Building a Moving LED Device for Calibrating the NuLat Detector

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The Neutrino Lattice Experiment (NuLat) is a neutrino detector consisting of 125 plastic scintillating cubes arranged in $5 \times 5 \times 5$ lattice. NuLat uses photomultiplier tubes (PMTs), currently on three sides of the detector, to amplify signals from positron annihilation and neutron capture resulting from inverse beta decay, which are transmitted through the detector by a total internal reflection process. These signals can then be read and measured using the detector's data acquisition system and analyzed. This summer, we designed, assembled, and began testing an apparatus that will be used to calibrate the detector by sending a short signal from an LED into each cube on the faces of the detector without PMTs. The light from the LED will be transmitted through the detector and then caught and amplified by the PMTs on the faces of the detector directly across from and orthogonal to the face where we sent the signal. The device, which consists of three linear actuators run by stepper motors, is designed to be able to move an LED in two dimensions to the center of each cube on one face of the detector at a time. The stepper motors are controlled by Adafruit Stepper Motor HAT drivers on a Raspberry Pi computer and programmed using the CircuitPython programming language. Since the apparatus will be able to send an identical signal into each cube, it will ultimately allow for the calibration of the gains of the PMTs.

I. INTRODUCTION

In the Standard Model of particle physics, the neutrino is required to be a massless particle with three different flavor eigenstates, which are the electron neutrino, tau neutrino, and muon neutrino, named for how they are generated. However, recent experiments, reveal the phenomenon of neutrino oscillation, where neutrinos' flavor eigenstates change over the course of its travel. The theory for neutrino oscillation is that the flavor eigenstate is a linear combination of mass eigenstates, which are states of definite mass, that change phase during travel, resulting in the detection of a flavor eigenstate not originally present. Therefore, neutrino oscillation shows reveals that the neutrino is, in fact, a massive particle. Further investigation has led to theory of a flavorless "sterile" neutrino, called so because they do not participate in the weak force like the neutrinos currently allowed by the Standard Model[1].

The Neutrino Lattice Experiment (NuLat) is a neutrino detector consisting of 125 plastic scintillating cubes arranged in a $5 \times 5 \times 5$ geometry based on the concept of a Raghavan Optical Lattice (ROL), which utilizes total internal reflection in a material with a certain index of refraction to direct light along a certain path, allowing for geometric reconstructions of reactions within the detector[2]. The main purposes for the NuLat detector include detecting electron antineutrinos from nuclear reactors and searching for the aforementioned possible "sterile" neutrinos, making use of a specific nuclear reaction called inverse beta decay. The signals from inverse beta decay are amplified using photomultiplier tubes (PMTs), and measured with the detector's data acquisition system[1].

Before actual data can be taken, the detector must be calibrated so that the signal received from each PMT is consistent. This can be accomplished by sending an identical signal into the center of each of the cubes on the three faces of the detector without PMTs, so the light can propagate through the detector to the PMTs directly across from and orthogonal to the cube where the signal was sent. To do that, we designed, assembled, and began testing a device that can move an LED with a known wavelength in an x-y plane to the center of each cube and pulse the LED on a short timescale to mimic a scintillation event.

II. INVERSE BETA DECAY

The inverse beta decay reaction utilized in the NuLat detector is given by

$$\overline{\nu} + p^+ \rightarrow n + e^+ \tag{1}$$

where an antineutrino, with an energy of at least 1.8 MeV to account for the difference in rest mass energy between a proton and a neutron, is captured by a proton, resulting in a neutron and a positron[3]. This causes time coincident events, signals with a known delay time between them, of positron energy deposition and annihilation followed by neutron capture. The positron, which carries most of the energy from the reaction and can therefore be detected directly, quickly annihilates with an electron, which releases 2 γ-rays that each have a known energy of 0.511 MeV due to the rest mass of an electron, 0.511 MeV/c^2, and conservation of momentum. The neutron travels and slows down for a certain distance and time before capture. The NuLat detector uses Lithium-6 for neutron capture due to its large neutron cross-section and clear signature of decay products, meaning that different types of decay events, such as beta- and gamma-type events, are easily distinguishable using pulse discrimination. This neutron capture on ^6Li results in a reaction,

