# Blackbody radiation shift in primary frequency standards

Peter Rosenbusch, Shougang Zhang* and André Clairon
LNE-SYRTE
Observatoire de Paris
61 av de l'Observatoire
75014 Paris, FRANCE
Peter.Rosenbusch@obspm.fr

***Abstract*— The principal coefficient $k_0$ for the blackbody radiation shift in primary frequency standards has been subject to discussion. We present extensive measurements of this shift performed on the SYRTE's atomic fountain clock, FO1. The DC Stark shift is measured at a range of electric fields reaching down to twice the rms ambient thermal field $E_{300K}$. Furthermore, the blackbody radiation shift is measured directly by inserting a heated graphite tube around the atom trajectory. The Stark measurement reaches an accuracy of $2\times10^{-3}$ for the principal coefficient. The direct measurement gives an accuracy of 4%. Both results confirm our earlier measurement [Simon *et al*Phys. Rev. A 57, 436 (1990)]. In the analysis a $3\times10^{-3}$ correction, due to a sign error in the theory must be made, so that the coefficient reads $k_0 = -2.282(4)\times10^{-10}$Hz/(V/m)$^2$.**

## I. Introduction

Today's primary frequency standards, atomic fountain clocks, reach an accuracy in the low $10^{-16}$ [1]. Among the largest sytematic effcts to be corrected for is the blackbody radiation shift. Its relative contribution is about $1.7\times10^{-14}$ at room temperature. An evaluation to below $10^{-16}$ implies its knowledge to better than 1%, whereas disagreement on the value for the principal coefficient is found in the literature. One direct measurement of the blackbody radiation shift in particular differs by 15% [2] from most experimental and theoretical evaluations leading to a longstanding controversy (Fig. 3). To clarify the situation, we present results that eliminate any ambiguity at a level of a few $10^{-17}$.

## II. Theory

The frequency shift of the Cs clock transition induced by the electric field of the ambient blackbody radiation has been calculated by Itano *et al* [3] as

$$\delta\nu_{BB} = k_0 E_{300}^2 \left(\frac{T}{300\text{K}}\right)^4 \left(1+\epsilon\left(\frac{T}{300\text{K}}\right)^2\right), \quad (1)$$

where $T$ is the ambient temperature and $E_{300} = 831.9$ V/m the rms electric field at 300 K derived from the Stefan-Boltzmann law. Since the main contribution of the blackbody radiation is at wavelengths much longer than any electric dipole transition coupling to the groundstate of Cs, the $T^4$ part of (1) is equivalent to the DC Stark scalar polarisability. Any tensorial part is averaged out by the isotropy of the radiation. The term in $T^6$ is a small correction taking the spectral distribution with respect to the D1 and D2 lines into account. $\epsilon$ has been calculated as 0.014 in [3] and recently recalculated by *ab initio* methods as 0.013 [4]. We suppose this value is good to 10% or better.

The main coefficient $k_0 = -\frac{8}{7}\frac{a_0}{h}$ with the Planck constant $h$, is the scalar DC polarisability of the clock transition, which can be deduced from measurements of the DC Stark shift. Sandars calculated the DC Stark shift as [5]

$$\delta\nu_{DC} = -\frac{1}{2}E^2\left(\frac{16}{7}\frac{a_0}{h} - \frac{1}{7}\frac{a_1}{h}f(\theta)\right). \quad (2)$$

Here the angle $\theta$ between the electric field and the quantisation aixs, typically the magnetic field, plays into the $f(\theta) = 3\cos^2\theta - 1$ term. Ulzega *et al*indicate a sign error in Sandars calculation so that (2) should rather read [6]

$$\delta\nu_{DC} = -\frac{1}{2}E^2\left(\frac{16}{7}a_0 + a_1\frac{3M^2-16}{28}f(\theta)\right), \quad (3)$$

