High-precision measurements of the Rb87 D-line tune-out wavelength

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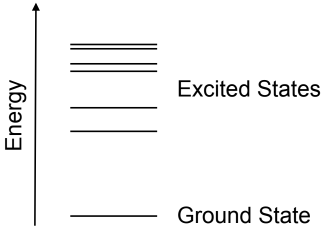
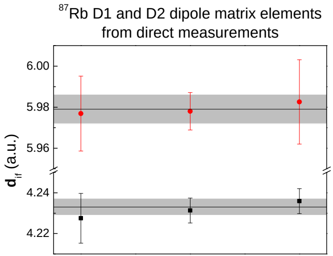
Outline

- Motivation
  - Dipole matrix elements
  - Atomic parity violation
- Stark effect and “tune-out” wavelengths
  - Polarization control
  - Results
- Vector polarizability

Dipole Matrix Elements

- Excited state energies known very well from spectroscopy $(E_f - E_i)$
- Need dipole matrix elements also
  - $|d_{if}| = \langle n' P_{J'} \| \mathbf{d} \| n S_J \rangle$
  - Lifetime
  - Oscillator Strength
  - Einstein A coefficient
- Difficult to measure directly in general
  - 0.2% error for lowest lying
    - Lifetime measurements
    - Better than typical
- Good enough for many applications



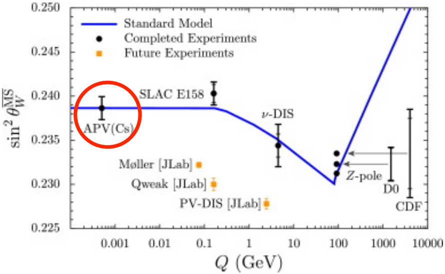


Dipole Matrix Elements

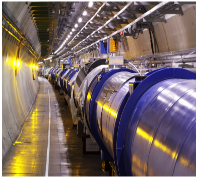
- Even more precision needed in some areas
- Atomic parity violation
- Atomic clocks
  - Precision limited by blackbody shift from environment
- Theoretical benchmark
  - Computational techniques
  - Phenomenological input
- Feshbach resonances

Atomic Parity Violation

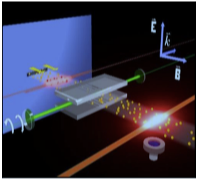
- Tabletop atomic experiment to test fundamental particle physics theory
  - Weak charge Q_W
- Competitive precision in low energy test of standard model



Bentz *et al. Phys. Lett.* ***B693***, 462 (2010)



High Energies



Low Energies

Cern, CU Boulder

Atomic Parity Violation

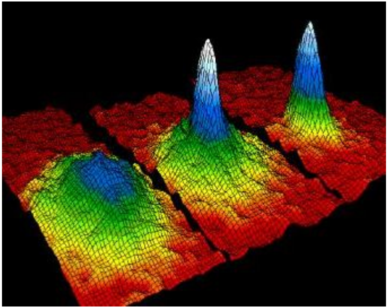
- From usual selection rules, $S \to P$ allowed, $S \to S$ forbidden
- APV - Nonzero $S \to S$ transition probability
- Very small effect
  - 4.5 a.u. vs. 10^{-11} a.u.!
- Cs APV experiment (1997)
  - Achieved 0.35% experimental uncertainty
  - To convert to measurement of weak charge, need dipole matrix elements
  - $Q_W^{SM} = -73.23(2)$
  - $Q_W^{Atomic} = -72.58(29)_{Exp}(32)_{Theory}$
    - 0.4% theoretical uncertainty from conversion
- No reason for new experiments until theory catches up

Atomic Parity Violation

- Precise knowledge of alkali atom matrix elements $|d_{if}|$ needed in analysis
- Infinite number of such matrix elements - all contribute
- Direct measurements not possible in general to high enough precision
    - Lowest known through lifetime measurements
- Beginning to develop framework to reduce uncertainties through measurements of tune-out wavelengths

