# Experimental Verification of the Shift of the Cesium Hyperfine Transition Frequency due to Blackbody Radiation

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An atomic-beam resonance apparatus has been used to measure the dynamic Stark shift of the ground-state hyperfine transition frequency in cesium ($\approx 9.2$ GHz) due to the electric field of blackbody radiation. The shift was measured as a function of the temperature of heated surfaces surrounding the atomic beam. The observed dependence of the transition frequency on temperature is in good agreement with theoretical predictions. At room temperature, the expected relative frequency shift is $-16.9 \times 10^{-15}$, whereas the experimental result is $-16.6(2.0) \times 10^{-15}$. [S0031-9007(96)02253-3]

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The interaction between atoms and the electric fields of blackbody radiation (BBR) produces two effects: Firstly, it drives atomic transitions and thereby shortens the lifetime of atomic states, an effect which has been clearly observed for Rydberg states [1] and also for metastable states [2]; both are strongly susceptible to this kind of perturbation [3]. Secondly, a dynamic Stark shift of the atomic energy levels is induced, which can be as large as about 2.5 kHz for Rydberg states (principal quantum number $n > 30$) [3,4] and which will possibly lead to significant frequency shifts in optical frequency standards as well [2]. Here we address the minute effect of BBR on atomic ground-state levels. In 1982, Itano, Lewis, and Wineland [5] pointed out that the electric field of isotropic blackbody radiation emitted from the surroundings of the atomic beam in a cesium atomic clock leads to a shift of the clock frequency in the same order of magnitude as the standard uncertainty of primary clocks of that time. Despite the elemental interest in the matter, up to now the frequency shift has not been verified experimentally, probably because of the technical difficulties encountered with such an experiment. The interest has been revitalized recently, when the first fountain frequency standard employing cold cesium atoms, the FO1 [6], became operational: The predicted frequency shift [5] amounts to about 6 times the standard uncertainty of the FO1. In this Letter we report on the first experimental observation of the blackbody frequency shift.

We recall first some properties of BBR. According to Planck's radiation law, at a given temperature *T*, the time averaged quadratic electric field strength of BBR is

$$\langle E^2(t)\rangle = (832\ \mathrm{V/m})^2 (T/300\ \mathrm{K})^4 \tag{1}$$

and the associated magnetic flux density is

$$\langle B^2(t)\rangle = (2.8\ \mu\mathrm{T})^2 (T/300\ \mathrm{K})^4. \tag{2}$$

At room temperature, BBR has its peak spectral density around a wavelength of 9 $\mu$m and the full width at half maximum of the spectrum is approximately 11 $\mu$m.

It has been known for some time that the hyperfine splitting interval in the ground state of cesium ($^{133}$Cs) is reduced in the presence of a *static* (dc) electric field. In the theoretical treatment [7–9], which followed the experiments made by Haun and Zacharias [10] and Mowat [11], the frequency shift is attributed to the differential polarizability of the two ground-state hyperfine levels. Mowat's results on the dc Stark shift had a relative uncertainty of $\approx 0.5\%$ and the theoretical results, in particular those by Lee *et al.* [9], agreed with Mowat's results within 1%. The dc Stark shift appears in this case as a third-order perturbation, and the relevant terms [e.g., Eqs. (15)–(18) in [7]] describe the admixture of excited $S$ and $P$ states to the ground state and include the frequencies of the electric dipole transitions connecting the ground state to excited states as resonance denominators. These frequencies are much higher than the bulk spectral distribution of BBR, and thus at room temperature BBR represents a *slowly varying perturbation* [3] to the ground-state hyperfine levels. The frequency shift in the dynamic case can thus be calculated using the rms value of the electric field strength of BBR. Including a corrective term $\chi$ which accounts for the separation in frequency between the BBR spectrum and the transition frequency of the $D1$ and the $D2$ line in $^{133}$Cs, one expects the following frequency shift [5]:

$$y_{\mathrm{BBR}} \equiv [\nu(T) - \nu_0]/\nu_0 = \beta\chi (T/300\ \mathrm{K})^4, \tag{3}$$

with $\beta = -16.9 \times 10^{-15}$ and $\chi = 1 + 0.014(T/300\ \mathrm{K})^2$. Here $\nu_0$ is the unperturbed hyperfine transition frequency of $^{133}$Cs, $\nu_0 = 9\,192\,631\,770$ Hz, which defines the duration of the second, $\nu(T)$ is the clock frequency of atoms which are subjected to radiation of a blackbody at temperature *T*, and $y_{\mathrm{BBR}}$ is the predicted frequency shift expressed as a relative quantity. The numerical factor $\beta$ is based on Eq. (1) and on the experimental results on the dc Stark effect [11]. It is assumed that the perturbing BBR is isotropic and unpolarized [5]. The effect of the BBR magnetic field (2) through the dynamic Zeeman effect leads only to a frequency shift of a few parts in $10^{17}$ and is thus at present not of particular interest [5].

