Final report -- NSF grant #01912369 (June 2025)

I. Background, summary of work, and personnel.

An important underlying motivation for these experiments -- a better understanding atomic structure in 3- and 4-valence-electron elements such as thallium, indium and lead -- was motivated by publications in the 1990's of high-precision measurements of parity nonconservation (PNC) in thallium and lead at the 1% level of experimental accuracy [1, 2]. For these experimental results to have full impact as a "table-top tests of particle physics", it is essential for the understanding of the atomic structure of these multi-valence-electron systems to be pushed to a similar 1% level of accuracy. More recently, the atomic theory group headed by Marianna Safronova has pioneered new atomic calculation method which uses a configuration interaction (CI) and an 'all-orders' approach to compute accurate wavefunctions for three and four-valence-electron systems [3,4].

During the previous grant cycle (2014-2018), we completed several measurements of the polarizability and hyperfine structure of trivalent indium, and showed excellent agreement with *ab initio* theoretical predictions at the 1% level. This work involved the use of a high-flux atomic beam apparatus with associated vacuum apparatus, and high-voltage electric field plates which allowed for precise calibration of electric fields up to 20 kV/cm/. We also developed schemes to perform two-step laser spectroscopy, producing Doppler-narrowed transitions; to lock diode lasers; to precisely calibrate Stark-induced frequency shifts; and to employ a very sensitive FM spectroscopy technique to detect weak absorption signals in the atomic beam environment.

In general, there are few experimental 'benchmark' measurements in the Pb system to test theory and guide its further refinement (unlike the situation in, for example, alkali systems), and given the substantial theory progress on this complex multi-valence system, we have pursued and completed the first atomic structure measurements of sufficient precision to test and guide the theory in lead. In particular, we have completed a series of high-precision transition amplitude measurement in Pb, first directly measuring for the first time the highly-forbidden $(6s^2 6p^2)\ ^3P_0 \rightarrow\ ^3P_2$ E2 transition at 939 nm and more recently measuring with substantially improved (sub 1%) precision the matrix elements for two excited-state E1 transitions. In all cases, we used a polarimetry technique similar to that used to measure parity nonconserving optical rotation in the work referenced above. Our method here allowed detection of milliradian-sized Faraday optical rotation spectra with residual noise near one microradian. By comparing the amplitude of the optical rotation signals for the E2 transition and the 1279 nm M1 transition under identical experimental conditions, and making use of the precisely calculable M1 transition amplitude, we measured the E2 and E1 amplitudes with sub-1% precision showing excellent agreement with the current *ab initio* predictions of atomic theory. This work was published in the fall of 2019 with two undergraduate honors thesis students as co-authors, along with two different NSF-funded postdocs, and our theory collaborators from the Safronova group [13].

An extremely important aspect of the ongoing work in the Majumder lab is the research training opportunities that we continue to provide for a large number of talented undergraduate students (see table at end of this report). Since the beginning of the current grant cycle, we have supported the senior thesis projects of seven students, and the extended research projects of many more students at all stages of their education. Nearly all of the thesis students have gone on to Ph.D. programs and have continued their research in the area of AMO physics (including at Harvard (3), U. Chicago, and Rice University). In a very difficult year in terms of graduate school

capacity and concerns about research support, our latest student, Carter Anderson ’25, will be beginning a Ph.D. in physics at U. Toronto where he is choosing between LIGO-related modeling work and AMO physics. Just this past week, attending the Atomic Physics Gordon Research Conference as a Discussion leader, I spent a stimulating and inspiring week where six former senior thesis students of mine, who have remained in the AMO field were in attendance (currently grad students, postdocs, and one faculty member).

This NSF-supported work involves the use of two types of major laboratory tools – several furnaces / vapor cell apparatuses, as well as a high-flux atomic beam apparatus - to complete a variety of precise laser spectroscopy measurements of the atomic structure of several heavy elements. Currently we utilize four (either commercial or home-built) ECDL laser systems in the laboratory (one near UV, one visible, two near IR). Having moving the entire experimental operation to a new, state-of-the-art laboratory science building in 2018, we now have expanded custom-constructed space (roughly 1000 sq. ft total) to work in.

Two former thesis students from this lab, Charlie Doret ’02 and Ben Augenbraun ’15 (both winners of the annual APS *LeRoy Apker Award* as senior undergraduates) have returned as faculty members at Williams College. Charlie has developed an active, successful, NSF-funded ion trapping lab. Ben has had a very productive start at Williams building up a new molecular spectroscopy laboratory. He and I have exciting plans to collaborate on an atomic beam project to demonstrate laser cooling of Pb atoms for the first time, and are sharing two rising senior thesis students (Elena Deegan-Krause ’26, and Charlene Peng ’26) who will work on related laser/optics/atomic beam/signal analysis projects. Meanwhile a third rising senior (Gautam Ramasamy ’26) will begin a thesis project on our vapor cell / isotope shift / hyperfine structure measurements in the fall, while spending the summer in the Zweirlein lab at MIT. Progress and plans on these project will be outlined below.

Having a set of three active AMO scientists with large, active groups of research students had made for an unusually strong ‘presence’ of this sub-field in our small liberal-arts-college environment. The synergistic ability to meet to informally talk about lasers and atomic physics ideas, to have students participate in large group meetings to share their work, and to share equipment and new ideas has already, and will continue to pay great benefits to BOTH the PIs and the students.