$M$ being the projection of the combined electric and nuclear spin onto the quantisation axis. Magnetic resonance measurements by the same group of Cs imbedded in solid He clearly distinguish between the two formulae and confirm the validity of (3) [7]. At the same time their theoretic value for $a_1$ [6] agrees within the error bars with three atomic beam measurements [8]–[10]. In the following we use the weighted mean of these three measurements,

$$a_1 = -3.51(16)\times10^{-12}\text{Hz/(V/m)}^2. \quad (4)$$

## III. DC Measurement

Equation (3) can be verified in an atomic fountain clock by exposing the atoms to a DC electric field during the Ramsey time. In 1998 the SYRTE performed such a measurement [11]. The electric field is created by two parallel copper plates of $0.1\times0.3\text{m}^2$ and $0.02\pm10^{-5}$m distance charged to 1 - 3 kV. The measured frequency shift follows the expression

$$\delta\nu_{DC} = -2.271(4)\times10^{-10}\text{Hz/(V/m)}^2E^2. \quad (5)$$

Criticism arose from the large difference between the lowest field applied in the experiment and $E_{300}$, even though the calculations leading to (3) do not indicate any deviation from the $E^2$ law. To eliminate any ambiguity, we here repeat the measurement in a field range from 2 to 50 $\times$ $E_{300}$, thereby bridging the gap.

The experimental set-up is identic to that of [11] only the distance between the microwave cavity and the bottom edge of the plates is reduced to 4.8 cm in order to increase sensitivity. The electric field is pulsed on when all atoms are 2 cm into the field plates, so that the fringe field is avoided. The field pulse is square in $E^2$ to $2 \times 10^{-4}$. The frequency shift is measured differentially alternating between configurations with and without field every 50 cycles. At 50 $\times$ $E_{300}$ the frequency shift is sufficiently strong to reach a $10^{-3}$ resolution in a couple of hours, whereas at $2 \times E_{300}$ it takes 10 days. The field induced frequency shift is deduced from the measured by integrating the sensitivity function.

The recorded data follow, within the statistic resolution equation (5). No significant deviation from the parabolic law is observed. The weighted mean gives the coefficient $-2.273(4) \times 10^{-10}$Hz/(V/m)$^2$ which agrees with that of [11] within the uncertainty. Taking the mean of the old and new value and using (3) and (4) we deduce for the principal coefficient of the blackbody radiation shift

$$k_0 = -2.282(4) \times 10^{-10}\text{Hz/(V/m)}^2. \qquad (6)$$

## IV. Direct Measurement

In a second experiment we measure directly the frequency shift induced by the blackbody radiation. Instead of the electric field plates, a graphite tube is inserted into the fountain's vacuum chamber. The tube of 1.6 cm inner diameter and 30 cm length is suspended 10 cm above the microwave cavity. A non-magnetic wire wound onto the graphite in a double helix allows AC resistive heating without magnetising the fountain's magnetic shielding. Heating the graphite introduces an additional shift on the atomic frequency during the Ramsey time.

The graphite can be heated up to 500 K with only 4 W of electric power, while two thermal shields and water cooling at the point of mechanical contact keep the rest of the set-up near room temperature. In fact, the temperature of the microwave cavity as measured from its resonance frequency increases by 6 K at most. The temperature of the graphite tube is measured by three Pt100 thermistors at its extremities and in the center, as well as the temperature of the outer thermal shield. The accuracy of the thermistors is 0.2 K. Fig. 1 shows a vertical cut through the experimental set-up.

The experimental sequence consists of a preliminary phase where the graphite is heated at constant current for a variable duration. Then the current is switched off and the atomic frequency is measured by comparison with another SYRTE fountain, FO2. During this period the graphite temperature does not drift by more than 2 K. By varying the durations of heating and measuring, different final temperatures can be realised. The mean temperature is stable to 1.5 K over a 33 hour run.

