High-Precision Measurements of Atomic Lead Transition Amplitudes and Static Polarizabilities

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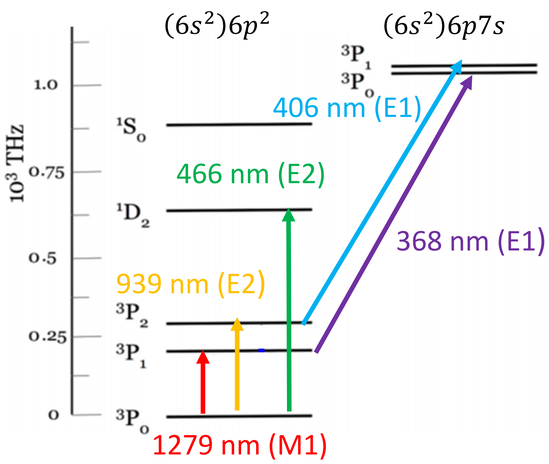
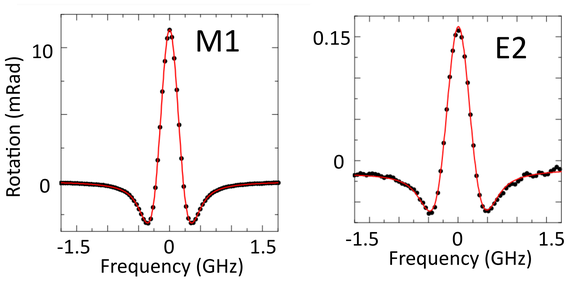
Background

- Heavy, multivalence elements are good testbeds for testing fundamental particle physics interactions → effects scale as ~Z^3.
- Atomic theory is challenging!
- Previous work with Group IIIA In [1] and Tl [2] tested *ab initio* multi-valence wavefunction models (Safronova group).
- New focus is on Group IV Pb. Improved atomic theory, but requires new, accurate experimental benchmarks.

Transitions in Pb

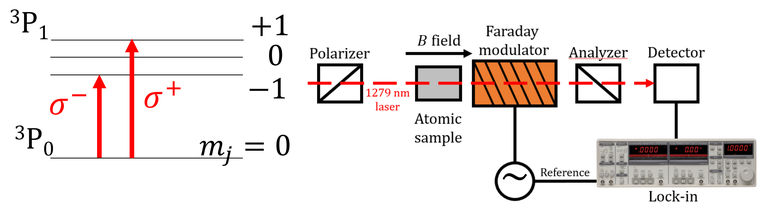


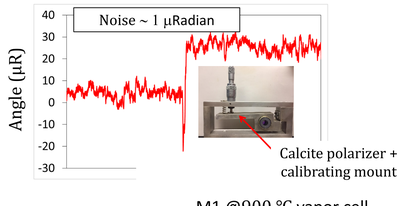
- **Previously**: First direct measurement of E2 (939nm). E2/M1 transition amplitude measured to 1 % [3].



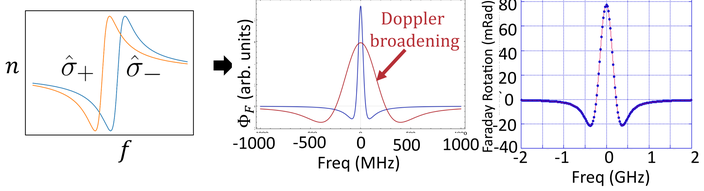
- **Ongoing work:** further precision amplitude measurements in Pb comparing E1 to M1 and E2 transitions.
- Pb Atomic Beam / polarizability measurements analogous to those completed in 2013 [4], 2016 [5], 2018 [1] in indium.

Faraday Rotation Spectroscopy (FRS)



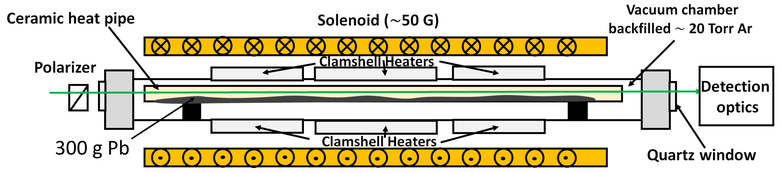


- Refractive indices for σ^- and σ^+ are now different due to Zeeman shift.
- Lock-in signal is proportional to: $\Phi_F \propto \mathrm{Re}(n_+(f)) - \mathrm{Re}(n_-(f))$.
- **Signal amplitude** $\propto \rho\, \ell\, \mathbf{B}$.



