Measurement of the fine-structure constant as a test of the Standard Model

Richard Parker
Testing QED with Alpha

\[ \alpha = \frac{1}{4\pi \varepsilon_0} \frac{e^2}{\hbar c} = \frac{1}{137.035999139(31)} \]  

(0.23 ppb) 2014 CODATA

**Neutral Atom**

\[ \alpha = \left[ \frac{2}{c} \frac{R_\infty}{u} \frac{M}{m_e} \frac{h}{u M} \right]^{1/2} \]

- Rydberg Constant: 0.006 ppb
- Cs mass in amu: 0.03 ppb
- Electron mass in amu: 0.02 ppb
- Recoil frequency measurement: 0.38 ppb

**Penning Trap**

\[ g - 2 = \sum_{n=1} \left( \frac{\alpha}{\pi} \right)^n a_n + a_{weak} + a_{QCD} \]

- (\(\hbar/m_{Rb}\)) → 0.62 ppb vs. 0.24 ppb
- (\(\hbar/m_{Cs}\)) → 0.20 ppb
Matter Wave Interferometry

Local Gravity

Gravity Gradients

Recoil Frequency

Newton’s G

Dark Energy

Gravitational Waves


Science, 349, 849 (2015)

Atom-interferometer measurement of $\alpha$

Ramsey-Bordé Interferometer

\[ \Phi_{RB} = 8n^2 \omega_r T - 2nkg(T + T')T - n\omega_m T \]

\[ \frac{1}{2} m v_r^2 = \hbar \left( \frac{\hbar k^2}{2m} \right) = \hbar \omega_r \]

\[ \begin{align*}
\omega_r & \rightarrow \hbar/m \rightarrow \alpha
\end{align*} \]
Simultaneous Conjugate Interferometers

\[ \Phi_{RB} = \pm 8n^2 \omega_r T \pm n \omega_m T + 2nk g(T + T')T \]
\[ \Phi_{RB, Diff} = 16n^2 \omega_r T - 2n \omega_m T \]
Multi-Photon Bragg Diffraction

\[ \Phi_{RB,Diff} = 16n^2 \omega_r T - 2n \omega_m T \]

Bragg gives you:

- More photons transferred per pulse (higher sensitivity)
- Atoms stay in same internal state (Zeeman, AC Stark systematics suppressed)
- But...
- Higher power needed
- Complicated phase shift between output ports
\[ \Delta \Phi_{RB+Bloch} = 16n(n + N)\omega_r T - 2n\omega_m T \]
Experimental Sequence

Atomic Fountain
- Polarization Gradient Cooling
  - 10⁸ atoms/sec → 4 m/s
  - 1 µK
- Raman Sideband Cooling
  - 300 nK (∼1νᵣ)
  - → F=4, m_F=0
- Rapid Adiabatic Passage
  - → F=3, m_F=0
  - ~0.05 νᵣ
- State Selection
- Velocity Selection x2
  - All in F=3, m_F=0
- Interferometer Sequence
- Fluorescence Detection
Phase Extraction

\[ \Delta \phi_+ \]

\[ \Delta \phi_- \]

\[ n = 5, N = 125 \]

**Graphs:**

- **Left Graph:**
  - Detected Fluorescence (arb. unit)
  - Time (ms)
  - N = 0, 25, 50, 125, 200

- **Right Graphs:**
  - Scatter plots for different time intervals (T = 5ms to 80ms)
Tricks for Increased Sensitivity