Because the atoms spend only part of the Ramsey time inside the graphite, we calculate an effective $T^4$ at every point along the atom trajectory taking the different temperatures, emissivities and geometries into account. Errors on $T^4_{eff}$ include uncertainties on the emissivities and on the physical distances of the cavity and the graphite tube, fluctuations on the initial position and launch velocity of the atomic cloud as well as temperature uncertainties in regions where no direct temperature measurement is recorded. However, the main uncertainty still arises from the 2 K temperature drifts/fluctuations during the measurement time. This leads to a total error on $T^4_{eff}$ of 2.4%. The overall frequency shift is calculated by integrating the local $T^4_{eff}$ with the sensitivity function.

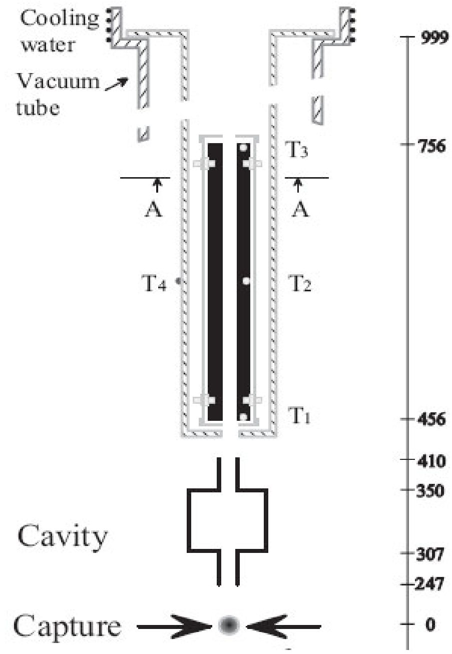


Fig. 1. Experimental set-up for the direct measurement of the black body radiation shift. Above the microwave cavity the atoms enter into a graphite tube which can be heated to 500 K. Its temperature is monitored using three Pt100 thermistors, $T_1$ to $T_3$ at the indicated positions. Thermistor $T_4$ measures the temperature of the second thermal screen. A scale of the relevant heights above the loading zone is given in mm.

About 20 measurement runs are performed going up to effective temperatures of 440 K. The data are well fitted by equation (1) yielding $k_0 = -2.23(9) \times 10^{-10}$Hz/(V/m)$^2$. Within the error this value confirms (6). Unfortunately, the measurement resolution is insufficient to identify the $T^6$ term.

## V. Discussion

Within their resolution, our measurements confirm the model (1). Repetition of the DC Stark shift at electric fields down to $2 \times E_{300}$ confirms our earlier published value. Due to a sign error in the evaluation of the DC Stark measurements the blackbody radiation shift coefficient $k_0$ has to be adjusted by $5 \times 10^{-3}$ resulting in a correction of the shift of $8 \times 10^{-17}$ at room temperature. The measurement error on this coefficient remains $2 \times 10^{-3}$ giving a frequency uncertainty of $3 \times 10^{-17}$.

The spectral term of (1) can be considered precise to 10% giving a frequency uncertainty of $2 \times 10^{-17}$. These values easily allow an evaluation of the blackbody radiation shift below $10^{-16}$ if the effective temperature is known to better than 0.5 K.

Our direct measurements have shown how difficult it is to actively stabilise the ambient radiation temperature. Considerable drifts can occur. Furthermore, temperature gradients lead to a shift varying along the atom trajectory. Effort has to be put into modeling the effective temperature based on the emissivities of the different materials used. A more straight forward approach is to let the temperature of the set-up equilibrate and drift with the laboratory temperature and to monitor it. Then, gradients are reduced to a minimum. Furthermore, radiation which enters the vacuum chamber by any of the view ports originates from the same temperature. Such temperature homogeneity comes the nearest to the ideal blackbody.

