Special Issue Papers

^{87}Rb Versus ^{133}Cs in Cold Atom Fountains: A Comparison

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(Invited Paper)

***Abstract*—We describe the operation of a laser cooled ^{87}Rb frequency standard and present a new measurement of the ^{87}Rb ground state hyperfine frequency with a relative accuracy of 2.4×10^{-15}, by comparison with a Cs fountain primary standard. The measured frequency is 6 834 682 610.904 333(17) Hz. An evaluation of the frequency shift induced by cold collisions gives $\Delta\nu/\nu_{Rb} = (-7.2 \pm 20) \times 10^{-24}\overline{n}$, where $\overline{n}$ is the average atomic density in cm^{-3}. With our present 1σ uncertainty of 10^{-15}, this measurement is still compatible with 0 and about 300 times smaller than for ^{133}Cs. We also report a test of a possible variation of the fine structure constant at the level of 2.7×10^{-14}yr^{-1}, comparing Rb and Cs cold atom fountains.**

I. Motivation

The construction of an atomic fountain operating with ^{87}Rb atoms has been motivated by two reasons. First, the collisional shift was predicted to be 15 times lower for ^{87}Rb than for ^{133}Cs [1]. Recent attempts to measure it tend to show that it should be even smaller, making its absolute evaluation an interesting challenge [2], [3]. As far as its amplitude is concerned, at least, these measurements agree that the collisional shift in ^{87}Rb should be 50 times lower than for ^{133}Cs. Because this frequency shift is one of the dominant terms in the uncertainty budget of Cs fountains [4], these prediction and preliminary results make Rb of much interest for the improvement of atomic frequency standards. The second point of interest is the fact that an accuracy in the 10^{-16} range should make it possible to search for a possible drift of the fine structure constant $\alpha = e^2/\hbar c$ with time [5]. This would provide a laboratory test within the $10^{-16} - 10^{-17}$ yr^{-1} range, a two orders of magnitude improvement over previous laboratory measurements.

II. The Experimental Apparatus

Our Rb cold atom frequency standard uses the fountain geometry [6], [7]. The experimental set-up is described in more details in [8], and we briefly recall its operation. The atoms are first cooled and trapped in a magneto-optical trap (MOT) [9], where they are optically pumped in the $F = 2$ ground state hyperfine level. Using laser diodes and a tapered optical amplifier providing up to 25 mW per cooling beam, we trapped up to 7.5×10^8 atoms spread among the $F = 2$ Zeeman sublevels. The atoms are launched upward using the moving molasses technique [7]. They are then adiabatically cooled [10] in the moving frame by slowly turning down the laser intensities after launch. The atomic cloud temperature is $\simeq 1.4\mu$K. The atoms are selected in the $F = 1, m_F = 0$ Zeeman sublevel by means of microwave and laser pulses. Passing twice through a cylindrical TE_{011} microwave cavity, they undergo a Ramsey interrogation. The populations of the two hyperfine levels are finally measured by laser-induced fluorescence. The density of atoms selected in $m_F = 0$, and averaged along the flight above the cavity, reaches 1×10^8 at.cm^{-3}. By means of four magnetic shields and an active compensation, external axial magnetic perturbations are attenuated by more than 5 orders of magnitude in the interrogation region. The Ramsey fringes obtained with our device are shown in Fig. 1. The central fringe has a 1.2 Hz FWHM, corresponding to a launch height of 20 cm above the microwave cavity. The noise on the transition probability at half central fringe is 1/800 per shot and results from the phase noise of the interrogation oscillator. The Allan standard deviation of the frequency fluctuations of the Rb clock is measured against an H-maser. The short-term stability is $1.5 \times 10^{-13}\tau^{-1/2}$, where τ is the integration time in seconds. As shown in Fig. 2, this stability decreases down to 1×10^{-15} after a 20000 s integration. When operating the clock at atomic resonance and using $\pi/4$ microwave pulses in the cavity, the transition probability ($\simeq 0.5$) becomes insensitive to the phase noise of the interrogation oscillator. The noise then drops down to 1/2400. This indicates a potential frequency stability of about $5 \times 10^{-14}\tau^{-1/2}$.

III. Measurement of the ^{87}Rb Ground State Hyperfine Splitting

As shown in Fig. 3, the BNM-LPTF is operating two Cs fountains [11], [12], the present Rb fountain, and a Cs thermal beam [13]. The interrogating microwave frequency of each clock is generated from the same local oscillator, which delivers a 100 MHz frequency with a low phase noise.