Coriolis Compensation

Without compensation

With compensation

x3.5 contrast gain

10\hbar k, T = 180ms

Stark Compensation

Up to N=200

>12M rad phase diff. measurable!
Diffraction Phase

$$\Delta \Phi_{RB+Bloch} = 16n(n + N)\omega_r T - 2n\omega_m T + \Phi_0$$

Measured Recoil Frequency

Recoil Frequency

$$\omega_m = 8(n + N)\omega_r + \frac{\Phi_0}{2nT}$$

Diffraction Phase
## Systematics

<table>
<thead>
<tr>
<th>Effect</th>
<th>$\delta\alpha/\alpha$ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Frequency</td>
<td>$-0.24 \pm 0.03$</td>
</tr>
<tr>
<td>Acceleration Gradient</td>
<td>$-1.79 \pm 0.02$</td>
</tr>
<tr>
<td>Gouy Phase</td>
<td>$-2.60 \pm 0.03$</td>
</tr>
<tr>
<td>Beam Alignment</td>
<td>$0.05 \pm 0.03$</td>
</tr>
<tr>
<td>BO Light Shift</td>
<td>$0 \pm 0.002$</td>
</tr>
<tr>
<td>Density Shift</td>
<td>$0 \pm 0.003$</td>
</tr>
<tr>
<td>Index of Refraction</td>
<td>$0 \pm 0.03$</td>
</tr>
<tr>
<td>Speckle Phase</td>
<td>$0 \pm 0.04$</td>
</tr>
<tr>
<td>Sagnac Effect</td>
<td>$0 \pm 0.001$</td>
</tr>
<tr>
<td>Mod. Frequency Wavenumber</td>
<td>$0 \pm 0.001$</td>
</tr>
<tr>
<td>Thermal Motion of Atoms</td>
<td>$0 \pm 0.08$</td>
</tr>
<tr>
<td>Non-Gaussian Waveform</td>
<td>$0 \pm 0.03$</td>
</tr>
<tr>
<td>Parasitic Interferometers</td>
<td>$0 \pm 0.03$</td>
</tr>
</tbody>
</table>

**Total Systematic Effects** $-4.58 \pm 0.12$

**Total Statistical Uncertainty** $\pm 0.16$
Parasitic Interferometers

$$\phi_p = \pm 8n_p(n_p + N)\omega_r T \pm n_p\omega_m T + \phi_c(n_p)$$
Clipping Phase

$$\Delta \Phi_{RB+Bloch} = 16n(n + N)\omega_r T - 2n\omega_m T + \Phi_0 + \eta T + ...$$

- Atom Motion $\rightarrow$ T-dependent diffraction phase
- Sensitive to pulse intensities, detection volume, ...
- 2-point Spatial Filtering
  - Reduce VS waist
  - Reduce detection volume

Estey, PRL 2015; Parker, PRA 2016
Data

Data taken from December 2016 to June 2017

0.16 ppb statistical uncertainty.
Systematic Checks

• Variation of alpha w.r.t.:
  – Beam Waist
  – Bloch order
  – Bloch power
  – Contrast
  – Detection region
  – $\omega_m$ mixing (RF)
  – $\omega_m$ mixing (optics)
  – Intensity balance between pulses
  – Delay of interferometer sequence
  – Bias B-field
  – Single-photon detuning
  – Data Analysis parameters (cuts, fitting, etc.)
The Fine Structure Constant

\[ \alpha = 1/137.035999046(27) \]

A 2.5σ tension:

\[ \delta \alpha = a_{\text{Penning Trap}} - a_{\text{SM}}(\alpha_{\text{CS}}) = -0.88(0.36) \times 10^{-12} \]
Could it be Dark Photons?

One explanation for the $3.4\sigma$ discrepancy in the muon $g_\mu - 2$

\[ \mathcal{L}_{\text{Dark Photon}} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{m^2}{2} A'_\mu A'^\mu - e e \bar{\psi} A'_\mu \gamma^\mu \psi \rightarrow \delta a > 0 \]
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$$\mathcal{L}_{\text{Dark Photon}} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{m_Y^2}{2} A'_\mu A'^\mu - ee\bar{\psi} A'_\mu \gamma^\mu \psi \rightarrow \delta a > 0$$
Axial-Vectors?

\[ a_{SM} + a_{\text{Dark Axial Vectors}}? \]
Future Upgrades

- Big Vacuum System
  - x20 waist → x400 supp.
- Pulsed Laser
  - x1000 eff. power
- EM/Acoustic Shielded Room
- 2 MOT Chambers
  - Better Fountain Alignment
- Science Chamber
  - Dark Matter studies
Thank you!

PI: Holger Müller

Postdoc: R. Parker

Grad: Chenghui Yu

Grad: Weicheng Zhong

Former Grad: Brian Estey
Comparing LKB and Berkeley

<table>
<thead>
<tr>
<th></th>
<th>LKB</th>
<th>Berkeley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamsplitter Type</td>
<td>Raman</td>
<td>Bragg</td>
</tr>
<tr>
<td>Momentum Splitting</td>
<td>$2\hbar k$</td>
<td>$10\hbar k$</td>
</tr>
<tr>
<td>Recoil Frequency</td>
<td>3.7 kHz</td>
<td>2.1 kHz</td>
</tr>
<tr>
<td>Interferometer Geometry</td>
<td><img src="image1" alt="Bloch" /></td>
<td><img src="image2" alt="Bloch" /></td>
</tr>
<tr>
<td>Phase Scaling</td>
<td>$\phi \sim nN\omega_r T$</td>
<td>$\phi \sim n(n + N)\omega_r T$</td>
</tr>
<tr>
<td>Dual Interferometers?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>$N_{\text{max}}$</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>10 ms</td>
<td>80 ms</td>
</tr>
<tr>
<td>Future Upgrades</td>
<td>BEC</td>
<td>Large Beam</td>
</tr>
</tbody>
</table>
Testing QED with Alpha

