Measurement of the Stark shift of the Cs hyperfine splitting in an atomic fountain

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(Received 8 August 1997)

We have used an atomic fountain frequency standard to perform a new measurement of the frequency shift induced by a static electric field E on the clock transition of the cesium $6\,^2S_{1/2}$ hyperfine splitting. The result in units of $\mathrm{Hz/(V/m)^2}$ is $\delta\nu_0 = -2.271(4)\times 10^{-10}E^2$. The accuracy of this measurement represents a tenfold improvement over previous values. This result is of importance for testing *ab initio* theoretical calculations of the cesium atomic structure as well as semiempirical models used in parity violation experiments. It will also allow a better evaluation of the frequency shift induced by the blackbody radiation in cesium frequency standards. [S1050-2947(98)02901-1]

PACS number(s): 32.60.+i

I. INTRODUCTION

The cesium atom is currently used in a variety of precision measurements such as parity violation, the search for a permanent electron dipole moment, atom interferometry, and frequency standards. Today, the most accurate time and frequency standards use cesium atoms in a fountain geometry [1–6], and, in our device, the accuracy is presently 2×10^{-15} [6,7]. In the quest for 10^{-16} accuracy, the two dominant uncertainty terms are the frequency shift induced by cold collisions [4,6] and the ac Stark shift induced by the blackbody radiation [8]. In Ref. [8], the relative shift was predicted with a few percent uncertainty to be $-1.69\times 10^{-14}(T/300)^4$, where T is the radiation temperature in K, and it was recently measured with a 10% uncertainty [9], still insufficient for a 10^{-16} accuracy. As discussed below, it can be shown that the blackbody radiation shift can be deduced from the dc Stark effect on the hyperfine splitting [8]. In this work, we take advantage of the long interaction time, the high-frequency stability, and the pulsed operation of our atomic fountain to measure the dc hyperfine Stark shift with a relative uncertainty of 2×10^{-3}, a tenfold improvement over previous measurements [10,11]. This value is of interest for atomic theory tests of the cesium atom, and will be an essential input in the evaluation of the blackbody shift in frequency standards using cold cesium atoms such as fountains and microgravity clocks [12] aiming at a 10^{-16} accuracy. We will first recall to what extent it is possible to deduce the blackbody shift from the knowledge of the frequency shift induced by a static electric field. Then we will describe our measurements of the Stark shift of the Cs clock transition.

II. THEORETICAL CONSIDERATIONS

A. Effect of a static electric field

The application of a static electric field on cesium atoms shifts the energy levels of the clock transition by the quadratic Stark effect [13]. It has been shown that the differential frequency shift induced by an electric field E on the $6\,^2S_{1/2}(F=3,M_F=0)$-$(F=4,M_F=0)$ clock transition is given by [14,15]

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

Here h is Planck's constant and α_{10} and α_{12} are, respectively, the contributions to the cesium static polarizability from the contact and the spin-dipolar interactions. The first term of Eq. (1) is independent of the direction of E. The second term depends on E_z which is the projection of E along the direction of the magnetic field B_0. Expression (1) is valid for any orientation of E under the condition that the frequency shift induced by B_0 on the Zeeman sublevels is appreciably larger than the second term of Eq. (1). This condition is fulfilled in our measurements described below. In the fountain, the electric field E is perpendicular to B_0 and the frequency shift $\delta\nu_0$ is given by

$$\delta\nu_0 = -\frac{1}{2}E^2\left(\frac{16}{7}\,\frac{\alpha_{10}}{h} + \frac{1}{7}\,\frac{\alpha_{12}}{h}\right), \tag{2}$$

$$\delta\nu_0 = k_0 E^2. \tag{3}$$

Previous measurements and theoretical considerations about the differential Stark shift induced on the transition $6\,^2S_{1/2}(F=4,M_F=-3)$-$(F=4,M_F=-4)$ give $\alpha_{12}/h = 137(8)\times 10^{-14}\ \mathrm{Hz/(V/m)^2}$ [16,17]. Using this result and our new measurement of k_0, we will deduce the scalar term α_{10} which is involved in the calculation of the blackbody shift.

B. Effect of the blackbody radiation

According to the Planck radiation law, the average electric field radiated by a blackbody at a temperature T is given by

$$\langle E^2\rangle = (831.9\ \ \mathrm{V/m})^2[T(\mathrm{K})/300]^4. \tag{4}$$

This electric field perturbs the cesium clock frequency by a differential ac Stark shift [8]. We can neglect the shift induced by the magnetic field of the blackbody radiation, which is typically 1000 times smaller at room temperature [8]. In the case of our atomic fountain, the thermal radiation seen by the atoms during the Ramsey microwave interaction is nearly the same as the radiation of a perfect blackbody, except that a small geometrical correction of about 1% must be applied so as to take into account the emissivity and the geometry of the vacuum tube.

