Blackbody radiation induced shift and minimization approaches
Motivation

Bordé-Ramsey spectroscopy ($\pi/2$ pulses)

$-\Phi_1 + \Phi_2 - \Phi_3 + \Phi_4 = \Delta \Phi$

Atomic Excitation (%) vs. $\nu_{\text{beat}} - \nu_c$ (kHz)

$^3S_1$

$^1P_1$

$^3P_0$

$^1S_0$

Detection 461 nm

Position/$\lambda_L$

0 0.5 1 1.5 2

Clock $\lambda_0 = 688$ nm

Lattice

09.12.2014 Dominika Fim
Outline

• BBR at room-temperature
• BBR induced shift and multipolar theory
  – Static and dynamic polarizability
• Reducing the uncertainty of $\alpha^{(\text{static})}$ and $\alpha^{(\text{dyn})}$
• Shielding the environment
  – At room temperature
  – Cryogenic environment
BBR at room-temperature

- 99% of the energy density of BBR is in the range of 3 THz – 67 THz (100 – 4.5 μm)
- maximum @17 THz (10μm)
- $V_{\text{BBR}} \ll \omega_{\text{clock}}$ and intermediate states
- Sr: transitions which couple to a clock state: 2.6μm (115 THz) and above
BBR induced shift

\[ \Delta \nu_{BBR} = - \frac{1}{2} \frac{\Delta \alpha(0)}{h} \langle E^2 \rangle_T [1 + \eta_{\text{clock}}(T)] \]

mean-squared electric field:

\[ \langle E^2 \rangle_T = [8.319430(15) \text{ V/cm}]^2 (T/300 \text{ K})^4 \]

dynamic correction:

\[ \eta_g = \frac{80/63 \pi^2}{\alpha_g^{(0)} T} \sum e \left| \frac{\langle e | D | g \rangle}{\omega_{eg}/T} \right|^2 (1 + \ldots) \]
Multipolar Theory

Relativistic theory of the BBR shift caused by multipolar components of the radiation:

• separation of $^3P_J$ states is comparable to the characteristic wave number of the BBR @300K
• contributions of the BBR induced M1 and E2 transitions may be enhanced

<table>
<thead>
<tr>
<th>Atom</th>
<th>$\delta\nu_{BBR}$ (Hz)</th>
<th>$\nu_0$ (Hz)</th>
<th>$\delta\nu_{BBR}/\nu_0$</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>$-0.258(7)$</td>
<td>$6.55 \times 10^{14}$</td>
<td>$-3.9 \times 10^{-16}$</td>
<td>$1 \times 10^{-17}$</td>
</tr>
<tr>
<td>Ca</td>
<td>$-1.171(17)$</td>
<td>$4.54 \times 10^{14}$</td>
<td>$-2.6 \times 10^{-15}$</td>
<td>$4 \times 10^{-17}$</td>
</tr>
<tr>
<td>Sr</td>
<td>$-2.354(32)$</td>
<td>$4.29 \times 10^{14}$</td>
<td>$-5.5 \times 10^{-15}$</td>
<td>$7 \times 10^{-17}$</td>
</tr>
<tr>
<td>Yb</td>
<td>$-1.34(13)$</td>
<td>$5.18 \times 10^{14}$</td>
<td>$-2.6 \times 10^{-15}$</td>
<td>$3 \times 10^{-16}$</td>
</tr>
</tbody>
</table>
Shifts related to static polarizability

For $10^{-18}$ uncertainty:
- uncertainty in $^3D_1$ dominate
- M1 comes into account
- E2 contribution can be neglected

<table>
<thead>
<tr>
<th>relative Uncertainty</th>
<th>Main contributing transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>static $</td>
<td>g&gt;$ polarizability</td>
</tr>
<tr>
<td></td>
<td>$5 \times 10^{-19}$</td>
</tr>
<tr>
<td></td>
<td>$5 \times 10^{-25}$</td>
</tr>
<tr>
<td>static $</td>
<td>e&gt;$ polarizability</td>
</tr>
<tr>
<td></td>
<td>$5.6 \times 10^{-20}$</td>
</tr>
<tr>
<td></td>
<td>$5.8 \times 10^{-23}$</td>
</tr>
</tbody>
</table>
Dynamic polarizability

$$\eta_{\text{clock}} = \frac{80/63\pi^2}{\alpha_g^{(0)} T} \sum_e \left| \frac{\langle e | D | g \rangle}{(\omega_{eg}/T)^3} \right|^2 (1 + ...)$$

