TOWARD TRAPPING LUTETIUM IONS

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Abstract
Highly deformed nuclei like that of $^{175}\mathrm{Lu}$ and $^{176}\mathrm{Lu}$ present a new avenue for the measurement of a nonzero nuclear magnetic quadrupole moment, which would be direct evidence of a CP-violating asymmetry in the laws of nature beyond the Standard Model of particle physics. I discuss some contributions I have made in my laboratory toward taking these measurements.

INTRODUCTION

The imbalance between matter and antimatter observed in the universe runs counter to the predictions of the Standard Model (SM) of particle physics. This suggests a fundamental asymmetry in nature and has inspired extensive exploration of beyond-standard-model (BSM) experiments and theories. As shown by Sakharov (Sakharov 1991), any quantum field theory that seeks to explain this matter-antimatter asymmetry must fulfill two key criteria: time-reversal symmetry (T) must be violated and the universe must evolve out of thermal equilibrium.

According to the CPT theorem, which ensures invariance under the combined operations of charge conjugation (C), parity transformation (P), and time reversal (T), any violation of T-symmetry necessarily implies a violation of CP symmetry, and vice versa. While the SM does incorporate CP violation, it is not sufficient in magnitude to account for the observed matter-antimatter imbalance. BSM models must propose new or modified sources of CP violation that can have detectable consequences at lower energy scales. Key among these are the electric dipole moments (EDMs) and magnetic quadrupole moments (MQMs) of charged particles like electrons and composite systems like nucleons (Pospelov and Ritz 2014; Yamaguchi and Yamanaka 2020; Yamaguchi and Yamanaka 2021; Flambaum, DeMille, and Kozlov 2014). EDMs and MQMs offer a set of observables that complement current searches for BSM particles in modern colliders, with the benefit of being executed on the scale of table-tops and at lower costs than accelerator facilities, while providing mass constraints on BSM particles that are comparable to (and can exceed) the ability of the Large Hadron Collider (Cairncross and Ye 2019).

In recent years, atoms and heavy molecules have emerged as powerful systems for detecting violations of CP symmetry (Sandars 1967). Molecules are particularly useful because their inter-atomic distances offer laboratory access to large effective fields ($> 10\mathrm{GV/cm}$) (Kozyryev and Hutzler 2017) which are otherwise difficult to produce in a laboratory setting. Among these, linear triatomic molecules offer distinct benefits over isoelectronic diatomic species used in current EDM experiments (Andreev et al. 2018; Cairncross, Gresh, et al. 2017), namely that the ℓ-doubling effect gives a small gap between energy levels with opposite parity (Kozyryev and Hutzler 2017), meaning a relatively weak electric field can fully polarize them; this ℓ-doublet can suppress external effects such as that of magnetic fields, meaning experiments on this can be highly sensitive to phenomena that are normally hidden beneath noise. Additionally, these molecules can be laser-cooled (Maison, Skripnikov, Flambaum, and Grau 2020).

The highly deformed nuclei of $^{175}\mathrm{Lu}$ and $^{176}\mathrm{Lu}$ suggest that they will have large nuclear MQMs, making them ideal candidates for table-top measurements; recent calculations suggest the CP-violating energy shift of $^{175}\mathrm{LuOH}^{+}$ and $^{176}\mathrm{LuOH}^{+}$ could be as much as 2 times larger than that of $^{173}\mathrm{YbOH}$ (Maison, Skripnikov, Flambaum, and Grau 2020), which has been a subject of study in other groups (Maison, Skripnikov, and Flambaum 2019). By ionizing the lutetium isotopologues, we can produce a similar electronic structure to that of neutral YbOH while opening them up to confinement via ion trapping techniques; this convenient similarity means we can use techniques already pioneered by other groups to work with a new species that could give greater precision.

In this paper, I will present on some of the steps I have taken towards realizing the goal of trapping lutetium and triatomic molecules of lutetium. I will outline my contributions toward data acquisition and noise reduction of measurements and the design and implementation of specialized equipment in our laboratory.