To deduce the blackbody shift accurately from the measurement of the frequency shift induced by a static electric field, we must take into account the frequency distribution of the electric field generated by a blackbody, and its orientation, which is a random function of time. Such a calculation was performed with an uncertainty of a few percent [8], and gives for a blackbody at a temperature T:

$$\delta\nu(T) = -\frac{8}{7}\frac{\alpha_{10}}{h}\Phi\left(\frac{T}{300}\right)^4\left[1+\varepsilon\left(\frac{T}{300}\right)^2\right] \qquad (5)$$

with

$$-\tfrac{8}{7}\alpha_{10}/h = -2.273\times 10^{-10}\ \mathrm{Hz/(V/m)^2},$$

$$\Phi = (832\ \mathrm{V/m})^2 \ \text{ and } \ \varepsilon = 1.4\times 10^{-2}.$$

This expression uses the coefficient α_{10} from the first term of Eq. (1). The second term of Eq. (1) vanishes when averaged over all the directions of E. The term ε is due to the spectral density of energy of the blackbody radiation. This term is estimated considering that the main contribution to the dipolar electric perturbation of the $6S_{1/2}$ states is due to the first P state. The uncertainty on estimation (5) is responsible for a 1×10^{-15} uncertainty on a Cs frequency standard operating at room temperature. Up to now, this accuracy was partly limited by the knowledge of α_{10} which was estimated from previous measurements of the dc Stark shift with a few percent uncertainty [10,11]. In order to improve the theoretical estimation of the blackbody shift by one order of magnitude, it is necessary to perform a measurement of the frequency shift induced by a static electric field on the clock transition $(F=3,M_F=0)$-$(F=4,M_F=0)$, with an accuracy of a few 10^{-3}. We have performed this measurement in an atomic fountain.

III. EXPERIMENT

A. Description

Our atomic fountain was previously described in detail [5]. Here we briefly recall its operation during the experiment on the differential Stark shift, depicted in Fig. 1. A few 10^8 Cs atoms are cooled down in a magneto-optical trap at a temperature of a few microkelvin. They are launched in the vertical direction by the moving molasses method. About 10^7 atoms are selected in the $F=3$, $m_F=0$ level, and pass upwards into a TE_{011} microwave cavity which is 30 cm above the cooling region, through a 10-mm-diameter hole. They follow a ballistic flight up to 45 cm above the microwave cavity. Then they fall down through the TE_{011} cavity again, and experience the second part of the Ramsey microwave interaction. The population of both hyperfine levels is measured by fluorescence in the bottom of the experiment. A vertical homogeneous magnetic field B_0 of magnitude 1.63×10^{-7} T resolves the field-sensitive transitions. For this experiment, two copper plates separated by 2-cm-long ceramic blocks were suspended 17 cm above the microwave cavity. The dimensions of the plates were 10×30

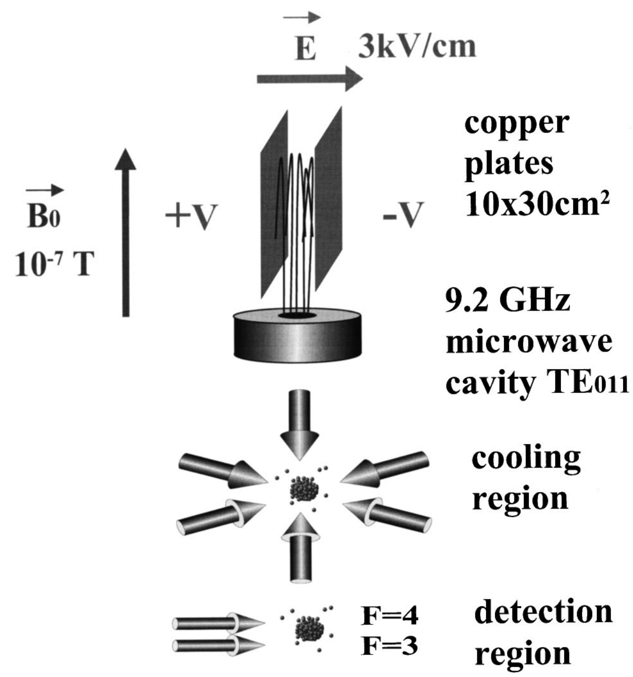

FIG. 1. Experimental setup.