II. Summary of Faraday rotation-based transition amplitude measurements

Fig. 1 shows various low-lying E1, M1, and E2 transitions in neutral lead. The 2019, 2024, and 2025 published work from our lab[13,15,16] alluded to above, represents the successful demonstration of applications of our precision optical rotation techniques to a series of Pb transition line strengths at or below the 1% level of precision, exceeding the accuracy of previous work, and in some cases measuring these line strengths for the first time. There, we were able to leverage the microradian-level resolution of this polarimetry technique, and the ability to compare observed signal sizes in two different transitions under identical experimental conditions. The fact that the 1279 nm M1 ground-state transition can be calculated with precision better than 0.1% allows us to use the observed M1 signal for

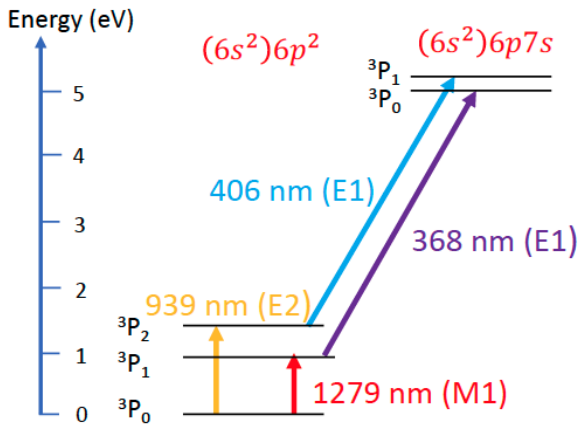


Fig 1: Relevant low-lying levels of Pb-208.

normalization, allowing an 'absolute' determination of the 'unknown' transition amplitude. Using isotopically-pure Pb-208 (courtesy of the Oak Ridge National Stable Isotope center), we can obtain a clean, single-peak, hyperfine-structure-free spectrum to work with in our vapor cell experiments.

1. Precision measurements of <E2> and <E1> transition amplitudes in heated Pb vapor cells. *[contributions from thesis students: Eli Hoenig '17 (U Chicago), Bingyi Wang '18 (Stanford), Patrick Postec '21 (Duke), Gabriel Patenotte '21 (Harvard), Abby Kinney '24 (U. Chicago), as well as postdocs: Milinda Rupasinghe (now faculty at SUNY/Oswego), Dan Maser (now faculty at Connecticut College), and John Lacy]*

Early on during this grant cycle, spurred by the new atomic theory calculations in Pb, we measured (for the first time) the very weak 939 nm electric quadrupole transition amplitude (see Fig. 1) by comparing the very small (100-mRad-sized) Faraday rotation signal of this transition in the presence of a ~10 G magnetic field to that of the slightly stronger M1 transition under identical vapor cell and magnetic field conditions. This result[13] agreed within the 1% error bars with ab initio theory. In this experiment the level of experimental precision was enabled by the use of a biaxial TGG Faraday glass to allow polarization modulation and lock-in detection for both transitions. The extremely high S/N ratio of this technique and the fact that the Faraday signal provides a clean, background free lineshape to analyze allows us to explore the amplitude ratio over a wide range of atomic densities and applied fields, aiding in systematic error exploration.

More recently, we have used a similar polarimetry apparatus to measure the linestrength of the 406 nm and 368 nm E1 transitions (see Fig. 1). The comparison of linestrengths of the E1 and M1 transitions was facilitated by the following fortuitous fact: While E1 transition linestrengths are ~five orders of magnitude larger than M1 linestrength, the Boltzmann factor governing the thermally-excited state population in the $^3P_1$ and $^3P_2$ levels in lead at our typical furnace temperatures (~ 1100 K) are about 10^{-5} and 10^{-6} respectively. Therefore, the apparent absorptivity of the 1279 M1 transition in a heated is cell turns out to be quite comparable to the absorptivity of both the $(6s^26p^2)\ ^3P_1 \rightarrow (6s^26p7s)\ ^3P_0$ E1 transition at 368 nm AND the $(6s^26p^2)\ ^3P_2 \rightarrow (6s^26p7s)\ ^3P_1$ E1 transition at 406 nm. A principal challenge in deducing the absolute an accurate E1 line strength here then becomes accurate, reliable determination of the cell temperature and associated thermal Boltzmann factor. Ultimately (see Fig 2) we achieved ± 1°C temperature accuracy using multiple precision thermocouples and the ability to separately control 3 pairs of furnace heaters. A second experimental challenge here is the fact that the TGG Faraday modulation glass used previously does not transmit in the UV. We successfully sourced and a 'disk' of uniaxial crystal of cerium fluoride (CeF_3), which is known to transmit in the UV and, with appropriate crystal axis orientation, exhibits a large Verdet constant. When precisely oriented and aligned, as we have done, it produces good transmission and optical rotation noise below 10 microradians – sufficient for our precision Faraday rotation needs. The birefringent properties of this crystal, however, have led to complications in the observed optical rotation lineshapes. This led us to do extensive modeling and experimental testing of the magneto-optical properties of this crystal, which has not been used for precision measurements such as ours. All of this successful modeling work led to a 'methods' paper recently published in the journal *Photonics*[15] with two recent student co-authors (Abby Kinney '24, now in the DeMille group at Chicago/JHU, and Gabriel Patenotte '21, now in the Ni group at Harvard)).

