Beating the standard quantum limit to measure time more accurately

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Summary

Our goal is to push the limits of clock accuracy. We would like to do this by using spin squeezed states in a strontium optical lattice atomic clock. In optical clocks, time is measured by probing an atomic transition in the optical spectrum. This allows for higher accuracy than the microwave atomic clocks used as frequency standards currently can achieve. As the name suggests, an optical lattice is used in optical lattice clocks to tightly confine the atoms, allowing for Doppler-free spectroscopy in the Lamb Dicke regime. To further improve clock performance, we would like to beat the standard quantum limit. By utilizing an optical cavity, we plan to engineer a spin squeezed state of the optical clock transition leading to theoretically achievable spectroscopic gains of up to 26 dB.

Optical atomic clocks

Compared to microwave transitions, optical clock transitions have similar absolute linewidths with higher center frequencies leading to lower fractional frequency uncertainty Δf/f. Therefore they routinely achieve lower uncertainty than clocks employing the microwave transistion of ^{133}Cs currently used as time standard.

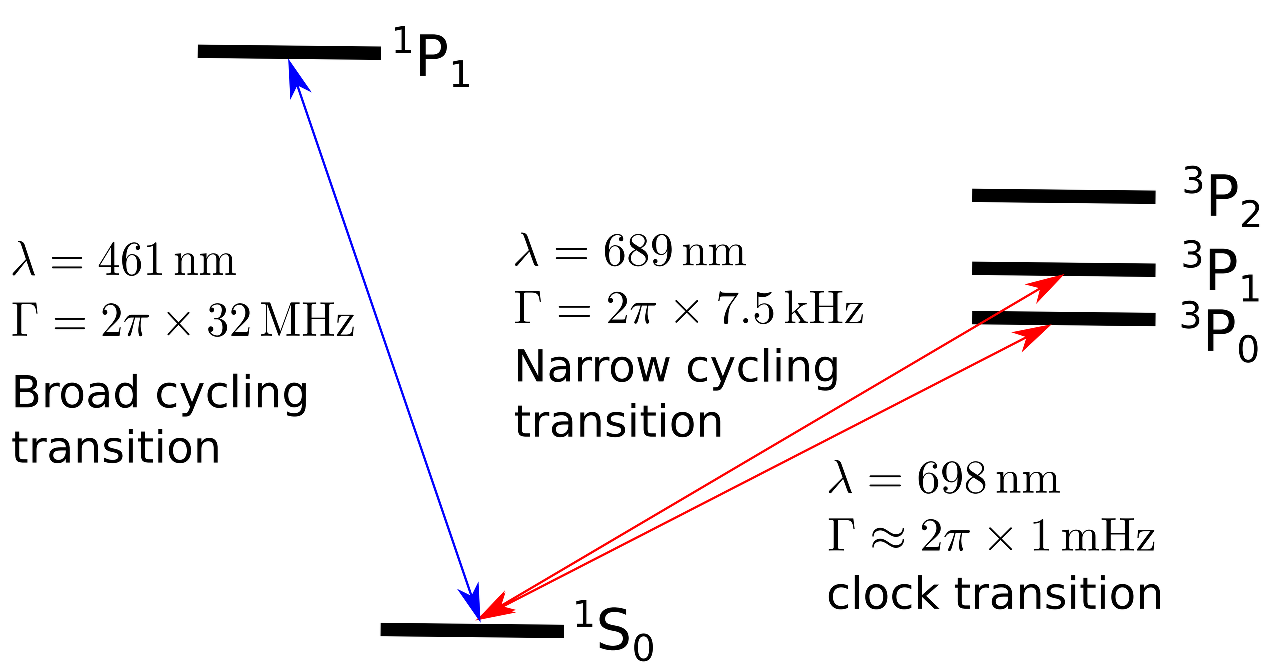
To achieve Doppler free spectroscopy of the clock transition, one has to strongly confine the atoms so that the motional state remains unchanged during probing (Lamb-Dicke regime). The strong confinement can be achieved in ion traps and with strong optical confinement. Traditionally the strong optical confinement was achieved with optical lattices, which will also be used in our work. Another option would be optical tweezer arrays.