We used an experimental atomic beam resonance apparatus with separated oscillatory fields [12] to observe the frequency shifting effect of BBR. The device, named CSX, has been operated in the Time-Unit Laboratory of the Physikalisch-Technische Bundesanstalt (PTB) since 1983 and was described in detail previously [13,14]. Briefly, the CSX is a frequency standard with magnetic state selection, an interaction length of 0.79 m, given by the length of the microwave cavity, and a mean velocity of 405 m/s of the atoms contributing to the hyperfine resonance signal. During our experiments, the atomic flux was chosen such that the short-term frequency instability, expressed by the Allan standard deviation $\sigma_y(\tau)$, was $3.5 \times 10^{-12}/(\tau/\mathrm{s})^{1/2}$. Frequency measurements were made using PTB's primary clock CS2 as a reference [15], and the relative frequency difference $y_{\mathrm{XR}} := [\nu(\mathrm{CSX}) - \nu(\mathrm{CS2})]/\nu(\mathrm{CS2})$ was recorded. Here $\nu(\mathrm{CS2})$ and $\nu(\mathrm{CSX})$ are the clock transition frequencies of the CS2 and the CSX, respectively, corrected for all systematic frequency shifts [12,15] except for the CSX cavity phase difference (see below). The combined frequency instability was $\sigma_y(\tau = 1d) = 18 \times 10^{-15}$ and $\sigma_y(\tau = 7d) = 7 \times 10^{-15}$ during normal CSX operation (data points at $T_{\mathrm{BBR}} \approx 300$ K in Fig. 3) and thus at the level which is estimated from the known noise sources in the clocks [12].

Equation (3) predicts a relative frequency shift of only about $10^{-13}$, even if the BBR source temperature is increased by as much as 200 K above room temperature. In order to observe the effect we took an approach which was already suggested in [5]. The atomic-beam path within the interaction region of the CSX was partially surrounded with tubes which could be heated by up to 200 K above room temperature. Figure 1 shows schematically the experimental setup with some details of the heated tubes and the temperature measurement. For technical reasons, the heated region was split into two parts, each 0.25 m in length. The tubes were surrounded by two coaxial reflective shields and were suspended with low thermal conductance from the support structure inside the CSX (not shown in Fig. 1). This was done in order to reduce the heat load on the microwave cavity, which finally warmed up by only 12 K when the heated tubes were at their maximum temperature of 485 K. Heating was performed by passing dc currents through four wires along the tubes. This had to be done without destroying the homogeneity of the weak quantization field, $B_c = 15.7\ \mu\mathrm{T}$. We chose a cycling mode, separating 2 or 3 min of heating from 9 min of taking frequency data. During the latter interval the dc current was switched off and the temperature of the tubes dropped by a few Kelvin exponentially with a time constant of 80 min. The temperature was measured using four thermocouples shown in Fig. 1, which allowed us to determine the temperature profile along the surface of the tubes and the time average of the temperature during the 9 min measurement interval.

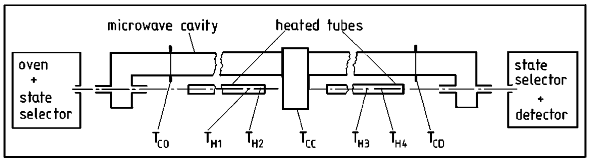

FIG. 1. Sketch of the experimental setup. The standard constituents of an atomic-beam resonance apparatus are shown very schematically, whereas the microwave cavity and the heated tubes are shown in larger detail. $T_{\mathrm{H1}}$–$T_{\mathrm{H4}}$ and $T_{\mathrm{CO}}$, $T_{\mathrm{CC}}$, and $T_{\mathrm{CD}}$ indicate the positions of the thermocouples attached to the heated tubes and the cavity, respectively.

