High-Precision Measurements of Atomic Structure in Pb and Other Multi-Valence Systems

John H. Lacy , Russell Blakey '23, Abby Kinney '24,
Charles Yang '24, Robin Wang '24, and P. K. Majumder

Department of Physics, Williams College, Williamstown, MA 01267 USA

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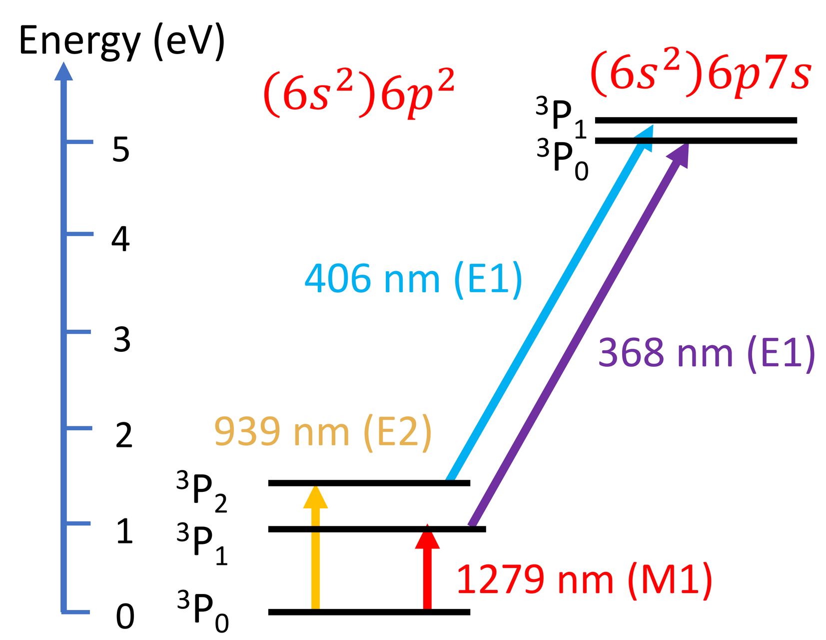
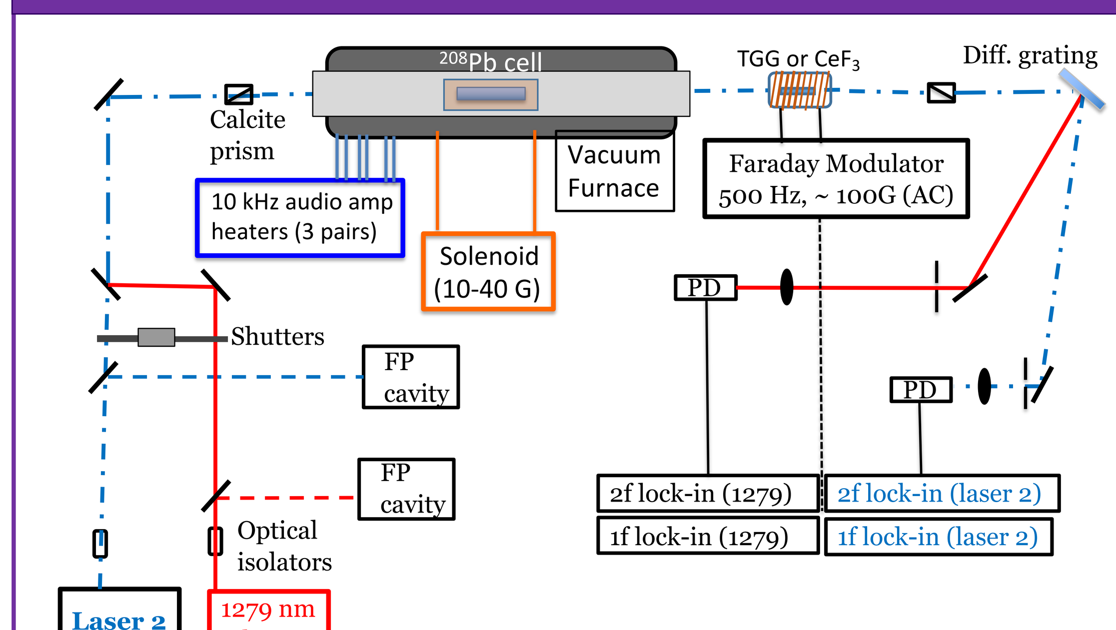
Background

