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Rapid Note

A cold atom clock in absence of gravity

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Abstract. We describe the operation of a cold atom clock in reduced gravity. We have recorded the cesium hyperfine resonance signal at a frequency near 9.2 GHz in the $\sim 10^{-2}$ g gravity environment produced by jet plane parabolic flights. With a resonance width of 7 Hz, the device operated in a regime which is not accessible on earth. In the much lower gravity level of a satellite, our cold cesium clock would outperform the fountains with a potential accuracy of 5×10^{-17}. This experiment paves the way to unprecedented performance in space applications such as tests of general relativity, global time dissemination, astronomy and geodesy.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 06.30.Ft Time and frequency

In atomic spectroscopy experiments, there is a fundamental limit to the frequency resolution, $\Delta\nu$, which is imposed by the duration T of the coherent interaction between the atoms and the electromagnetic field: $\Delta\nu \propto 1/T$. The frequency stability and accuracy of atomic clocks have steadily improved with the decrease of $\Delta\nu$ permitted by electromagnetic traps and laser cooling techniques. Today the most accurate frequency standards are cold atom clocks which, on Earth, operate in a fountain geometry [1,2] and laser cooled ion clocks confined in electromagnetic traps [3,4]. The caesium fountain operates with the hyperfine transition near 9.2 GHz used to define the S.I. unit of time, the second. Its accuracy is presently 2×10^{-15}, the best value ever reported [5]. The observation time of trapped charged particles can exceed that of free neutral atoms, but the perturbations caused by the Coulomb interaction and by the trapping fields degrade the accuracy and restrict the particle number to small values ($N \leq 100$). Traps for neutral atoms severely shift the energy levels involved in the clock operation [6]. By contrast, atoms in a fountain or in microgravity are nearly unperturbed. N is much larger ($N \sim 10^6$–10^7), only limited by the frequency shift induced by collisions between the atoms [7,8].

Cesium atoms are easily cooled to a temperature of $\sim 2\,\mu$K corresponding to an r.m.s. velocity $\delta v \sim 1$ cm/s [9]. A cesium fountain of height $H = 0.6$ m yields a resonance width $\Delta\nu = 0.7$ Hz ($T = 0.7$ s), two orders of magnitude narrower than in conventional thermal beam devices [10]. Because of gravity, the atoms do not keep their low velocity and T increases only as $H^{1/2}$. A duration close to one second is therefore a natural limit for a reasonably tall fountain. By contrast, in microgravity conditions, T could increase up to 10 seconds with a simple and compact device, giving $\Delta\nu = 0.05$ Hz [11,12]. The corresponding height of a fountain would be 120 m, an unrealistic value with respect to many technical aspects, such as magnetic field control, temperature homogeneity...

Transferring a laboratory-bound cold atom clock into an automated experiment suitable for satellite use poses many technical challenges. Our space clock prototype constitutes an essential step towards the next generation of precision time-keeping. The clock, depicted in Figures 1 and 2, consists of three main parts: a vacuum tube, an optical bench and a microwave source. The core of the device is the vacuum chamber in which cesium atoms are first captured and cooled in optical molasses [13]. They are then launched through a 20 cm long microwave cavity with two 1cm diameter entrance and exit holes. Finally their internal state is determined by light induced fluorescence. The atoms spend half of their free flight time inside the microwave cavity. The device operates in a pulsed mode and this measurement sequence is repeated at an adjustable rate between 0.1 and 2 Hz. The cooling region contains a 10^{-6} Pa cesium vapor. Around 10^7 atoms

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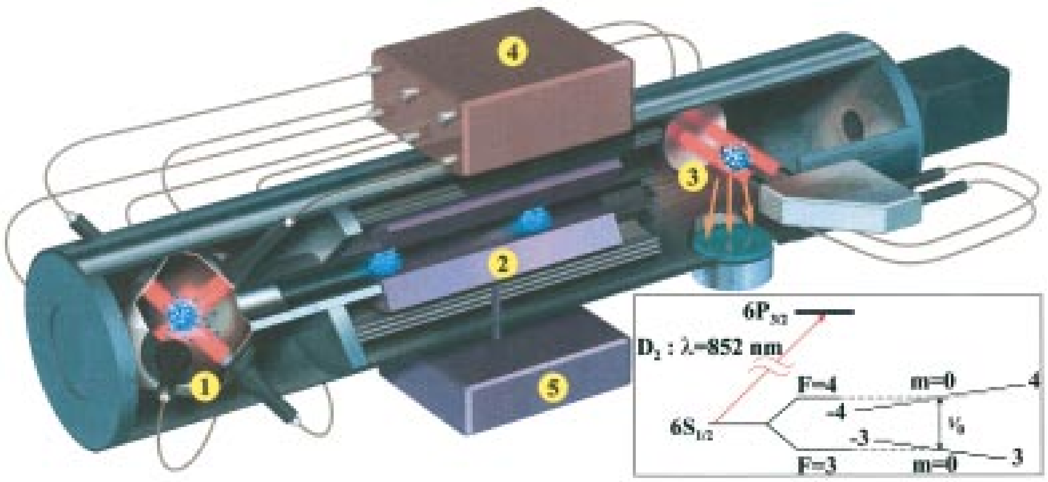

