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

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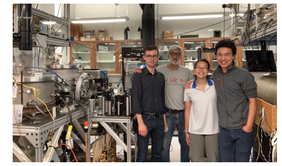
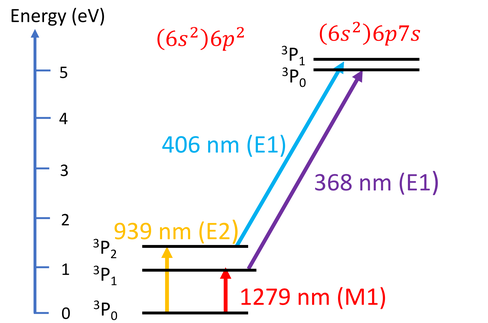
Work supported by NSF grant #1912369



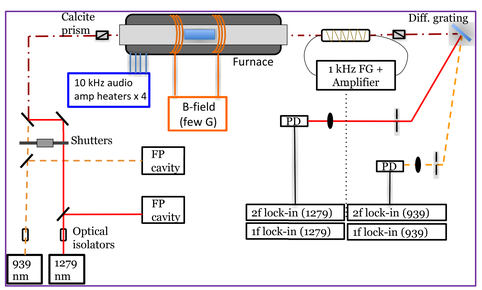
Background

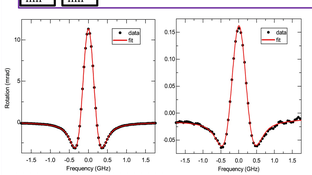
- Heavy, multivalence elements are good testbeds for testing fundamental particle physics interactions → effects scale as ~Z^3. → Atomic theory is challenging!
- Previous work with Group IIIA In and Tl tested *ab initio* multi-valence wavefunction models (Majumder + Safronova group collaborations).
-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

Pb energy levels (group IV)



2019 E2/M1 measurement





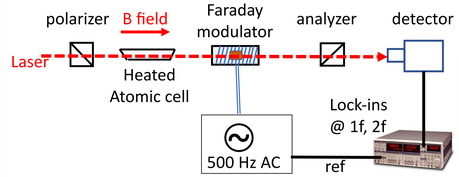
- M1 amplitude precisely calculable, → 'normalization'

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 $(6s^26p^2)\ ^3P_0 \rightarrow {}^3P_2$ electric-quadrupole-transition amplitude in ^{208}Pb
  D.M. Maser et al., Phys. Rev. A **100**, 052506 (2019)

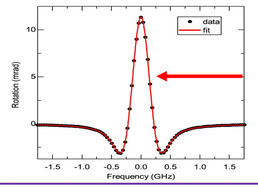
Broadband Faraday Rotation Spectroscopy (from UV → IR)



- ❖ typical 'extinction': 10^{-5}
- ❖ modulation ~ few mRad

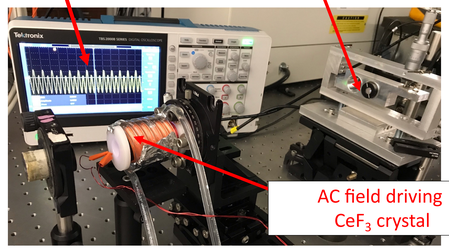
- **1f demodulation** → Faraday rotation
- **2f demodulation** → Transmission/Absorption
- **For small fields (~ 10 G), lineshape is 'derivative of dispersion' (symmetric) curve**
- **Signal amplitude** ∝ $[\rho\, \ell\, \mathbf{B}\, \langle \mathbf{M} \rangle^2]$

S/N ratio ~ 5000:1 for 'forbidden' M1

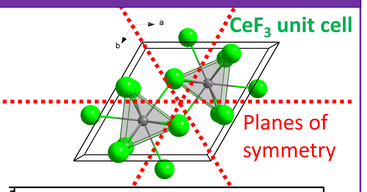


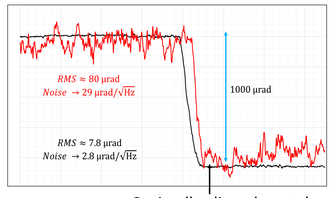
1f and 2f polarization modulation signals

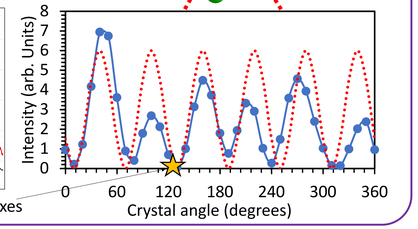
Glan-Thompson calcite polarizer with differential micrometer + lever for rotation calibration



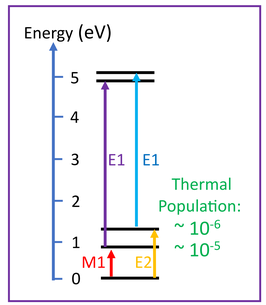
- ❖ New choice of Faraday rotator: **CeF_3**
- ❖ Transmission: 0.3 μm → 10 μm
- ❖ Very large Verdet constant improves S/N ratio
- ❖ Microradian resolution from UV to IR!
- ❖ Very sensitive to crystal orientation