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TABLE I
FREQUENCY SHIFTS AND RELATED UNCERTAINTIES FOR A SET-UP TEMPERATURE.[1]

Effect	Frequency shift (10^{-5} Hz)	Uncertainty (10^{-15})
First order Doppler	0.0	0.5
Gravitational redshift	+5.2	0.5
Second order Zeeman	+14.1	0.5
Black body radiation	−8.1	0.5
Microwave leakage, Ramsey and Rabi pulling...	0	1.5
Collisions	−0.13	0.6
Total uncertainty	—	1.9

[1] $T = 296\,\mathrm{K}$, a magnetic field $B = 50\,\mathrm{nT}$, an average atomic density $\overline{n} = 2.5 \times 10^{7}\,\mathrm{cm}^{-3}$, and an atomic resonance quality factor of 6.2×10^{9}. The redshift corresponds to a height above the geoid of 65(5) m.

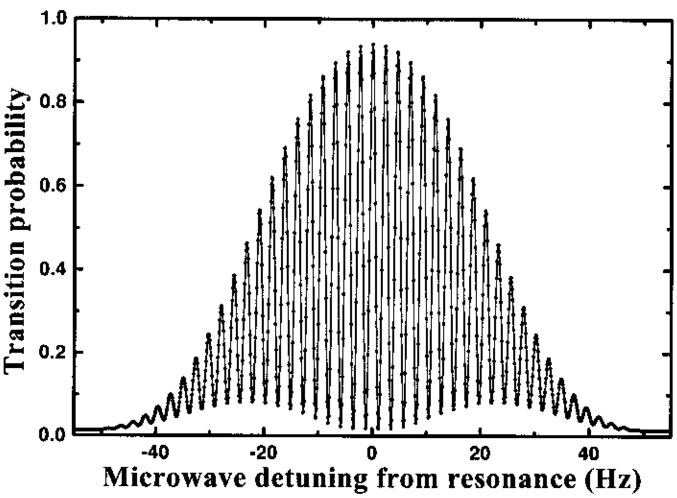

Fig. 1. Ramsey fringes of the rubidium fountain. The transition probability $N_{F=2}/(N_{F=1} + N_{F=2})$ is plotted as a function of microwave frequency detuning.

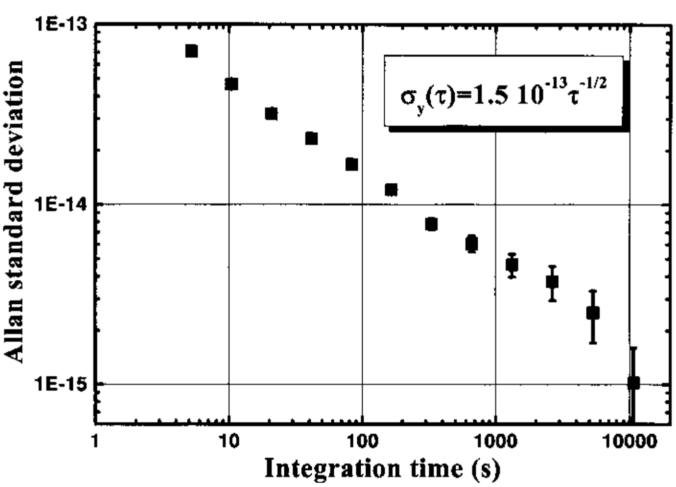

Fig. 2. Allan standard deviation, $\sigma_y(\tau)$, of the rubidium fountain against the H-Maser. 8×10^{6} detected atoms. The short-term stability is limited by the phase noise of the local oscillator.