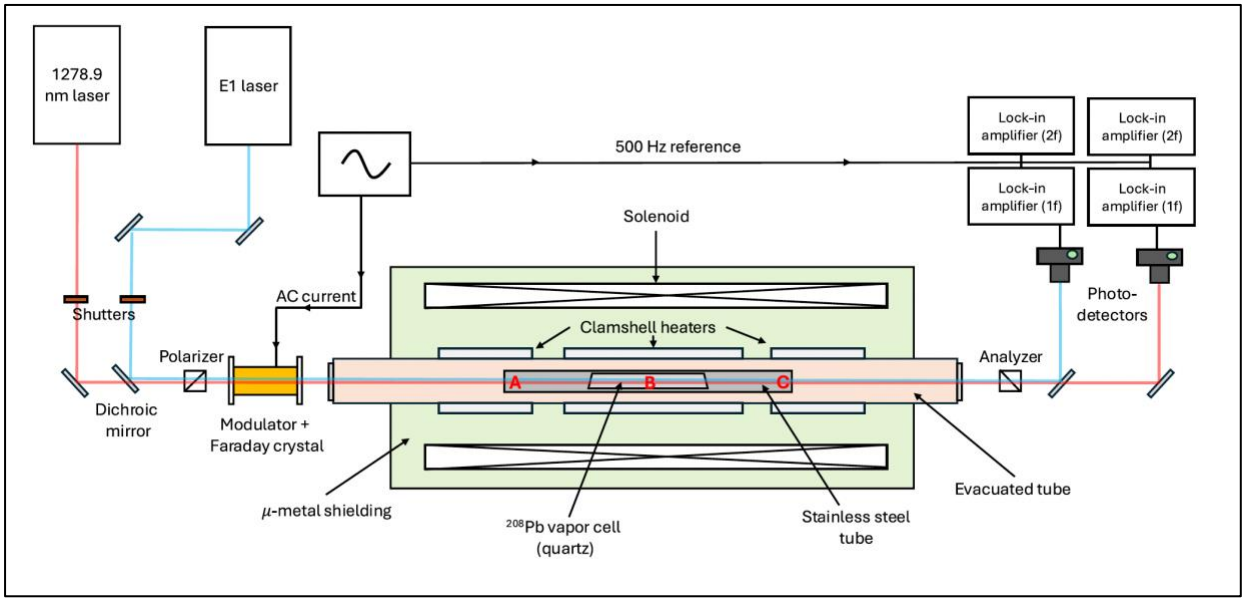


Fig 2: Schematic of transition amplitude comparison through precision Faraday rotation spectroscopy setup. A, B and C refer to S-type thermocouples embedded in a stainless steel housing containing the Pb cell.

With apparatus tested and modeled, we collected substantial data for both Faraday rotation AND direct transmission to compare E1 and M1 signals during 2024. Fig. 3 shows examples of single ~15 second scans for each of the three transitions under identical vapor cell conditions. These ~ 10 milliradian-sized optical rotation signals have sufficient S/N ratios sufficient to achieve 1% statistical accuracy in amplitude ratios quite quickly. As described in our recent publication[16], this experimental observable can then be linked to the <E1> matrix elements in a fairly straightforward way. For one, the cell density and magnetic field strengths are 'common' to the E1 and M1 scans. Since component Gaussian and Lorentzian widths in our Voigt convolution fits to the lineshapes are quite different, a factor accounting for these differences must be included, as must the aforementioned Boltzmann thermal population ratio. Finally, as noted above, the <M1> matrix element is known to 0.1% accuracy[13].

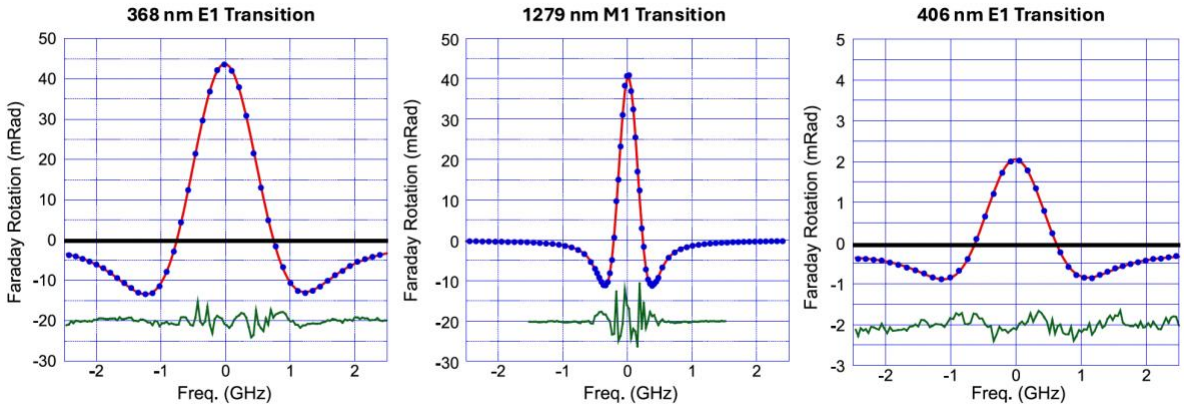


Fig 3: Example of single Faraday rotation scans taken under identical experimental conditions for the two E1 transitions and the M1 'normalization' transition. The order-of-magnitude smaller signal for the 406 nm E1 transition reflects the smaller Boltzmann thermal population of the $^3P_2$ level (rather than the intrinsic size of the transition amplitude).

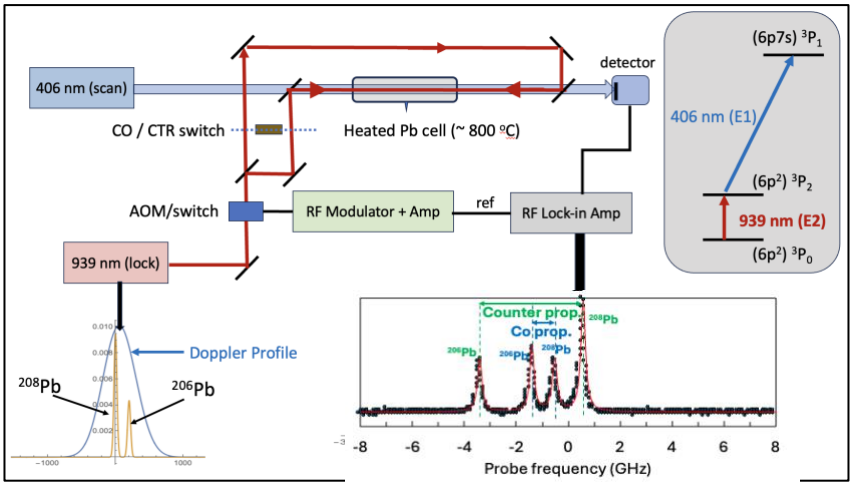
Table 1 summarizes three new transition amplitude measurements completed during this grant cycle along with the new *ab initio* theory predictions from the Safronova group. Our measurements are either the first such experimental values in lead (E2 case) or nearly an order of magnitude improvements over older values made in a discharge source environment[15]. The outstanding agreement here as well as the level of experimental accuracy provides good motivation for further theory development and experimental work in the future.

