High-Accuracy Measurement of the Blackbody Radiation Frequency Shift of the Ground-State Hyperfine Transition in ^{133}Cs

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We report a high-accuracy direct measurement of the blackbody radiation shift of the ^{133}Cs ground-state hyperfine transition. This frequency shift is one of the largest systematic frequency biases encountered in realizing the current definition of the International System of Units (SI) second. Uncertainty in the blackbody radiation frequency shift correction has led to its being the focus of intense theoretical effort by a variety of research groups. Our experimental measurement of the shift used three primary frequency standards operating at different temperatures. We achieved an uncertainty a factor of five smaller than the previous best direct measurement. These results tend to validate the claimed accuracy of the recently calculated values.

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Introduction.—The blackbody radiation (BBR) shift causes a well-known bias of the hyperfine ground-state transition frequency in ^{133}Cs used in the International System of Units (SI) system to define the second. Uncertainty in this frequency shift is an important systematic uncertainty in many of the best primary frequency standards [1]. We present here a direct measurement of the BBR shift through comparison of three laser-cooled Cs fountain primary frequency standards: one operated at 317 K and the other two at 81 and 89 K.

The second in the SI system of units is defined as the duration of 9 192 631 770.0 periods of the radiation corresponding to the transition between the two ground-state hyperfine levels ($F = 3$ and $F = 4$) in ^{133}Cs. The definition is for a Cs atom at rest in a 0 K environment. The correction for the fractional frequency shift caused by operation of a Cs frequency standard at 300 K is several parts in 10^{14}, making this shift one of the larger systematic offsets in most primary standards. Of course, what is ultimately important is not the magnitude of the shift, but rather its uncertainty; currently, this uncertainty is a significant contribution to the inaccuracy of many primary frequency standards.

The BBR shift is a result of the blackbody radiation field causing an ac Stark shift of the energy levels of the Cs atom, and has been calculated several times since its importance in frequency standards was first discussed by Itano *et al.* [2]. For many years the calculation in Itano *et al.*, which used the experimental value of the dc Stark shift, was used to calculate the BBR frequency shift and its associated uncertainty. A recalculation, along with measurements of the BBR shift that are significantly shifted from the accepted value [3–5], were recently presented. This led to several groups expending significant effort to make modern calculations of the BBR shift [6–8] with claimed uncertainties much smaller than any direct measurements of the effect. They also confirmed the original shift as calculated in [2] within the limits of that calculation.

The BBR fractional frequency shift is often written in the form

$$\frac{\delta\omega}{\omega_0} = \beta\left(\frac{T}{T_0}\right)^4\left[1 + \varepsilon\left(\frac{T}{T_0}\right)^2\right], \tag{1}$$

where $\delta\omega/\omega_0$ is the BBR fractional frequency shift, T_0 is generally specified as 300 K, T is the actual temperature of the radiation field seen by the atoms, and β, ε are coefficients generated by theoretical calculation. β is defined by the relation $\beta = k_0 E_{300}^2/\omega_0$, where k_0 is the dc Stark shift coefficient and E_{300} is the rms electric field associated with a 300 K blackbody. E_{300}^2 can be directly calculated from the Stefan-Boltzmann law as $E_{300} = 831.94$ V/m. The coefficient ε is calculated and the generally accepted value is $\varepsilon = 0.013(1)$ [7]. The most accurate and complete calculations of k_0 are from Derevianko's group with confirmatory calculations by several other groups [6–8]. The value for k_0, taken from [6], is $k_0 = -(2.271 \pm 0.008) \times 10^{-10}$ Hz/(V/m)^2. This gives $\beta = (-1.710 \pm 0.006) \times 10^{-14}$. k_0 has also been measured through dc Stark shift measurements using a Cs fountain with results given in [9]. An extension to and reanalysis of the results in [9] giving a somewhat different result for k_0 is presented in a conference proceeding [10]. Here we refer to the result of measuring the frequency of a cesium standard at differing temperatures and solving Eq. (1) for β as a direct determination of β. We refer to the result of a dc Stark (k_0) measurement and a resulting calculation of β as an indirect determination of β.