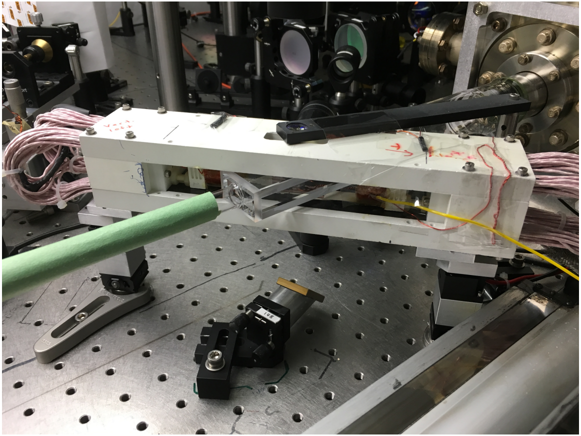
Bose-Einstein Condensate

- Create BEC in standard fashion
  - MOT
  - Magnetic quadrupole trap
  - rf evaporation
- Load atoms into "wave-guide"
  - 2π x $(5.1, 1.1, 3.2)$ Hz
  - Interferometer along weakest direction



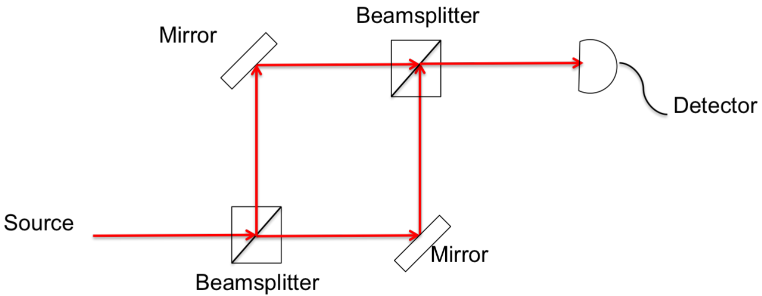
www.bec.nist.gov

Bose-Einstein Condensate



2π x $(5.1, 1.1, 3.2)$ Hz

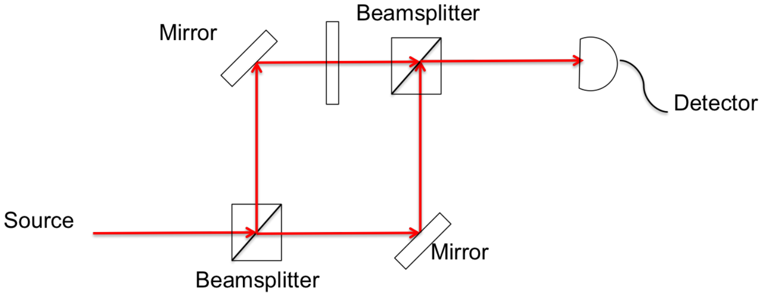
Interferometry



- Split source and propagate along two paths
- Difference in phase at output - constructive vs. destructive interference

$$\vec{E} = \vec{E}_0 e^{i\phi} = \vec{E}_0 e^{i(\omega t - kz)}$$

Interferometry



- Split source and propagate along two paths
- Difference in phase at output - constructive vs. destructive interference

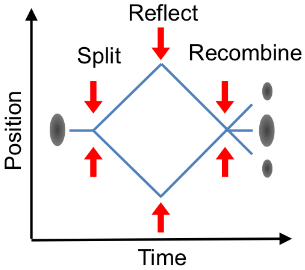
$$\vec{E} = \vec{E_0} e^{i\phi} = \vec{E_0} e^{i(\omega t - kz)}$$

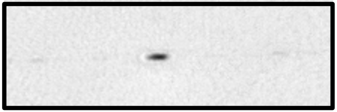
- Light interferometers measure time (optical path length) differences

Atom Interferometry

$$\phi = \frac{S}{\hbar} = \frac{\int E \mathrm{d}t}{\hbar}$$

- Analogous to light interferometer
- Atoms sensitive to many more phenomena - electromagnetic fields, gravity, accelerations, inter-atomic interactions, etc.
- Colder (slower) atoms = longer interrogation times





BEC before split

Atom Interferometry

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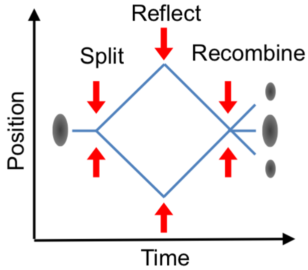

Split

Atom Interferometry

$$\phi = \frac{S}{\hbar} = \frac{\int E\mathrm{d}t}{\hbar}$$

- Analogous to light interferometer
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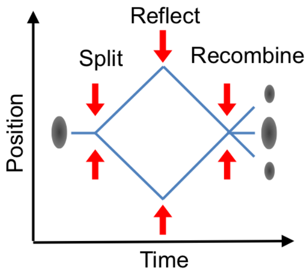