The inner surface of the tubes was painted with 3M Nextel black paint [16] and served as the source of thermal radiation. The emissivity of the surface, averaged over the BBR spectrum, is estimated from data on the hemispherical spectral reflectance of the paint at room temperature [17] to be 0.961(5). The atomic beam passes along the axis of the tubes. The on-axis intensity of BBR was calculated by integrating over the spectral emittance of the surface of the tubes. The emittance was determined from the spatial distribution of the temperature $(T^4)$, averaged over the 9 min measurement interval, and the assumption of BBR emission according to Lambert's law of cosines. This assumption is reasonably well fulfilled for the paint [17]. BBR is concentrated to the region inside the two heated tubes as shown in Fig. 2. The time-averaged temperature in the central section of a tube is named $T_{\mathrm{BBR}}$ further on. Based on the BBR intensity profile (Fig. 2), on the temperature $T_{\mathrm{BBR}}$ and on Eq. (3), we obtained prediction values of the frequency shift, e.g., $y_{\mathrm{BBR}} = -69 \times 10^{-15}$ at the highest temperature used during the experiments. The systematic uncertainty of the predictions is estimated to about 5%, relatively, based on

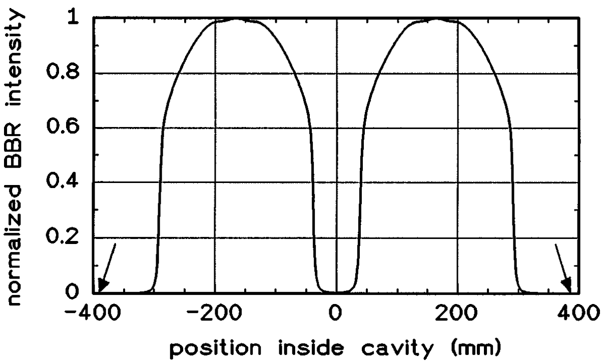

FIG. 2. Normalized intensity of blackbody radiation which is emitted from the inner surface of the heated tubes in the interaction region of the CSX. The calculation included integration over the surface emittance as given by the temperature distribution along the heated tubes and the assumption of BBR emission according to Lambert's law of cosines. Outside the tubes, the BBR intensity is assumed to correspond to the temperature of the CSX vacuum tank. The two arrows indicate the beginning and the end of the drift region of the cavity (see Fig. 1.

the uncertainty of the temperature measurement (absolute value and profile), of the emissivity of the surface of the tubes, and of $\beta$ in Eq. (3) [5,9].

Observation of the small predicted effect required careful control of all systematic frequency shifts aside from the BBR effect. In particular, we studied the impact of the heat generated inside the apparatus on its performance. It was expected that an increase of the cavity temperature would entail a change of the dimensions of the microwave cavity, resulting in a change of the resonance frequency and eventually of the end-to-end phase difference $\phi$ of the cavity. When the cavity resonance frequency is detuned from $\nu_0$, one has to expect a shift of the realized clock transition frequency. The effect, commonly named cavity pulling [12], was of order $10^{-15}$ only, mostly because of the low loaded cavity $Q$ value employed in our cavity design. The realized cavity design, however, entailed a significant sensitivity of $\phi$ on the temperature of the cavity: In the case of a weakly coupled cavity, $\phi$ is proportional to the difference in the electrical length, $\Delta L$, between the two arms of the cavity with respect to the central feed junction, but it is insensitive to the total length of the cavity. Only a weak impact of temperature through a change of $\Delta L$ could be expected in this case. In our case, however, the coupling is tight—the loaded $Q$ value is only 400—and the fields in the cavity close to the feed are distorted with respect to the intrinsic mode pattern. As De Marchi *et al.* pointed out [18], $\phi$ becomes, in this case, proportional to $D\Delta L (D > 1)$, $D$ not only depending on the coupling parameters, but also on the cavity dimensions and thus annoyingly also on its temperature.

We decided to study separately the impact of both the temperature distribution along the cavity and of the mean temperature on the CSX clock frequency. Three thermocouples were attached to the waveguide (see Fig. 1 for the notation). At first we introduced a large temperature gradient along the cavity by heating only one of the tubes at a time. $\nu(\mathrm{CSX})$ decreased by $260 \times 10^{-15}$ when the temperature difference $T_{\mathrm{CO}}$-$T_{\mathrm{CD}}$ was increased by 1 K. Next we analyzed the influence of the mean cavity temperature. Here we had to separate between the effect of the dimensional sensitivity of $\phi$ and the effect of BBR under study. We varied the cavity temperature by up to 15 K simply by adjusting the temperature in the CSX laboratory between 288 K and 303 K. In doing so the intensity and spectrum of BBR inside the CSX was not significantly altered and only the cavity effect showed up in frequency changes. The clock frequency was decreased by $7.2 \times 10^{-15}$ in relative units when $T_{\mathrm{CC}}$ was increased by 1 K. The magnitude of both effects is larger by a factor of 2 to 3 than a first estimate based on De Marchi's theory [18] and deserves further studies.

