Measurement of the 7P Excited-State Polarizabilities in Atomic Indium

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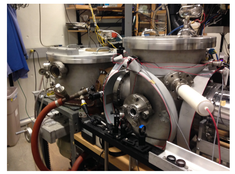
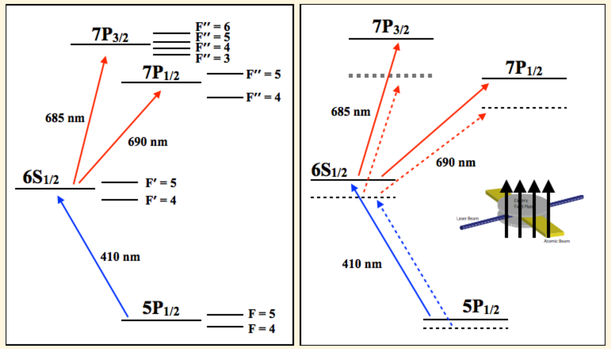


Background

- Laser spectroscopy to test accuracy, guide refinement of *ab initio* theory calculations for Group IIIA (ns^2np^1) atoms
- Such theory essential for tests of fundamental physics and symmetry violations in these systems (PNC, EDM, *etc.*)

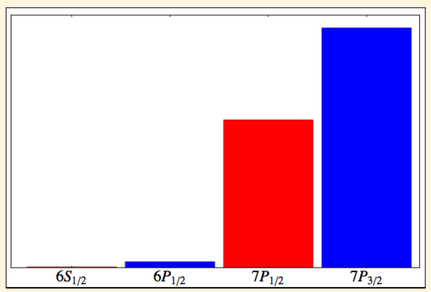


Two-Step Laser Spectroscopy

- Access ΔL-forbidden states with two E1 transitions
- Lock 410 nm diode laser to first-step transition, scan overlapping ECDL through second-step transition
- Produces 'Doppler-free' spectra

Stark Shift and Scalar Polarizability

- Energy shift scales quadratically with applied electric field: $\Delta E = -\frac{1}{2}\alpha_0\mathcal{E}^2$ for 'scalar polarizability' α_0
- 2013 one-step measurement of $\alpha_0(6S_{1/2}) = 1049.5(6.2)a_0^3$ in excellent agreement with theory
- 2016 two-step measurement of $\alpha_0(6P_{1/2}) = 7590(37)a_0^3$ also agrees (falls *between* two theory methods)
- Expected $\alpha_0(7P_{1/2}) \sim 185000a_0^3$ (Safronova 2016)
- Expected $\alpha_0(7P_{3/2}) \sim 300000a_0^3$ (Safronova 2016)



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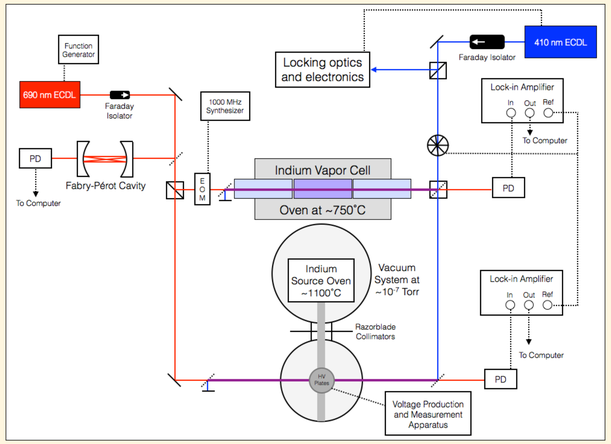
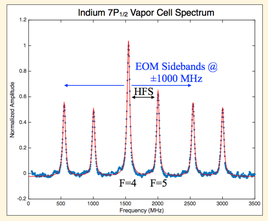
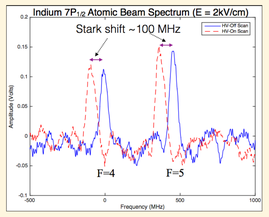
Experimental Setup



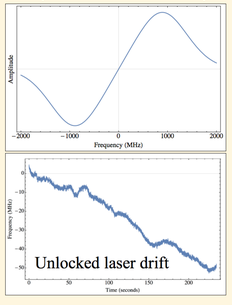
- Chop locked 410 nm beam at $f_{\text{chop}} \sim 1$ kHz, scan counter-propagating 690 nm (685 nm) ECDL over $6S_{1/2} - 7P_{1/2(3/2)}$ hyperfine resonances
- Lock-in demodulate red absorption at f_{chop} to resolve small signal (second-step line ~ 50x weaker than previous experiment)
- Observe in atomic beam (precisely calibrated electric field) *and* field-free vapor cell (frequency reference/calibration)

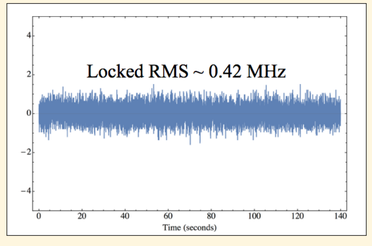




410 nm Laser Locking

- Lock to $5P_{1/2} - 6S_{1/2}$ resonance in auxiliary vapor cell using FM spectroscopy method (yields dispersive locking signal)
- Adjust lock to *Stark-shifted* resonance using AOM technique