After recombination

- Phase determined by ratio of atoms at rest to total, N_0/N

Stark Effect

$$U = -\frac{1}{2}\alpha\langle\mathcal{E}^2\rangle = -\frac{\alpha I}{2\epsilon_0 c}$$

- Energy shift due to applied electric field
  - Static or AC
  - Dynamic polarizability
- Difficult to calibrate intensity
  - Atoms inside vacuum chamber
- Want polarizability α
  - Dependence on dipole matrix elements

Polarizability

$$\alpha_i(\omega) = \frac{1}{\hbar} \sum_f \frac{2\omega_{if}}{\omega_{if}^2 - \omega^2} |d_{if}|^2 + \alpha_c + \alpha_{cv}$$

- α_c = core contribution
- α_{cv} = core-valence correction
- $5P$ states dominate

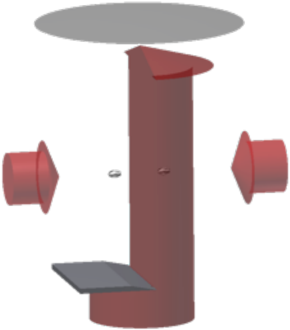
$$\alpha(\omega) = \frac{2}{\hbar} \frac{\omega_{5P_{1/2}}}{\omega_{1/2}^2 - \omega^2} |d_{1/2}|^2 + \frac{2}{\hbar} \frac{\omega_{5P_{3/2}}}{\omega_{3/2}^2 - \omega^2} |d_{3/2}|^2 + \alpha_{tail} + \alpha_c + \alpha_{cv}$$

- α_{tail} = valence contributions $>$ 5P
- Difficult to calculate
  - Infinite number of matrix elements
  - Calculated up to $n = 12$
  - Uncertainty in tail same scale as value

Previous Meaurement (2008)

$$U = -\frac{1}{2}\alpha\langle\mathcal{E}^2\rangle = -\frac{\alpha I}{2\epsilon_0 c}$$

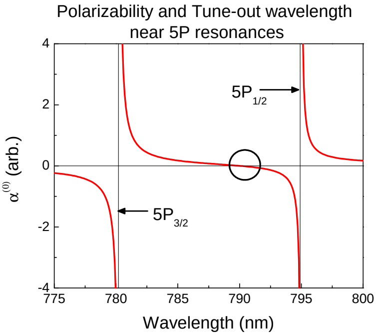
- Measured by former student Ben Deissler (PhD 2008)
  - $\alpha(780.23\,\mathrm{nm}) = \frac{4\pi\epsilon_0}{10^{25}}$ x $(8.37 \pm 0.24)\,\mathrm{m}^3$
  - $\alpha(808.37\,\mathrm{nm}) = \frac{4\pi\epsilon_0}{10^{28}}$ x $(9.48 \pm 0.25)\,\mathrm{m}^3$
- Deviations from predicted values about 3%
  - Attributed primarily to intensity calibration
- Need way to reduce dependence on intensity calibration



Tune-out wavelength

$$\alpha_i(\omega) = \frac{1}{\hbar}\sum_f \frac{2\omega_{if}}{\omega_{if}^2 - \omega^2}|d_{if}|^2 + \alpha_c + \alpha_{cv}$$

- Zero in polarizability between resonances
- Extract info on $|d_{if}|$, α_c, α_{cv}
  - Mainly depends on $$R = \frac{|d_{3/2}|^2}{|d_{1/2}|^2}$$
- Sensitive to polarization of light
  - Switch to spherical tensor form



Spherical tensors

$$U = -\frac{\langle \mathcal{E}^2 \rangle}{2} \left\{ \overset{\text{Scalar}}{\alpha^{(0)}} - \frac{1}{2} \mathcal{V} \cos\chi \, \overset{\text{Vector}}{\alpha^{(1)}} + \left[\frac{3\cos^2(\xi) - 1}{2} \right] \overset{\text{Tensor}}{\alpha^{(2)}} \right\}$$

- Dependence on polarization more obvious
- $\mathcal{V}$ - fourth Stoke's parameter
  - ± 1 for $\sigma^{\pm}$
- $\cos\chi = \hat{k} \cdot \hat{b}$
- $\cos\xi = \hat{\epsilon} \cdot \hat{b}$
  - Angle of linear polarization w.r.t. magnetic field
- Near tune-out wavelength
  - $\alpha^{(1)} = 25000$ au
  - $d\alpha^{(0)}/d\lambda = -2500$ au/nm
  - Want sub-picometer uncertainty

