Spin Squeezed $^{171}$Yb Atomic Clock beyond the Standard Quantum Limit

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Introduction
State of the art optical lattice clocks have the relative uncertainty of $10^{-18}$, and are rapidly approaching the standard quantum limit (SQL) of the quantum projection noise. This limit has been overcome with a spin squeezed atomic clock on a microwave transition. We apply this technique to optical transition and try to exceed the SQL in an optical lattice clock of visible light transition to expand the boundaries of precision time metrology.

Spin Squeezing
An ordinary coherent ensemble of independent two level systems has an uncertainty distribution symmetric with respect to the population difference and phase directions. With spin squeezing, which is essentially a correlated behavior of many entangled spins, we can distort the error distribution and get smaller uncertainty in a certain direction, with an increased uncertainty in the other direction.

Spin Squeezed clock
Time measurement by an atomic clock is the fine tuning of a local oscillator (i.e., a laser) to a very narrow transition called a clock transition. This is performed by a measurement of phase difference between the local oscillator and the atomic transitions. This is most easily accomplished using a Ramsey sequence where the atoms are placed in an equal superposition of the ground and excited states. With spin squeezing, we can reduce the phase uncertainty => smaller noise in phase measurement => better precision.

Cavity Feedback Squeezing
Relevant Hamiltonian:
$$H = \hbar \gamma S_z^2$$
We get this term using a high finesse cavity probed with light of large detuning. Cavity around atoms + light detuned from a transition
$$\rightarrow AC \text{ Stark shift per atom } \propto \text{ photon number in cavity } \propto \text{ atom number}$$
$$\rightarrow H \propto S_z^2$$
On Bloch sphere, rotation in phase direction is proportional to $S_z$.

Effect of $S_z$ Hamiltonian on a coherent spin state

Cavity Design
Asymmetric cavity with micro mirror
Modeled Finesse of the Cavity
$\mathcal{F} \approx 25,000$ for squeezing laser
$\mathcal{F} \approx 3,200$ for trapping laser
Expected Atom number $\sim 10^{6}$

Why asymmetric cavity?
Important factor: Coefficient
$$\eta = \frac{4g^2}{\kappa \Gamma} = \frac{24 \mathcal{F}}{10^4 \kappa^2 \Gamma^2} \quad (\text{for single atom})$$
High cooperativity (especially $\eta \gg 1$, strongly coupled limit)
⇒ interesting states even beyond squeezed state

Asymmetric Cavity: High cooperativity + sufficient space for laser and atomic beam access

Lasers
399 nm: ECDL with DAVLL lock
556 nm: fiber laser + SHG
578 nm: IR laser (DFB+LD) + SHG
759 nm: DBR laser
1389 nm: DFB laser
556, 578 nm: locked to ultrastable cavity
IR laser for 578nm and 759nm laser have narrowing system with optical feedback from a long external cavity.

Other Recent Progress
- Cooling by 399 nm laser/installing ultrastable cavity
- Optimizing main cavity properties
- Oven and heated window have been improved.
- Trying to get trapped atoms.
- Establishing the controlling system.
- Once we have atoms trapped and install the cavity, we can start the experiment.

Reference