Lead Transition	Transition Type and wavelength	Experimental reduced matrix element (a.u.)	*Ab initio* Theory value (a.u)
$(6p^2)^3P_0 \rightarrow (6p^2)^3P_2$	**E2 (939 nm)**	**8.91(9)**	**8.88(5)**
$(6p^2)^3P_1 \rightarrow (6p7s)^3P_0$	**E1 (368 nm)**	**1.89(1)**	**1.92(6)**
$(6p^2)^3P_2 \rightarrow (6p7s)^3P_1$	**E1 (406 nm)**	**3.01(2)**	**2.99(9)**

Table 1: summary of recent lead precision transition amplitude measurements and theory

2. Two-color, two-step, Doppler-free spectroscopy in Pb: Isotope shifts and hyperfine constants
[Contributions of thesis students: Charlotte Jones '22 (MIT/Lincoln Labs, Laser development group); Charles Yang '24, (Ph.D. program Rice Univ); Carter Anderson '25, (Ph.D. program U. Toronto). For 2025-26: Gautam Ramasamy '26]

Recently, we have been pursuing a new spectroscopic scheme to measure Doppler-free spectra in heated vapor cells to obtain a set of transition isotope shift (TIS) and hyperfine structure (HFS) measurements in lead. Referring to Fig. 1, we separately are exploring the $(6p^2)^3P_0 \rightarrow (6p^2)^3P_2 \rightarrow (6p7s)^3P_1$ (E2 + E1 transition) pathway as well as the $(6p^2)^3P_0 \rightarrow (6p^2)^3P_1 \rightarrow (6p7s)^3P_0$ (M1 + E1 transition) pathway. Isotope shifts and hyperfine constants were measured several decades ago for some (not all) of these states/transitions. In particular, the $^3P_2$ state and the 939 nm E2 transition required to reach that state have not been previously studied. Lead has four stable isotopes, three I=0 even isotopes (208, 206, 204) as well as the I=1/2 Pb-207 isotope. We have obtained vacuum quartz vapor cells with individual purified isotopic samples in each (courtesy of the Oak Ridge national stable isotope center). We have ECDL systems in our laboratory at all four relevant transition wavelengths (two IR, one blue, one near-UV). Our evacuated furnace (used for the Faraday polarimetry spectroscopy described above), can reach and stabilize vapor cell temperatures up to 900°C. Currently we arrange a pair of cells in 'series' each containing one of the four Pb isotopes in the center of our furnace.



Here we update recent work on the E2+E1 pathway, using a pair of overlapping lasers, one locked at 939 nm, one scanning at 406 nm. Taking first the example of two even isotopes (Pb 208 and 206) and referring to Fig. 4, the $^3P_2$ excited state of the ($6s^26p^2$) ground-state configuration is the starting point of a strongly-allowed E1 transition to the excited ($6s^26p7s$) $^3P_1$ state at 406 nm. Given that even at 'furnace' temperatures the thermal population of this state is roughly 10^{-6}, spectroscopic detection of this transition even in a dense atomic sample is challenging, and any evidence we do see of absorption is highly Doppler broadened. With the aid of a Toptica 939 nm DL100 laser capable of delivering more than 50 mW of power, we can drive **some** population from the ground state to the $^3P_2$ excited state via the 'forbidden' E2 transition. While we are likely exciting no more than about 0.01% of the atoms to the $^3P_2$ state, even that fraction is a vast increase over the thermal population. One can therefore overlap IR and blue lasers in a heated vapor cell (see Fig. 4), and, by modulating the IR beam and using lock-in detection, one can easily detect a clean, background-free 406 nm absorption signal. However, using a conventional chopping wheel modulating at frequencies near 1kHz, the excited atoms rethermalize in times much shorter than the modulation period. Therefore we use an AOM as a'fast switch' to modulate the pump at frequencies near 1 MHz and perform RF lock-in detection. This modulation is fast enough to prevent collisional rethermalization. As suggested in Fig. 4, if we for example lock the first step laser near the Doppler-broadened (and overlapping) absorption features of the 208 AND 206 isotopes, we excite (different) velocity classes of each to the intermediate state. If we then scan the frequency of the blue second-step laser across the E1 transition resonances of the two isotopes, the output of the RF lock produces Doppler-free peaks. The presence of FOUR peaks reflects the simultaneous pumping in counterpropagating directions with respect to the blue probe beam. The spectrum we obtain reflects both the TIS of the second-step blue transition (large, ~2.5 GHz), but also has an 'imprint' from the first step TIS due to the distinct Doppler shifts of the velocity classes selected for each isotope. The counterpropagating geometry reverses these relative Doppler shifts. As a nice bonus, the Doppler shift originating from the 1st step excitation that is manifested in the second-step spectrum is amplified several fold since the blue frequency is ~2.5x larger than the IR frequency. As can be seen in the figure we can obtain high S/N ratio four-peak spectrum (here single 15 sec scan). Using averages and differences in the various fitted peak splittings, we can deduce the Pb-208/206 TIS for BOTH TRANSITIONS in this single spectrum. We have already collected sets of scans that suggest that we can obtain sub-MHz statistical precision in such TIS values in modest data collection time.