- dynamic Shift $\delta E_g^{(\text{dyn})}$ is insignificant
- Dynamic Shift of $\delta E_e^{(\text{dyn})}$ has a bigger effect: dipole transitions are at lower frequencies
Reducing approaches

• Reducing the uncertainty of $\alpha^{\text{static}}$
• Reducing the uncertainty of $\alpha^{\text{dyn}}$
• Shielding the environment
  – At room temperature
  – Cryogenic environment
Reducing the uncertainty of $\alpha^{(\text{static})}$

High accuracy correction of blackbody radiation shift in an optical lattice clock

Thomas Middelmann, Stephan Falke,* Christian Lisdat, and Uwe Sterr
Physikalisches-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
(Dated: October 30, 2012)
Reducing the uncertainty of $\alpha^{(\text{static})}$

$$\Delta \nu_i = \nu_{\text{res}} - \nu_i \quad i = A, B, C$$

$$\Delta V_A \equiv 0$$

$$\Delta V_B \equiv \Delta V$$

$$\Delta V_C \equiv -\Delta V$$

$$\Delta V = 100, 200, \ldots, 700 \text{ V}$$

frequency shift in a dc field:

$$\Delta \nu_{\text{dc}} = \frac{\nu_B + \nu_C}{2} - \nu_A$$
Reducing the uncertainty of $\alpha^{(\text{static})}$

static polarizability:

$$\Delta \alpha_{dc} = 2\hbar \frac{d^2}{\Delta V^2} \Delta \nu_{dc}$$

Differential dc polarizability:

$$\Delta \alpha = 4.07873(11) \times 10^{-39} \, \text{Cm}^2/\text{V}$$
Reducing the uncertainty of $\alpha^{(\text{dyn})}$

1. calculate ac polarizability of clock states using Einstein coefficients $A_{ki}$:
2. Integrate the differential ac-Stark shift over the Planck distribution

\[ \eta_{\text{clock}} = \frac{80/63 \pi^2}{\alpha_g^{(0)} T} \sum_e \frac{\langle e|D|g\rangle}{(\omega_{eg}/T)^3} (1 + \ldots) \]

Used values:
- static dc polarizability in combination with observables, e.g. magic wavelength
- atomic lifetimes
- slope of differential $\alpha$ and ac Stark shifts of the laser field to adjust $A_{ki}$
Reducing the uncertainty of $\alpha^{(\text{dyn})}$

Determination of the $5d6s^3D_1$ state lifetime and blackbody radiation clock shift in Yb

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(Dated: August 3, 2012)

PHYSICAL REVIEW A 86, 051404(R) (2012)
Reducing the uncertainty of $\alpha^{(\text{dyn})}$

\[ \eta_a = \frac{80/63\pi^2}{\alpha_a^{(0)} T} \sum_b \frac{|\langle b|D|a\rangle|^2}{(\omega_{ab}/T)^3} (1 + \ldots) \]

Largest contribution to $^3P_0$:
- $^3D_1$ state 96%
  - minimize $\Delta \nu_{\text{dyn}}$ by a lifetime measurement
  \[ y(t) = A \times \Theta(t - t_0)[e^{-(t-t_0)/\tau_a} - e^{-(t-t_0)/\tau_b}] + y_0 \]
  - combine existing polarizability data with atomic theory: semi-empirical technique

$\Delta \nu_{\text{BBR}} = -1.2774(6)$ Hz
Shielding the environment

Atomic Clock with $1 \times 10^{-18}$ Room-Temperature Blackbody Stark Uncertainty

