Measurements of Cesium Polarizability in Atomic Clock via Light Frequency Shift

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***Abstract*—Experimental schemes are developed that use alternative current electric field from additional near-resonance or far-resonance light in Cesium(Cs) atomic clock to measure the static dipole polarizability, differential polarizability of the ground states, and the forbidden tensor polarizability of Cs atom via light frequency shift.**

I. INTRODUCTION

The static dipole polarizability[1], the differential polarizability of the ground states[2], and the forbidden tensor polarizability[3] of Cs are conventionally measured with static electric field. But here, we proposed convenient experimental schemes of measuring these parameters with alternative current electric field from additional near-resonance or far-resonance light in Cs atomic clock.

First, the static dipole polarizability will be derived from the measured reduced matrix elements via light shift, since it non-linearly depends on light detuning and light power (saturation effect). Experimentally, one just simply adds an additional near-resonance light to cause a large light shift, and accurately measures its dependents on light detuning and power.

The differential polarizability of the ground states, which related to Black-Body Radiation(BBR) shift correction of primary atomic clock, is proposed to be measured with far-off-resonance light from a CO_2 laser, which provides light wavelength very close the spectral peak of BBR. The final sensitivity will be limited by light power calibration. But, a better than 10% accuracy will be helpful to clarify the puzzle from the recent BBR experimental result[4].

Third, a proposal is presented to build a relationship of the forbidden tensor polarizability(contribution from the spin-dipolar interaction) and the differential polarizability of the ground states via measure them under the same experimental condition, thus the absolute calibration of the electric field(light power) can be avoided. With Sandars' expressions[5,6], this relationship can be built with high accuracy determined by the accuracy of clock used. This result will dramatically improve the accuracy of the forbidden tensor polarizability, which is 7.5% in[3,6], if the measurement is done on a fountain configuration.

These proposed experiments, can be done in usual thermal beam or fountain clock without adjusting clock system anything in most clock configuration.

II. STATIC DIPOLE POLARIZABILITY

Light frequency shift [7-9] is a main issue in an optically pumped Cs frequency standard, which should be avoided or decreased to a tolerable value. In a fountain clock, it can be avoided by using mechanical shutters to block light entering the interaction region[10].

If an additional laser beam is added to the interaction region, there is no doubt that one can measure the induced light shift with very high accuracy in a fountain clock. The measured light frequency shift is a function of laser intensity, laser detuning, and the reduced matrix elements [7],

$$\Delta\nu_{light-shift} = F(I_{laser}, \Delta\omega_{laser}, D_J) \qquad (1)$$

where $D_J = \left\langle 6P_J \| D \| 6S_{1/2} \right\rangle$ for the intermediate states $6P_{1/2}$ and $6P_{3/2}$. It is worth noting that almost 96% of the static dipole polarizability is attributed from the intermediate $6P_{1/2}$ and $6P_{3/2}$ states[11],

$$\alpha_{6P_J} = \frac{1}{3}\left(\frac{D_{1/2}^2}{\nu_{1/2}} + \frac{D_{3/2}^2}{\nu_{3/2}} \right) \qquad (2)$$

where $\nu_{1/2}, \nu_{3/2}$ are the transition frequency from states $6P_{1/2}$ and $6P_{3/2}$ to the ground state $6S_{1/2}$.

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D_J can be deduced from (1) once the light frequency shift is measured accurately via laser intensity I_{laser} and laser detuning $\Delta\omega_{laser}$ of the additional laser beam. Particularly, when the added laser intensity is strong enough to cause saturation effect, the light frequency shift of (1) will be a non-linear function of laser intensity and laser detuning. In this case, it will be possible to avoid the absolute measurement of the laser intensity. Then give us the advantage to deduce the reduced matrix elements with higher accuracy because we only need to measure the laser frequency detuning and relative laser intensities.

III. DIFFERENTIAL POLARIZABILITY OF THE GROUND STATES

With the scalar differential polarizability α_{10} between the two ground state F=3 and F=4 introduced by Sanders [5], the BBR shift[2,4,12-15] is,

$$\delta\nu = -\frac{8}{7}\frac{\alpha_{10}}{h}\left\langle E^2(T=300K)\right\rangle\left(\frac{T(K)}{300}\right)^4 \times\left[1+\varepsilon\left(\frac{T(K)}{300}\right)^2\right] \quad (3)$$

where $\varepsilon = 1.2\times10^{-2}$.

According to the Plank radiation law, the calculated mean-squared electric field of BBR is[2,15],

$$\left\langle E^2(T)\right\rangle = (831.9V/m)^2[T(K)/300]^4 \quad (4)$$

and it is assumed the BBR is isotropic and unpolarized.

At room temperature, the peak of BBR spectral density is around a frequency of $1.8\times10^{13}Hz$, which is much lower than the transition frequency between the ground state and $6P_J$ state. Thus the BBR is only a slowly varying perturbation to the clock transition, and the ac Stark shift induced by BBR can be approximated by the dc Stark shift induced by the rms electric field [14]. Based on this consideration, the BBR shift corrections in all current fountain clocks have used the measured scalar differential polarizability with a static electric field [2]. These fountain clocks have frequency uncertainty of 7×10^{-16} [16].

But most recently, an Italian group[4] gave us 15% smaller results by directly heating the fountain clock apparatus. This means a 2.5×10^{-15} fractional frequency difference, much higher than the claimed fountain clock frequency uncertainty of 7×10^{-16}.