- 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 and Tl tested *ab initio* multi-valence wavefunction models (Majumder + Safronova group collaborations).
- New focus is on Group IV Pb (two existing precise PNC experimental results). Improved atomic theory, but requires new, accurate experimental benchmarks…
  - Comprehensive isotope shift (re)measurements
  - Polarizability measurements
  - Transition amplitude measurements

Pb energy levels (group IV)



Two-laser Faraday Rotation setup for Transition amplitude measurements



2019 $\langle E2 \rangle$ amplitude result

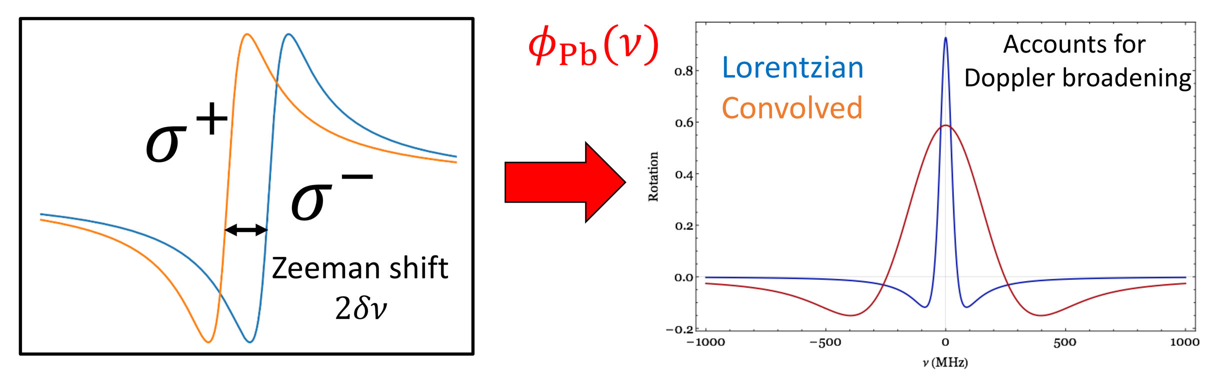
- M1 amplitude precisely calculable, → 'normalization'

EXP: <E2> = 8.91(9) a.u.
TH: <E2> = 8.88(5) a.u.

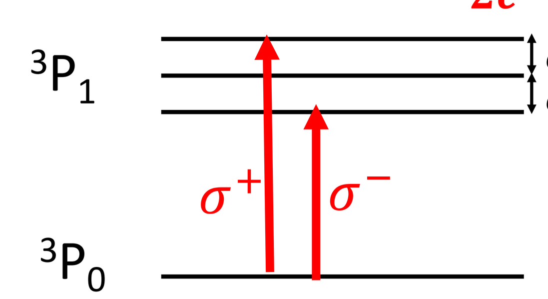
- **Majumder group + Safronova group:** High-precision measurement and *ab initio* calculation of the ($6s^26p^2$) $^3P_0$ → $^3P_2$ electric-quadrupole-transition amplitude in ^{208}Pb
D.M. Maser *et al.*, Phys. Rev. A **100**, 052506 (2019).

Broadband Faraday Rotation Spectroscopy (from UV → IR)

