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Spin squeezing and metrology on the cesium clock transition beyond the projection noise limit

Optical atomic clocks based on neutral atoms [1] are about to become the most precise measurement instruments ever constructed. They measure the frequency of radiation that drives a transition between two long-lived atomic states in an ensemble of cold atoms. Quantum projection noise ultimately limits the precision with which this frequency can be measured. Its origin are quantum mechanical fuctuations in the outcomes of thousands simultaneously executed measurements that determine the internal state of each atom in the ensemble.

The objective of our experiment is to prepare the atoms in a specific collective quantum mechanical state (a so called entangled state), which possesses non-classical correlations amongst the atoms such that the measurements of the average atomic internal state displays a reduced noise.

In 2009 we demonstrated how to generate such an entangled state by performing quantum-non-demolition (QND) measurements on an optically dense cloud of $N = 10^5$ cold cesium atoms. We achieved a degree of squeezing that in principle would allow for an improvement of the precision of our atomic clock by > 3 dB. In June of 2009 this work was published in the Proceedings of the National Academy of Science [2]. Since then our work was targeted towards using the entangled state to actually perform a clock measurement beyond the projection noise limit.

A projection noise limited atomic clock operating with N atoms can can measure phase fluctuations of a reference oscillator with a precision of $1/\sqrt{N}$. For our atomic microwave clock this corresponds to a phase uncertainty of only $\delta\varphi = 0.18°$. Since we learned that especially on short time scales the precision of our atomic clock exceeded that of our microwave reference oscillator by orders of magnitude, a key step in the implementation of the squeezing augmented clock sequence was the construction of a low phase-noise microwave synthesizer chain: A dielectric resonator oscillator is phase-locked to an oven stabilized quartz oscillator which itself is slowly referenced to the atomic clocks of the Global Positioning System (GPS). By combining this oscillator with a direct digital synthesis (DDS) board we now can shape our microwave pulses with a precise timing of 4 ns steps and control their phase digitally and precisely.

With this versatile source we then systematically investigated the influence of inhomogeneous microwave coupling and took first steps towards a quantum-tomographic analysis of the spin squeezed state that we prepared. We developed a tomography microwave pulse sequence that is robust against to coupling inhomogeneities and improved our bichromatic QND measurements [2] by changing the interferometer configuration [3, 4] that is used to dispersively probe the atomic populations in the lock levels.

Finally we developed a modified Ramsey-sequence to measure the atomic transition frequency and implemented a full clock-protocol that takes advantage of the reduced projection noise that spin-squeezing can provide: Over a short integration time the squeezing enhanced atomic clock performs better by 1.1 dB compared to using standard Ramsey spectroscopy [5]. In fact, the phase sensitivity of our clock is so high that already with an interrogation time of less than 100 μs we can resolve fluctuations of the clock-transition frequency by 7:5 Hz between successive experimental cycles that are ≈ 5 s apart. We attribute this technical noise mainly to instabilities in the trapping potentials. In an ongoing effort we are replacing the old trapping laser for a fiber laser and are hoping to increase our trap lifetime and to decrease the intensity noise. However, since no “magic" trapping wavelengths for the Cesium clock states exist, trap induced level shifts most likely will remain a precision limiting factor.

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