Most Cs frequency standards are operated slightly above room temperature in order to facilitate control of the resonant frequency of the Ramsey microwave cavity. Using the calculated β from [6] and $T = 320$ K as typical, we find that the fractional frequency shift due to BBR is 22.46×10^{-15} with an uncertainty of 8×10^{-17} due to the uncertainty in the coefficient β. This uncertainty does not include any contribution from uncertainties due to lack of knowledge of the blackbody spectrum, lack of isotropy in the radiation field due to the enclosure, etc. Under the same conditions, using the value of k_0 presented in [10] we obtain a BBR shift of 22.57×10^{-15} with an uncertainty of 4×10^{-17}. While the two values are in agreement, the difference caused by the use of the value of β derived from [6] vs β from [10] is more than $\delta\omega/\omega_o = 1.1 \times 10^{-16}$, a significant fraction of the total uncertainty of many primary frequency standards.

Of the methods for estimating the BBR shift, a measurement of the dc scalar hyperfine polarizability of the atom typically produces the smallest uncertainty in the shift; it is, however, not a direct measurement of the BBR shift. Typically direct measurement of β by comparing the frequency of a standard at a variety of temperatures does not compete well with the uncertainties available through either calculation or indirect (dc Stark shift) measurements of the BBR. β has been directly measured previously [10,11]. For example, the previous best direct measurement of the coefficient β in [10], has an uncertainty of 5%, compared to the claimed uncertainty of 0.35% for the calculated result.

We present here a measurement of the coefficient β in (1) using the U.S.primary frequency standards, NIST-F1 and NIST-F2 at NIST (National Institute of Standards and Technology) and the Italian primary frequency standard, IT-CSF2 (Istituto Nazionale di Ricerca Metrologica) at INRIM. The ^{133}Cs primary frequency standards all operate at different temperatures, NIST-F1 is operated at a temperature of 317.35(10) K while NIST-F2 operates at 81.0 (10) K and IT-CSF2 operates at 89.4(10) K. A series of measurements were performed during which at least two of the standards were operated simultaneously. Both NIST standards are referenced to the same hydrogen maser and the two data sets (NIST-F1 and NIST-F2 vs maser, for example) are typically differenced on a second-by-second basis, thereby eliminating the hydrogen maser as a source of noise and producing a direct measurement of the uncorrected frequency of NIST-F1 against the uncorrected frequency of NIST-F2. In the case of IT-CSF2, which is located in Torino, Italy, the comparison to NIST-F1 is via two-way satellite time transfer and the comparison is typically over the entire run of the fountains (typically 20 days or so).

The frequency standards in question are all well characterized and the frequency shifts of each have been measured over several years [12–17]. NIST-F1 is typically corrected for five systematic biases: a frequency shift due to gravitational redshift, the BBR frequency shift, second-order Zeeman frequency shift, spin-exchange collision shift, and a statistically insignificant microwave frequency shift [12]. NIST-F2 and IT-CSF2 have a similar list of corrections with differing magnitudes and uncertainties [17,18].

Because we are measuring β in Eq. (1), which will involve the difference between the measured NIST-F1 and NIST-F2 (IT-CSF2) frequencies, several components of the error budgets for the standards are effectively eliminated. In particular, for the NIST comparison, the gravitational redshift is replaced by the relative redshift due to the height difference between the two fountains (~0.75 m, F2 is lower) with no requirement to correct to the reference geoid of Earth. The NIST-INRIM data are geoid referenced with a total of 30 cm uncertainty ($\delta\omega/\omega_0 = 3 \times 10^{-17}$).

Additionally, because the BBR frequency shift of NIST-F1 is the object of measurement, it is also removed from the NIST-F1 error budget (as are the much smaller BBR shifts of NIST-F2 and IT-CSF2). The result of these operations is

$$\Delta F = (F1_{\text{raw freq}} - F1_{\text{Corrections}}) - (F2_{\text{raw freq}} - F2_{\text{Corrections}}) - \delta F_{\text{grav}} \quad (2)$$

where ΔF is the difference between the measured NIST-F1 and NIST-F2 (IT-CSF2) BBR frequency shifts, $F1_{\text{raw freq}}$ is the measured $F1$ frequency, $F1_{\text{corrections}}$ is the correction for the systematic biases in Table 1, with the exception of the BBR shift and δF_{grav} is the frequency correction for the

TABLE I. Systematic frequency biases in NIST-F1 and NIST-F2 for which corrections are made. All values are in units of fractional frequency $\times 10^{-15}$.