Having these experimental data at hand, we were able to calculate and apply corrections to all data taken when BBR was admitted and to eliminate the unwanted effects to a large extent. Figure 3 depicts the frequency measurement results $y_{\mathrm{XR}}$ as a function of the relevant temperature $T_{\mathrm{BBR}}$, which were corrected to demonstrate only the effect of BBR. Each point represents a 5 to 7 day average value. The data are shown together with the predicted frequency shifts which were normalized to the experimental results at room temperature. Here the measurement value of $y_{\mathrm{XR}}$ corresponds to the CSX frequency offset with respect to the CS2 which is attributed to the stationary cavity phase difference $\phi$.

The predicted decrease of the clock frequency with increasing temperature $T_{\mathrm{BBR}}$ is clearly confirmed. As there is no reason to question the $T^4$ dependence of the frequency shift which follows from Planck's radiation law, we interpret the results in terms of $\beta$ in Eq. (3). A polynomial fitted to the data yielded $\beta_e = -16.6(2.0) \times 10^{-15}$. Clearly the uncertainty obtained in our study is larger than that of the previous dc measurements [10,11], and the difference between our experimental value and the previously accepted value of $\beta$ is insignificant. In our case the uncertainty is dictated by the limited number of data points and the frequency instability of the CSX and the reference clock. The frequency deviation of the individual data points from the polynomial regression corresponds to a frequency instability of $9.5 \times 10^{-15}$, which is obviously about 35% larger than observed in normal operation of the CSX without heating the tubes. A possible reason for this is that the changes of $\phi$ with temperature could not be estimated accurately enough. Here it proved as a drawback that in case of the CSX a reversal of the direction of the atomic beam—the traditional method to measure the $\phi$ in primary clocks [12,15]—could not be made.

From a fundamental point of view the realization of the time unit second has to rely on the observation of unperturbed atoms and, in view of this, a perturbation of the ground state energy levels of cesium has not been taken into account properly until recently. Within our

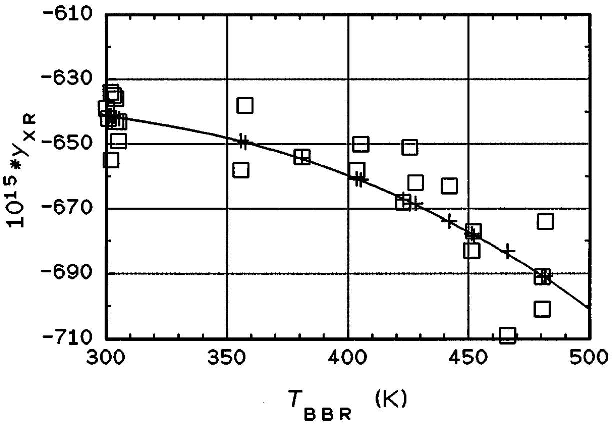

FIG. 3. Experimental frequency data $y_{\mathrm{XR}}$ (□) as a function of temperature $T_{\mathrm{BBR}}$ in comparison with the predicted frequency shifts (+) due to BBR. The solid line is a polynomial through the prediction values, facilitating the interpretation of the data.

statistical measurement uncertainty our experimental data confirm the previous theoretical predictions and justify the current steering process of the scale unit of international atomic time TAI [19]. The frequency shift due to the static or the dynamic Stark effect in a cesium clock is independent of the atomic transition linewidth, and thus its determination is a challenging task in view of the potential standard uncertainty of fountain type atomic clocks. As mentioned above, the correction to be applied at room temperature is about 6 times larger than the presently estimated standard uncertainty of the FO1 [6]. Its determination will have to include a detailed analysis of the temperature and the emissivity of the inner walls of the vacuum chamber of the device. The uncertainty in the numerical factor $\beta$ is not at all negligible, and a measurement of the frequency shift due to the static or dynamic Stark effect with reduced uncertainty appears desirable.

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