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Optical atomic clock based on entangled quantum states of trapped ^{40}Ca^{+} ions

Nowadays, optical atomic clocks based on trapped ions regularly reach relative systematic uncertainties in the region of 10^{-18}. This resolution can be used to resolve height differences in geodesy and for the search for variation of fundamental constants, dark matter coupling to classical matter, or other new physics concepts [1], [2]. The fundamental quantum projection noise (QPN) limits frequency resolution of a single ion resulting in long averaging times to reach the systematic uncertainty level. This can be decreased by prolonging the interrogation time between the atomic system and the clock laser or scaling the number of ions being probed simultaneously. A third method is the use of entangled quantum states. However, it is still under investigation which measurement protocol based on entangled quantum states improves the statistical uncertainty compared to classical measurements and in the presence of noise and spontaneous decay [3], [4], [5]. Here we focus on the applicability of entanglement within a clock measurement scheme, investigating the region of sub-lifetime interrogation times on a two-particle maximal entangled state. Two ^{40}Ca^{+} ions are stored within a segmented linear Paul trap, cooled close to the ground state of motion by electromagnetic-induced transparency and resolved sideband cooling. The ions are prepared with a single-ion addressing beam into two opposing Zeeman states of the S$_{-1/2}$ ground state. Using a Cirac-Zoller gate, a Ramsey-like interferometer is opened, which is employed to measure the phase evolution of a superposition of two-ion Green-Horn-Zeilinger (GHZ) states against the clock laser. The accumulated phase is mapped onto GHZ states of different parity. We compare this scheme against a classical variant of this experiment, where the correlation between two independent Ramsey interferometers is used [6]. The phase evolution of the two ion states is protected against common-mode magnetic field noise, enhancing the coherence time of the GHZ-state close to the natural lifetime limited of those states (550 ms). These so-called decoherence-free substates (DFS) are prepared with a fidelity of greater than 95 %, mostly limited by the single ion addressing performance and the high-frequency phase noise of the clock laser. A clock servo operation is implemented with the measured parity signal. The frequency stability of the parity signal was measured against the ^{87}Sr lattice clock at PTB [7], demonstrating a stability of 6.2 $\cdot 10^{-16}\sqrt{\frac{\tau}{1s}}$. This statistical uncertainty is still limited by technical noise, mostly fiber length fluctuations within the path of the clock laser to the experiment. In future experiments we aim for a demonstration of a purely quantum projection noise limited stability.

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