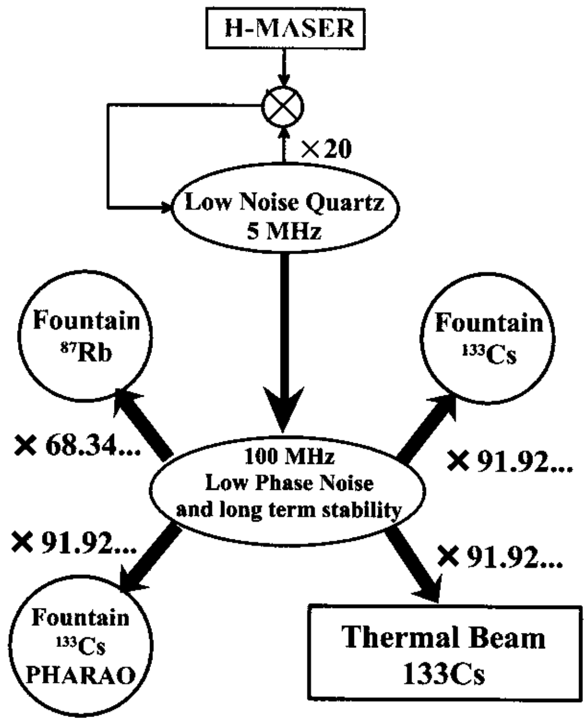

Fig. 3. The LPTF's clock ensemble.

This frequency is synthesized from a 5 MHz low noise BVA quartz weakly locked on the H-maser. Thus, it is possible to compare directly each clock with one of the others and reject the noise induced by the H-maser frequency fluctuations. Using one Cs fountain, we tracked the H- maser frequency with a 1.4×10^{-15} accuracy. Then, we corrected the measured Rb frequency to take into account different systematic shifts listed in Table I. Our new value for the ^{87}Rb hyperfine frequency is 6 834 682 610.904 333(17) Hz. The resulting relative accuracy is 2.4×10^{-15}. This measurement is in agreement with our previous value [8]. Its accuracy has been improved by a factor 6, by reducing microwave leakage and magnetic field fluctuations in the interrogation region.

IV. SEARCHING FOR THE COLLISIONAL SHIFT IN ^{87}RB

A long-term stability of $1-2\times10^{-15}$ has made it possible to search for the shift induced by cold atom collisions in Rb. By changing the loading duration of the MOT, we varied the average atomic density from 2×10^{6} to $1\times10^{8}\,\mathrm{cm}^{-3}$. The atomic density was deduced from the time of flight signals and from the size of the atomic cloud just after launch, measured on a CCD camera. From the time of flight signals, we can determine the final size and temperature of the atomic cloud in the detection region. From the collected fluorescence, we deduced the total number of detected atoms present in each hyperfine level. In Fig. 4, we have plotted the relative collisional frequency shift in Rb as a function of the average atomic density $\overline{n}$ [see (3)]. Each measurement has a resolution of $\sim 1\times10^{-15}$. A least square linear fit to the data points shows that the relative collisional frequency shift is proportional to $\overline{n}$ with a slope of $(-7.2\pm20)\times10^{-24}\,\mathrm{cm}^3$. This collisional shift is about 300 times lower for ^{87}Rb than for ^{133}Cs [14], [15]. With our present resolution, this ^{87}Rb measurement is consistent with zero. In Fig. 4, the dashed lines represent one standard deviation of the slope. Such a surprising result leads us to wonder whether any other density-dependent effect could mimic the collisional shift. Indeed, it is well-known that a large number of atoms may modify the phase of the microwave field inside the cavity (cavity pulling). Because it is different for each interaction, this phase shift induces a frequency shift (pulling or pushing) of the clock, the sign of which depends on the initially selected hyperfine atomic state [16]. In our experiment, the cavity has a quality factor of $\sim$ 10 000 and is tuned $+1\ \eta$ Hz above the atomic resonance. At the highest densities achieved in our apparatus (10^8 at/cm^3), preliminary calculations predict that this "cavity pulling" has the same order of magnitude as the resolution of our measurements ($\simeq 10^{-15}$). We are presently doing additional experiments in order to test these calculations and measure the frequency shift induced by cavity pulling. However, an accidental compensation of the collisional shift with the cavity pulling cannot be ruled out, but it is unlikely for two reasons. First, this compensation is possible only if the collisional shift is positive, in contradiction with theory [1]. In addition, changing the initial hyperfine state did not result in a shift larger than our resolution ($\simeq 10^{-15}$). Indeed, preparing the atoms in the hyperfine $F=2$ state, all m_F Zeeman sublevels being equipopulated, should result in a cavity pulling having the same sign as the total collisional shift (the shifts induced by the different m_F states are expected to have the same sign [1]). The density dependent frequency shift that we have measured (Fig. 4) is thus the result of both cold atom collisions and cavity pulling; but it represents an upper value for the collisional shift, $\simeq$ 300 times lower for Rb than for Cs[1].