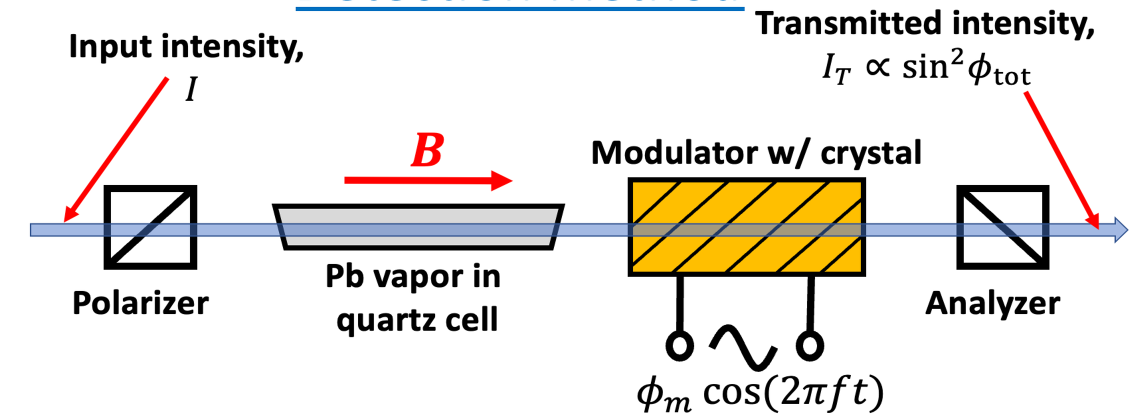
Line shape



Optical rotation: $\Phi_{Pb} = \frac{\omega l}{2c}(n_+ - n_-)$



Detection method



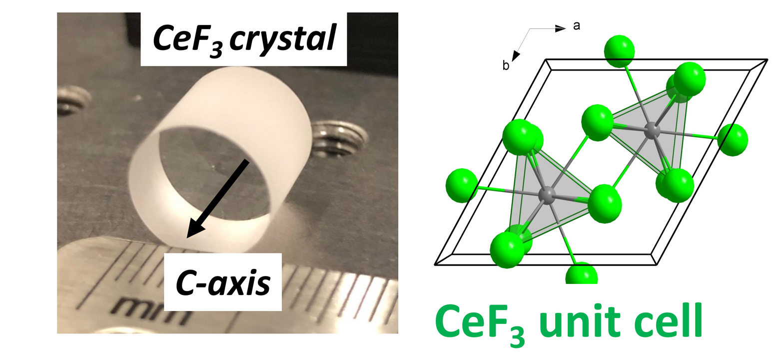
$$I_T \approx I(\nu)[2\phi_{Pb}(\nu)\phi_m \cos(2\pi f t) + \frac{\phi_m^2}{2}\cos(2\pi(2f)\,t) + \cdots]$$

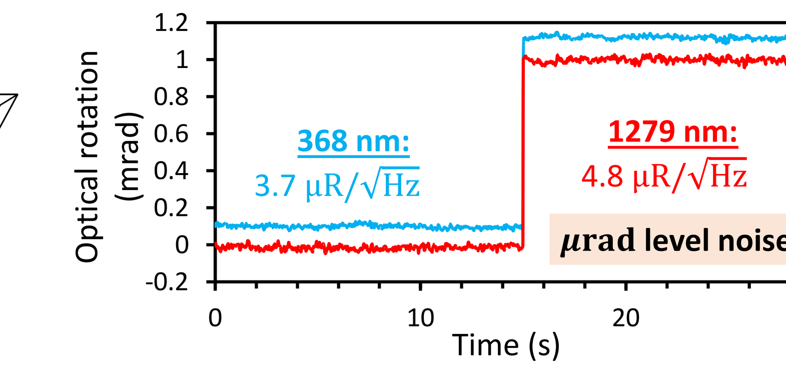
$I(\nu)$, Transmission spectrum; $\phi_{Pb}(\nu)$, Faraday rotation; ϕ_m, modulation amplitude

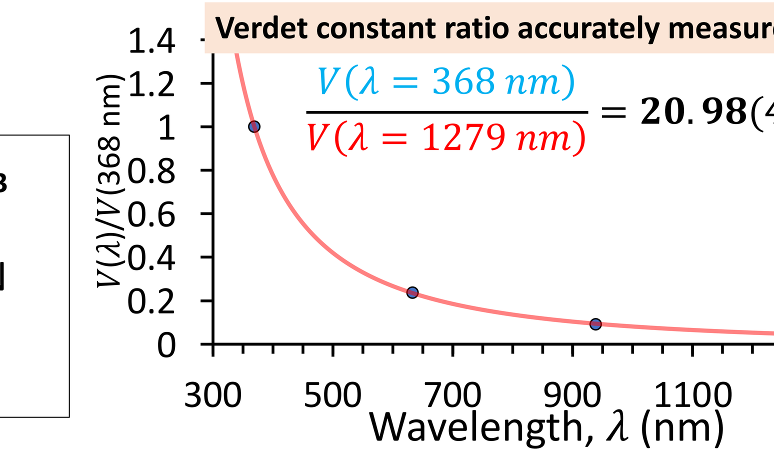
Lock-in signals:
$1f$: $2I(\nu)\phi_{Pb}(\nu)\phi_m$ $2f$: $I(\nu)\frac{\phi_m^2}{2}$