To avoid sytematic uncertainties, the energy shift introduced by the trapping light for the clock excited and ground state should be the same so that the frequency of the transition remains unaffected. Wavelengths for which that condition is fulfilled are called "magic wavelengths".

^{87}Sr, the ideal clock atom

- two cycling transition (broad and narrow) for efficient laser cooling
- two magic wavelengths at 505 and 813 nm (used in the experiment)
- a very narrow line clock transition

Simplified level diagram



The standard quantum limit

$|{\downarrow}\rangle$ . . . clock transition ground state (^{1}S$_0$)
$|{\uparrow}\rangle$ . . . clock transition excited state (^{3}P$_0$)

Superposition state for a single atom:

$$|\psi\rangle = \sqrt{1-p}\,|{\downarrow}\rangle + \sqrt{p}|{\uparrow}\rangle$$

N independent atoms in that state:

$$|\Psi\rangle = \bigotimes_{i=1}^{N} |\psi\rangle_i$$

To probe the frequency of the clock transition, the transition is driven with a certain probe frequency and the number of atoms in $|{\downarrow}\rangle$ and $|{\uparrow}\rangle$ is measured.

Measurement outcomes for the number of atoms in the excited state

$$\hat{N}_{\uparrow} = \sum_{i=1}^{N} |\uparrow\rangle_i\langle\uparrow|$$

follow the binomial distribution with expectation value $\langle \hat{N}_{\uparrow}\rangle = pN$ and variance $\langle(\Delta\hat{N}_{\uparrow})^2\rangle = p(1-p)N$, leading to the well known scaling $\sqrt{\langle(\Delta\hat{N}_{\uparrow})^2\rangle} / \langle\hat{N}_{\uparrow}\rangle \propto 1/\sqrt{N}$

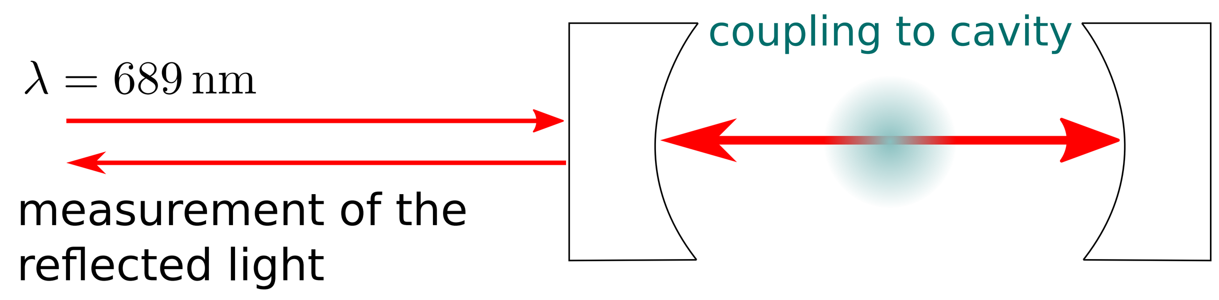
Beating the standard quantum limit

To beat the standard quantum limit, the independence of the different atoms needs to be broken. This can be achieved by interactions between the atoms or by collective measurements.

Direct interactions between the atoms are one possibility, but they also influence the frequency of the clock transition and could therefore lead to systematic uncertainties.

Cavities can be used for collective measurements and cavity mediated interactions. Here a cavity will be used to generate a spin squeezed state and measure the atomic population in the ground state via the vaccum Rabi splitting.

Collective measurement via the Vaccum Rabi splitting



The cavity resonance shows up as a dip in the reflection. If there are atoms in the cavity, the single resonace splits into two. The splitting is proportional to the squareroot of the number of atoms coupling to the cavity (number of atoms in ^{1}S$_0$). The measurement is collective since one cannot tell which atom of the cloud interacts with the cavity mode. The collective measurment prepares the atoms in a squeezed state which can subsequently be used in a Ramsey sequence.

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Max-Kade fellowship project

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