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Prospects for Cesium Primary Standards at the National Bureau of Standards

L. L. Lewis, F. L. Walls, and D. A. Howe

Time and Frequency Division, National Bureau of Standards, Boulder, CO 80303

An application of optical pumping, in conjunction with a number of design improvements, may permit the development of a cesium primary standard with an accuracy an order of magnitude better than that of our present primary frequency standards, NBS-4 and NBS-6. Limitations to short-term stability, as well as possible errors in accuracy, are discussed.

Key words: atomic clock; atomic frequency standards; cesium frequency standard; light shift; optical pumping.

1. Introduction

The United States' primary frequency standard, NBS-6, was placed into service in 1975. This cesium standard has an accuracy of about 8×10^{-14}, long-term stability better than 1×10^{-14}, and short-term stability of about $5 \times 10^{-13}\ \tau^{-1/2}$. Research in progress at NBS is directed towards the design of a new cesium standard with an order of magnitude improvement in accuracy and long-term stability and a factor of two or three improvement in short-term stability. Much of this improvement may be obtained through the use of optical pumping state preparation and fluorescence detection, and the rest of the advancement will come from a number of technological innovations in the clock system.

The accuracy of NBS-6 is limited in large part by microwave phase shifts associated with losses in the Ramsey cavity [1]. The results of the 1980 evaluation of NBS-6 are given in Table 1, clearly illustrating this fact. The size of the apparent shift of the microwave resonance frequency is approximately

$$\Delta \nu_{\phi} = \frac{\Delta \phi}{\pi} \Delta \nu_{\mu}, \qquad (1)$$

where $\Delta \phi$ includes both end-to-end and distributed cavity phase shift, and $\Delta \nu_{\mu}$ is the microwave linewidth of the central Ramsey feature. Since $\Delta\nu_{\mu} \sim 30$ Hz, one concludes from Table 1 that $\Delta\phi \sim 3 \times 10^{-4}$ radian. This is a reasonable value for a cavity structure as large as the one used in NBS-6 [2]. Assuming a linear dependence of the distributed cavity phase shift upon position across the microwave cavity window of $\sim 1 \times 10^{-14}$ rad/mm [1, 2], it would be necessary to obtain retrace of the cesium beam to within $\sim 100\ \mu$m in order to ensure a frequency error associated with the cavity phase shift of less than 10^{-14}. We believe that the use of optical pumping state preparation and fluorescence detection techniques in a cesium atomic beam frequency standard should make

TABLE 1. *NBS-6 uncertainties, 1980 evaluation.*

	Source of Uncertainty	Bias ($\sigma_y \times 10^{13}$)	Uncertainty ($\times 10^{13}$)
1.	(a) Cavity Phase Shift (for one direction) (residual first-order Doppler Shift)	3.3 (typical)	0.80
	(b) Second-order Doppler Shift	−2.8 (typical)	0.10
2.	Pulling by neighboring transitions	+0.3	0.20
3.	Magnetic Field Effects		
	(a) Offset due to finite field	+1767 (typical)	0.02
	(b) Magnetic field inhomogeneity	+0.02	0.02
	(c) Majorana Transitions	—	?
4.	Servo System Offset		
	(a) Amplifier offsets	0	0.1
	(b) Second harmonic distortion	0	0.2
5.	RF Spectrum	0	0.1
6.	Cavity Pulling	0	0.01
	RMS error due to systematic frequency biases		0.87
	Random Uncertainty		0.15

such a precision retrace possible. In addition, different microwave cavity structures than that used in NBS-6 may reduce the cavity phase shift dependence upon position, thereby relaxing the retrace requirement by as much as an order of magnitude.

The effect of Majorana transitions on the accuracy of Cs standards is not clear. Various authors [3] have suggested that they may produce uncertainties as large as one part in 10^{12}. If optical pumping is used for state preparation and detection, such Majorana transitions should not occur, since a uniform C-field strength can be maintained throughout the clock. In addition, by using laser techniques, it should be possible to measure Majorana transitions which might occur.

Optical pumping may reduce other sources of uncertainty as well. If only a single magnetic sublevel is prepared, there will be no $\Delta m_f = 0$ neighboring transitions which would shift the central resonance. This would permit a much lower value of C-field, which would relax restrictions on measurement of the finite field, as well as reduce the effect of magnetic field inhomogeneities and magnetic field changes with time.

The other contributions to uncertainty listed in Table 1 are not considered to be serious limitations to accuracy at the 10^{-14} level, assuming some reasonable improvements in electronics and measurement techniques are made. However, as discussed below, the introduction of optical pumping will create new sources of error which must be considered.