Proportional to Verdet constant, $V(\lambda)$

Cerium fluoride crystal modulator



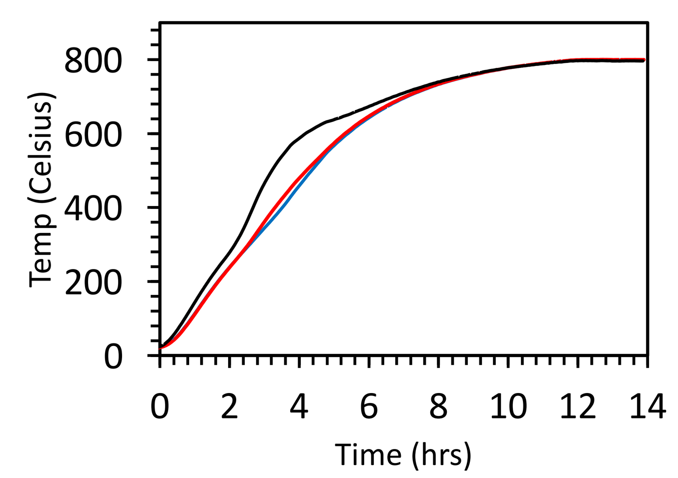




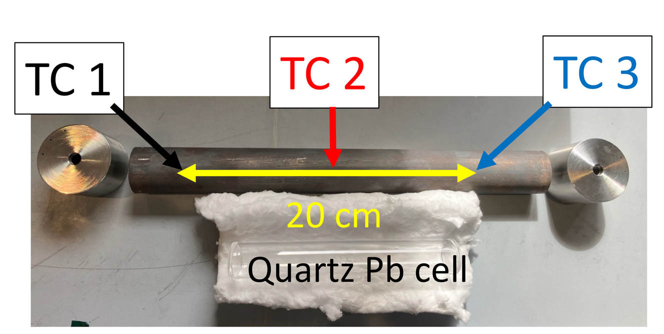
- New choice of Faraday rotator: **CeF$_3$**
- Operates: 300 nm → 10 μm
- Large Verdet constant improves S/N
- μRadian resolution from UV to IR!
- Very sensitive to crystal orientation

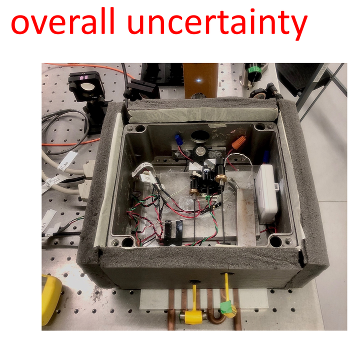
Precise measurements of E1 amplitudes using (thermally) excited states

Sample temperature /Boltzmann factor



- Evacuated Furnace
- Quartz cell embedded in SS tube + endcaps
- 3-zone heating elements for 'uniformity'
- 3 S-type TC's (± 1.5° K) + SR630 reader
- → overall Temp variance/accuracy: ~ ±1 °K
- → ~ 0.5% contribution to overall uncertainty

