Measurement and Cancellation of the Cold Collision Frequency Shift in an ^{87}Rb Fountain Clock

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We measure a cold collision frequency shift in an ^{87}Rb fountain clock that is fractionally 30 times smaller than that for Cs. The shift is $-0.38(8)$ mHz for a density of $1.0(6) \times 10^9$ cm^{-3}. We study the cavity pulling of the atomic transition and use it to cancel the cold collision shift. We also measure the partial frequency shifts of each clock state finding $2(\lambda_{10} - \lambda_{20})/(\lambda_{10} + \lambda_{20}) = 0.1(6)$.

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Supercooled atomic gases offer many benefits for precision measurements, especially for atomic clocks. The principal benefits are narrower linewidths and smaller Doppler shifts [1]. Unfortunately, the large de Broglie wavelengths of atoms at μK temperatures lead 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 due to resonances in both the triplet and singlet scattering channels [2,3]. 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 realize the clock's accuracy [4].

Here we demonstrate a laser-cooled ^{87}Rb fountain clock and report a measurement of a small cold collision frequency shift. A remarkable persistence of an ^{87}Rb Bose-Einstein condensate in two spin states showed that the singlet and triplet scattering lengths should be nearly equal [5]. Therefore, a shift an order of magnitude smaller than that for Cs is expected [6,7]. Here we measure a small shift and, because it is small, we can cancel it by detuning a microwave cavity in the clock. Thus, an ^{87}Rb clock can run at higher density, achieving greater short-term stability and accuracy simultaneously.

A schematic of our ^{87}Rb fountain clock is shown in Fig. 1. Using 0.9 W of light from a Ti:sapphire laser delivered by an optical fiber, atoms are collected from the room temperature Rb vapor in the vapor-cell magneto-optical trap (MOT). The atoms are launched upwards and cooled to 1.8 μK in the moving frame. The atoms then pass through two microwave cavities that are normally used to prepare half of the atoms in the $5S_{1/2}|F = 1, m_F = 0\rangle$ state [8]. Here, to achieve high density, the selection cavities are not used; instead, we optically pump the atoms into $|1,-1\rangle$ just below the clock cavity. We use successive pulses of circularly polarized light from diode lasers tuned to the $5S_{1/2}$ $F = 2 \rightarrow 5P_{3/2}$ $F' = 1'$ and $1 \rightarrow 1'$ transitions. Microwaves from a horn transfer atoms from $|1,-1\rangle$ to $|2,0\rangle$ while a 35 mG horizontal magnetic field is applied along the direction of the optical pumping beams. A vertical magnetic field of 3.5 mG is then applied below the clock cavity as the horizontal field is switched off. Microwaves from the horn transfer a variable number of atoms from $|2,0\rangle$ to $|1,0\rangle$. Any atoms remaining in $F = 2$ are cleared with light tuned to the $2 \rightarrow 3'$ transition. In this way, we can vary the density, preparing a maximum of 70% of the atoms in $|1,0\rangle$ at a temperature of 5 μK with fewer than 1% in $|1,\pm 1\rangle$. To prepare the atoms in $|2,0\rangle$, we add another microwave pulse to transfer the atoms in $|1,0\rangle$ to $|2,0\rangle$ and then repump any atoms in $F = 1$ with light tuned to $1 \rightarrow 2'$.

The state prepared atoms enter the magnetic shielding and experience a 6.8 GHz microwave pulse in the rectangular TE_{102} clock cavity, creating a coherent superposition of $|1,0\rangle$ and $|2,0\rangle$. This coherence precesses as the atoms are slowed by gravity and return through the clock cavity. The second microwave pulse converts the phase