DATA ACQUISITION

A tabletop atomic experiment fundamentally involves shining light of a specific wavelength on atoms sealed in a closed chamber, which will excite the electrons in the atoms to higher energy levels, and viewing the light that is emitted when the electrons go back down in energy. The number of emissions per unit time is relatively small compared to many external sources of noise, such as light in the room and thermal noise on the CMOS chip that collects the light we are measuring. In order to get good measurements that are distinguishable from noise, we need to reduce the light entering the sensors that does not come from our experiments. I designed two specialized components and a "light-tight box" to prevent light from reaching our sensors. As a demonstration of the impact on the background noise in the system, Fig. 1 shows two images taken under otherwise identical circumstances: one of the images shows the sample chamber without (Fig. 1a) and with (Fig. 1b) one of these modifications. A rudimentary analysis indicates that one of these modifications reduced background counts by a factor of 12.5.

(a)

(b)

Figure 1: a) A (nearly completely blown out) sample image of the background light in our sample chamber without noise-reducing modifications. b) A sample image of the background light in our sample chamber with a modification covering the windows.

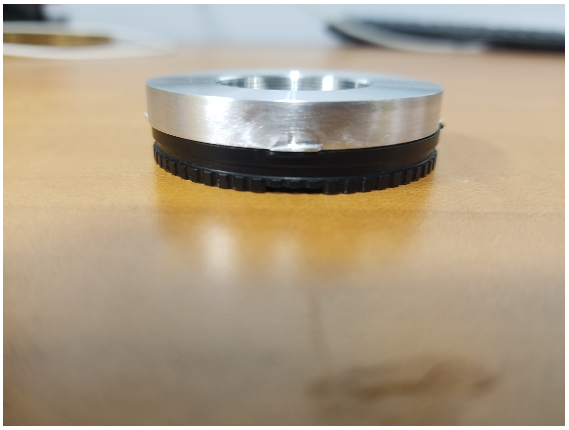


Figure 2: Direct comparison between newly designed window modifiers (silver) and original window covers (black).

Window Baffles

The proposed experiments are set to take place in a Montana Instruments Cryostation model s200, which consists of an octagonal-base cylindrical chamber with $40\mathrm{mm}$ diameter windows on each side and on the lid of the chamber. Six of these side windows will be used to access the lutetium with lasers for the purposes of ionization, cooling, and spin-manipulation. Due to the size of the windows, much exterior light can enter the chamber and reflect off the surfaces, which can be measured by our sensors which are located in a box attached to the top window of the Cryostation. While the manufacturer of the chamber provides window covers that completely cover windows, they do not offer a component that can reduce light entry or allow for the attachment of optical components like lenses, filters, or blocks, so I needed to design and fabricate components that can interface with the windows and a standard commercially available lens tube. As shown in Fig. 2, the piece consists of thick aluminum with wings on the sides to attach to the sample chamber and a tapped hole along the central axis for the attachment of SM1 thread (a common screw type in optical applications).

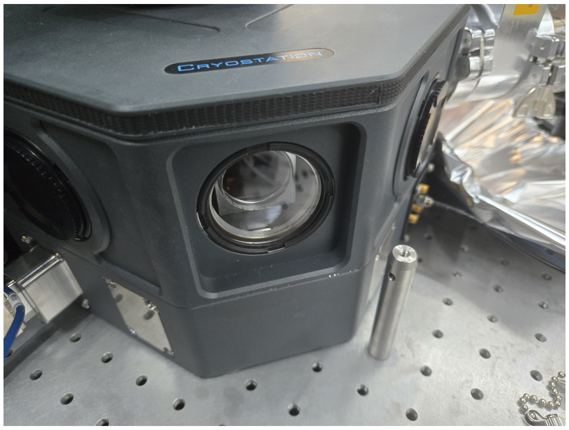
The piece offers modularity in what we can attach to the sample chamber. Our current configurations (see Fig. 3b) see a long lens tube and a nearly-closed iris on the entry and exit windows for a laser path; this offers a secondary benefit in lab work, as it gives us smaller error in laser centering and alignment (i.e. we can send lasers directly through the center of the sample chamber with high reliability and reproducibility).

