Observation of the cesium clock transition using laser-cooled atoms in a vapor cell

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Cesium atoms in a vapor cell have been trapped and cooled by using light from laser diodes. The $6S\ F = 4, m = 0 \rightarrow 6S\ F = 3, m = 0$ hyperfine clock transition was excited as these atoms then fell 2.5 cm in darkness. We observed a linewidth of 8 Hz with good signal-to-noise ratio. This gave a short-term fractional frequency resolution of $6.5 \times 10^{-12}/\sqrt{\text{sec}}$, and there is potential for substantial improvement. The apparatus is extremely simple and compact, consisting of a small cesium vapor cell and two diode lasers.

There has been much interest lately in the use of extremely cold neutral atoms for precision measurements of microwave clock transitions.[1–3] This interest results primarily from the potential for high resolution and small systematic errors. We have reported observation of the clock transition in laser-cooled cesium atoms,[1] and Kasevich *et al.*[2] observed the corresponding transition in cooled sodium atoms. Although narrow linewidths were observed, these experiments required large vacuum apparatus and had relatively low signal-to-noise ratios. Here we report the observation of the $6S\ F = 4, m_F = 0$ to $6S\ F = 3, m_F = 0$ clock transition in a sample of laser-cooled (10-μK) cesium atoms in a small vapor cell. Since a good signal-to-noise ratio was achieved by using inexpensive diode lasers, this is clearly an attractive technology for use in a high-performance, compact, and portable atomic clock.

In this experiment cesium atoms in a low-pressure vapor were optically trapped. The trapped atoms were then cooled further and optically pumped into the $6S\ |F, m_F\rangle = |4, 0\rangle$ state. Subsequently all light was switched off, permitting the atoms to fall in the dark under the force of gravity. As the atoms fell, two microwave pulses were applied to drive the transition to the $|3, 0\rangle$ state. Finally, the light was turned back on to monitor the fraction of the atoms making the transition. This cycle was repeated at different microwave frequencies to observe the Ramsey line shape.

The atoms were trapped through a Zeeman-shift spontaneous-force optical trap as in our previous research.[4] This trap uses the light pressure from six orthogonal intersecting laser beams. The light pressure is made to vary with the position of the atoms by a weak magnetic field gradient. This, combined with a red detuned laser frequency, produces a damped harmonic potential. Two diode lasers whose frequencies were stabilized by optical feedback from diffraction gratings[5] were used for the trapping, cooling, pumping, and probing of the atomic sample. The relevant transitions excited by the lasers are shown in Fig. 1. Light from the trap laser, which was detuned 6 MHz to the red of the $6S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 5$ cycling transition, was split into three beams 0.6 cm in diameter with 2 mW of power per beam. The beams were aligned to intersect perpendicularly in the center of the cell, then reflect back on themselves. To prevent atoms from accumulating in the $F = 3$ ground state, light from the pump laser, tuned to the $6S_{1/2}, F = 3 \rightarrow 6P_{3/2}, F' = 4$ transition, also illuminated the intersection region. The magnetic field gradient ($\approx$10 G/cm) was produced by an anti-Helmholtz coil pair wound around the cell. As shown in Fig. 2, the cell was a cylinder of fused-silica glass with six windows attached to it. A small cesium reservoir cooled to −20°C kept the pressure of cesium vapor in the cell at $\approx 1 \times 10^{-8}$ Torr. A 1-L/sec ion pump attached to a small sidearm evacuated any gas (primarily H_2 and He) that diffused into the cell. Fluorescence light

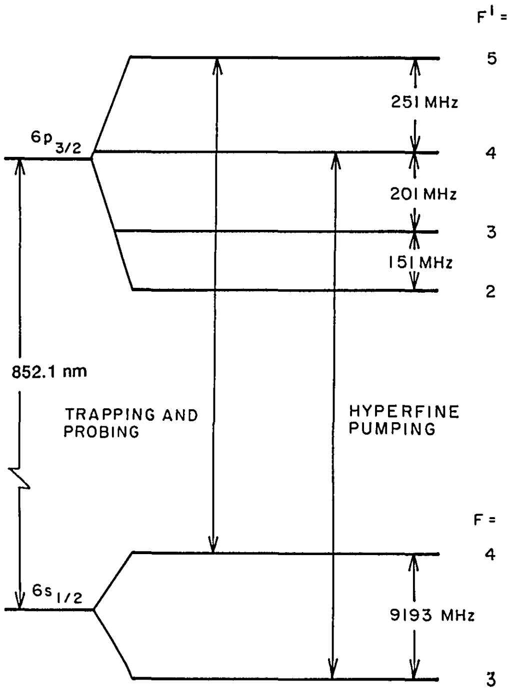

Fig. 1. Cesium energy-level diagram showing the relevant transitions.