Physical effect	Magnitude in NIST-F1	Uncertainty in NIST-F1	Magnitude in NIST-F2	Uncertainty in NIST-F2
Second-order Zeeman	180.01	0.03	285.02	0.03
Spin-exchange nonlinearity	0.0	0.03	0.0	0.02
Microwave power dependent	0.026	0.12	0.01	0.098
Gravitational effects	0	0	0.082	0.001
Total		0.13		0.10

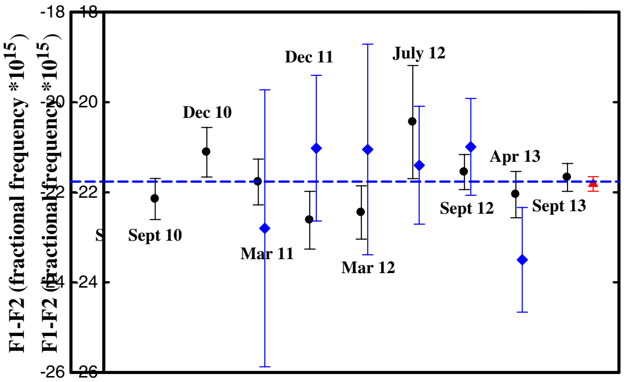

FIG. 1 (color online). The measurement of the blackbody radiation shift between NIST-F1 and NIST-F2 (black circles) and NIST-F1 vs IT-CsF2 (blue diamonds). The weighted average of the measurements is shown as the last point (red triangle). The expected value using [6] is shown as a dashed (blue) line. The relatively large error bars on the NIST-F1 vs IT-CsF2 comparisons are due to the noise imposed by the time-transfer process.

difference in gravitational potential between the two standards. The frequency data and corrections for NIST-F2 have similar notation. The uncertainty budget for IT-CSF2 is not shown, but is quite similar to that of NIST-F2. Our measurements of ΔF are plotted in Fig. 1. These measurements span a total of three years. Each point in Fig. 1 represents many days (ranging from 10 to 45 d) of frequency measurement, with the error bars being generally proportional to the inverse square root of the total measurement time.

The microwave structure and frequency synthesis of the three clocks are essentially identical [12,17,18] with the exception of the cavity Q in the F2 frequency standards being about a factor of 2 higher as a result of the higher electrical conductivity of copper at low temperature. This common geometry results in the common-mode suppression of many microwave-related shifts in the standards. In particular, distributed cavity phase effects are partially cancelled and any possible microwave recoil shift is rejected [19–20].

Primary frequency standards are typically characterized by a statistical uncertainty (type A) and an uncertainty from effects that are estimated by nonstatistical means (type B). Generally the type A uncertainties can be reduced by averaging while the type B uncertainties cannot. It is expected that the uncertainties on $F1$ are uncorrelated with those on either of the $F2$ frequency standards. In these fountains the spin-exchange frequency shift is predominantly type A and subject to averaging with a small residual type B component shown in Table 1.

The effective temperature of the radiation field in both fountains is estimated using measurements of the wall temperatures at several locations along the atomic trajectory coupled with estimates of solid angles subtended by various apertures into and out of the Ramsey interrogation region. All three fountains have a similar structure for the region in which the blackbody temperature must be estimated; here we describe the structure and techniques used to estimate the radiation field in NIST-F2.

The region below the microwave cavity used for Ramsey interrogation contains the state selection microwave cavity as well as 15 cm of 1 cm diameter copper tubing through which the atoms enter the Ramsey interrogation region. The opening of this entrance tube is a source of room temperature photons into the cryogenic Ramsey interrogation region of the frequency standard. The entrance tube, state selection cavity, Ramsey cavity, and the drift region are all nominally at 80 K. The lower 8 cm of the copper tubing is threaded to prevent high-angle room-temperature reflected optical photons from entering the Ramsey interrogation region. The state selection cavity provides further light trapping of these high angle room temperature optical photons, thus a 1 cm diameter disk of 291 K radiation enters the bottom end of the region and the rest of the walls are nominally at 80 K. Temperature gradients in the low temperature section are measured and used in the modeling of the radiation field. The region above the microwave cavity is a closed ended tube with a light trap at the top end. The light trap (also at 80 K) prevents 291 K photons that entered the bottom from making a second pass through the system. The entire structure is C101 copper that is somewhat oxidized and has been etched to a matte finish: the emissivity is predicted to be greater than 0.25 [21].

