Cancellation of the Cold Collision Frequency Shift in an ^{87}Rb Clock by Cavity Pulling

Chad Fertig and Kurt Gibble

Department of Physics, P. O. Box 208120, Yale University, New Haven, CT 06520-8120

Laser cooling offers many benefits for atomic clocks, especially narrower linewidths and smaller Doppler shifts. Unfortunately, the large deBroglie wavelengths of atoms at μK temperatures leads to often large collision cross sections. The SI second is based on the ground state hyperfine transition in Cs. This transition has a particularly large frequency-shift collision cross-section[1] due to resonances in both the triplet and singlet scattering channels. The large frequency shift cross section demands that laser-cooled Cs clocks operate at low densities to achieve high accuracy. This reduces the short-term stability, lengthening the averaging time needed to achieve the clock's accuracy [2]. We demonstrate a laser-cooled ^{87}Rb fountain clock and report a measurement of a small cold-collision frequency shift. Because the shift is small, we can cancel it by detuning a microwave cavity in the clock allowing an ^{87}Rb clock to run at higher density, achieving greater short-term stability and accuracy simultaneously.

Our clock has a short-term stability of $\delta\nu/\nu{=}2.6{\times}10^{-13}$ for 1 s of averaging, which is limited by our quartz local oscillator. To measure the cold collision shift, we vary the atomic density on successive fountain launches and look for a relative shift of the Ramsey fringes. In Fig. 1(a) we show a series of measurements of the frequency as a function of density(circles) for atoms prepared in both $|1,0\rangle$ and $|2,0\rangle$. The extrapolated shift for a density of $1.0(6){\times}10^9\mathrm{cm}^{-3}$ is $-0.38(8)$ mHz. We also show the shift for Cs [1] which is 30 times larger. The measured shift agrees with that calculated in [3] and also a recent reanalysis of the ^{87}Rb interactions.

The only other clock error that is explicitly density dependent is the pulling of the transition frequency by the coupling of the atoms to the microwave cavity. When the cavity is detuned from the atomic transition frequency, the magnetic field radiated by the atoms is phase shifted relative to the field in the cavity. The Bloch vector precesses about the total field leading to a precession rate of the phase proportional to $\mu_0\hbar\mu_{\mathrm{B}}^2\mathrm{N}\omega\delta/(\delta^2+\Gamma^2)\mathrm{V}_{\mathrm{cav}}$ [6]. Here, N is the number of atoms, ω is the transition frequency, δ is the cavity detuning, Γ is the cavity HWHM, $\mathrm{V}_{\mathrm{cav}}$ is the effective cavity volume, and μ_{B} is the Bohr magneton.

In Fig. 1(a) we also show the measured density dependent frequency shift when we detune the clock cavity by $\pm\Gamma$ for atoms prepared in $|1,0\rangle$ (diamonds and squares). The cavity detuning can significantly influence the density dependence. By detuning the cavity (inset), we cancel the cold collision shift when atoms are prepared in $|1,0\rangle$ giving a long-term immunity to variations in the number of atoms.

We show the cavity pulling effects in Fig 1(b). We plot the density dependent shift versus the atomic transition probability during the first cavity passage for $\mathrm{n}{=}10^9\mathrm{cm}^{-3}$. For a cavity tuned below the atomic resonance, $\delta{=}{-}\Gamma$, and atoms prepared in $|1,0\rangle$, the frequency shift is positive and large for a small transition probability (open squares and dashed line). When the

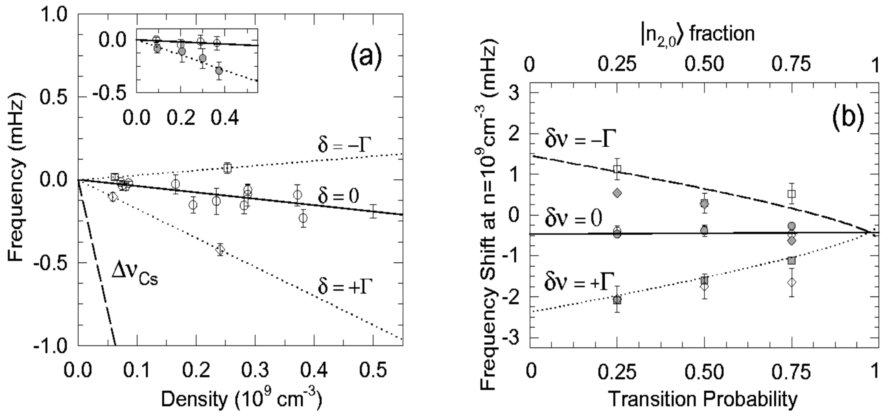

Figure 1: (a)Measured ^{87}Rb cold collision shift (circles and solid line). The shift is -0.38(8) mHz for a density of 1.0(6)×10$^9 cm^{-3}$. The dashed line is the shift for Cs[1]. The dotted lines (diamonds and squares) show the density dependence for clock cavity detunings of δ=±Γ. Inset shows a cancelled (larger) density dependent shift for $\delta = -30$kHz for atoms prepared in $|1,0\rangle(|2,0\rangle)$. (b)Density dependent shift versus transition probability on each clock cavity passage for cavity detunings of $\delta = +\Gamma$ (diamonds and dotted) and -Γ (squares and dashed line). Open (filled) data points are for atoms prepared in $|1,0\rangle$ ($|2,0\rangle$). For δ=0, the circles and solid line are plotted versus the fraction of atoms in $|2,0\rangle$ in the fountain, giving the individual shift contributions from $|1,0\rangle$ and $|2,0\rangle$.

atoms are prepared in $|2,0\rangle$, the filled squares show a large negative density dependent shift for a small transition probability. The dotted line and open (filled) diamonds show the opposite density dependence for δ=+Γ, and $|1,0\rangle$ ($|2,0\rangle$) state preparation. We measure the cavity response using the AC Zeeman shift of the clock states due to a strong microwave sideband[5].

The cancellation of the small cold collision shift will allow ^{87}Rb clocks to simultaneously achieve an accuracy of 1×10^{-17} and high short-term stability of 1.8×10^{-14}. Juggling atoms by launching every 45 ms[7] can increase the short-term stability to 4×10^{-15} for 1 s of averaging, giving an unprecedented combination of stability and accuracy.

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