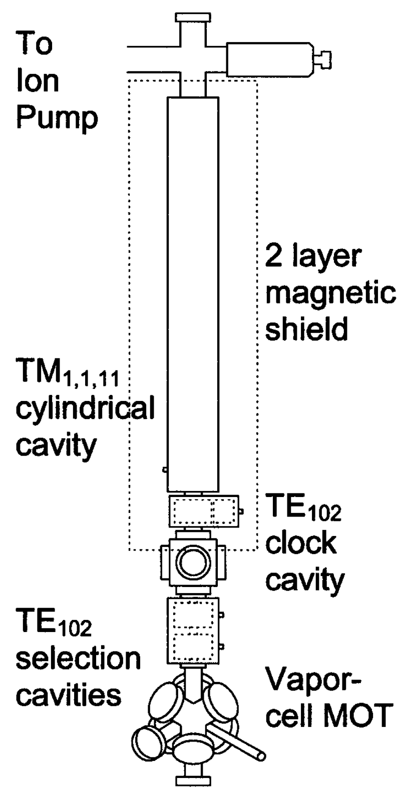

FIG. 1. Schematic of the ^{87}Rb fountain clock.

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difference between the atomic coherence and the microwave field into a population difference. We detect the transition probability using a laser tuned to $2 \rightarrow 3'$ producing Ramsey fringes as in Fig. 2. To normalize the fringes, we also detect the total number of atoms by repumping the population in $|1,0\rangle$ using a laser beam tuned to $1 \rightarrow 2'$, followed by a second detection laser pulse. The time between the microwave interactions in Fig. 2 is $T = 0.526$ s which gives a linewidth of $\Delta\nu = 0.950$ Hz. With our detection signal-to-noise $S/N = 500$ on a single launch, the atomic frequency can be determined in 1 s with a precision of $\delta\nu/\nu = \Delta\nu/\pi\nu S/N = 9 \times 10^{-14}$. However, the short-term instability of the local oscillator limits S/N to 200 or $\delta\nu/\nu = 2.1 \times 10^{-13}$ for 1 s of averaging.

During the precession time above the clock cavity, collisions between cold atoms shift the phase of their coherence, producing a frequency shift of the clock. To measure this frequency shift, we vary the atomic density on successive fountain launches and look for a relative shift of the Ramsey fringes. In Fig. 3 we show the frequency as a function of density (circles) for atoms prepared in both $|1,0\rangle$ and $|2,0\rangle$ [9]. The extrapolated shift for a density of $1.0(6) \times 10^9$ cm^{-3} is $-0.38(8)$ mHz. We also show the shift for Cs which is fractionally 30 times larger [2]. The measured shift agrees with that calculated in [6] and also recent reanalyses of the ^{87}Rb interactions [10,11].

The measured frequency differences in Fig. 3 have a precision of $\pm 2 \times 10^{-15}$. At the 10^{-15} level, there are several potential error sources. The only source that is explicitly density dependent is the pulling of the transition frequency by the coupling of the atoms to the microwave cavity [12]. In NMR, the effect is known as radiation damping where the field radiated by the magnetization of the sample builds up in the microwave cavity causing the Bloch vector to decay [13]. In hydrogen masers, the effect is called cavity pulling and is used to cancel the collisional frequency shift [14]. Here, more apparent than the decay of the atomic coherence is a small phase shift. When cavity is detuned from the atomic transition frequency, the 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 phase shift proportional to $\mu_0 \hbar \mu_B^2 N \omega \delta/(\delta^2 + \Gamma^2) V_{cav}$ [15]. Here, N is the number of atoms, ω is the transition frequency, δ is the cavity detuning, Γ is the cavity HWHM, V_{cav} is the effective cavity volume, and μ_B is the Bohr magneton.

In Fig. 3 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 intentionally detuning the cavity to $\delta = -30$ kHz, the density dependence is canceled (larger) for atoms prepared in $|1,0\rangle$ ($|2,0\rangle$). This has advantages for ensuring immunity to long-term variations in the number of trapped atoms. Moreover, density extrapolations can be more accurate since the extrapolation does not depend on accurate density ratios [16].