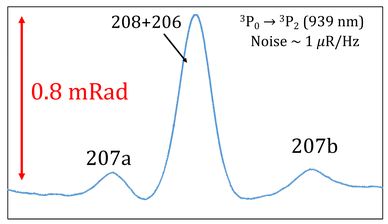
Towards Direct Measurement of $^3P_0 \rightarrow {}^1D_2$ (466 nm) Transition

- $^3P_0 \rightarrow {}^1D_2$ (466 nm) extremely weak: $\left(\frac{E2(466\text{ nm})}{E2(939\text{ nm})}\right)^2 \approx \frac{1}{200}$
- Heat Pipe Oven (HPO) can improve this:



	2019 vapor cell	2021 HPO	Enhancement factor
Max temp.	900˚C	~1100˚C	**X 10**
interaction length	10 cm	~40 cm	**X 4**
B-field	10 G	50 G	**X 5**

→ Based on preliminary tests, should be able to see 466 (forbidden E2) transition of ~ 50-100 μRad



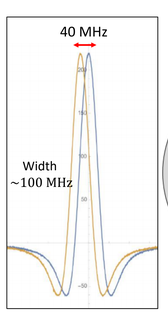
Natural abundance scan with HPO (900˚C)

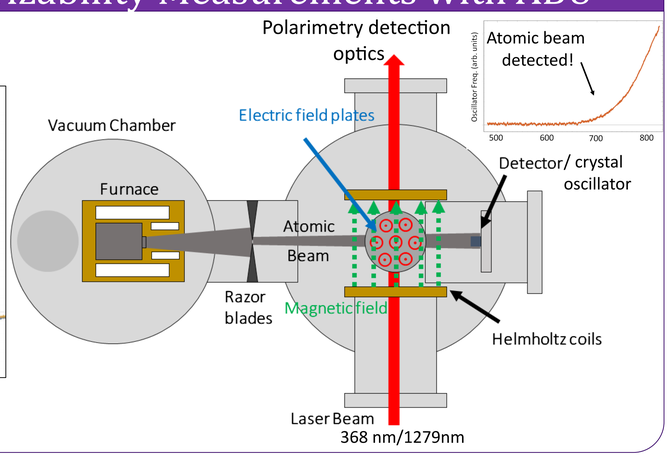
NEXT STEPS

- Optimize signal for 939 nm (E2) transition.
- Measure 939 nm isotope shifts directly with isotopically enriched cells.
- Frequency doubling setup for 466 nm laser.

Towards Static Atomic Polarizability Measurements with ABU

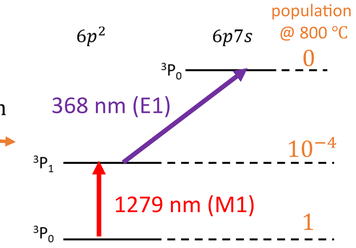
- Quadratic Stark shift: $\Delta E = -\frac{1}{2}\alpha\mathcal{E}^2$, where measured polarizability, α, can be compared to *ab initio* theory.
- ABU provides x15 geometrical Doppler narrowing.
- Expected shift of 40 MHz for 368 nm E1 transition with $\mathcal{E}$=20 kV/cm easily resolvable given ~100 MHz ABU linewidth.

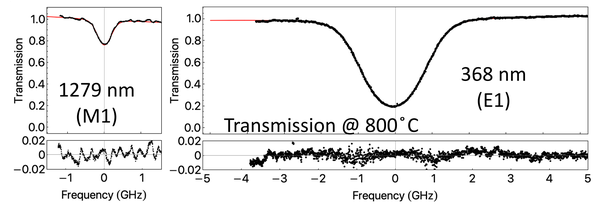




Absorption Spectroscopy of Pb in Vapor Cell

- $\left(\frac{M1(1279\text{ nm})}{E1\,(368\text{ nm})}\right)^2 \sim 10^{-5}$
- But, state population depends on Boltzmann factor
- Comparable optical depths @ 800 °C.





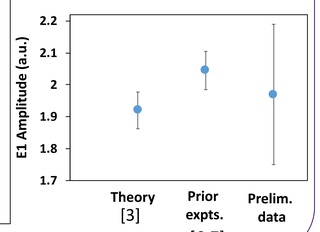
$$\frac{\alpha_0^{E1}}{\alpha_0^{M1}} = \frac{A_{E1}^2}{A_{M1}^2} e^{\frac{-0.97eV}{k_B T}} \frac{C_{E1}^0}{C_{M1}^0} \frac{f_{E1}}{f_{M1}} \left(\frac{cea_0}{\mu_B}\right)^2$$

Optical depth ratio | Transition strength ratio | Boltzmann factor | Line shape ratio @ resonance | Frequency ratio | Fundamental constants

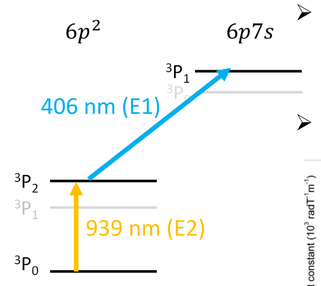
EXPERIMENTAL CHALLENGES

- Accurate and precise determination of temp. (~1-2˚C).
- Accounting for non-resonant light.
- Stimulated emission of E1 transition.
- Fitting of line shapes.

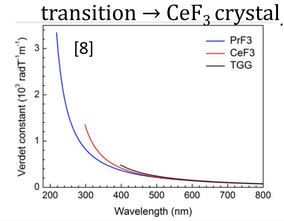
A_{E1}: 1.97(1)(22) a.u.



Future Goals



- Measure 406 nm (E1)/ 939 nm (E2) ratio using optical polarimetry.
- UV polarimetry of 368 nm transition → CeF_3 crystal



References – see accompanying presentation