$\times 1.5\ \mathrm{cm}^3$. With this geometry, the atoms can experience a homogeneous electric field for a duration of about 0.4 s. The plates were manufactured with a flatness of 10 μm. A voltage of $\pm V$, symmetric about the ground potential, is applied to each of the plates in order to generate an horizontal electric field from 0 to 3000 V/cm. The 15-cm-diameter copper tube which surrounds the plates and the microwave cavity are at the ground potential. A computation of the electric field for this geometry was performed by the Laboratoire de Genie Electrique de Paris (LGEP). This computation gives a map of the electric field along the pass of the atoms. It also demonstrates that the homogeneity of the field intensity is better than 10^{-3} in a $6\times 26\times 1\ \mathrm{cm}^3$ parallelepiped centered between the two plates. The atoms which are detected are transversally selected on their way down by the 10-mm-diameter aperture of the cavity, and they are well within the high homogeneity region of the electric field. With respect to the vertical direction, the maximum radius of the atom ball when it exits the plates on its way down is $\sigma_x = 1.2$ cm for a 5-μK atom temperature. Under these conditions, we modeled the effect of the electric-field inhomogeneity and of the vertical velocity distribution on the evaluation of k_0.

B. Evaluation of k_0

We have measured the frequency shift $\delta\nu_{\mathrm{meas}}$ of the central Ramsey fringe corresponding to the $(F=3,M_F=0)$-$(F=4,M_F=0)$ clock transition when an electric field E is applied between the copper plates over a span from 0 to 3000 V/cm. For this purpose, the device is locked to the central Ramsey fringe, and its frequency is compared to a hydrogen maser. We have measured $\delta\nu_{\mathrm{meas}}$ for four different launching velocities, and for four different values of the electric field. Each measurement is averaged over 10 000 s, and has a resolution of about 10^{-4} Hz, mainly limited by the stability of the voltage applied on the plates. The maximum shift $\delta\nu_{\mathrm{meas}}$ was about 20 Hz. When the electric field is ap-

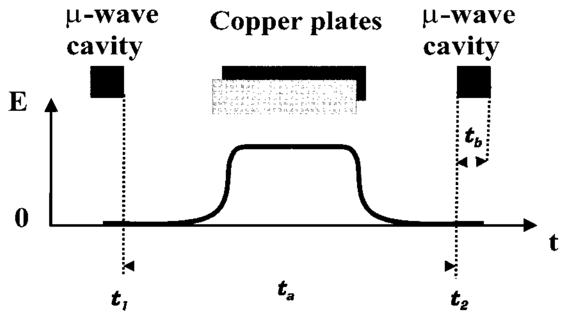

FIG. 2. Evolution of the electric field during the ballistic flight of the atoms.

plied, the average atomic frequency above the cavity differs from the atomic frequency inside the cavity. As shown in Ref. [18], the resonance pattern becomes asymmetrical in that case, and the observed shift $\delta\nu_{\mathrm{meas}}$ must be increased by a small correction factor γ of about 2%. We have computed the parameter γ in the case of a Ramsey interaction with a TE_{011} cavity. The value of γ is proportional to t_c/t_a, and also depends on the microwave power (t_c and t_a are the transit times inside the cavity and above the cavity, respectively). We experimentally verified the dependence of γ on the previous parameters. The accuracy of the value of γ is better than 0.5%, mainly limited by the experimental uncertainty of the microwave power. According to Eq. (3), we obtain

$$\delta\nu_0 = k_0 \frac{\int_{t_1}^{t_2} E^2 dt}{t_2 - t_1}, \tag{6}$$

with

$$\delta\nu_0 = \delta\nu_{\mathrm{meas}}(1+\gamma). \tag{7}$$

The frequency shift due to the electric field is averaged between the time t_1, when the atoms have just experienced the first microwave interaction, and t_2, when the atoms are starting to experience the second microwave interaction (Fig. 2). We estimate $\delta\nu_0$ from Eq. (7), with an uncertainty of 10^{-3}.

