Precision Time Measurement and a Novel Two-Photon Clock Scheme

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Abstract: We propose a novel two-photon excitation scheme for the $^{1}S_0 \rightarrow ^{3}P_0$ optical clock transition that works in the absence of hyperfine structure and applied magnetic fields. Experimental progress in Hg is discussed.

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The frontiers of precision time measurement in atomic clocks have been rapidly advancing in the last decade [1, 2, 3, 4, 5, 6]. Improvements in frequency standards advance metrology for everyday applications such as GPS and for tests of fundamental physics. Current optical-frequency atomic clocks based on the electric dipole $E1$ forbidden $^{1}S_0 \rightarrow ^{3}P_0$ transition require either hyperfine structure or an applied magnetic field to induce mixing of the $^{3}P_0$ and $^{3}P_1$ levels. This reduces the lifetime of the $^{3}P_0$ level and thus the fundamental resolution of the clock. We propose an excitation scheme utilizing a two-photon excitation coupling the $^{1}S_0$ ground state to the $^{3}P_0$ clock state through an allowed $E1$ and $M1$ excitation sequence. Utilizing a two-photon transition with counter-propagating laser beams eliminates the first-order Doppler-broadening and thus permits the use of a hot vapor cell of Hg atoms. This largely increases the number of atoms addressed compared to ion frequency standards [1, 2, 3, 4] and introduces simpler initial state preparation compared to neutral frequency standards that employ an optical lattice [5, 6].

The transition rate using this two-photon excitation scheme is given by:

$$ R_{2\gamma} = \frac{N \frac{4 I^2}{\hbar^2 c^2 \epsilon_0^2} \langle ^{3}P_0 | \mu | ^{3}P_1 \rangle^2 \frac{\langle ^{3}P_1 | d | ^{1}S_0 \rangle^2}{\Gamma \Delta^2} \approx N \frac{I^2}{\Gamma} \times 10^{-10} $$

where $N$ is the number of atoms sampled, $I$ is the excitation laser intensity, $\langle ^{3}P_0 | \mu | ^{3}P_1 \rangle$ is the magnetic dipole matrix element, $\langle ^{3}P_1 | d | ^{1}S_0 \rangle_{E1}$ is the electric dipole matrix element, $\Gamma$ is the experimentally broadened linewidth of the transition, and $\Delta$ is the detuning of an excitation photon’s energy from the intermediate $^{3}P_1$ level. It is experimentally feasible to achieve $I > 10^{10} \frac{W}{m^2}$, and $N > 10^8 \#$. In the first phase of this experiment we anticipate $\Gamma \ll 10^8 [Hz]$ and expect to detect transitions at a rate of a few Hertz.

To drive the $^{1}S_0 \rightarrow ^{3}P_0$ transition in neutral Hg we have developed a high power, narrow linewidth laser system at 531 nm. A fiber amplified 1062nm laser has been doubled using a PPMgO:SLT crystal to produce CW powers of 5.5 W. Population in the metastable $^{3}P_0$ level can be detected using an NH$_3$ buffer gas which induces $^{3}P_0$ relaxation [7]. The presence of NH$_3$ broadens the transition linewidth but serves as an expedient tool to determine clock state population and demonstrate the viability of this clock scheme. An alternate, non-broadening detection scheme involves sampling the $E1$ allowed $^{3}P_0 \rightarrow ^{3}S_1$ transition.

References