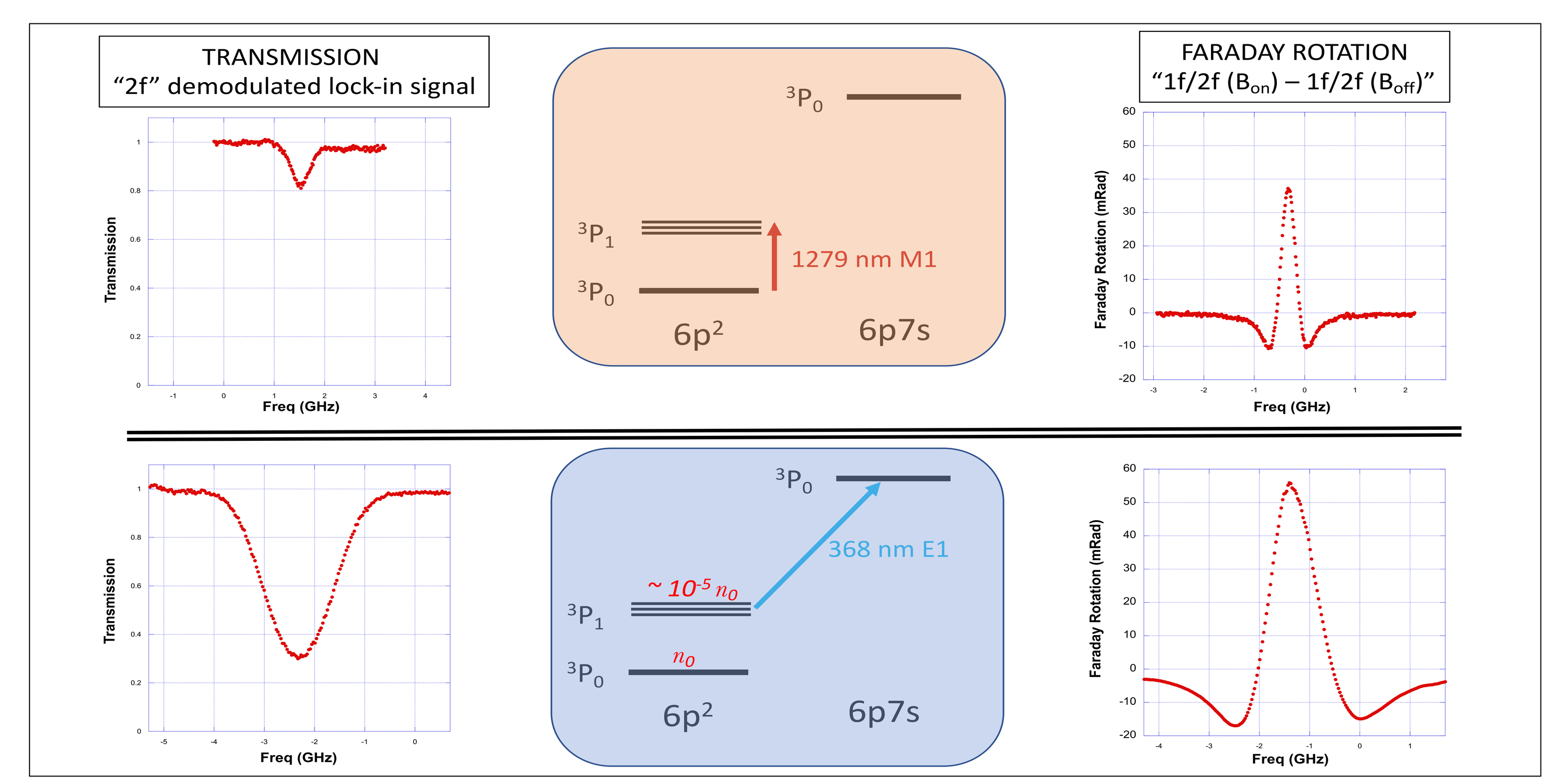




ECDL (UV diode) in sealed box
Operating at -8C → 368.3 nm

SAMPLE DATA (~1 min)

- One set of field-on / field-off scans for each
- Angle independently calibrated

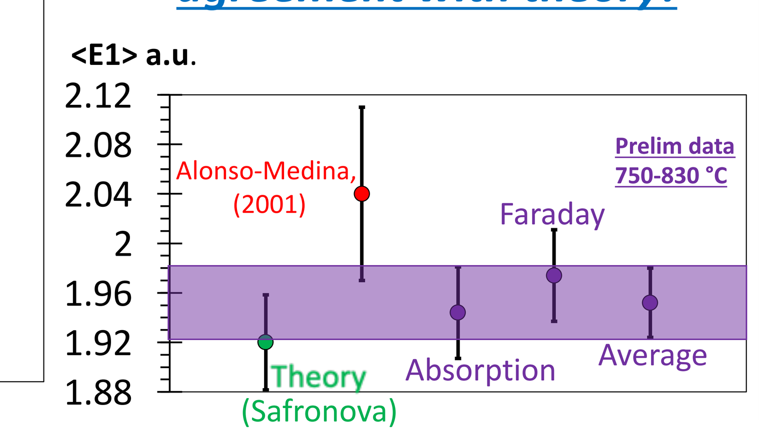


$$\frac{\Phi_0^{E1}}{\Phi_0^{M1}} = \frac{C_{E1}^0(\gamma,\sigma,B,T)}{C_{M1}^0(\gamma,\sigma,B,T)} \frac{n_0\, e^{\frac{-0.97eV}{kT}}}{n_0} \frac{\omega_{E1}}{\omega_{M1}} \left(\frac{ea_0}{\mu_B/c}\right)^2 \frac{\langle E1\rangle^2}{\langle M1\rangle^2}$$

Measured Faraday rotation peak amplitudes; Lineshape factors (from fit); Boltzmann factor; QM transition amplitudes

<M1> = 1.293(1) au]

Preliminary data in agreement with theory!