We have also developed a successful scheme to simultaneously excite one even isotope plus the Pb-207 isotope. The hyperfine constant of the latter is much larger than the first-step Doppler width, so that the simple scheme described above will not simultaneously pump both isotopes in this case. We have introduced a fiber-based EOM device to span the even-odd isotopic peaks. Using RF frequencies in the 1 – 2 GHz range, we lock the 939 nm 1st step laser to a point midway between the isotopes and the 1st - order sidebands then are near resonant with each transition peak. Figure 5 shows the idea – the black lines indicate the $^3P_2$ Pb-207 hyperfine peaks (dotted line indicated the center of gravity whose small shift from the blue Pb-208 peak is defines as the TIS). Here the green pump beam frequency components again excite

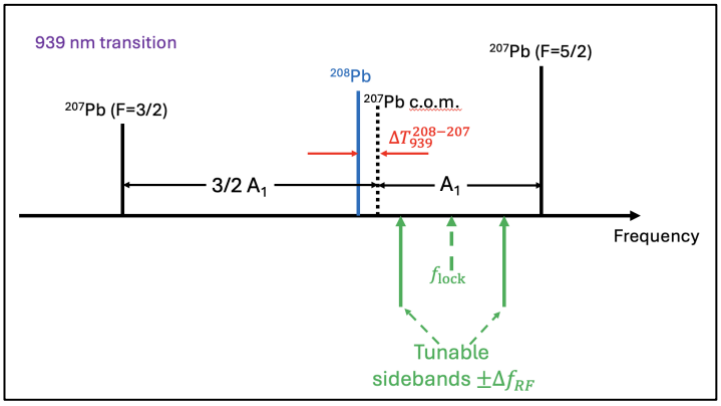


Fig 5: Even + odd isotope excitation via fiber-based tunable EOM sidebands.

different velocity classes of the even isotope and the F=5/2 Pb-207 component. Tuning the RF frequency driving the EOM systematically adjusts those velocity classes and associated Doppler shifts. By comparing the measured peak splittings in the 2nd step spectrum and comparing the case of CO and COUNTER propagating pump geometry we can again (with independent measurements of the Pb-207 hyperfine constant, "A_1" in figure above) obtain the true 208-207 isotope shift.

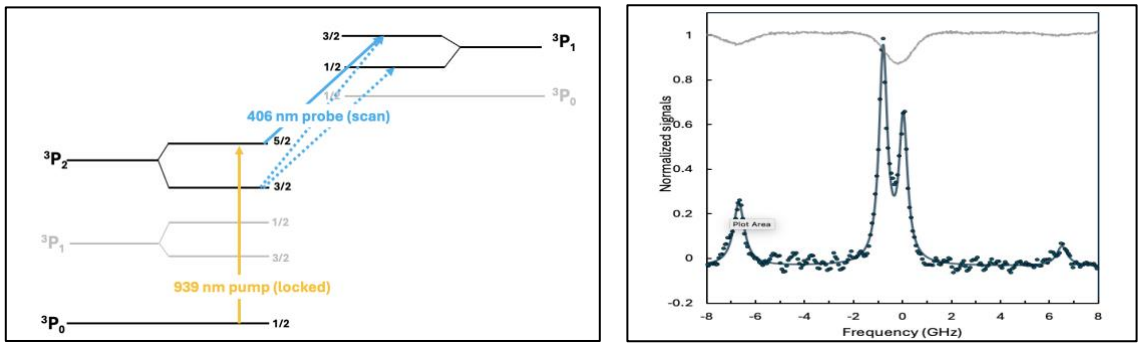


Fig 6: Left – level diagram showing pumping of Pb-207 isotope to the F=5/2 state (orange) as well as the three 'allowed' hyperfine transitions at 406 nm for the $^3P_2$ excited state.
Right – recent spectrum showing large center peaks from the Pb-208 isotope and also the F=5/2 → F=3/2 Pb-207 peak. Also clearly evident are the F=3/2 → F=1/2 peak (far left) and the small F=3/2 → F=3/2 peak (far right). The direct 406 nm Doppler-broadened absorption dips are shown at the top of the plot.

We had (understandably) assumed that for either pump geometry we would obtain only two peaks in our blue 2nd step spectrum: that of the Pb-208 isotope and that of the Pb-207 transition from the $^3P_2$ (F=5/2) level up to the $(6p7s)^3P_1$ (F=3/2) level. Referring to Fig. 6, we have quite surprisingly seen clear evidence of the additional two hyperfine transitions originating from the $^3P_2$ (F=3/2) level – see dotted blue lines in level diagram and extra peaks at left and right of the experimental spectrum. This must mean that, even with our fast modulation and Doppler-free technique, there are some hyperfine-mixing collisions which do not change velocity (or do so negligibly) which populate the $^3P_2$ (F=3/2) level. The spectrum at the right clearly shows these additional hyperfine transition components! We certainly intend to explore this further by studying the size and lineshape details of these unexpected peaks as a function of Pb vapor density and AOM modulation frequency. At any rate, the two central peaks in the Fig. 6 spectrum already show promising S/N ratio, and by complementing spectra like this with COUNTER propagating pump spectra we are confident of also achieveing sub-MHz TIS values for even-odd isotope pair comparisons. This work is moving forward quickly this summer with postdoc John Lacy and rising sophomore Ben Wien '28 (funded by this NSF grant) and the PI all contributing.