The measured temperatures are used to derive a temperature map $T(z)$. At each point along the atomic trajectory the total radiation field is calculated using a solid-angle emissivity weighted $T^4(z)$. This radiation field is now averaged over the atomic trajectory which strongly weights the upper end of the trajectory where the atom spends the bulk of the interrogation time. This procedure gives an effective temperature for the radiation field to be used in Eq. (1). As a crude check of the model we can calculate the solid angle subtended by the room temperature entrance aperture averaged over the atomic trajectory to be 8×10^{-5} sr. A 291 K source subtending that solid angle changes the effective temperature of the BBR field by 0.3 K at the 81 K temperature of NIST-F2, consistent with the more complete model actually used.

The overall uncertainty in the radiation temperature is a result of simplifications inherent in the model, uncertainty in the various emissivities used in the model, calibration errors in the temperature sensors and possible heat conduction down the leads of the Pt RTDs. The combined uncertainties of these effects give a total temperature uncertainty of much less than 1 K. We take 1 K as the uncertainty in the effective temperature. The procedure for NIST-F1 is similar with an estimated 0.1 K uncertainty.

The results of 15 different frequency measurement campaigns (9 internal to NIST, 6 using IT-CsF2) made between September of 2010 and August 2013 are shown in Fig. 1.

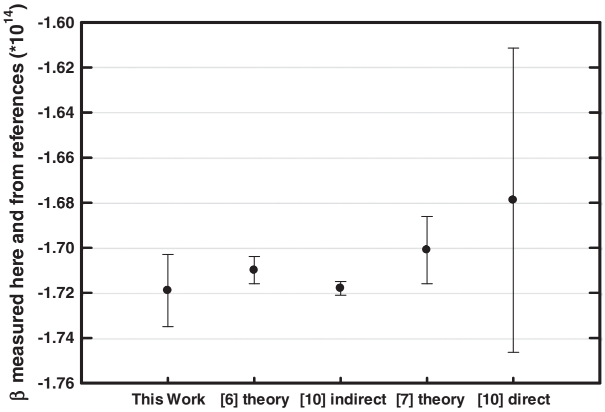

FIG. 2. A comparison between various measurements and calculations of β, some derived theoretically, measured here, as well as previous direct and indirect measurements. Reference [10] contains both a direct and indirect determination of β.

The weighted average of all of the measurements is $\Delta\omega/\omega = (-21.74 \pm 0.20) \times 10^{-15}$, which includes both type A and B uncertainties. In the NIST-F1 vs NIST-F2 measurements, the type A and B uncertainties are essentially equal in size. As a result of the extra type A uncertainty imposed by the time transfer process, the NIST-F1 vs IT-CSF2 results are dominated by type A uncertainties. Using the measured temperatures of the three standards along with Eq. (1), we can infer a measured value for β and from that, derive a measured value for k_0. As previously discussed, we take the uncertainties in the effective temperature of the BBR fields to be 1 and 0.1 K for NIST-F2 and NIST-F1, respectively. This gives $\beta = -(1.719 \pm 0.016) \times 10^{-14}$, in good agreement with both the calculated value of $\beta = -(1.710 \pm 0.006) \times 10^{-14}$ [6] and the indirectly measured value of $\beta = -(1.718 \pm 0.003) \times 10^{-14}$ [10]. The present measurement of β with its sub-1% uncertainty constitutes the best direct measurement to date of the blackbody radiation shift in ^{133}Cs, with the previous best result, taken from [10], also shown in Fig. 2. The result given here is a very stringent test of the theoretical calculations in [2,5–8] as well as a stringent test of the three frequency standards used in making the measurements.

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