[1]The absolute value of the atomic average density reported here is preliminary and is presently under further evaluation. Comparing various methods seems to indicate an overestimate by a factor 3 on the densities reported in Fig. 4.

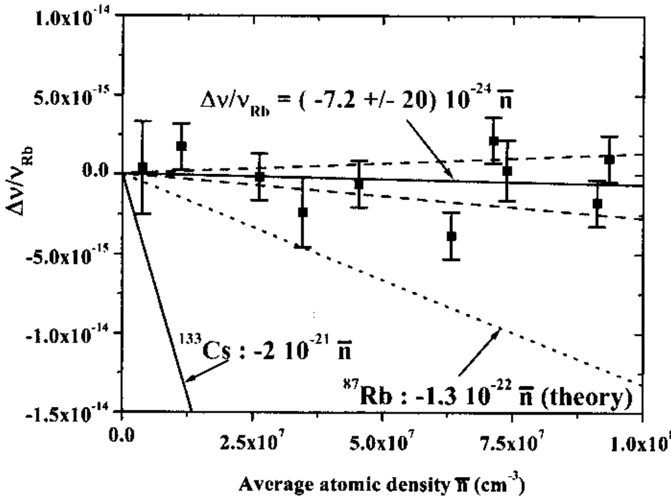

Fig. 4. ^{87}Rb relative frequency shift for atoms initially prepared in $F=1, m_F=0$, versus the average atomic density $\overline{n}$ (see footnote 1). Solid line: least square linear fit. Dashed lines: one standard deviation of the slope. Dotted line: theoretical prediction of [1]. For comparison, the measured relative frequency shift for ^{133}Cs also is shown in [14] and [15].

Such a result leads us to revisit the ultimate performance of cold atom fountain standards. Consider a fountain operating in the quantum projection noise regime, which has been demonstrated in [17]. The short-term stability is inversely proportional to $\sqrt{N_{at}}$ as shown in the following expression, where N_{at} is the number of detected atoms:

$$\sigma_y(\tau)=\frac{1}{\pi Q_{at}\sqrt{N_{at}}}\sqrt{\frac{T_c}{\tau}}. \quad (1)$$

Let us further assume that $\sigma_1 \ll a$ and that $\sigma_2 \gg a$, where σ_1 (σ_2) is the RMS radius of the atomic cloud during the first (second) passage through the cavity, and a is the cavity hole radius. This is typically the case when working with a MOT, and it is a reasonable approximation with optical molasses. Hence, N_{at} and $\overline{n}$ are given by the expressions:

$$N_{at}=N_0\times\frac{a^2}{2\sigma_2^2} \quad (2)$$

$$\bar{n}=N_0\times\frac{1}{2\sqrt{2}(2\pi)^{3/2}}\times\frac{1}{\sigma_2\sigma_1^2}. \quad (3)$$

Assuming that the atomic density is controlled at the 5% level, the long term stability σ_{LT} is related to the short-term stability $\sigma_y(\tau)$ by:

$$\sigma_{LT}=\frac{5}{100}K\frac{1}{\sigma_y^2(\tau=1s)}\frac{1}{(\pi Q_{at})^2}T_c\frac{1}{\sqrt{2}(2\pi)^{3/2}}\frac{\sigma_2}{\sigma_1^2a^2} \quad (4)$$

where K is the relative collisional frequency shift factor: $K_{Cs}\simeq -2\times10^{-21}\,\mathrm{cm}^3$. For Rb, an upper value for K_{Rb} is $-2\times10^{-23}\,\mathrm{cm}^3$. For comparison, we consider a rubidium fountain and a cesium fountain operating with the same quality factor Q_{at} so that systematic effects other than the collisional shift are similar. Under these assumptions, Fig. 5 represents the trade-off between the long-term