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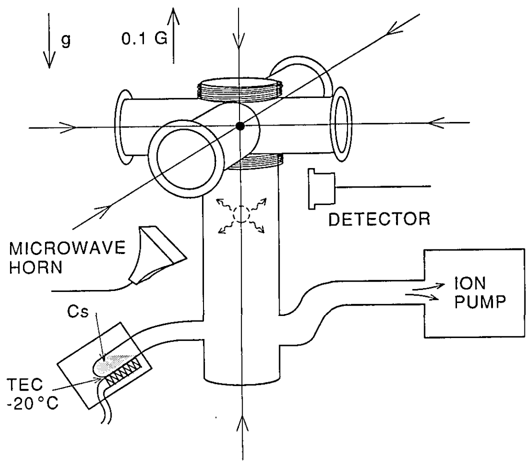

Fig. 2. Vapor cell with fluorescence detector and microwave horn. The arrows show the directions of the trapping laser beams. TEC, thermoelectric cooler.

from the dropped atoms was detected by a 1-cm^2 silicon photodiode placed against the cell wall 2.5 cm below the optical trap region.

The time sequence used to observe the microwave resonance is given in Table 1. Starting with no trapped atoms at $t = 0$, the number of atoms in the Zeeman-shift spontaneous optical trap would increase as $N[1 - \exp(-t/\tau)]$, where N is 2×10^7 and τ is 0.6 sec. After 1 sec the trap contained approximately 1.6×10^7 atoms at a temperature of ~300 μK, in a volume of <1 mm^3. The atoms were further cooled to ≈10 μK by turning off the anti-Helmholtz coils to provide the conditions for optical molasses for 5 msec. This temperature was measured by loading the atoms in a magnetostatic trap and measuring the size of the atom cloud as in Ref. 4. Next the sample was pumped into the $|4, 0\rangle$ state by blocking the trap laser (but not the pump laser) and turning on both a 100-mG uniform magnetic field and a weak laser beam linearly polarized along the magnetic field direction. This laser field was applied to the atoms for 100 μsec and was obtained by taking part of the trap laser output and tuning it to the $6S_{1/2}, F = 4 \rightarrow 6P_{3/2}, F' = 4$ transition by using an acousto-optic modulator. Because the $|F, m_F\rangle = |4, 0\rangle \rightarrow |F', m_{F'}\rangle = |4', 0'\rangle$ is forbidden, more than 95% of the atoms were pumped into the $|4, 0\rangle$ state. After this sample preparation all light was turned off, leaving a cloud of 1.6×10^7 atoms that was estimated to be ≈20 μK in the $|4, 0\rangle$ state and occupied a 1-mm^3 sphere. This cloud then spread slowly as it fell toward the bottom of the cell.

As the atoms dropped, we drove the 9.193-GHz magnetic-field-independent $|4, 0\rangle \rightarrow |3, 0\rangle$ transition. This transition was excited by two separate[6] 5-msec pulses of microwave radiation with $\mathbf{B}_{\mu\mathrm{rad}}$ polarized along the 100-mG field. The first pulse was applied just as the atoms started to fall; the second pulse was applied 65 msec later, after the atoms had fallen 2.5 cm. A microwave horn driven from a tunable source was used to irradiate the atoms with an intensity of ~20 nW/cm^2.

We next sequentially measured the populations of the $|4, 0\rangle$ and $|3, 0\rangle$ states to find the microwave transition probability. By determining both populations we obtain the probability independent of the number of atoms in the drop. The $F = 4$ population immediately following the second Ramsey pulse was found by monitoring the atom fluorescence excited by a 1-mW beam of the cycling 4 → 5′ light from the trap laser. We recorded the photodiode signal (F_4) that showed a fluorescence peak that decayed away in 2 msec owing to the $F = 4$ atoms' being pushed away from the detector region and accelerated out of resonance owing to the pressure exerted by the exciting light. After 7 msec there was no longer fluorescence from the $F = 4$ state atoms, and the 4 → 5′ light was switched off. The $F = 3$ atoms, which still remained, were then pumped back into the $F = 4$ ground state by illuminating them for 2 msec with the 3–4′ pump laser light. Finally, the 4–5′ trap light was again applied for 7 msec, and the resulting fluorescence signal (F_3) indicated how many atoms had been left in the $F = 3$ state. The probability of the $|4, 0\rangle \rightarrow |3, 0\rangle$ transition, independent of the number of atoms in the sample, is then given by $P = F_3/(\alpha F_4 + F_3)$. In general, the constant α is not 1 because the 9-msec delay between measurements F_4 and F_3 causes the falling atoms to be at slightly different spatial locations and have different detection efficiencies. The value of α was determined simply by taking the slope of the plot of F_3 versus F_4. The entire time sequence between trapping and detection lasted ~1.1 sec, including 1.0 sec for the optical trap buildup time. After each cycle the microwave frequency was increased by 1 Hz, and the sequence was repeated.