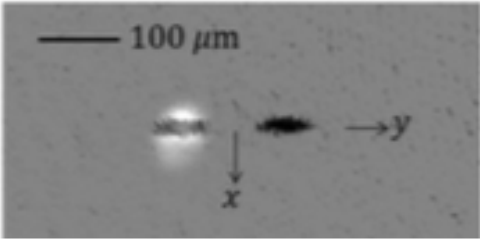
Spherical tensors

$$U = -\frac{\langle \mathcal{E}^2 \rangle}{2} \left\{ \alpha^{(0)} - \frac{1}{2} \mathcal{V} \cos\chi \, \alpha^{(1)} + \left[\frac{3\cos^2(\xi) - 1}{2} \right] \alpha^{(2)} \right\}$$

- Need to control $|\mathcal{V}\cos\chi|$ to better than 10^{-5}
  - Better than typically maintained through vacuum window
  - Stress-induced birefringence
- Remove tensor polarizability later to report zero in $\alpha^{(0)}$
  - $\lambda^{(0)}$
- Use atoms to linearize light

Stark Interferometer

- Allow one packet of interferometer to pass through Stark beam (twice)
- Vary intensity to measure rate of phase buildup
- Make measurements at different wavelengths around tune-out



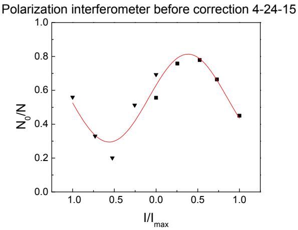
Polarization Control

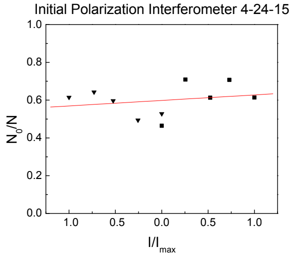
$$U = -\frac{\langle \mathcal{E}^2 \rangle}{2} \left\{ \alpha^{(0)} - \frac{1}{2} \mathcal{V} \cos\chi \, \alpha^{(1)} + \left[\frac{3\cos^2(\xi) - 1}{2} \right] \alpha^{(2)} \right\}$$

- Atoms held in Time Orbiting Potential (TOP) magnetic trap
  - Magnetic bias rotates at 12 kHz
  - Stark light aligned in plane of rotation
- Constant reversal of σ^+ and σ^-
  - $\langle \cos\chi \rangle = 0$
- Time averaging alone not enough

Polarization Control

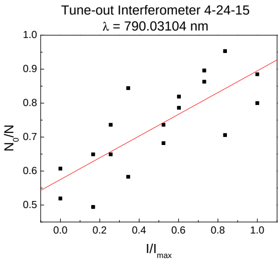
- Also want $\langle \mathcal{V} \rangle = 0$
- Interferometer run with Stark light pulsing
  - On for half of rotating bias period
- Phase buildup asymmetric when imbalance of σ^+ and σ^-
- Adjust external waveplate to correct imbalance
  - QWP at 780 nm
  - Need 0.1° precision - $\mathcal{V} \approx 2 \text{ x } 10^{-3}$
- Properly set when phase symmetric and small

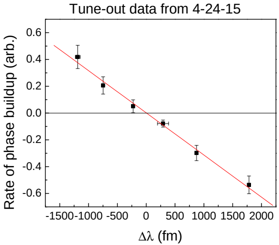




Tune-out Wavelength

- A total of 21 tune-out measurements made over 2 months
- Upper figure 1 hour
  - One point on lower figure
- Lower figure 1 day
- Check polarization before and after α measurement to assess drift
  - Typical drift over day 60 fm
  - Likely due to thermal fluctuations
  - Taken as polarization uncertainty for measurement





Tensor Polarizability

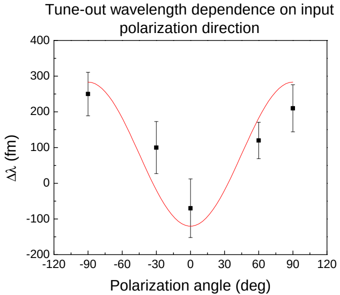
$$U = -\frac{\langle \mathcal{E}^2 \rangle}{2} \left\{ \alpha^{(0)} + \left[\frac{3\cos^2(\xi) - 1}{2} \right] \alpha^{(2)} \right\}$$