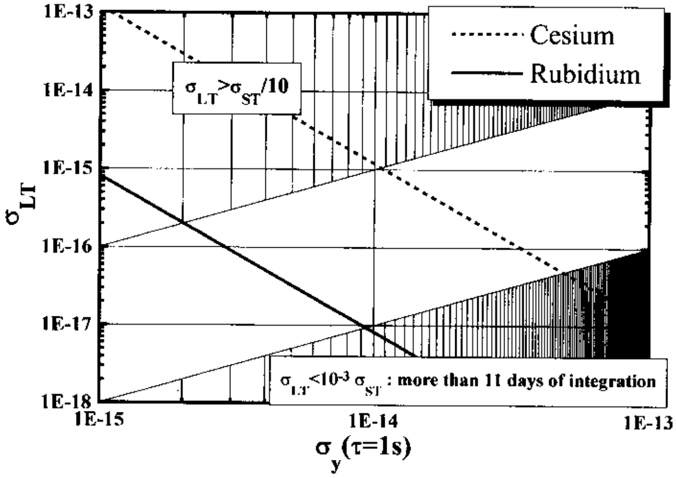

Fig. 5. Comparison between Rb and Cs fountains operating in the quantum projection noise limited regime.

and short-term stability for both alkali. On this graph, the hatched domains correspond to integrations lasting less than 100 s or more than 10^6 s ($\simeq$ 11 days).

As an example, consider first a Cs fountain. Assuming a number of detected atoms $N_{at} = 2.3 \times 10^6$, the quantum projection noise limited short-term stability is $2.3 \times 10^{-14}\tau^{-1/2}$ and the average atomic density is $2.2 \times 10^6\,\text{cm}^{-3}$. Within 10^4 s of integration ($\sim$3 hours), the relative stability reaches a cold-collision-limited floor near 2.3×10^{-16}. In this regime, the short-term stability of a Cs fountain can be improved only by increasing the number of detected atoms, at the expense of a higher long-term stability floor. Using Rb instead, with $N_{at} = 7.3 \times 10^7$, we find a short-term stability of $4.3 \times 10^{-15}\tau^{-1/2}$. Within the same integration duration of 10^4 s, the long-term stability in principle now reaches a floor near 4.4×10^{-17}.

However, several other systematic effects have never been controlled in the 10^{-16} range yet (cf. Table I). Furthermore, reaching the cold-collision-limited floor in a reasonable amount of time with Rb requires a short-term stability unprecedented in atomic frequency standards. As a conclusion to this simple comparison, it is now clear that using Rb rather than Cs makes the uncertainty due to collisional frequency shift negligible at the 10^{-16} level and opens the way to investigating other sources of limitations (cavity pulling, Ramsey pulling,...). However, for Cs, more sophisticated interrogation schemes (juggling fountains [18], space clocks [19],...) have been proposed to reduce the cold collision floor.

V. Search for Variations of the Fine Structure Constant

The achievement of high precision clocks opens the way for several new experiments. Interest in the search for a possible drift of the fine structure constant α has been renewed by recent theoretical developments [20] and cosmological observations [21]. The high accuracy of cold atom fountain frequency standards can be used to perform a laboratory test of $\dot{\alpha}/\alpha$ at the level of 10^{-16} per year.

As shown in [5], the ratio of the hyperfine energies of two different atomic species depends on the fine structure constant α:

$$\frac{d}{dt}\ln\left(\frac{\nu_{Cs}}{\nu_{Rb}}\right) = 0.45 \times \frac{\dot{\alpha}}{\alpha}. \tag{5}$$

Over a period of 13 months, we have performed two measurements of the Rb ground state hyperfine frequency on LPTF's Rb fountain, using a Cs fountain as a reference. The uncertainties on these two measurements are, respectively, 1.3×10^{-14} and 2.4×10^{-15}. We thus find: $\dot{\alpha}/\alpha = (1.8 \pm 2.7) \times 10^{-14}\,\text{yr}^{-1}$, which is consistent with zero. The accuracy of this test is on the same order of magnitude as the previously reported laboratory test ($\dot{\alpha}/\alpha \leq 3.7 \times 10^{-14}\,\text{yr}^{-1}$) [5].

In order to improve our measurement of variations of α, we intend to build a dual fountain operating simultaneously with both Cs and Rb atoms. In this apparatus, Cs and Rb atoms will be launched so that interrogation of the hyperfine energies of both alkali occur at the same time. Hence, some of the systematic effects altering the comparison between the two hyperfine frequencies can be partially rejected: magnetic field fluctuations, room temperature variations... As shown in [5], the relative frequency drift of a Hg^+ ion frequency standard against Cs would be -3.1 times the relative frequency drift of Rb versus Cs. In the future, comparing Cs and Rb fountains with a Hg^+ ion frequency standard [22] will thus provide a clear signature of α variations, if any.

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