We acquired the Ramsey line shape shown in Fig. 3. The linewidth of 8 Hz is consistent with the pulse separation time. The solid curve is a theoretical fit using the Ramsey two-pulse transition probability with different microwave phases and field strengths for the two spatial locations of the falling atom cloud. The finite fringe contrast is due to the difficulty of providing the proper phase and field strengths at two

Table 1. Time Sequence Used to Observe the Microwave Transition[a]

Time	Process
0–1.0 sec	Buildup of atoms in optical trap
Next 1 msec	Anti-Helmholtz coils turned off
Next 5 msec	Molasses cooling
Next 1 msec	Turning on uniform 100-mG field and turning off 4 → 5′ trap/molasses light
Next 0.1 msec	4 → 4′ light on for optical pumping
Next 1 msec	Turning off remaining light (3 → 4′)
Next 5 msec	Apply microwave pulse 1
Next 65 msec	Atoms fall in the dark
Next 5 msec	Apply microwave pulse 2
Next 7 msec	4 → 5′ light on, excites and pushes away $F = 4$ atoms
Next 2 msec	3 → 4′ light on, transfers $F = 3$ atoms to $F = 4$
Next 7 msec	4 → 5′ light on, excites and pushes away $F = 4$ atoms
Next 1 msec	Anti-Helmholtz coils turned on

[a] Turning-on or turning-off times represent the switching time; the time duration of all other switching was negligible.

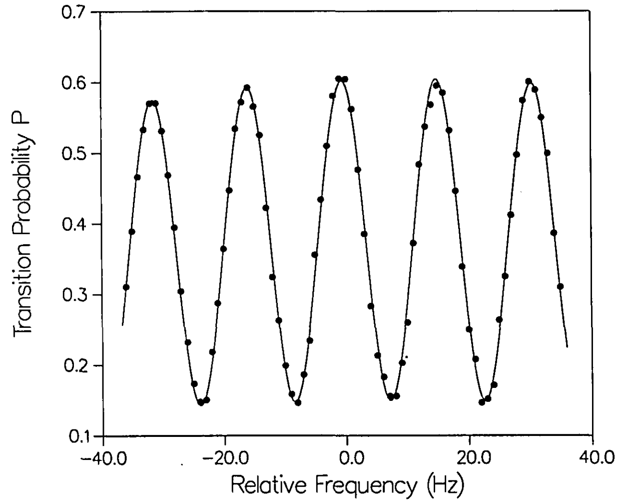

Fig. 3. Resonance spectrum of the |4, 0⟩ → |3, 0⟩ transition. The solid dots are the data, and the solid curve is a theoretical fit. Most of the dots represent the average of four measurements.

positions in space using a single horn. One striking characteristic of the line shape is the large number of interference fringes, in contrast to the Ramsey line shape observed in beam machine experiments.

The uncertainty in the measurement of P was 0.006 per drop. This uncertainty was dominated not by fluctuations in the signal but rather by fluctuations in the background light, which was scattered into the detector by both the cell windows and the background cesium vapor. If we take the maximum frequency resolution ($P \approx 0.5$) to be the linewidth divided by 1.57 times the signal-to-noise ratio (85), we have a fractional frequency resolution of $\pm 6.5 \times 10^{-12}/\sqrt{\mathrm{sec}}$, which represents a factor-of-25 improvement over that reported in Ref. 2 and a factor-of-20 improvement over our previous research.[1]

It should be straightforward to extend the technology demonstrated here to make a compact high-performance atomic clock. The most obvious change is to provide a standing-wave microwave field to eliminate Doppler and phase shifts. A natural way to incorporate such microwave field improvements would be to launch the atoms up through a microwave cavity in a fountain as in Ref. 2. Although we could not use a fountain in this research because of the geometry of our cell, this is a straightforward addition. Another advantage provided by a fountain is the doubling of the observation time for a given cell size. The final advantage of a fountain is that as the cold atoms fall back down they can be recaptured and used for the next cycle. This would reduce the filling time required for the trap and thus improve the duty cycle of the clock by as much as a factor of 10.

It should also be possible to improve significantly the signal-to-noise ratio by reducing the fluctuations in the background light. These were primarily due to mechanical vibrations of the apparatus, which was necessarily elongated and flimsy because of the cell geometry. A more rigid and compact system, which is also designed to reduce the amount of scattered light, might well approach the shot-noise-limited signal-to-noise ratio. For operation near the optimum value of $P = 1/2$, the shot noise will be determined by the $\sqrt{n}$ fluctuation in the number of atoms making a transition. For our atomic sample this signal-to-noise ratio would be 3.0×10^3 per drop, which would yield excellent short-term frequency stability. Although none of our research has dealt with long-term accuracy, there are reasons to expect that a clock based on this technology would be quite good. The low velocities of the atoms reduce the problem of Doppler shifts, and the small interaction volume simplifies the problem of shielding against stray magnetic fields.

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