- $\langle \mathcal{V} \cos\chi \rangle = 0$
- Depends on angle of linear polarization w.r.t. plane of rotating magnetic field
- Introduces shift in tune-out wavelength
- Couldn't accurately set ξ prior to taking data
  - Difficult to determine plane of bias rotation
  - Several measurements at different angles of linear polarization
- Remove $\alpha^{(2)}$ term to get $\lambda^{(0)}$

Tune-out Wavelength

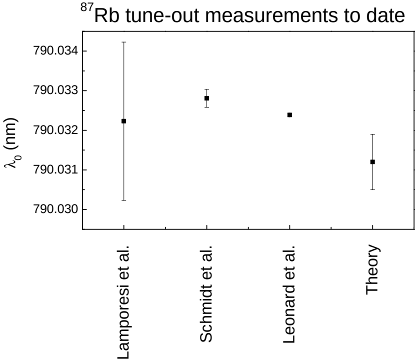
$$\lambda_0(\theta) = \lambda^{(0)} - \frac{\alpha^{(2)}}{d\alpha^{(0)}/d\lambda}\left(\frac{3}{4}\cos^2\theta - \frac{1}{2}\right)$$

- Measurements at different polarization angles
- Tensor polarizability well resolved
- $\lambda^{(0)}$ zero in scalar polarizability
- $\dfrac{\alpha^{(2)}}{d\alpha^{(0)}/d\lambda} = 538.5(4)$ fm
    - Straightforward to calculate from theory due to strong dependence on D_1 and D_2
- Zero in scalar polarizability at $\lambda_0 = 790.032388(32)$ nm

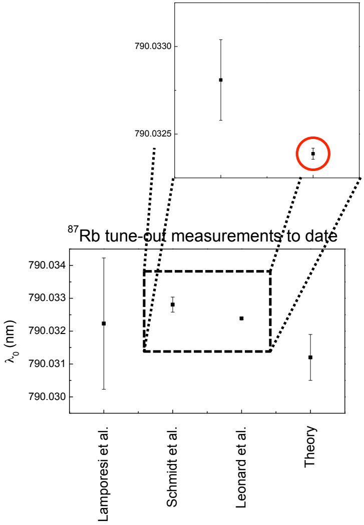


Tune-out Wavelength

- Several other measurements in ^{87}Rb
  - Referenced to $F = 2$ groundstate
- Tune-outs also measured in K, Na, He
  - Larger uncertainties for now



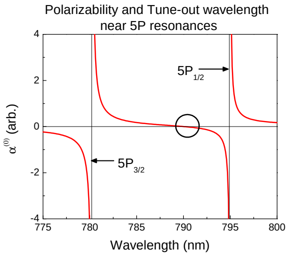
Tune-out Wavelength

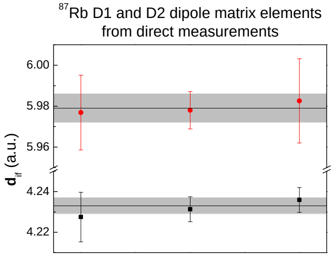


Ratios of Matrix Elements and Benchmarks

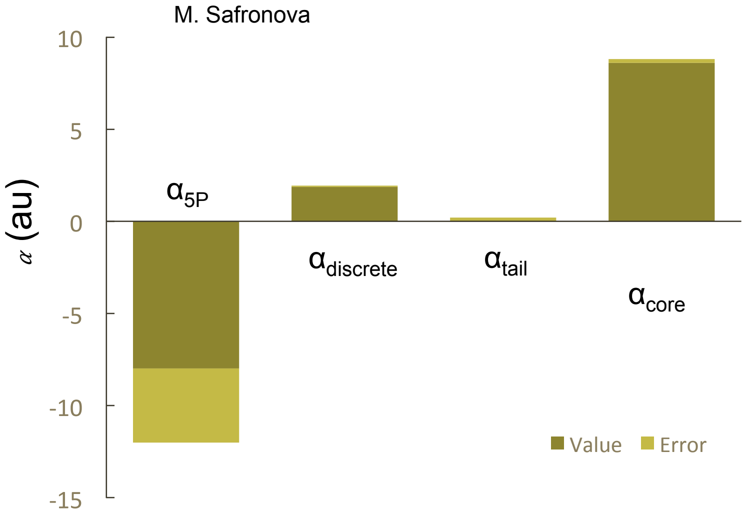
$$\alpha^{(0)} = A + |d_{1/2}|^2 \left(\frac{\alpha^{(0)}_{5P_{1/2}}}{|d_{1/2}|^2} + \frac{\alpha^{(0)}_{5P_{3/2}}}{|d_{3/2}|^2} R \right)$$