2. Optical Pumping and Fluorescence Detection

The development of high performance, cw, single-mode diodes for the communications industry has fortunately provided an optical pumping source appropriate for use in atomic frequency standards. The linewidth, intensity noise, frequency noise, and wavelength tuning characteristics of these devices make them very attractive for this purpose [4]. At the present time, it is reasonable to expect laser diodes to operate tuned to an atomic transition for months at a time.

The first use of laser diodes to optically pump a cesium beam atomic clock was made by Arditi and Picqué [5]. They used a single GaAlAs laser tuned to the D_2 line of Cs (852 nm) in order to pump atoms into one of the $F=3, 4$ ground-state hyperfine levels (Fig. 1). Detection of a microwave transition within the Ramsey cavity was accomplished by fluorescence detection using the same laser.

The work at the National Bureau of Standards (NBS) has moved in a somewhat different direction, requiring more than one laser. It is possible to pump nearly every Cs atom in an atomic beam into a single magnetic sublevel [6]. If one laser is tuned to the 6 $^2S_{1/2}$ $F=3 \rightarrow 6\ ^2P_{3/2}$ $F'=4$ transition, and a second laser is tuned to the 6 $^2S_{1/2}$ $F=4 \rightarrow 6\ ^2P_{3/2}$ $F'=4$ transition with plane electric polarization parallel to a weak magnetic field (π-polarization), only atoms in the $F=4$, $m_F=0$ sublevel of the ground state will remain unaffected. This selection rule is clear when one notes that the Clebsch-Gordon coefficient $\langle Fjm_Fm_j\,|F'm_{F'}\rangle = \langle F100\,|\,F0\rangle = 0$, where j is the angular momentum of the photon. Eventually, most of the atoms will be pumped into this magnetic sublevel. Alternatively, a similar arrangement can pump atoms into the $F=3$, $m_F=0$ state.

Fluorescence detection can be performed with a third laser which is tuned to either the $F=4 \rightarrow F'=5$ or the

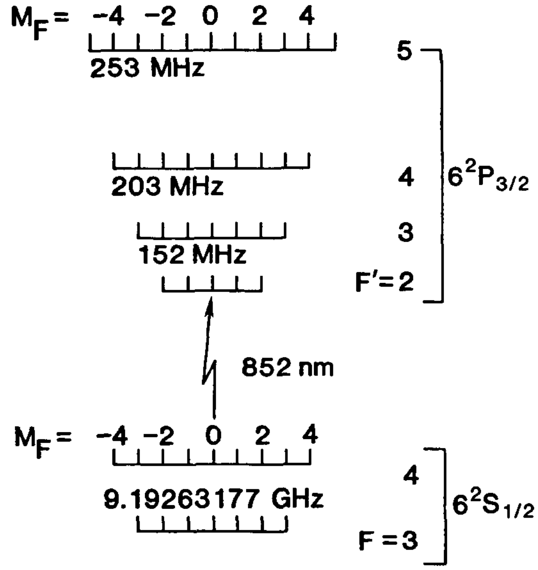

FIGURE 1. *Term diagram for* ^{133}*Cs.*

$F=3 \rightarrow F'=2$ transition. In these two cases (with appropriate polarization of the $F=3 \rightarrow F'=2$ laser light to avoid pumping into the $m_F=\pm3$ sublevels), atoms in the excited state return to the original ground-state hyperfine level. Thus, a large number of fluorescence photons (limited by excited-state energy separations) may be obtained from each atom in the atomic beam. This technique should permit unity quantum detection efficiency, even if the light collection efficiency is considerably less than one. However, as discussed below, there may be systematic effects which would make this detection method undesirable. In this case, it is still possible to use a laser tuned to a pumping transition, and take care to obtain a high collection efficiency at the detector. An additional advantage a pumping transition provides in detection is that every atom is weighted equally regardless of velocity, which may provide immunity from certain systematics. On the other hand, detection by fluorescence on a cycling transition produces a relatively larger signal for slower atoms which remain in the laser beam longer, which would increase the effective microwave Q. Still another advantage of optical pumping is that it should be possible to operate atomic beams in opposite directions simultaneously without interference. This would permit direct measurement of retrace, as well as very rapid modulation of beam direction (or even continuous operation of two beams) for purposes of cancellation of cavity phase shift. A final consideration in the use of fluorescence detection is that the laser beam can be made to intersect the atomic beam at a slight angle, thereby selecting low velocity atoms. This would cause an increase in the microwave transition Q, with some accompanying loss of signal. This result is a consequence of the Doppler shift, which changes the effective velocity distribution of the cesium beam. As further experiments are performed, the relative merits of these various detection methods will become clearer.

Using values of atomic beam current $I_B = 1.0$ nA (6×10^9 atoms/s) and microwave transition $Q \sim 10^8$, it should be possible to obtain stabilities of $\sim 1 \times 10^{-13}$ $\tau^{-1/2}$, even if a pumping transition is used for detection purposes. The high beam current suggested here would come partially from the increased number of useful cesium atoms (a factor of 8 more than that of NBS-6, through optical pumping of all magnetic sublevels), and partially from new oven design. A reflux-type oven is presently under consideration.