We observe several unique characteristics of the cavity pulling. For example, it not only reverses with the cavity detuning δ but also with the initial population inversion of $|1,0\rangle$ and $|2,0\rangle$. The cavity pulling also depends on the transition probability during each cavity passage. For a 0.5 transition probability on the first interaction ($\pi/2$ pulse), $\delta > 0$ pulls the frequency lower (higher) for atoms prepared in $|1,0\rangle$ ($|2,0\rangle$). On the second $\pi/2$ pulse, if the microwave frequency is tuned to the side of a Ramsey fringe,

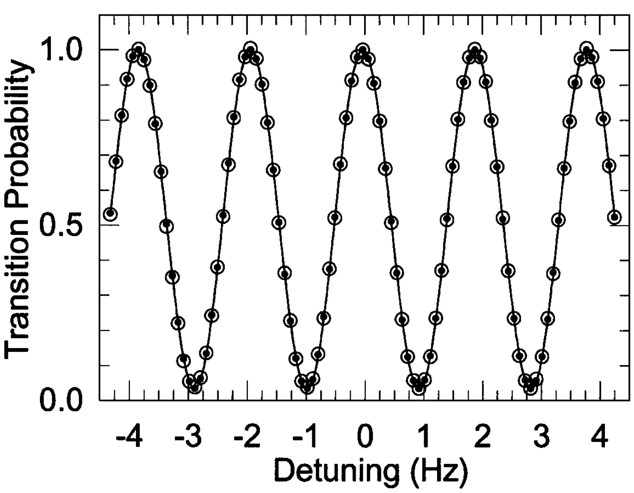

FIG. 2. ^{87}Rb Ramsey fringes at 6.834 GHz. The large circles are the data and the small are a fit to the data. The linewidth is 0.95 Hz.

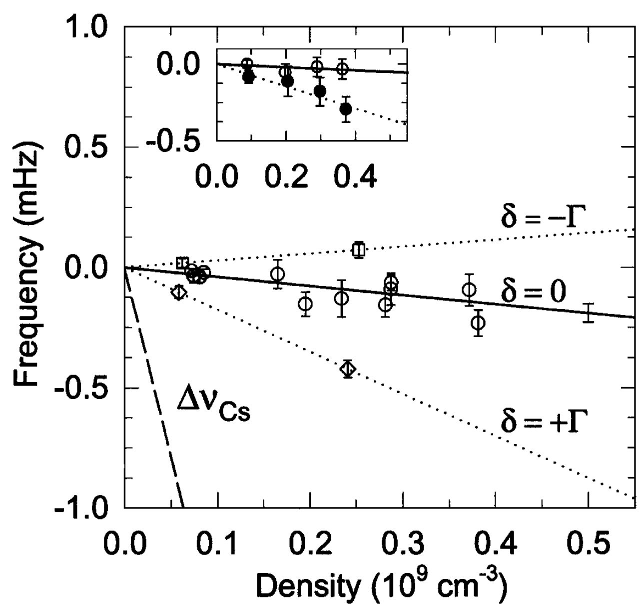

FIG. 3. Measured ^{87}Rb cold collision shift (circles and solid line). The shift is $-0.38(8)$ mHz for a density of $1.0(6) \times 10^9$ cm^{-3}. The dashed line is the shift for Cs [2]. The dotted lines (diamonds and squares) show the density dependence for clock cavity detunings of $\delta = \pm\Gamma$. Inset shows a canceled (larger) density dependent shift for $\delta = -30$ kHz for atoms prepared in $|1,0\rangle$ ($|2,0\rangle$).

the microwave field is phase shifted by $\pi/2$ so that it is parallel or antiparallel to the Bloch vector. Therefore, the Bloch vector does not precess and the cavity pulling has no first order effect during the second interaction. For a transition probability of 0.25 on both passages (0.33π pulse), the cavity pulls in the same direction during both passages since the Bloch vector precesses during both. However, the effect of the second passage is small because the number of atoms is 8 times less due to their ballistic expansion. For a transition probability of 0.75 (0.67π pulse), the first cavity passage has a small effect as the Bloch vector is first perturbed in one direction as it precesses to $\Theta = \pi/2$ and then the direction of the perturbation reverses once there is a population inversion. On the second passage, the perturbation remains reversed and the total pulling is small.