- $R = |d_{3/2}/d_{1/2}|^2$
- A includes contributions from α_c, α_{cv}, and valence terms above $5P$
  - $A = 10.70(12)$ au from theory
  - $d_{1/2} = 4.233(4)$ au from direct measurements
- From direct measurements, R = 1.995(7)
- From tune-out wavelength, R = 1.99221(3)





Contributions from Theory



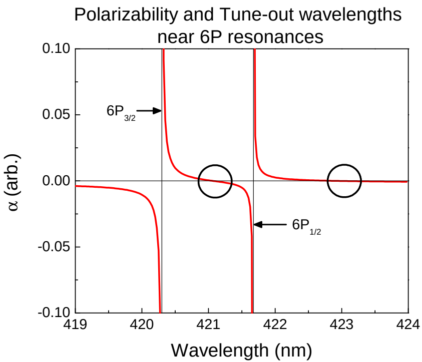
Experiment accuracy = 0.1 au

Implications for Theory

- From tune-out wavelength, R = 1.99221(3)
- Benchmark for theory
  - From M. Safronova, $R = 1.9919(5)$
  - Need to include additional effects
- Breit Interaction
  - Relativistic correction to Coulomb interaction
- QED effects
  - Radiative corrections
- Both effects 5x smaller than theoretical uncertainty
  - Come in at 5 x 10^{-5} level
  - Compare to 3 x 10^{-5} from tune-out measurement
  - Need more precise calculations

Other Tune-out Wavelengths

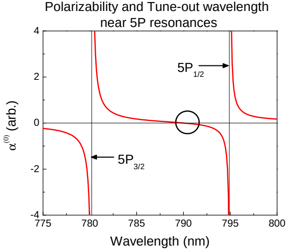
- Tune-out between any two resonances
- More ratios to determine higher lying matrix elements
- Begin to separate out various contributions
- Will also measure vector polarizability
  - $\langle \mathcal{V} \cos \chi \rangle \neq 0$

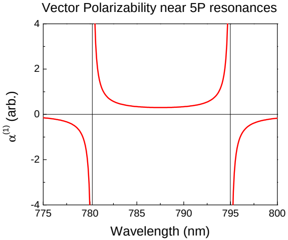


Vector Polarizability

$$U = -\frac{\langle \mathcal{E}^2 \rangle}{2} \left\{ \alpha^{(0)} - \frac{1}{2} \mathcal{V} \cos\chi \, \alpha^{(1)} \right\}$$

- Intentionally introduce circular polarization in controlled manner
- Measure ratio $\alpha^{(1)}/\alpha^{(0)}$ at several points around tune-out wavelength
- What does vector polarizability get us?





Vector Polarizability

Scalar: $\alpha^{(0)} = \frac{1}{3\hbar} \sum_f |D_{if}|^2 \frac{\omega_{if}}{\omega_{if}^2 - \omega^2} + \alpha_c + \alpha_{cv}^{(0)}$

Vector: $\alpha^{(1)} = \frac{1}{3\hbar} \sum_f C_{J'} |D_{if}|^2 \frac{\omega}{\omega_{if}^2 - \omega^2} + \alpha_{cv}^{(1)}$

- Look at one pair of n' states

$$\alpha_{n'}^{(0)} = \frac{\omega_{n'_{3/2}}}{\omega_{n'_{3/2}}^2 - \omega^2} |d_{n'_{3/2}}|^2 + \frac{\omega_{n'_{1/2}}}{\omega_{n'_{1/2}}^2 - \omega^2} |d_{n'_{1/2}}|^2$$

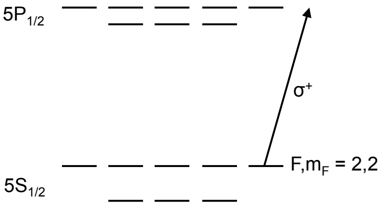
$$\alpha_{n'}^{(1)} = \frac{\omega}{\omega_{n'_{3/2}}^2 - \omega^2} |d_{n'_{3/2}}|^2 - 2 \frac{\omega}{\omega_{n'_{1/2}}^2 - \omega^2} |d_{n'_{1/2}}|^2$$