3. Additional Uncertainties and Biases

Perhaps the most serious source of frequency uncertainty introduced by optical pumping techniques is that of near-resonant light shifts [7, 8]. Although it should be possible to prevent stray laser light from entering the microwave region, fluorescence light from the atoms will pass through the cavity, and interact with atoms in the "C" region, changing the ground-state hyperfine splitting slightly. The form of this light shift is dispersive, but averaging over excited-state hyperfine levels and including Doppler shifts associated with the Maxwellian velocity distribution in the atomic beam, gives a nonzero value for the shift. Preliminary calculations have been made at NBS [9] for the frequency shift from fluorescence light for pumping by two lasers of π-polarization, with the C-field transverse to the atomic beam direction, and including the effect of the tensor light shift [8]. The computations, assuming lasers of equal power driving the $F = 4 \rightarrow F' = 4$ and $F = 3 \rightarrow F' = 4$ transitions in the pumping region, give a light shift of approximately 4 Hz for a power flux of 1 μW/cm^2 at the site of the cesium atom in the C-field region. A simple computer calculation gives ten as the average number of photons emitted per atom in this pumping scheme. Referring to Fig. 2, reasonable values of the clock dimensions would be $l_1 = l_2 = l_3 = 50$ cm, and $L = 200$ cm. Assuming a beam flux of 6×10^9 atoms/s at the detection region, and a free aperture of 2 mm everywhere in the cesium beam, the total fluorescent power arriving at the first window of the Ramsey cavity from the pumping region would be about 2×10^{-5} μW/cm^2. This gives a fractional frequency shift of $\sim 9 \times 10^{-15}$, which is comparable to the desired accuracy. Additional collimation of the atomic beam before the pumping region would reduce this predicted light shift by a factor of ten or more. Nevertheless, a more careful calculation of the effect will be made, including the effective velocity distribution associated with cycling fluorescence detection, and including the shift caused by light originating in the detection region. In addition, versions of optically pumped frequency standards being considered contain provision for measurement of the light shift.

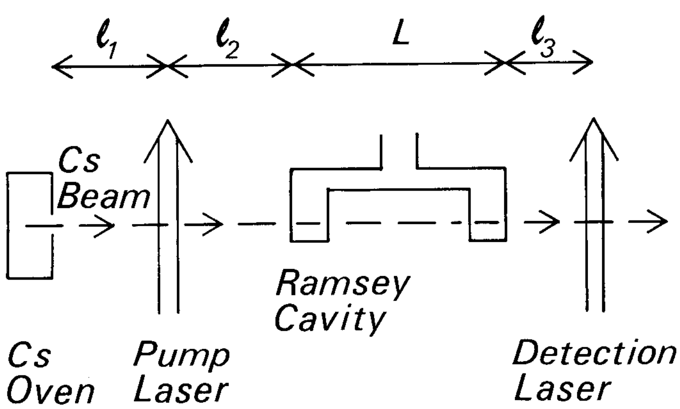

FIGURE 2. *Schematic of Cs atomic beam frequency standard.*

A second source of trouble associated with the laser optical pumping is deflection of the atomic beam through photon recoil. The deflection is about 1.6×10^{-5} rad/photon for an average atomic velocity of ~ 200 m/s, and proportionately greater for slower velocities. If the Cs beam is irradiated symmetrically on two sides, an expansion of the atomic beam should occur, with magnitude $\sim 5 \times 10^{-5}$ rad. With the same assumptions used above to estimate the limitations imposed by beam retrace, this should give an uncertainty in frequency considerably less than 10^{-15}.

Still another correction to the Cs microwave frequency, not unique to optical pumping, but which has not been fully considered in the past, is the light shift caused by blackbody radiation. The ac Zeeman shift of the ground-state hfs of Cs, due to the magnetic field of the blackbody radiation is only $\sim 10^{-16}$ [11]. However, the light shift associated with the rms electric field of the blackbody radiation is considerably larger [10]. The approximate magnitude of the shift correction at $T = 300$ K is about

$$\frac{\delta \nu_{ss}}{\nu_{hfs}} = -1.8 \times 10^{-14} . \qquad (2)$$

The sensitivity of an anticipated new cesium primary standard would be adequate to measure this effect in a suitably designed apparatus.

4. Conclusion

Optical pumping techniques may improve both the accuracy and short-term stability of Cs primary frequency standards. The greatest anticipated improvement comes from better retrace upon beam reversal. New problems associated with laser diode optical pumping will require serious consideration, but are not seen as major obstacles to the design of an improved standard.

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