K. Beloy,¹,* N. Hinkley,¹,² N. B. Phillips,¹ J. A. Sherman,¹ M. Schioppo,¹ J. Lehman,¹ A. Feldman,¹ L. M. Hanssen,³ C. W. Oates,¹ and A. D. Ludlow¹,†

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(Received 28 August 2014; published 24 December 2014)

PRL 113, 260801 (2014)
In-vacuum radiation shield

Shield is passively coupled to the surrounding vacuum chamber, where temperature inhomogeneities exist:

- radiation model
  - model internal surface of the shield and windows (e) as opaque, diffuse, graybody surfaces
  - apertures: disk-shaped blackbody surfaces
- copper construction
- platinum resistance temperature detectors
- windows nearly opaque to BBR
- two apertures
- high emissivity carbon nanotube coating (e)
- boron nitride holding rings (f)
- plastic support posts (g)
- stainless steel support plate (g)
Gray Body

- curve for a graybody is proportional to Planck's curve
- spectral radiant emittance for a selective radiator varies not only with temperature but also with wavelength
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  - apertures: disk-shaped blackbody surfaces

\[ T_{\text{eff}}^4 = \frac{c}{4\sigma} u = \sum_i \left( \frac{\Omega_i^{\text{eff}}}{4\pi} \right) T_i^4 \]
Effective solid angles derived from a finite-element radiation analysis

$\epsilon$ – coating and window emissivity

Coatings at high emissivity:
- minimizes the corresponding sensitivity to the precise emissivity value

Coating: multiwall carbon nanotubes
- highly thermally
- electrically conductive
- high surface emissivity: $\epsilon > 0.8$
Experimental validation

- Directly observe the dependence by the BBR shift by heating the shield
- Validation of $T_{\text{eff}}$
- implemented Room-temperature radiation shield
- total uncertainty for BBR shift: $1 \times 10^{-18}$

Replacing Yb inside our shield with Mg, Ca, Sr, or Hg, for example, the uncertainty from the BBR environment would be $9 \times 10^{-20}$, $6 \times 10^{-19}$, $1 \times 10^{-18}$, or $4 \times 10^{-20}$, respectively [8,24]. Because the BBR environment uncertainty has now
Cryogenic environment

Cryogenic optical lattice clocks

Ichiro Ushijima\textsuperscript{1,2,3}\textdagger, Masao Takamoto\textsuperscript{1,2,4}\textdagger, Manoj Das\textsuperscript{1,2,4}, Takuya Ohkubo\textsuperscript{1,2,3} and Hidetoshi Katori\textsuperscript{1,2,3,4}*

Katori et al., NPHOTON.2015.5

RIKEN, Saitama, Japan
Cryogenic chamber

- 2 cryogenic clocks cooled to 95 K
- temperature measured with platinum resistance thermometer and controlled
- cooper chamber (6cm³) has 2 apertures for introducing lasers & atoms
- black coated: 10-30μm with low resistivity
- transport atoms from MOT into cryo region by frequency chirp
Temperature dependent BBR shift

- 400 ms π- pulse excitation
- ~2 Hz room- temperature shift
- BBR field trough apertures cancels out in \[ \Delta v(T_1, T_2) = v_2(T_2) - v_1(T_1) \]

\[
\begin{align*}
T &= 95.00(4) \text{ K} \\
n_{BBR}^{95K} &= -21.55(4) \text{ mHz} \\
T_{RT} &= 296(5) \text{ K} \\
n_{BBR}^{RT} &= -1.54(33) \text{ mHz} \\
n_{BBR}^{95K} + n_{BBR}^{RT} + n_{BBR}^{RT(\gamma)} &= -23.26(37) \text{ mHz}
\end{align*}
\]

Dynamic contribution: \(5 \times 10^{-19}\)

\[ v_{dyn} = -0.148,0(26) \text{ Hz} \]
Conclusion

• BBR induced shift has a static and a dynamic contribution
• Uncertainties in involved transitions lead to a shift uncertainty
• Knowledge of static polarizability was improved by an order of magnitude
• Shielding the environment leads to lower uncertainty in temperature
Thank you for your attention!