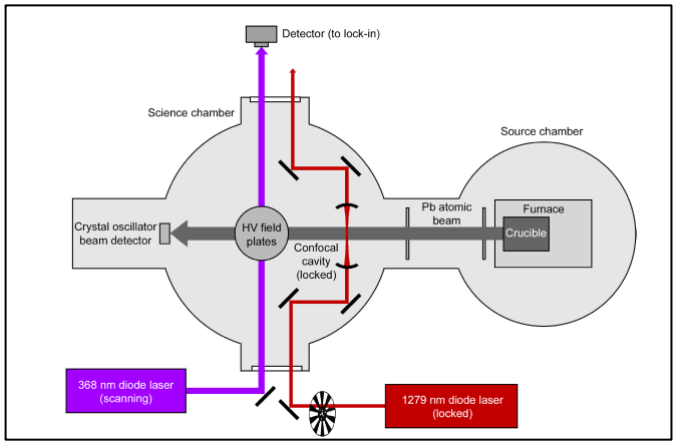
3. Ongoing/Upcoming: Atomic Beam Stark-effect and Laser Cooling experiments in Lead.
[contributions of thesis students: Abdullah Nasir '20 (Ph.D program, Harvard Univ); Gabriel Patenotte '21 (Ph.D. program, Harvard Univ.); Robin Wang '24 (Ph.D. program, Harvard Univ.); for 2025-26: Elena Deegan-Krause '26 and Charlene Peng '26]

As noted, we have extensive group experience in making precision measurements of atomic polarizabilities by measuring Stark shifts in atomic transitions using transverse laser spectroscopy in the presence of precisely-calibrated electric fields. We have now extended prior work in indium and thallium to lead. A lead crucible and effusive atomic beam source has been

built and tested. Using a beam detector that relies on resonant frequency shifts of a quartz crystal upon Pb mass deposition, we have determined that the beam density follows the expected vapor pressure vs. temperature relationship. As suggested in previous annual reports and laid out in detail in the renewal proposal now being considered for future funding, we have a series of planned measurements in lead using this long-standing experimental system in our laboratory. Recent thesis students (listed in red above) have contributed to developing laser and optical systems for this work, as well as experimental design and theoretical modeling of various proposed experiments to measure Stark shifts and Stark-induced amplitudes in our lead atomic beam. Looking ahead, we are also already in preparation to develop a new frequency-doubled laser system, fluorescence detection system, and experimental layout to demonstrate for the first time laser cooling in the lead system. This latter project will bring together apparatus and atomic beam expertise from our group and the laser-cooling expertise (and CW Ti-Sapphire laser) of newly-arrived Assistant Professor Ben Augenbraun (a former Apker-award-winning thesis student in our lab, a highly-successful graduate of the Doyle Cold Molecule lab, and now already engaged in new molecular spectroscopy work at Williams with a number of undergraduates). The PI and Prof. Augenbraun will co-supervise two rising seniors over the next year (Elena Deegan-Krause ’26 and Charlene Peng ’26) who have already begun preparatory work towards our laser cooling project goals this summer (Elena is supported by this soon-to-expire NSF grant).

As a first step that serves both goals (laser cooling, Stark-effect precision measurements to test atomic theory), we are developing a downstream fluorescence detection system using an existing 368 nm UV ECDL system in our lab (used already for the Faraday/transition amplitude work described above). That laser will be directed transversely to the atomic beam, and locked to the excited state $(6p^2)^3P_1 \rightarrow (6p7s)3P_0$ E1 transition which will eventually be the target for laser cooling. This is a ‘Type II’ closed cycling transition originating from a J=1 state. To start we will demonstrate the detectability of the small thermal Boltzmann population residing in this metatstable $^3P_1$ state. With suitable collection optics, a PMT device, and a magnetic field to ‘scramble’ the J=1 substates, we will demonstrate optical cycling (a key feature for enabling laser cooling, obviously). Detecting many photons per metastable atom should make this small population detectible with high precision. Having demonstrated good detectability of this metastable-state population, we would introduce the 1279 nm M1 laser in our lab. While this is a ’weak’ transition, we have already demonstrated that we can substantially enhance the very small thermal population by at least an order of magnitude, so that high-resolution M1 spectroscopy of the ground-state $^3P_0 \rightarrow {}^3P_1$ will yield Doppler-narrowed (~30 MHz wide) M1 resonance not previously seen in an atomic beam environment. It will then be straightforward to add to the M1 interaction region our high-voltage electric field plate system. By adding in large (~20 kV/cm), very-well-calibrated static fields we enhance the strength of the 1279 nm transition by 10-20% via the Stark-induced E1 amplitudes – something that will provide a unique and precise test of *ab initio* lead atomic theory.

We also plan to directly measure the DC polarizability within the 368 nm E1 transition by scanning that laser over the transition in the presence of this DC electric field, and pre-pumping the metastable state via an upstream resonant M1 cavity interaction region. This cavity and the procedure to lock and modulate the M1 laser (facilitating lock-in detection of the E1 signal) represented work by an outstanding recent thesis student, Robin Wang ’24, now in the Ni cold molecule group at Harvard. Fig. 7 shows the idea here. In a recent experiment-theory co-authored paper [13], our theory collaborators calculated this polarizability, and we expect to measure this with sub-1% precision (as we have done in multiple thallium and indium atomic beam experiments over the years).



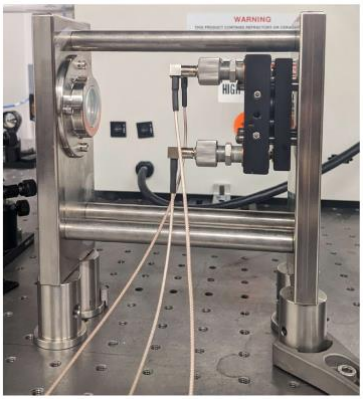


Fig 7: (left) Top-down view of vacuum chamber outline, Pb crucible source, collimators, and both 'pre-pump' IR laser cavity and UV / HV electric field interaction region with chopping wheel and lock-in detection. (right) Custom-designed 10-cm confocal cavity with finesse near 50 (PZT mirror control visible).