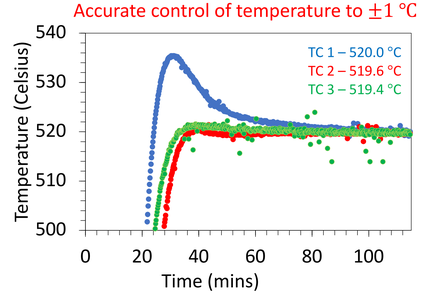


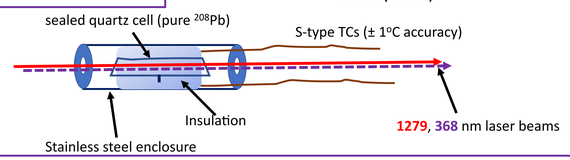


Precise measurements of E1 amplitudes using (thermally) excited states

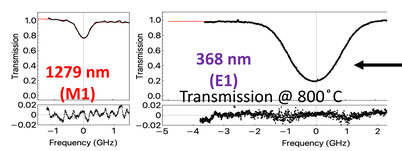


Accurate control of temperature to ±1 °C





- ❖ For 368 nm $(6p^2)\ ^3P_1 \rightarrow (6p7s)\ ^3P_0$: <E1>/<M1> ≈ 10^5; but Boltzmann thermal population ≈ 10^{-5} !!
- ❖ Must determine cell temperature: ± 2 °C accuracy for < 1% systematic error in eventual E1 amplitude determination.
- ❖ Similar story for $^3P_2$ level: 50x smaller population, still easily measurable 406 nm E1 transition: $(6p^2)\ ^3P_2 \rightarrow (6p7s)\ ^3P_1$
- ❖ And 406/368 nm E1/E1 comparison gives ratio of amplitudes *nearly independent of temperature*….

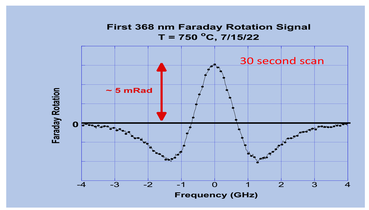


Solve for E1

Transmission spectroscopy
prelim. data from 2021:
<E1> = 2.1(1) a.u. (<M1> known)

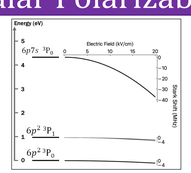
$$\frac{\alpha_0^{E1}}{\alpha_0^{M1}} = \frac{E1^2}{M1^2}\, e^{\frac{-0.97eV}{k_B T}}\, \frac{C_{E1}^0}{C_{M1}^0}\, \frac{f_{E1}}{f_{M1}}\, \left(\frac{cea_0}{\mu_B}\right)^2$$

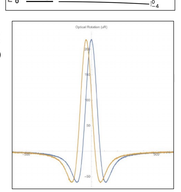
Measured Optical Depth ratio | QM transition strengths | Boltzmann factor | Lineshape ratio at resonance | Frequency ratio | Fundamental constants



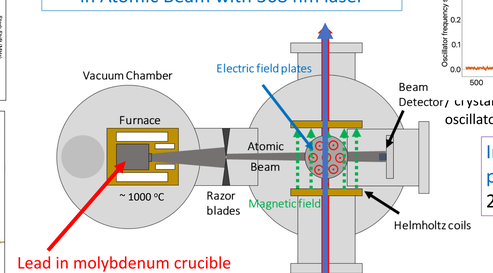
Towards Lead Scalar Polarizability Measurements in an Atomic Beam

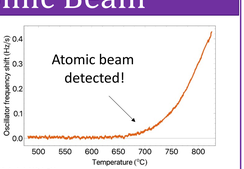
- Quadratic Stark shift: $\Delta E = -\frac{1}{2}\alpha \mathcal{E}^2$
- Atomic polarizabilities, α, calculable given atomic wavefunctions → measurements of α serve as excellent benchmark test of theories.
- ABU provides 15x geometrical narrowing of lineshapes compared with vapor cell @ same temp → much easier to measure frequency shifts .
- Expected shift of 40 MHz for $^3P_1 \rightarrow (6p7s)\ ^3P_0$ E1 transition with $\mathcal{E}$=20 kV/cm easily resolvable





Transverse Faraday Rotation Spectroscopy in Atomic Beam with 368 nm laser

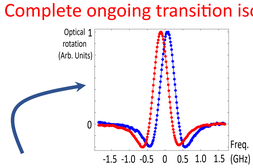


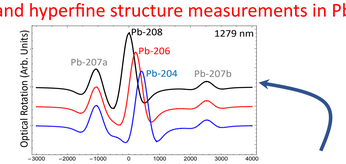


Indium ABU / polarizability results: 2013, 2016, 2018

Future Work

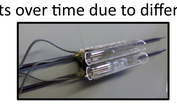
- ❖ Similar TA ratio measurements in Pb, Tl, Ba using forbidden & excited-state E1 transitions
- ❖ Complete ongoing transition isotope shift and hyperfine structure measurements in Pb

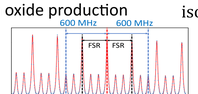




Side-by-side cells of separate isotopes: systematic drifts over time due to differences in oxide production

50:50 blends in same cell → same shift for both isotopes. ^{207}Pb as common reference





^{207}Pb +^{20x}Pb

Accurate frequency calibration – sub-MHz level