Here, a new experimental scheme to measure the BBR shift in Cs clock is proposed. With an added far-off-resonance light from a CO_2 laser, which provides $10.6\mu m$ light wavelength very close the spectral peak of BBR. By the Stefan-Boltzmann law[15],

$$\left\langle E^2(T)\right\rangle = \frac{4\sigma T^4}{\varepsilon_0 c} \quad (5)$$

where σ is the Stefan-Boltzmann constant, $\sigma = 5.67\times10^{-8}JK^{-4}m^{-2}s^{-1}$.

On the other hand, the laser intensity can be expressed as,

$$I = \frac{\varepsilon_0 c}{2}E^2 \quad (6)$$

Since the BBR or CO_2 laser is still only a slowly varying perturbation to the clock transition, combining (5) and (6), we can say the room temperature $T=300K$ BBR corresponding to $92mW/cm^2$ CO_2 laser. In other way, $1.5W/cm^2$ CO_2 laser simulates a $T=600K$ BBR or an electric field of $\left\langle E^2\right\rangle = (3300V/m)^2$.

It should be noted that, the frequency shift for Cs $^2S_{1/2}$ (F=3, M_F=0) ↔ (F=4, M_F=0) clock transition is[2,5],

$$\delta\nu = -\frac{1}{2}E^2\left(\frac{16}{7}\frac{\alpha_{10}}{h}\right) - \frac{1}{4}\left(3E_Z^2 - E^2\right)\left(-\frac{2}{7}\frac{\alpha_{12}}{h}\right) \quad (7)$$

For real BBR, the second term will vanish after averaging over all directions of the BBR electric field E. But for a CO_2 laser beam passing through the atomic fountain clock system, the C field B_0 direction should be considered as follow[5,6],

$$\delta\nu = \begin{cases} -\frac{1}{2}E^2\left(\frac{16}{7}\frac{\alpha_{10}}{h} + \frac{1}{7}\frac{\alpha_{12}}{h}\right) & E\perp B_0 \\ -\frac{1}{2}E^2\left(\frac{16}{7}\frac{\alpha_{10}}{h} - \frac{2}{7}\frac{\alpha_{12}}{h}\right) & E\,//\,B_0 \end{cases} \quad (8)$$

The first and second expression in (8) corresponding to the C field configuration of parallel to the CO_2 laser polarization direction or perpendicular to the the CO_2 laser polarization direction respectively. And the α_{12} term can be calculated with previous measurements [3,6].

In the experiment by heating the whole fountain clock apparatus, the temperature can not be changed too much, only less than 50K in[4]. And the direct heating[4,14] will cause cavity variation and increase outgasing of vacuum material. These effects in direct heating experiment[4,14] limit the measurement accuracy of BBR shift. On the other hand, the measurement with the static electric field in a fountain clock system[2] gives the doubt of the correction of equivalence between ac and dc Stark shift[15]. This doubt can be avoided in this presented new experimental scheme since one can use an ac electric field from a CO_2 laser to simulate the BBR. Furthermore, in this new scheme, the mixed effects from direct heating are also avoided, and this scheme will dramatically simplify the experimental systems. Or say, one does not have to put heaters inside vacuum chamber or wrap the whole fountain clock system and heat it.

Clearly, the final sensitivity of new scheme will be limited only by CO_2 laser light power calibration. But, a better than 5% accuracy will be very helpful to clarify the puzzle arose from the recent BBR experimental result[4,15].

This proposed measurement can be done in a usual thermal beam or fountain clock without adjusting clock system anything in most clock configuration.

IV. Relationship of the Forbidden Tensor Polarizability and the Differential Polarizability

The measured forbidden tensor polarizability can be used to test the atomic structure calculations [3,5,6]. But the most recent experimental result of the Cs forbidden tensor polarizability only provides an uncertainty of 7.5%[3,6]. The main issue is the relative orientation can not be calibrated with high accuracy.

Given the C field direction is in the horizontal direction in a fountain clock system, and one can change the direction of the CO_2 laser polarization horizontally, then the maximum and the minimum values of (7) are expressed by (8). Thus the ratio of these two values in (8) will be,

$$R = \frac{16\alpha_{10} + \alpha_{12}}{16\alpha_{10} - \alpha_{12}} \quad (9)$$

Under the experimental condition of $1.5W/cm^2$ CO_2 laser, i.e. $\langle E^2 \rangle = (3300V/m)^2$, the fractional frequency shift of a Cs clock due to the α_{12} term is only 2×10^{-15}. Therefore, in order to reach much higher accuracy of the relationship of the forbidden tensor polarizability and the differential polarizability of the ground states, high power CO_2 laser needed. In this situation, the static dipole polarizability may change the transition frequency of states $6P_J$ to the ground state $6S_{1/2}$ too much, and corresponding effects have to be considered in experiment. The dipole force of CO_2 laser may change the atomic movement.

The advantage of this scheme is the calibration of the absolute value of the laser intensity (electric field) is avoided. The relationship of (9) is deduced from (7), (8) under the condition that two frequency shift values are measured with the same CO_2 laser intensity, but one does not have to know what the absolute value of the CO_2 laser intensity is. Once the accuracy of R in (9) can be reached better than 7.5%, then the α_{12} deduced from (9) will be helpful for comparison with previous measurements or for check atomic structure calculations.

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