Having demonstrated and optimized optical cycling in our fluorescence detection system, we would be ready to introduce a much higher power UV laser light (50-100 mW instead of 5 mW) to undertake the first demonstrate of (transverse) laser cooling in lead. That will require frequency-doubling a CW Ti-Sapphire laser (in the Augenbraun lab presently) tuned to 736 nm and making use of a bowtie enhancement cavity containing a phase-matched crystal (likely LBO) to produce the necessary amount of 368 nm light. Luckily, we believe we can add a new doubling crystal into an existing commercial doubling cavity system (Laser Analytical Systems) purchased many years ago for UV laser production in thallium at the nearby wavelength of 378 nm. Rising thesis student Charlene Peng '26 will focus the first part of her senior year on achieving high-efficiency frequency-doubling for this purpose. With sufficient UV laser capacity, we would then counterpropagate and multipass fiber-launched 368 nm light transverse to the atomic beam. We would start by enhancing the metastable population (as described above) with our M1 pre-pump scheme. Then, with the fluorescence detection system now outfitted with a camera with sufficient resolution to map the transverse distribution of the atomic beam roughly 1 meter downstream, we expect to demonstrate substantial narrowing/cooling of the atomic beam (see Fig. 8). We are excited about the prospects of this work.

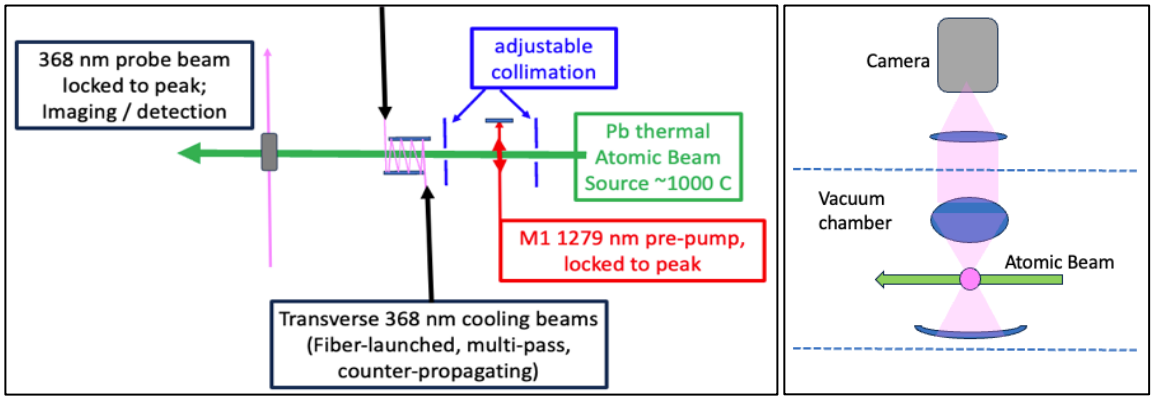


Fig 8: (left) Top-down sketch of transverse laser-cooling scheme including multipass 'pre-pump' to metastable $^3P_1$ state, multipass cooling stage using counter-propagating fiber-launched beams, and imaging and detection region roughly 1 m downstream.
(right) side-on sketch suggesting simple arrangement of collimating and imaging lenses, collection mirror and camera/detector for fluorescence imaging of the atomic beam.

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Papers, talks, conference participation, students supervised during this grant cycle

Published Manuscripts

1. "High-precision measurement and ab initio calculation of the $(6s^2 6p^2)\ ^3P_0 \rightarrow {}^3P_2$ electric-quadrupole-transition amplitude in ^{208}Pb", Daniel L. Maser, Eli Hoenig '17, B.-Y. Wang, '18, P. M. Rupasinghe, S. G. Porsev, M. S. Safronova, and P. K. Majumder, *Phys. Rev.* **A** 100, 052506 (2019).

2. "Broadband High-Precision Faraday Rotation Spectroscopy with Uniaxial Single Crystal CeF_3 Modulator", J. H. Lacy, G. E. Patenotte '21, A. C. Kinney '24, and P. K. Majumder, *Photonics 11, 303 (2024), ISSN 2304-6732, URL https://www.mdpi.com/2304-6732/11/4/304*.

3. "High-precision measurements of electric-dipole-transition amplitudes in excited statesof ^{208}Pb using Faraday rotation spectroscopy", John H. Lacy, Abby C. Kinney '24 , and P. K. Majumder, *Phys. Rev.* **A** 111, 042808 (2025).

Invited talks

"Heavy metal, cheap lasers, and tests of fundamental physics", Amherst College department colloquium, 2/7/20.

"Heavy metal, cheap lasers, and tests of precision measurements of atomic structure", Columbia University, AMO seminar, 3/24/23.

"Heavy metals, lasers, and 'precision' atomic spectroscopy at Williams", Williams College, summer research talk to all students and faculty in the sciences, 6/25/24.

Discussion leader and speaker for Atomic Physics *Gordon Research Conference* "Novel applications of AMO physics", Salve Regina Univ., Newport RI, 6/18/25.

Conference presentations w/students, 2019-2025

1. "High-Precision Measurement of Electric Quadrupole Amplitude in Lead using Faraday Rotation Spectroscopy", Daniel Maser, Eli Hoenig '17, Bingyi Wang '18, and P.K. Majumder. *contributed talk at DAMOP 2019, Milwaukee, WI, June 2019*

2. "Precise Measurements of transition amplitudes, polarizabilities, and isotope shifts in lead, thallium, and tin using Faraday Rotation Spectroscopy", Protik K. Majumder, Daniel Maser, Gabriel Patenotte '21, and Sameer Khanbhai '21. *contributed poster at DAMOP 2019, Milwaukee, WI, June 2019.*

3. "High-Precision Transition Amplitude and Polarizability Measurements in Atomic Lead using Faraday Rotation Spectroscopy", John H. Lacy, Abdullah Nasir '20, Gabriel Patenotte '21, and P.K. Majumder. *contributed poster to DAMOP 2020 (virtual) meeting, June 1-5, 2020.*