From the images in Fig. 3, we can see clearly that light could enter the uncovered windows (Fig. 3a) from a wide cone of vision, while the baffled windows (Fig. 3b) drastically reduce the size of the angle of light that can enter the system.

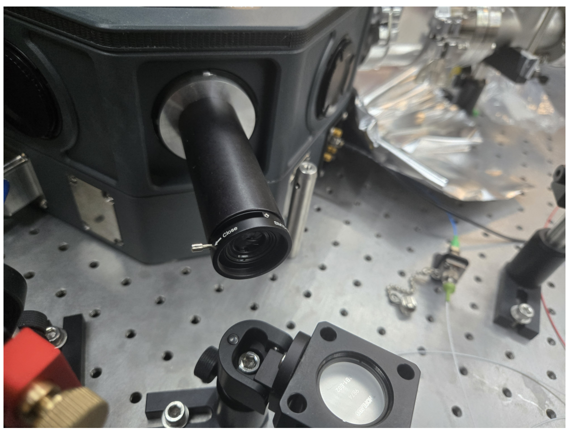
Sensor Box

The sensors we plan to use for measurements sit in a box consisting of an extruded aluminum frame and expanded PVC walls, with a $60\mathrm{mm} \times 60\mathrm{mm}$ square hole on one side aimed at a periscopic mirror which would have sat freely above the lid window of the sample chamber (it no longer sits freely, as will be explained in the next section). The hole in the sensor box was partially covered by placing a rail system through the hole, adorned with blackout fabric (see Fig. 4). Because the sensor box, periscopic mirror, and chamber lid were uncoupled, we found it difficult to reconfigure the imaging system following regular maintenance; the lack of coupling at the box also allowed light to enter the system through the edges of the entrance hole if we did not use several layers of blackout tape, which needed to be replaced after maintenance.

To both improve on ease of replacement and reduce light pollution, I replaced the extruded PVC side with an aluminum sheet with a $2\mathrm{in}$ diameter hole which allows for the placement of a $2\mathrm{in}$ lens tube that can directly attach to the periscopic mirror. This reduces light pollution through the tighter tolerance in the hole and physically links the mirror to the imaging box,



(a)



(b)

Figure 3: a) An uncovered window on the sample chamber. b) A window with modified cover, lens tube, and iris attached. This modification allows laser access while still protecting the chamber from most exterior light.

making optical realignment simpler following maintenance.

Chamber-Camera Coupling Device

Approximately 14% of the light that scatters off the atoms in our chamber will be collected and collimated by an aspherical lens and reflected off a periscopic mirror to be sent into the sensor box for measurement. Originally, the periscopic mirror sat freely on top of the lid of the sample chamber, which opened the imaging system up to misalignment under perturbations; additionally, the mirror sat a small distance above the lid with only a layer of blackout fabric between it and exterior sources of light, which was not completely sufficient to prevent noise from obscuring our small signal. To fix both of these issues simultaneously, I designed another component to fit onto the sample chamber that can couple to the periscopic apparatus. This coupler (see Fig. 5) connects to the sample chamber in the same manner as the modified window covers outlined above and features a $42\mathrm{mm}$ central hole to maximize light collection; the outer diameter is $2.2\mathrm{in}$ to allow for interfacing with a commercially available coupling sleeve, which allows for the periscopic mirror to be reliably and securely aligned with the lid of the sample chamber while permitting rotational freedom. This rotational freedom permits us to use the device in future projects with altered arrangements of our devices. The rotational freedom is constrained at the sensor box, as outlined in the section above.

Figure 4: A periscopic mirror sits above the lid window of the sample chamber, sending light into the sensor box.

