FLUORESCENT LIGHT SHIFT IN OPTICALLY PUMPED CESIUM STANDARDS

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Abstract

We have calculated the light shift in an optically pumped cesium beam frequency standard caused by fluorescence co-propagating with the atomic beam. Both scalar and tensor contributions are included to give the dependence on light polarization. The results provide design criteria for proposed new standards.

The light shift, or light-induced AC Stark shift, is a potential source of error in proposed optically pumped atomic beam frequency standards that is not present in existing cesium standards. This shift can be quite large (parts in 10^9) while the atoms are directly exposed to a light beam intense enough to produce optical pumping [1]. But in an atomic beam the optical pumping and resonance observation regions are spatially separated. Careful design can minimize scattering of pumping light into the observation region. However, fluorescence by the pumped atoms can still propagate along the direction of the atomic beam into the observation region to produce a light shift. The present investigation was made to establish a quantitative estimate for this fluorescence-induced light shift and its dependence on design parameters.

We first find the light shift as a function of the light intensity bathing the atoms. Later we will relate the intensity to the atomic beam flux and propagation distances.

Brillet [2] has already made a calculation of the scalar [3] part of the light shift. We wish to also include the tensor [3] part to determine the dependence of the shift on polarization of the light. Rather than using the formalism of Mathur et al. [4] we have chosen to begin with a basic formula for the energy shift of a state g [5]:

$$\Delta E_g = \hbar \sum_n V_{ng}^2 \frac{(\omega-\omega_{ng}-\vec{k}\cdot\vec{v})}{(\omega-\omega_{ng}-\vec{k}\cdot\vec{v})^2+\frac{1}{4}\Gamma_{ng}^2} \qquad (1)$$

Here ω and $\vec{k}$ are the frequency and wave vector of monochromatic exciting light, $\vec{v}$ is the velocity of the atomic absorber, ω_{ng} is the transition frequency between g and an excited state n, Γ_{ng} is the spontaneous emission rate from n to g, and V_{ng}, ω_{ng}, ω, and Γ_{ng} are all in angular frequency units. The state g is either the F=3 or F=4, m_F=0 ground electronic state of cesium, the levels involved in the clock transition. Equation (1) can be derived by second order perturbation theory with (1/2) Γ_{ng} brought in as an imaginary part of the excited state energy [6].

Using the Wigner-Eckart theorem and angular momentum algebra V_{ng}^2 can be written as a constant times the light intensity times a factor which depends only on the light polarization and the angular momentum quantum numbers of the states n and g. The detuning dependence, averaged over the velocities in the atomic beam, can be expressed in terms of a dimensionless integral function

$$D(\delta,\varepsilon) = \int_0^\infty \frac{(\delta-u)\,2u^3e^{-u^2}du}{(\delta-u)^2+\varepsilon^2}$$

which we have evaluated numerically. The relative light shift of the clock transition (frequency ω_o) can then be written

$$\frac{\Delta E_g}{h\omega_o} = CI_q \sum_n (a_{ng}^q)^2\, D(\delta_{ng},\varepsilon) \qquad (2)$$

where $C = \mu^2/(2\omega_o\varepsilon_o h^2 c k\alpha) = 1.33 \times 10^{-7}$ m^2/W, I_q is the light intensity having polarization q, a_{ng}^q is the angular momentum factor, $\delta_{ng} = (\omega-\omega_{ng})/k\alpha$ is the detuning variable and $\varepsilon = \frac{1}{2}\Gamma/k\alpha = 0.01$. The Doppler width in a gas with most probable velocity α [7] is 0.83 $k\alpha$. The reduced electric dipole matrix element μ is related to the excited state lifetime by $1/\tau = \Gamma = \mu^2k^3/3\pi\varepsilon_o\hbar$. For pumping of the D2 transition to the $^2P_{3/2}$ electronic state the sum over n includes those m_F values allowed by the light polarization and all three allowed F values, since the Doppler width is comparable to the hyperfine structure separation. For unpolarized light a summation must also be made over q. Equation (2) holds for monochromatic light co-propagating with the atomic beam, as for example, pumping light scattered along the beam.