Experimental details / systematics exploration

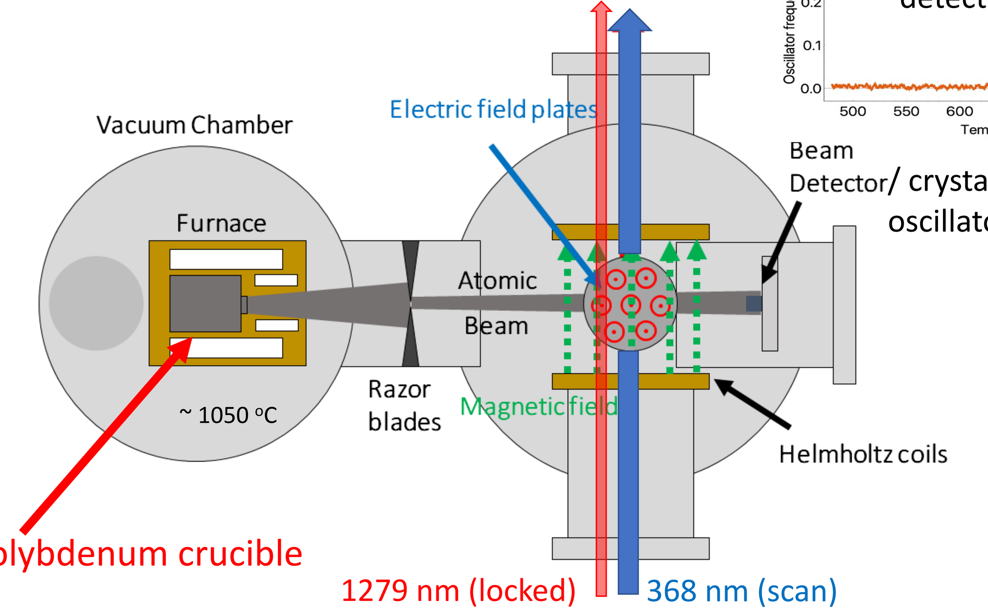
- Accessible temperature range: 700 – 850 C (order of mag in density)
- Can extract <E1> from either Transmission or Faraday signal
- Extensive line shape modeling / fitting (fix Doppler, B-field, fit for Lorentz)
- Remove Faraday/angle background with 'field-off' scans
- Calibrated FP cavities for frequency axis determination
- Similar experiment with 406 nm E1 transition

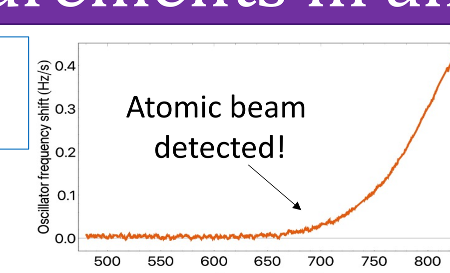
Towards Lead Scalar Polarizability Measurements in an Atomic Beam

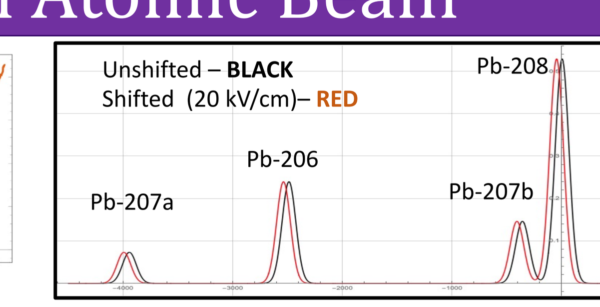
- Quadratic Stark shift: $\Delta E = -\frac{1}{2}\alpha_0\mathcal{E}^2$
- Scalar polarizability, α_0, calculable given atomic wavefunctions → measurements of α_0 serve as excellent benchmark test of theories.
- Expected shift of ~ 50 MHz for $^3P_1$ → $(6p7s)$ $^3P_0$ E1 transition with $\mathcal{E} \approx 20$ kV/cm - easily resolvable