Fig. 1. Principle of operation of the micro-gravity clock. (1) cesium atoms are captured in optical molasses. (2) They are slowly launched through a microwave cavity fed by a frequency synthesizer (5) and tuned to 9.2 GHz. (3) The atom's internal state is probed by light induced fluorescence. The distance from (1) to (3) is 40 cm. (4) The optical bench (not to scale) contains the laser system and delivers the cooling and detection beams *via* optical fibers. Insert: the cesium relevant energy levels. The S.I. second is defined using the $F = 3, m = 0 \rightarrow F' = 4, m = 0$ transition in the $6S_{1/2}$ electronic ground state at $\nu_0 = 9.192631770$ GHz. A small DC magnetic field (3×10^{-7} Tesla) shifts the $m \neq 0$ Zeeman substates by $m \times 1$ kHz. Laser manipulation and detection of the atoms are performed using the optical transition $6S_{1/2} \rightarrow 6P_{3/2}$ at 852 nm.

are captured in 300 ms in optical molasses consisting of six independent laser beams each of $1/e^2$ diameter 16 mm and power 10 mW. The polarization of the beams is the so-called lin⊥lin configuration [9]. The atoms are launched in the (1,1,1) direction in the trihedron defined by the beam directions (see Fig. 1) using the *moving molasses* technique [2,14]: if we impose a frequency difference Δf between the beams pointing towards the cavity and away from the cavity, the atoms are launched with a velocity given by: $V = \frac{\sqrt{3}}{2}\lambda\Delta f$, where $\lambda = 852$ nm is the optical wavelength of the laser light tuned to the cesium D_2 resonance line. V can be precisely adjusted between 10 m/s and 5 cm/s, corresponding to transit times in the cavity between 20 ms and 4 s. The lower limit for V is determined by the velocity spread δv due to the finite temperature of the atoms. At 2 μK and for $V = 5$ cm/s, the atomic sample is still reasonably monokinetic ($\delta v/V = 0.2$) and the number of detected atoms is still large, $\sim$1% of the initial number. The microwave cavity is a Cu-Cr-Zr alloy cylinder which is resonant at 9.192 GHz in the TE_{013} mode [15,16]. The residual pressure in the cavity and detection region is less than 10^{-8} Pa. It is maintained by graphite cesium getters and a 20 l/s ion pump. At this pressure, the average time between two collisions involving a cold atom and the 300 K background gas is $\sim$200 s, much longer than the travel time of the atoms through the device. Four layers of magnetic shields and 3 solenoid coils allow a control of the magnetic field at a level of 10^{-10} Tesla. A 3×10^{-7} Tesla longitudinal bias field is applied over the vacuum chamber volume to resolve the various Zeeman transitions (Fig. 1).

Laser light for cooling, launching and detecting the atoms is provided by an *all-diode* laser system on a separate optical bench enclosed in a temperature-regulated box at 30 ± 1 °C. Light is guided to the vacuum tube by eight single mode optical fibers. A Distributed Bragg Reflector (DBR) diode laser, spectrally narrowed to 500 kHz by weak optical feedback, provides the light for detecting the atoms on the $F = 4 \rightarrow F' = 5$ optical transition. It also injects two 150 mW slave lasers which produce the six cooling and launching beams. Acousto-optic modulators (AOMs) allow fine tuning of the light frequencies and fast (1 μs) switch-off of the laser beams after launching. In addition 8 mechanical shutters ensure complete light extinction during the microwave interaction.

The interrogation field which feeds the microwave cavity is synthesized by a frequency chain. We first multiply by 920 the 10 MHz output of an ultra-stable quartz crystal oscillator specially designed for low acceleration sensitivity ($5 \times 10^{-12}/g$) [17]. This signal is then mixed with the output signal of a $\sim$ 7 MHz synthesizer so that the interrogation field is tunable around the cesium hyperfine frequency.

The clock prototype was tested in the reduced gravity of aircraft parabolic flights on three consecutive days. The A-300 Airbus plane carried out 90 times the following acceleration sequence: 120 s at 1 g, 20 s at 1.8 g, 20 s at $\sim 10^{-2}\,g$ and 20 s at 1.8 g, giving in total 30 minutes of reduced gravity. In Figure 3 we show two resonance signals recorded during the reduced gravity periods. In Figure 3a, the atoms are launched with a velocity of 4 m/s. The total transit time from the capture zone to the detection zone is 100 ms and the time T the atoms spend inside the cavity is 50 ms. The measured resonance linewidth is 14 Hz, in agreement with our theoretical model of the

(a)

(b)

Fig. 2. (a) The clock tube with 3 layers of magnetic shields removed. The total length is 110 cm. The cooling region with its fiber connectors is at bottom. (b) The optical bench. The *all-diode*-laser system for atom manipulation fits in a temperature regulated $65 \times 65 \times 15\,\mathrm{cm}^3$ box.