\[ a_{SM} = \frac{g_e - 2}{2} = \sum_{n=1} (\frac{\alpha}{\pi})^n a_n + a_{\text{weak}} + a_{\text{hadronic}} \]

\[ a_{SM}(\alpha_{CS}) = 0.00115965218161(23) \]
Dark photon Limits

New NA64 data

- NA64 (new)
- ge-2 Berkeley PCL (50%/90%)
- ge-2 Berkeley CLs (90%)
- ge-2 Berkeley PCL (16%/90%)

epsilon vs. mA'(GeV)
Speckle Phase

- Anomalous residuals $\rightarrow$ $\sim$ 1 ppb
- Dust, scratches, scattering on wall
- 2 Problems:
  - Inhomogenous Rabi frequency
  - Phase shift due to transverse kicks
- Fiber doesn’t make Gaussian beams
- Spatial Filtering via Apodizer + Fountain Alignment Monitor

$200$ Apodizing Filter
Laser Frequency

Time domain – Femtosecond pulses

Frequency domain – Frequency comb

\[ f_n = nf_r + f_{\text{offset}} \]

Frequency residual = 10 kHz \(\rightarrow\) 0.03 ppb

Laser frequency as a function of power send into the spectroscopy
Gravity Gradient

\[ \Delta \Phi = 16n(n + N)\omega_r T - 2n\omega_m T \]

\[ + \frac{4}{3} n\omega_r \gamma T \left[ n \left( 2T^2 + 3(T_1' + T_2') + 3(T_1' + T_2')^2 \right) + N \left( 2T^2 + 6TT_2' + 6T_2'^2 \right) \right] \]

\[ \Delta \phi = 2\gamma n\omega_r T^2 \left( 2N(2T + T_2') + n(2T + T_1' + T_2') \right) \]

\[ \gamma = 1.295(32) \times 10^{-6} \frac{m}{s^2 m} \]

Shift in alpha = -1.41 +/- 0.02 ppb
Gouy Phase Systematic

\[ E(r, z) = E_0 \frac{w_0}{w(z)} e^{-\frac{r^2}{w(z)^2}} e^{-i k (z-z_0)} - \frac{ikr^2}{2R(z-z_0)} + i \zeta(z-z_0) \]

\[ z_R = \frac{\pi w_0^2}{\lambda} \sim 50 \text{ m} \quad w(z) = w_0 \sqrt{1 + \frac{Z^2}{Z_R^2}} \]

\[ \zeta(z) = \tan^{-1}\left(\frac{Z}{Z_R}\right) \quad R(z) = z \left(1 + \frac{Z_R^2}{Z^2}\right) \]

\[ k_{eff} = k - \frac{1}{Z_R} + \frac{z_0^2}{Z_R^3} + \frac{kr^2}{2Z_R^2} + O\left(\frac{Z_0^2}{Z_R^2}\right) \]

Knife edge measured

Estimated based on atom position using Monte Carlo simulation
Revised Gouy Phase

\[
\frac{\delta k_{\text{eff}}}{k_{\text{eff}}} = -\frac{\lambda^2}{2\pi^2 w_0^2} \left( 1 - \frac{z_0^2}{z_R^2} - \frac{r^2}{w_0^2} \right)
\]

• Previously used knife-edge measurements to verify beam was Gaussian (within error)
• Suspected not Gaussian, based on 3D propagation
• With Scanning-slit/CCD, determined not Gaussian
• Use Monte Carlo to determine on-axis and wavefront-curvature corrections
French Effect

\[
\frac{\delta k}{k} = \frac{1}{2k^2} \frac{\nabla^2 E}{E}
\]

- Small-scale intensity variations can lead to dramatic changes in Gouy phase
- Doesn’t average out!
- Can be >10ppb for LKB
- Use 3D Monte Carlo, CCD images, and Bloch Efficiency data to estimate effect
- <0.1 ppb for us
$\alpha$ vs Integration Region

Varying Diameter of Integration Region

(Corrected Recoil Freq - Avg)/Avg (ppb in alpha, not h/m)

Diameter of Integration Region (mm)
$\alpha$ vs Bloch Power

Varying Bloch Power

(Corrected Recoil Freq - Avg)/Avg (ppb in alpha, not h/m)

Bloch Power (mV on Arb. Waveform Generator)
State Selection

\[ \vec{k}_1, \vec{k}_2, \nu \]

\[ \sigma^+ \]

F=3, m_F=0

Frequency (MHz)

A.U.

12.0 12.2 12.4 12.6 12.8 13.0 13.2
Velocity Selection

- $2\mu k$ of atoms has velocity spread
  $\sim 2$cm/sec
  After 1s of time of flight, atoms will drift out of interferometer beams

- $100\mu s$ selection pulse selects about 1/10 of atoms corresponding to hundreds of nK