Indium ABU / polarizability results: 2013, 2016, 2018

Transverse ABU Spectroscopy with "chopped" 1279 + 368 nm laser



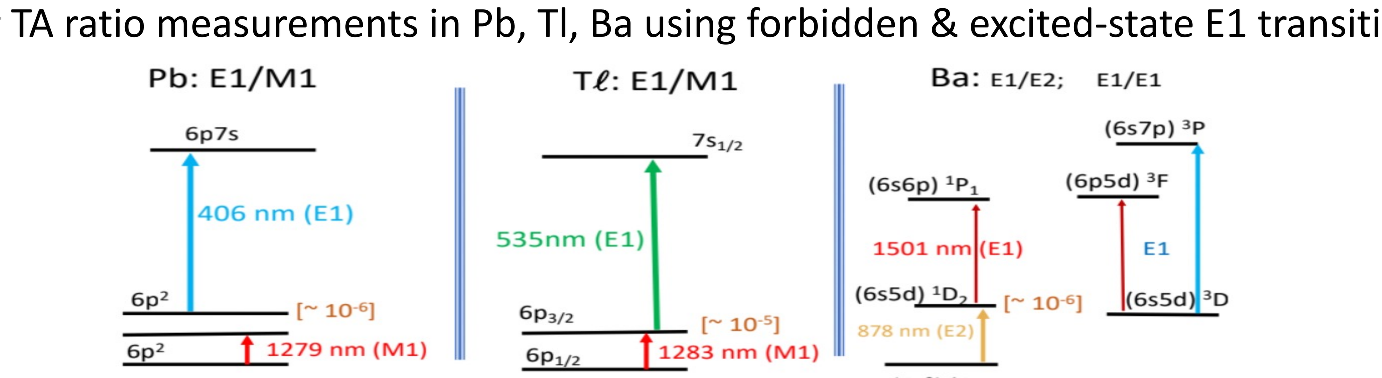




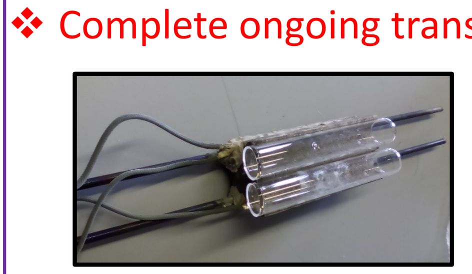
Quantity (rel. to vapor cell @ 800 °C)	Vapor cell in furnace	Atomic beam (@ 1050°C)
Peak absorption cross section	σ_0	σ_0 ×10 (Doppler narrowing)
$^3P_1$ number density	n_0	n_0 × 50 (M1 pre – pumping) × 10 (thermal/Boltzmann) × 10^{-4} (Geometrical loss)
Interaction length	ℓ	ℓ × 0.2 (atomic beam width)
Optical depth	**1**	**0.1**

Future Work

- Similar TA ratio measurements in Pb, Tl, Ba using forbidden & excited-state E1 transitions

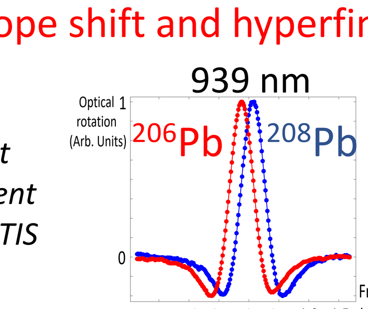


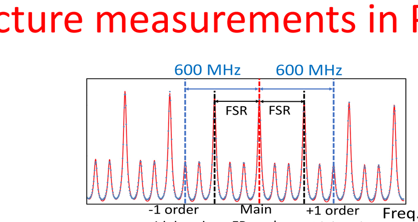
- Complete ongoing transition isotope shift and hyperfine structure measurements in Pb



Isotopically pure Pb samples

First direct measurement of 939 nm TIS





Enabled by accurate frequency calibration – sub-MHz level