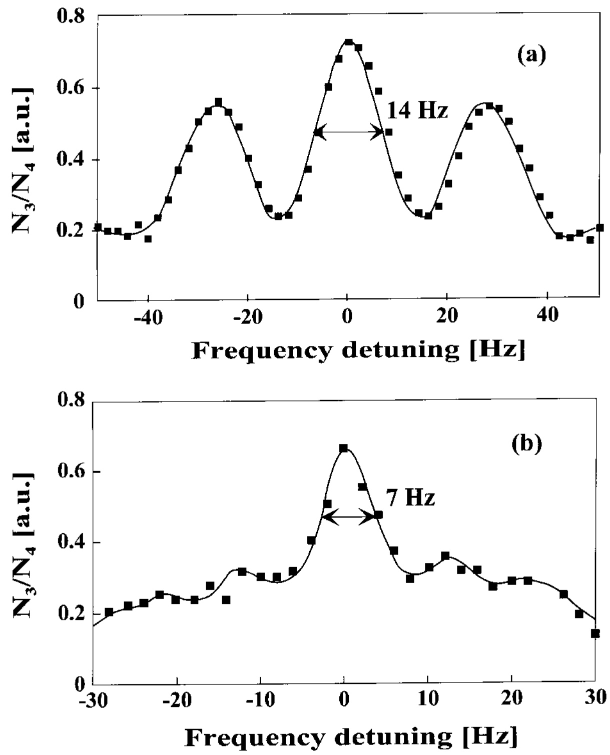

Fig. 3. Resonance signals recorded in reduced gravity for two launching velocities: (a) 4 m/s and (b) 2 m/s. Plotted is the ratio of the number of atoms having undergone the microwave transition and detected in $F = 3, m_F = 0$ over the number of atoms detected in $F = 4$, spread among the 9 Zeeman substates. The microwave frequency applied to the cavity is swept in 2 Hz steps around the cesium hyperfine frequency near 9.2 GHz. Each point corresponds to one operation cycle of the clock of duration 1 s.

interaction between the atoms and the magnetic field of the TE_{013} mode. In Figure 3b, the atomic velocity is reduced to 2 m/s resulting in a resonance width of 7 Hz[1]. On Earth, atoms which are launched upwards at 2 m/s turn around inside the microwave cavity and do not reach the detection region. Hence the absence of gravity allows operation of the device in conditions which are not accessible on Earth. With $\sim 1 \times 10^{-2}\,g$ gravity residuals, we could not significantly reduce further the atomic velocity, because the atoms, drifting away from the cavity axis by a distance larger than the diameter of the exit hole, are no longer detected.

By contrast, operating the same device in the $\sim 10^{-6} g$ gravity of an earth orbiting satellite would enable a spectacular reduction of the line width down to ~ 0.1 Hz.

[1] The shape of the resonance strongly depends on the microwave power. In Figure 3b, the power is closer to its optimum value (maximum transition probability) than in 3a. Second, the reduced contrast in (b) is due to a residual light shift caused by incomplete extinction of laser light during the microwave interrogation. The mechanical shutters were not activated in the plane for technical reasons.

This figure would outperform the Earth-bound atomic fountains by a factor of 10. In discussing the ultimate performance of this space clock, one has to take into account a number of other important effects such as frequency shifts due to blackbody radiation and collisions as well as the influence of the transverse temperature of the atoms and of the phase noise of the interrogation oscillator [18]. These effects lead to a compromise between the short-term stability and the accuracy of the clock. In space increasing the interaction time is obtained by decreasing the atom's launching velocity, as opposed to the fountain case. A low velocity reduces the residual Doppler effect and allows the use of a lower bias magnetic field. Furthermore, microgravity brings the unique capability of varying the launching velocity by two orders of magnitude for the evaluation of systematic shifts and for exploring the stability-accuracy compromise. Associated with a low phase noise interrogation oscillator [19], cesium atoms in space have the potential to give a frequency stability (Allan deviation) of $2\times10^{-14}\tau^{-1/2}$, where τ is the integration time in seconds. This stability would reach 7×10^{-17} in one day together with an accuracy of 5×10^{-17}. Even better performances can be expected with a rubidium microgravity clock, since the frequency shift due to cold collisions is predicted to be more than one order of magnitude lower than in cesium [20].

Space missions with this ultra-stable clock and adequate time/frequency transfer methods using microwave [21] or visible light pulses [22] open new avenues in both fundamental physics and applications [18]. As an example, the fractional frequency shift due to the Einstein effect between a clock on board the international space station orbiting at 450 km and an Earth-based clock is $+4.5\times10^{-11}$. With a clock accuracy of 1×10^{-16}, this prediction of general relativity could be tested at $\sim2\times10^{-6}$, an improvement of a factor 30 over the 1976 test using Hydrogen masers [21]. Finally an important application of this space clock is the dissemination of a highly stable time scale accessible on a worldwide basis with a stability of ~10 ps per day. Such a time scale would represent a 100-fold gain over the present GPS system and herald a new era in millimeter-scale positioning, long-distance clock synchronization, very large baseline interferometry and geodesy.

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