We show the cavity pulling effects in Fig. 4. We plot the density-dependent shift versus the atomic transition probability during the first cavity passage for $n = 10^9$ 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). For atoms 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 $\delta = +\Gamma$, and $|1,0\rangle$ ($|2,0\rangle$) state preparation.

To model the data in Fig. 4, we account for the different cold collision frequency shifts λ_{10} and λ_{20} due to the $|1,0\rangle$ and $|2,0\rangle$ populations, and the cavity pulling. For no cavity pulling ($\delta = 0$), we do not see a shift as a function of the population in $|2,0\rangle$ during the precession time. We model the 18 measurements in Fig. 4 accounting for the partial frequency shift cross sections and the cavity pulling by integrating the time evolution of the Bloch vector as the atom passes through the microwave field profile of the clock cavity. The model agrees, and we find $2(\lambda_{10} - \lambda_{20})/(\lambda_{10} + \lambda_{20}) = 0.1(6)$. This helps to constrain the ^{87}Rb interactions; a recent examination suggests either -1.63 or 0.08 [10].

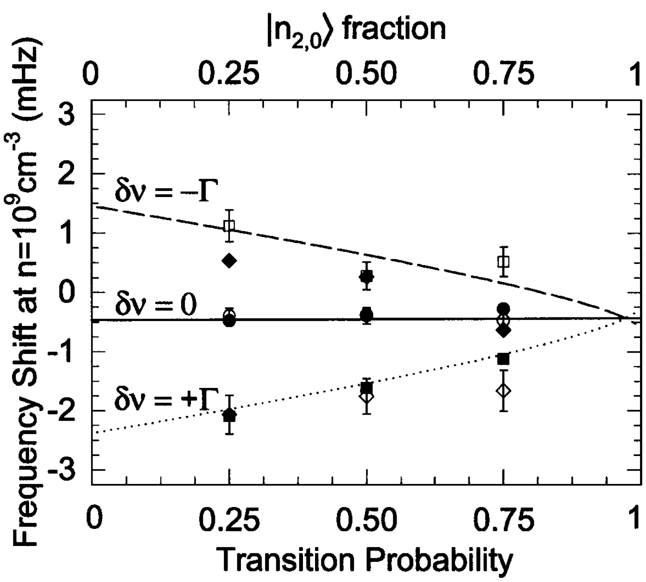

FIG. 4. Density dependent shift versus transition probability on a single clock cavity passage for clock cavity detunings of $\delta = +\Gamma$ (diamonds and dotted line) and $-\Gamma$ (squares and dashed line). Open (filled) data points are for atoms prepared in $|1,0\rangle$ ($|2,0\rangle$). For $\delta = 0$, 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 $|2,0\rangle$. Typical error bars are shown for open points.

We tune the clock cavity by $\delta = \pm\Gamma$ by changing its temperature by ∓ 2.5 K. To measure the frequency response of the cavity, we use the ac Zeeman shift of the clock states due to a strong microwave sideband [8]. The loaded Q of our copper clock cavity is 13 000 ($\Gamma = 251$ kHz), and it is tuned with an accuracy of 5 kHz [17].