- Contributions from $n'P_{1/2}$ and $n'P_{3/2}$ can be isolated

Vector Polarizability Polarization Control

- Pulse for $t << \tau_{TOP}$ and adjust relative phase
  - Fine control over $\langle \cos\chi \rangle$
- Need new method to determine polarization
  - Want $\mathcal{V} = +1$
- Use σ^+ light tuned to D1 resonance
  - No resonant transition
  - Minimize scattering rate using external waveplate

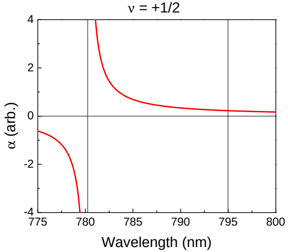
Energy Level Diagram
$5S_{1/2} \rightarrow 5P_{1/2}$

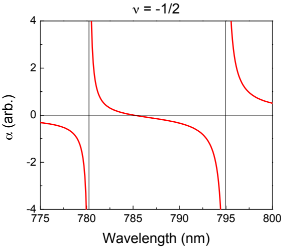


Vector Polarizability

$$\alpha \approx \frac{1}{6}\left(\frac{|D_1|^2(1-2\nu)}{\omega_{1/2}-\omega}+\frac{|D_2|^2(1+\nu)}{\omega_{3/2}-\omega}\right)$$

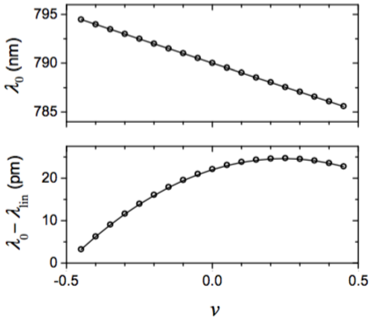
- Circular polarization shifts tune-out location
- ν can vary from -1/2 to +1/2
- Possible to prevent tune-out wavelength altogether
- Tune over 2/3 range between D_1 and D_2
  - 785 nm to 795 nm
- Make measurements of shifted tune-out wavelength





Vector Polarizability

- Adjust $\langle \mathcal{V} \cos \chi \rangle$ in controlled manner
  - $d\lambda_0/d\nu$ almost linear over full range
  - Deviation from linear is of interest
- Deviations on picometer scale
  - Compare to 32 fm uncertainty in tune-out measurement



Vector Polarizability

- Current theoretical values and their uncertainties
  - $\alpha_c = 9.08(5)$ au
  - $\alpha_{cv}^{(0)} = -0.37(4)$ au
  - $\alpha_{cv}^{(1)} \sim -0.04(4)$ au
  - $T_{1/2} = 0.022(22)$ au
  - $T_{3/2} = 0.075(75)$ au
- $\alpha_{cv}^{(1)}$ approximated from $\alpha_{cv}^{(0)}$
- Tail terms have $n' > 12$

Vector Polarizability

- Polarization and frequency dependence ultimately allow separation of the contributions
- Simulated 3 tune-out and multiple vector polarizability measurements

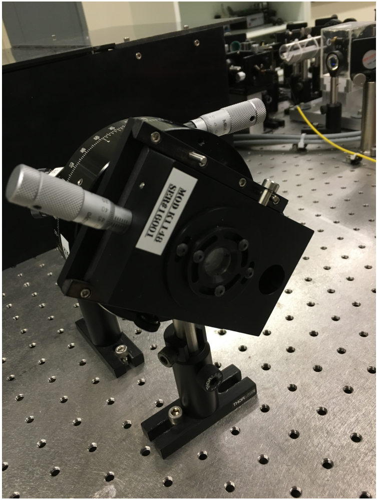
	Parameter	Model Estimate	Model Error	Fit Error
Ratios	$R_{5,3/2}$	1.99221	3×10^{-5}	3×10^{-5}
	$R_{6,1/2}$	0.00584	3×10^{-5}	2×10^{-6}
	$R_{6,3/2}$	0.01526	5×10^{-5}	5×10^{-6}
Core	$\alpha_c + \alpha_{cv}^{(0)}$	8.71	9×10^{-2}	3×10^{-2}
	$\alpha_{cv}^{(1)}$	-0.04	4×10^{-2}	9×10^{-3}
Tails	$\|t_{1/2}\|^2$	0.009	9×10^{-3}	1×10^{-3}
	$\|t_{3/2}\|^2$	0.03	3×10^{-2}	3×10^{-3}