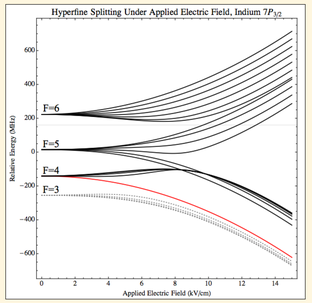




$7P_{3/2}$ Polarizability Work

Energy Eigenvalues

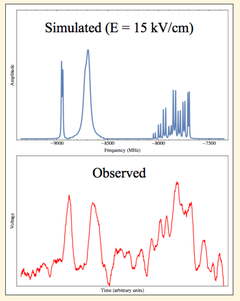
- $J = 3/2$ state admits scalar *and* tensor polarizabilities
- Scalar polarizability (α_0): homogeneous shift of all sublevels
- Tensor polarizability (α_2): splitting of $|Fm_F\rangle$ sublevels



- Diagonalize Stark Hamiltonian to determine eigenvalues (R.W. Schmeider, AJP **40** (1972))
- ΔF selection rules allow excitation of $F'' = 4, 5, 6$ only – gives resolved $|4, 4\rangle$ sublevel (shown in red) at $\mathcal{E} \approx 15$ kV/cm

Atomic Beam Lineshape Simulations

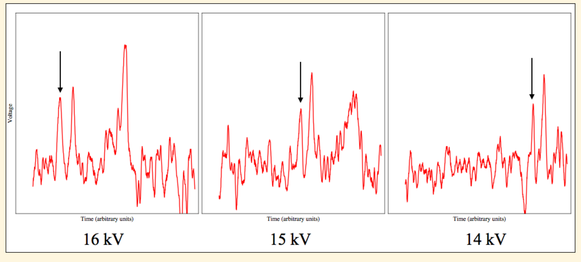
- Diagonalize 60×60 Hamiltonian describing generalized three-level system in the presence of two near-resonant laser fields
- Near $\mathcal{E} = 15$ kV/cm: fully resolved $|4, 4\rangle$ sublevel, 'composite peak' ($|5, 5\text{-}4\rangle$ and $|4, 3...0\rangle$ sublevels), and wide $F = 5, 6$ feature



Scalar Polarizability Extraction

- Extract α_0 by measuring shift of resolved $|4, 4\rangle$ sublevel
- Use α_2 theory value – at 15% level – from Safronova (2016)
- α_2 uncertainty leads to $\sim 1\%$ theory uncertainty in α_0 ($\alpha_2/\alpha_0 \sim 0.06$)

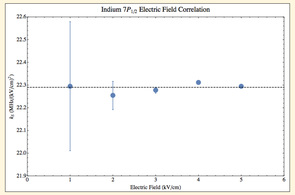
$$\Delta E_{|4,4\rangle}(\mathcal{E}) = -\tfrac{1}{2}\alpha_0\mathcal{E}^2 - f_{\text{tens}}(\alpha_2, \mathcal{E})$$

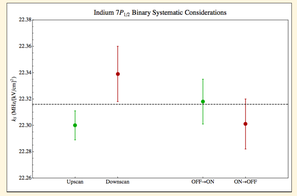


Preliminary Results

$7P_{1/2}$ Scalar Polarizability

- Preliminary result: $\alpha_0(7P_{1/2}) = 1.8064(32)\times10^5\ a_0^3$
- Dominated by contribution from nearby $6D_{3/2}$ state – allows indirect, precise measurement of $\langle 6D_{3/2}||d||7P_{1/2}\rangle = 21.16(4)$ a.u.
- Contains statistical and systematic error contributions
- Requires further data acquisition and systematic error analysis

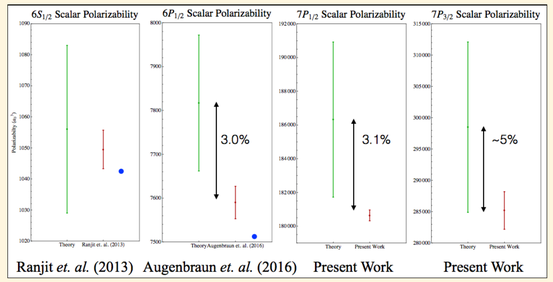




$7P_{3/2}$ Scalar Polarizability

- *Very* preliminary result: $\alpha_0(7P_{3/2}) = 2.852(30)\times10^5\ a_0^3$
- Dominated by α_2 theory error bar at $\sim 1\%$ level
- Requires more data acquisition and systematic error analysis

Recap: Comparisons with Theory



- Two theory approaches:
  1. Coupled-Cluster (CC): perturbative, hydrogenic approach – consistently *overestimates* experiment (green, above)
  2. Configuration Interaction + All Order (CI+All): three-valence – consistently *underestimates* experiment (blue, above – not calculated for $7P$ states)

Future Work

Indium Work

- Collect more $7P_{1/2}$ data and analyze further systematics
- Collect *much* more $7P_{3/2}$ data and begin analyzing systematics
- Pursue further theory work towards *tensor* polarizability extraction

Long-Term Goals

- Begin thallium and/or lead work in the atomic beam