Although cavity pulling and the cold collision shift are the only systematic errors that explicitly depend on the atomic density, it is important to control all errors near the level of 10^{-15}. Our frequency reference is a 5 MHz quartz oscillator that is successively frequency multiplied and then mixed with a low frequency synthesizer to make 6834.6 MHz. Considerable care is taken to avoid line pulling by spurious frequencies and 60 Hz phase modulation [18]. We test for line pulling and microwave leakage by observing the clock frequency while driving $\pi/2$, $3\pi/2$, ..., $11\pi/2$ pulses and also adjust the fringe spacing to be most sensitive to 60 Hz harmonics. These effects are below 8×10^{-16} and the density dependent component is below 1×10^{-16}. Inhomogeneities in the state preparation can combine with other errors, such as the distributed cavity phase shift, to mimic a density-dependent frequency shift. To probe this, we select atoms with $\pi/2$, ..., $9\pi/2$ pulses from the microwave horn and find no shifts at the level of 7×10^{-16}. Further, we take data by selecting 1/4 of the atoms with both 0.33π and 1.67π pulses. The quadratic Zeeman shift from the 710 μG bias field shifts the clock's frequency by 4.3×10^{-14}. Over the top 4 cm of the fountain, the field is homogeneous over the volume sampled by the atoms to 1 μG and the gradient is less than 20 μG/cm producing systematic errors less than 1×10^{-16}. Finally, we check for an ac Stark shift due to the lasers and find the density dependent component to be below 2×10^{-16}.

The atomic density is measured using laser absorption. An attenuated 1 mm laser beam is apertured, aimed vertically through the center of the clock cavity, and then centered on the ball of atoms. We frequency scan a 50 μs pulse over 40 MHz near the $2 \rightarrow 3'$ transition at 9 times throughout the fountain trajectory. We measure the vertical size of the atomic sample on the upward and downward passages through the detection region, with and without state preparation. We model the evolution of the atomic density as a ballistic expansion of uncorrelated Gaussian velocity and spatial distributions and account for the heat added during the state preparation. We calculate the time-averaged density for the atoms that we detect below the clock cavity. This effective density depends on the transverse velocity and spatial distributions, and we extract this information from the time evolution of the vertical optical thickness of the sample. Without independent corroboration, it is difficult to be certain about the absolute density scale to better than 60%. With convincing experimental tests of our model of cavity pulling, the cavity pulling could be used to measure accurately and independently the atomic density.

Intentional detuning of the microwave cavity is widely used in hydrogen masers to cancel the spin-exchange frequency shift due to collisions [14]. For masers, this spin-exchange tuning is not complete. The hyperfine shift in both room-temperature and cryogenic H masers arises because the collisions not only modify the frequency, but also the linewidth. This leads to a quadratic density dependence of the frequency that cannot be entirely canceled by cavity tuning [19]. For fountains, the cold atoms do not diffuse during the precession time so that the atomic linewidth is essentially determined only by the transit broadening [20]. However, the collision shift is proportional to the time-averaged density throughout the fountain, whereas the cavity pulling is proportional to the number of atoms, and essentially only during the first cavity passage. Therefore, spin-exchange tuning in a fountain does not rigorously cancel the collision shift. Nonetheless, spin-exchange tuning will enhance the stability and accuracy of laser-cooled fountain clocks because the time-averaged density is correlated with the number of atoms for three reasons: (1) Much of the collision shift occurs just after the first cavity passage when the density is high; (2) fluctuations in the number of atoms are correlated with the initial atomic volume; and (3) the temperature is typically more stable than the number of atoms. In future designs, one could include a few varactor-tuned dormant cavities in the precession region above the clock cavity with appropriate apertures to cancel the cold collision shift over a suitably wide range of trapped atom densities and temperatures [21].

The small cold collision shift will allow ^{87}Rb clocks to simultaneously achieve high accuracy and high short-term stability. Using our state selection cavities instead of optical pumping, and making the source more diffuse and weaker, will reduce the average density in the fountain by a factor of 100. With a 15 mm diameter cavity aperture, we can detect 7×10^6 atoms per launch yielding a short-term stability of 1.8×10^{-14}. This will produce an uncanceled collision shift of 2×10^{-16} that can be canceled with a likely accuracy of 1×10^{-17}. Juggling atoms by launching every 45 ms [22] 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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Note added.—Y. Sortais *et al.* have also measured the collision shift for ^{87}Rb to be $-0.05(18)$ mHz for $n = 10^9$ cm^{-3} [23].

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