a GPS reference, the red line is without cavity drift compensation, and the green line is with cavity drift compensation.

Outlook

So far, we have successfully demonstrated generation and imaging of arbitrary 2D tweezer arrays of atoms; Rydberg dressing of atoms in a MOT [8]; and detection of single atoms trapped in individual 532 nm tweezers [7].

In order to achieve our goal of spin-squeezing using Rydberg atoms [1], we still need to find and measure the clock transition; reach single atoms in a tweezer array [4,5]; and show Rydberg dressing in an array.

References

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