- Model error based on 790 nm tune-out measurement

Vector Polarizability

- In the process of setting polarization
  - σ^+ light tuned to D_1 resonance
  - Correcting for chamber birefringence, stray fields, etc.
- Acquired Babinet-Soleil Compensator
  - Calibrate waveplates at different wavelengths
  - Accurately change $\sigma^+ \rightarrow \sigma^-$ along with field reversal to test polarization and field corrections

Babinet-Soleil Compensator



Conclusions

- Measured longest tune-out wavelength in ^{87}Rb
  - $\lambda_0 = 790.032388(32)$ nm
  - R $= 1.99221(3)$
- Used R as a benchmark for theory
  - $R_{Theory} = 1.9919(5)$
- Measurements of other tune-out wavelengths
  - Near 420 nm and 360 nm
- Measurements of vector polarizability
  - Separate out contributions beyond what tune-out wavelengths alone can do

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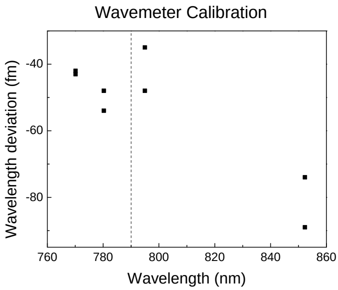
Wavemeter Calibration

Add what we used as correction with error bars

- Wavemeter specced to 10^{-6} - Not good enough
- Calibrated it using well known lines in several atomic species
  - ^{39}K D_1
  - ^{87}Rb D_2
  - ^{85}Rb D_1
  - ^{133}Cs D_2



Including Hyperfine Structure

$$\alpha_{5P}^{(0)} = \frac{10}{\hbar\sqrt{15}} \sum_{J',F'} \frac{|d_{J'}|^2\omega'}{\omega'^2-\omega^2}(-1)^{1+F'}(2F'+1)$$

$$x \begin{Bmatrix} 2 & 1 & F' \\ 1 & 2 & 0 \end{Bmatrix} \begin{Bmatrix} F' & 3/2 & J' \\ 1/2 & 1 & 2 \end{Bmatrix}^2$$

$$\alpha_{5P}^{(1)} = \frac{10}{\hbar\sqrt{15}} \sum_{J',F'} \frac{|d_{J'}|^2\omega}{\omega'^2-\omega^2}(-1)^{1+F'}(2F'+1)$$

$$x \begin{Bmatrix} 2 & 1 & F' \\ 1 & 2 & 1 \end{Bmatrix} \begin{Bmatrix} F' & 3/2 & J' \\ 1/2 & 1 & 2 \end{Bmatrix}^2$$

$$\alpha_{5P}^{(2)} = \frac{20}{\hbar\sqrt{15}} \sum_{J',F'} \frac{|d_{J'}|^2\omega'}{\omega'^2-\omega^2}(-1)^{F'}(2F'+1)$$

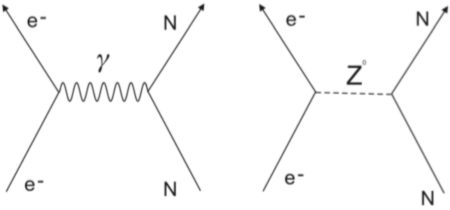
$$x \begin{Bmatrix} 2 & 1 & F' \\ 1 & 2 & 2 \end{Bmatrix} \begin{Bmatrix} F' & 3/2 & J' \\ 1/2 & 1 & 2 \end{Bmatrix}^2$$

Parity Non Conservation

$$E_{PNC}^{Theory} =$$

$$\sum_{n'=6}^{\infty}\left(\frac{\langle 7S|\mathbf{d}|n'P_{1/2}\rangle\langle n'P_{1/2}|H_{PNC}|6S\rangle}{E_{6S}-E_{n'P_{1/2}}}+\frac{\langle 7S|H_{PNC}|n'P_{1/2}\rangle\langle n'P_{1/2}|\mathbf{d}|6S\rangle}{E_{7S}-E_{n'P_{1/2}}}\right)$$

- $Q_W^{SM} = -73.23(2)$
- $Q_W^{Atomic} = -72.58(29)_{Exp}(32)_{Theory}$
- Differ by 1.5σ



(a)H_{EM} (b)H_{PNC}

Parity Non Conservation

$$\frac{\mathrm{Im}(E_{PNC})}{\beta} = i\frac{Q_W}{\beta N}k_{PNC}$$

- k_{PNC} contains all relevant parity conserving and PNC matrix elements
- Mixing of $S_{1/2}$ and $P_{1/2}$ states
- Weak interaction not parity conserving