For fluorescence emitted by beam atoms the frequency ω also has a Doppler shift and hyperfine components to be averaged over. When this is done we obtain a result similar to Eq. (2) except that the summation includes the different frequencies and polarization of the fluorescence and the integral D is replaced by the dual velocity integral function

$$D(\delta,\varepsilon) = \int_0^\infty D(\delta+u,\varepsilon)\, 2u^3e^{-u^2}du$$

Its arguments are $\delta_{n'g'ng} = (\omega_{n'g'}-\omega_{ng})/k\alpha$ and $2\varepsilon = \Gamma/k\alpha = 0.02$ where n' and g' are the initial and final states of the fluorescing atom. Evaluation of the summation and dual velocity integral leads to the coefficients in the table below:

Light Shift Coefficients		
Fluorescing State F'	Polarization π	σ
2	3.1	6.9
3	-2.6	-1.3
4	-5.6	-5.1
5	1.3	4.8

Each coefficient is to be multiplied by $10^{-8}I$ where the light intensity I is in W/m^2. For unpolarized light (2/3 σ polarization and 1/3 π polarization) our result for F' = 4 is about 1/4 the corresponding result of Brillet [2].

We now estimate the fluorescent light intensity arising from optical pumping. The intensity reaching beam atoms from atoms excited a distance d away is

$$I_q = I_{at}\, N_q P_q \hbar\omega / 4\pi d^2$$

where I_{at} is the atomic beam intensity in atoms per second at the point of excitation, N_q is the mean number of photons of polarization q emitted by each atom, and P_q describes the angular dependence for polarization q. N_q may be greater than one, especially for a cycling transition. If the magnetic field is parallel to the beam, the polarization is all σ. If the field is perpendicular to the beam, the polarization is half σ and half π.

With Ramsey excitation of the clock transition the observed light shift will be predominantly the average shift occurring in the drift region between the microwave cavity ends (see Fig. 1). The required average of $1/d^2$ is $1/\ell_2(\ell_2+\ell_3)$ where ℓ_2 is the distance from the point of excitation to the beginning of the drift region and ℓ_3 is the length of the drift region. The atomic beam intensity is proportional to $1/\ell_1^2$ where ℓ_1 is the distance from the beam source to the point of excitation. The inverse dependence on $\ell_1^2\,\ell_2(\ell_2+\ell_3)$ of the light shift provides a guide for design of new standards. Fluorescence from the detection region is usually negligible because the atomic beam flux is so much smaller there.

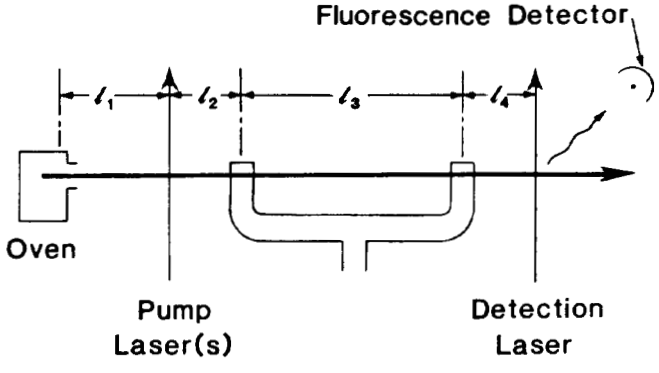

Fig. 1. Schematic of an optically pumped cesium beam standard.

For a typical commercial cesium beam tube we may have beam intensities at the optical pumping position of about 3×10^{11} atoms/sec. Using ℓ_2 = 5 cm, ℓ_3 = 10 cm and N = 3/4 photons per atom for pumping on the F = 3 to F' = 4 transition we obtain an average drift region intensity of 6×10^{-7} W/m^2. With the magnetic field perpendicular to the atomic beam the relative light shift is 3×10^{-14}.

For a proposed primary standard the atomic beam intensity would be about 8×10^{10} atom/sec. Using ℓ_2 = 10 cm, ℓ_3 = 1.4 m and N = 1/2 photon per atom for pumping on the F = 4 to F' = 3 transition we obtain an average fluorescence intensity in the drift region of 5×10^{-9} W/m^2. With the magnetic field parallel to the atomic beam the relative light shift will be only 6×10^{-17}.

On the basis of these estimates we can conclude that the light shift should be included in the error budget of any optically pumped cesium standard. However, it need not be the limiting factor in the overall accuracy of a well-designed standard. In fact, to experimentally observe the fluorescence-induced light shift it may be necessary to introduce an extra light beam very close to the cavity entrance (small ℓ_2) which drives a cycling transition (large N).

References

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