4. "High-Precision Measurements of Atomic Lead Transition Amplitudes and Static Polarizabilities", John H. Lacy, Gabriel Patenotte '21, Patrick Postec '21and P.K. Majumder. *contributed poster to DAMOP 2021 (virtual) meeting, June 1-5, 2021.*

5. "Precise transition amplitude and polarizability measurements in ^{208}Pb", John H. Lacy, P.K. Majumder, Gabriel Patenotte '21. *Contributed poster to DAMOP 2022, May 31-June 3, Orlando, FL.*

6. **"**Transition Isotope Shifts (TIS) and Hyperfine Structure (HFS) Measurements in Low-Lying Transitions of Atomic Lead", John H. Lacy, Charlotte Jones '22, and P.K. Majumder. *Contributed poster to DAMOP 2022, May 31-June 3, Orlando, FL.*

7. "High-precision Measurements of Atomic Structure in Pb and other Multi-valence Systems", John H. Lacy, Gabriel Patenotte '21, Abby Kinney '24, Charles Yang '24, and P.K. Majumder. *Contributed poster to ICAP 2022, July 2022, Toronto, CA*.

8. "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, and P.K. Majumder. *Contributed poster to DAMOP 2023, June 5-9, 2023, Spokane, WA.*

9. **"**Precise atomic structure measurements in Pb using vapor-cell and atomic-beam spectroscopy", John Lacy, Robin Wang '24, Abby Kinney '24, Charles Yang '24, and P.K. Majumder. *Contributed poster to DAMOP 2024, June 3-7, 2024, Ft. Worth, TX.*

10. "Precision transition amplitude measurements in Pb-208", John H. Lacy, Abby C. Kinney '24, and P.K. Majumder, *Contributed talk to DAMOP 20224, June 3-7, 2024, Ft. Worth, TX.*

11. "High-precision atomic structure measurements in Pb and other multi-valence atomic systems", P.K. Majumder, J.H. Lacy, Robin Wang '24, and Abby Kinney '24. *Contributed poster to ICAP 2024, July 15-19, 2024, London, U.K.*

12. "Precision isotope shift and hyperfine constant measurements in low-lying lead transitions using Doppler-free, two-color spectroscopy", J.H. Lacy, Carter Anderson '25, and P.K. Majumder, *contributed poster to Atomic Physics Gordon Research Conference*, June 2025, Newport RI.

Undergraduate students supervised during this grant cycle:

Name/class	Research period	**Project**	Post-Graduate Activities
Abdullah Nasir '20	6/19 – 6/20 **(senior thesis)**	Polarimetry and Polarizability measurements in Lead in a new atomic beam apparatus	Physics Ph.D. program **Harvard University**
Gabriel Patenotte '21	9/19 – 6/21 **(RA; senior thesis)**	368 nm laser development; atomic beam development; E1/M1 transition amplitudes	Physics Ph.D. program **Harvard University**
Patrick Postec '21	6/20 – 5/21 (RA; **senior thesis**)	Development of heat pipe oven spectroscopy for Faraday rotation meas of forbidden E2	Materials science Ph.D. program **Duke University**
Declan Smith '21	6/19 – 12/19 (summer, fall RA)	Developing new dual-isotope polarimeter system	Physics Ph.D. program **Boston University**
Duncan McCarthy '21	6/19-8/19 (summer RA)	Development of new laser and optical tools for polarimetry	Physics Ph.D. program **U. British Columbia**
Charlotte Jones '22	9/20 – (acad year RA; **senior thesis**)	Development of new 406 nm laser source; E1/M1 transition linestrengths using polarimetry	Research assistant, Laser development group, MIT/Lincoln Labs
Russell Blakey '23	Summer '21, 22-23 ind. study	Isotope shifts at 939 nm using dual Faraday polarimeter	Seeking research positions Then Ph.D. in physics
Robin Wang '24	6/21 – Summer, starting **senior thesis**	Laser, cavity design and construction for atomic beam polarizability in Pb at 368 nm	Quantum Sci. & Eng. Program **Harvard University**
Abby Kinney '24	9/21 – summer, starting **senior thesis**	UV/IR and Blue/IR transition amplitude measurements using Faraday Rotation Spectroscopy	Physics Ph.D. program **Univ. of Chicago**
Charles Yang '24	Summer, starting **senior thesis**	Blue laser Doppler-free spectroscopy of Pb	Physics Ph.D. program **Rice University**
Carter Anderson '25	Senior Thesis	Two-step Doppler-free isotope shift, HFS spectroscopy	Physics Ph.D. program **U. Toronto**
Saad Waheed '25	Summer 2023, Term-time RA	Atomic beam and Faraday polarimetry projects	Applied Math Ph.D. program **Univ. of Chicago**

Ruby Yager ‘25	Term-Time RA	Optics, electronics, data analysis for polarimetry expts	Physics major
Miles Kodama ‘26	Term-time RA	Doppler-free 406 nm spectroscopy expt	Applying to Ph.D. programs Fall 2025
Gautam Ramaswamy ‘26	Summer 2024 **senior thesis**	406 nm spectroscopy and isotope shift measurements	Applying to Ph.D. programs Fall 2025
Karleigh Bath ‘25	Summer 2024	406 nm spectroscopy; isotope shift measurements	Physics Major (Bryn Mawr College)
Elena Deegan-Krause ‘26	**Senior thesis 2025-26** (Co-supervised)	Pb atomic beam fluorescence detection, Stark-effect spectroscopy	
Charlene Peng ‘26	**Senior thesis 2025-26** (co-supervised)	Frequency-doubled UV laser system and Pb transverse laser cooling	
Ben Wien ‘28	Summer 2025	2-step, 2-color isotope shift and HFS spectroscopy in Pb	