We have chosen this approach in our standard fountain operation. The temperature drifts with the lab temperature and is monitored at various position on the vacuum tube as well as outside the view ports. The blackbody radiation shift is then corrected synchronously. Fig. 2 shows a temperature recording over one month using Pt100 thermistors. The measured gradients are smaller than 0.1 K. The calibration error of the thermistors is specified as 0.2 K. We take this as the uncertainty on our temperature measurement, which leads to an uncertainty in $\delta\nu_{BB}$ of $5 \times 10^{-17}$. At this level of precision one might also include the $1.3 \times 10^{-17}$ error caused by the omission of the AC Zeeman shift due to the thermal magnetic field [3]. Hence, the total uncertainty is $\delta\nu_{BB} \leq 6 \times 10^{-17}$.

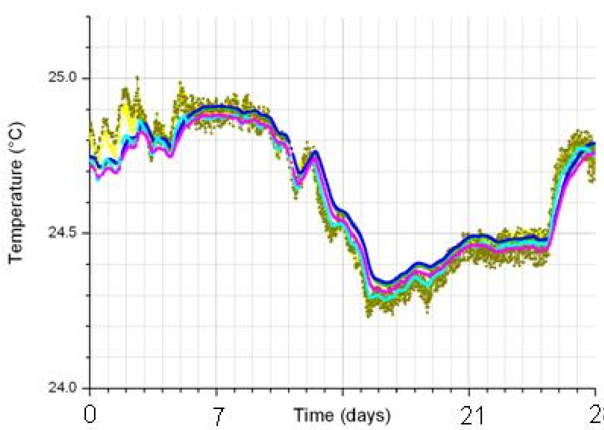


Fig. 2. Temperature recordings of the fountain's set-up: The three "calm" curves stem from three thermistors on the vacuum tube placed at the extremities and the center of the drift zone. The other more noisy curves measure the laboratory temperature just outside the view ports. No active temperature stabilisation is applied other than air conditioning.

## VI. Conclusion

We have revisited the blackbody radiation shift of primary frequency standards. An atomic fountain clock was used for two series of measurements. The DC Stark shift of the clock transition was measured in an electric field range of $2 \times E_{300}$ to $50 \times E_{300}$. The value of our former publication [11] was confirmed. Using a recent re-calculation of the tensor polarisability we deduce $k_0 = -2.281(4) \times 10^{-10}$Hz/(V/m)$^2$ for the principal coefficient of the blackbody radiation shift. The second series measured the blackbody radiation shift directly by surrounding the atoms with a heated graphite tube. The clock stability and temperature drifts limited the measurement error to 4%. Within the error, the model of Itano *et al* [3] and the above coefficient were confirmed. We have also shown that standard clock operation without active temperature stabilisation reduces the temperature error to 0.2 K. This ensemble of improvements allows the reduction of the frequency uncertainty due to the blackbody radiation to $6 \times 10^{-17}$ without ambiguity.

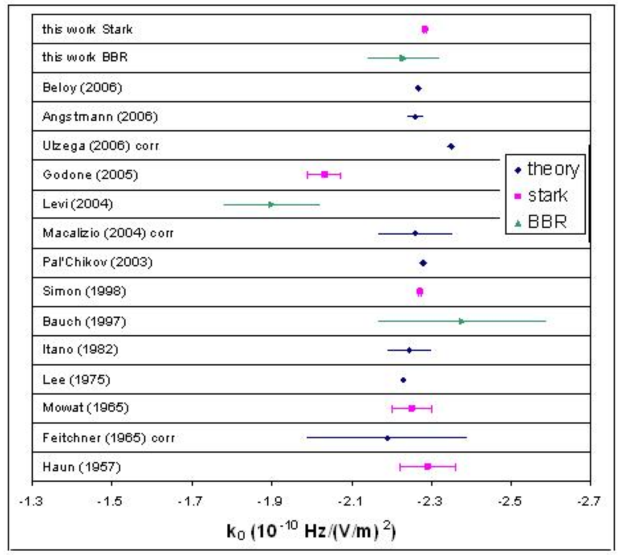


Fig. 3. Literature values of $k_0$ from [4] and references therein together with the here presented measurements. Some errorbars are smaller than the dot size. Three theoric values have been corrected for the contribution of continuum states as suggested in [4] and [12].

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