The evaluation of k_0 depends on the accuracy of the calculation of the integral term in Eq. (6). The geometrical uncertainties on the relative position of the microwave cavity and of the copper plates limits the accuracy on the evaluation of the integral term. We used two different experimental methods to reduce this uncertainty to a level of 10^{-4}. We first performed measurements of the frequency shift induced by a fixed value of the electric field when the atoms are launched to different heights above the microwave cavity. An analysis of those results using the computation of the electric field enables the minimization of the influence of the relative position of the microwave cavity and the copper plates. We recalculate the positions by minimizing the difference between the results obtained for different launching velocities. The second experimental method consists in switching on the voltage on the copper plates during a time Δt when the atoms are passing in the highly homogeneous electric-field region centered in between the two plates. In this case, expression (6) becomes

$$\delta\nu_0 = k_0 E^2 \frac{\Delta t}{t_2 - t_1}. \tag{8}$$

The switching times of the voltage are recorded on a digital oscilloscope, and a small correction of their parasitic effect (2×10^{-3}) is applied to calculation (8). These two measurements are in good agreement at a level of 5×10^{-4}. The main remaining source of geometric uncertainty comes from the relative position of the cooling region of the Cs atoms and of the microwave cavity. This effect causes a 10^{-3} uncertainty in the calculation of k_0.

We increased the value of the vertical magnetic field B_0 in our atomic fountain by a factor of 2 to see if there is any dependence of $\delta\nu_{\mathrm{meas}}$ on the value of B_0. We observed no variations at a level of a few 10^{-4}. The influence of the motional magnetic field ''seen'' by the cesium atoms moving in a static electric field was calculated to be negligible for a 10^{-3} accuracy estimation of k. We calculated the effect of the electric field gradient on the motion of the atoms, and it is also negligible in our case [19]. The main uncertainties on the measurement of k_0 are listed in Table I.

TABLE I. The main uncertainties in the measurement of k_0.

Physical origin	Uncertainty$\times 10^3$
Fringe asymmetry	1
Relative position of the cooling region and the microwave cavity	1
Voltage applied on the plates	0.3
Distance between the copper plates	0.5
Velocity distribution of the atoms	0.3
Frequency stability	<0.1
Computation of the electric field	0.5
Total uncertainty (1σ)	2

IV. RESULTS

The proportionality of the frequency shift with the square of the electric field given by Eq. (3) was verified with an accuracy of 5×10^{-4} for 0 V/cm$<E<$3000 V/cm. We find

$$k_0 = -2.271(4)\times10^{-10}\ \mathrm{Hz/(V/m)^2}. \tag{9}$$

From Eq. (2) and from the previous estimations of α_{12} [16,17], we can deduce α_{10} which is the relevant term for the evaluation of the blackbody shift:

$$-\tfrac{8}{7}\alpha_{10}/h = -2.273(4)\times10^{-10}\ \ \mathrm{Hz/(V/m)^2}.$$

This result is in agreement with previous measurements, although ten times more precise:

$$k_0' = -2.29(3)\times10^{-10}\ \ \mathrm{Hz/(V/m)^2}, \tag{10}$$

$$k_0' = -2.25(5)\times10^{-10}\ \ \mathrm{Hz/(V/m)^2}, \tag{11}$$

We are using here the notation k_0' instead of k_0 because the previous measurements were performed with a different geometrical configuration for E and B_0 than in our experiment. According to Eq. (1), this causes a slight difference between k_0 and k_0'. However, this difference is not significant in comparison with the experimental uncertainties on k_0'.

V. CONCLUSION

The measurement of the frequency shift of the cesium hyperfine splitting due to an electric field has allowed an evaluation of the scalar term α_{10} related to the cesium polarizability to an accuracy of 2×10^{-3}. This demonstrates the ability of a pulsed atomic fountain to perform high-precision measurements. The measured value of α_{10} enables a future theoretical evaluation of the blackbody shift in Cs frequency standards in the spirit of [8] with an accuracy of 10^{-16}. We are now replacing the copper plates by a graphite tube heated from room temperature to 500 K, in order to perform a direct measurement of the blackbody shift. We expect to be able to determine the term ε in Eq. (5) experimentally with this new experiment. Comparing this direct measurement with the new theoretical value should give confidence in the evaluation of the blackbody shift at the 10^{-16} level.

ACKNOWLEDGMENTS

We acknowledge the assistance of A. Gerard, P. Aynié, M. Lours, M. Dequin, L. Volodimer, S. Bize, and P. Lemonde, all from the BNM-LPTF, C. Mandache from the Institute for Atomic Physics, (Bucharest, Romania), and Wang Yiqiu from Beijing University. We wish to thank M. L. Mathieu, O. Mathieu, and L. Pichon for the helpful computations performed at the LGEP. We especially thank W. M. Itano from the National Institute of Standards and Technology (NIST), and M. A. Bouchiat and C. Salomon from the Laboratoire Kastler Brossel (LKB) for helpful advice.

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