EQUIPMENT

Ion trapping requires direct control over six primary electrodes and can use as many as six secondary electrodes to produce confining electric

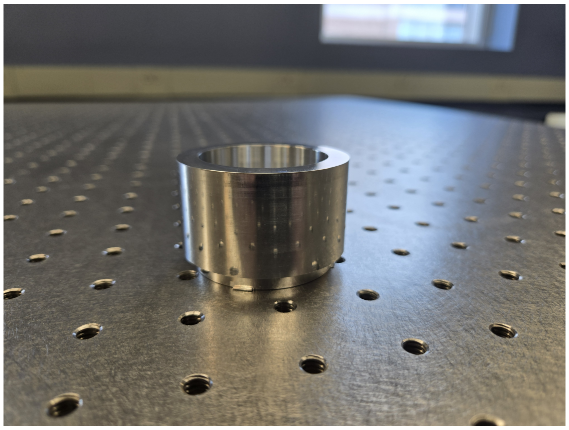


Figure 5: The coupling device fits onto the sample chamber at the bottom and has a $2.2\mathrm{in}$ outer diameter made to match with a $2\mathrm{in}$ lens tube, allowing for coupling via a coupling sleeve. This design allows semi-rigid connection while maintaining rotational freedom, permitting the design and layout of the experiment to change in future projects.

fields. I designed two circuit boards to aid in simplifying circuit connections.

The first board consists of four sets of four BNC connectors (sharing ground) terminating to four 5-pinouts (see Fig. 6) that can directly interface with the exterior of the sample chamber. On each BNC port is a $10\mathrm{kHz}$ first-order low-pass RC filter that attenuates higher-frequency noise. The board connects a digital-to-analog converter through the sample chamber to two of the primary electrodes and all of the secondary electrodes and gives us the freedom to place other circuits in the chamber if they become necessary in future projects.

The second board connects a radio-frequency (rf) alternating signal to the remaining four primary electrodes. Due to noise considerations, much of the cabling that carries the rf signal must be housed in coaxial cables, and any solid-core wiring must be minimized, so this board is an uncoated Rogers board that can be placed in a vacuum chamber without depositing debris and oils into the environment and can sit directly beneath the ion trap (see Fig. 7).

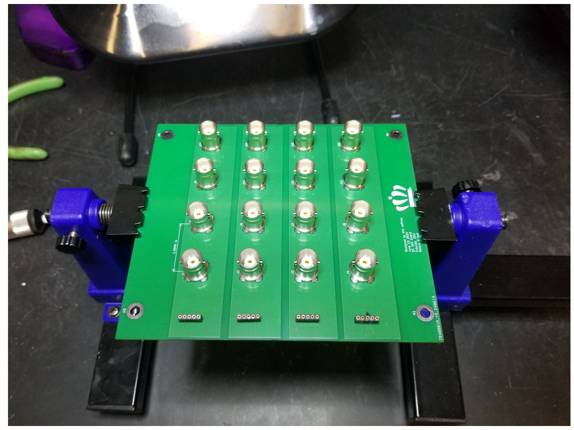


Figure 6: Four-by-four BNC array board for connecting DC and low-frequency AC signals to the interior of the sample chamber.

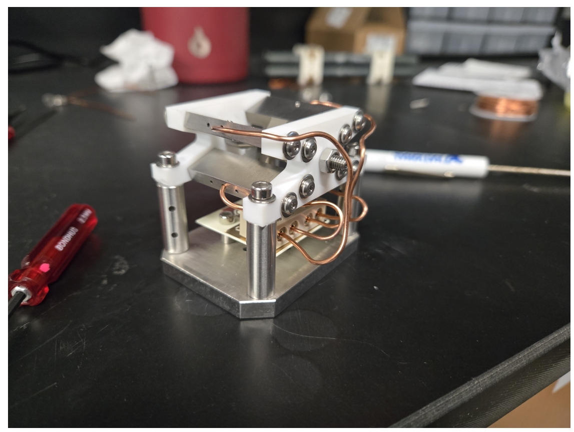


Figure 7: Sample configuration of ion trap connected to the rf-board seated beneath.

SUMMARY

I have given an outline of some of the work I was able to perform in the pursuit of trapping lutetium and triatomic molecules of lutetium. I aim to further develop tools and equipment in our laboratory to aid in our goals. With these tools and improvements, I will perform experiments on Ba^{+} that will aid in the development of quantum information techniques that will be implemented on ionized lutetium and triatomic lutetium molecules to make high-precision measurements for a nonzero nuclear MQM, with expected results on an order comparable to contemporary experiments at groups such as JILA.

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