$$^6Li + n \rightarrow ^7 Li \rightarrow \alpha + ^3 H + 4.8 \text{ MeV}, \quad (2)$$

where ^6Li enters an excited state to become the unstable ^7Li before decaying into an alpha particle and Tritium and releasing 4.8 MeV of energy. Therefore, the signature of an antineutrino detected using NuLat is the energy deposition from the positron, then the 0.511 MeV γ-rays released by positron annihilation followed by the 4.8 MeV released by neutron capture on ^6Li[1].

III. THE NULAT DETECTOR

As previously stated, light is directed through the NuLat detector by total internal reflection due to its ROL design. When a beam of light crosses a boundary between two materials with different indices of refraction, it will bend toward or away from the normal depending on these values. If light crosses a boundary at an angle greater than a certain angle known as the critical angle, it will undergo total internal reflection, meaning that the is light is completely reflected at the boundary. The critical angle is given by Snell's law,

$$\theta_c = \sin^{-1}(\frac{n_2}{n_1}), \quad (3)$$

where n_1 is index of refraction of the material the light is original material the light is traveling through, and n_2 is the index of refraction of the material at the boundary[2]. NuLat makes use of plastic cubes with an index of refraction $n = 1.52$ that are separated by air, which has an index of refraction of approximately 1.00[1]. This forces light to only have the ability to travel in certain directions through the detector, as the light will reflect off of boundaries where the angle of incidence is greater than the critical angle but propagate through boundaries where the angle of incidence is less than the critical angle. Because of this total internal reflection process, it is possible to geometrically analyze events within the detector[2].

After NuLat receives a signal which then travels through the detector, the signal is caught and amplified by photomultiplier tubes, of which there are currently 75, one for each outward-facing surface on each cube on three faces of the detector. The exterior of the detector showing the faces of the detector with the PMTs installed is shown in figure 1. Photomultiplier tubes are vacuum tubes with a photocathode, multiple dynodes, and an anode that amplify signals of electromagnetic radiation. When incident photons hit the photocathode, a small number of electrons are released due to the photoelectric effect, which are then multiplied by a series of electrodes which known as dynodes. When the photoelectrons strike a dynode, more electrons are released, creating a chain where more and more electrons are released at each dynode, resulting in amplification of the original signal that depends on the set voltage of the dynodes[4]. NuLat uses Hamamatsu 10533 PMTs, which have 10 dynode stages[5]. By sending an identical signal into each cube on the three faces of the detector without PMTs, the gains of PMTs can be calibrated. The light from the signal will be sent to the PMTs across from and orthogonal to the cube were we sent the signal, allowing us to measure the strength of the signal from each PMT using the data acquisition system so that we can see what voltage the PMTs should be set at for a consistent signal.

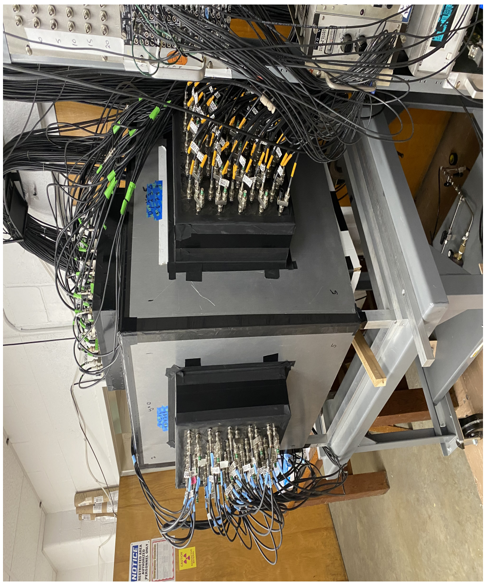

FIG. 1: Exterior of the NuLat detector. The scintillating cube lattice is inside, and PMTs are currently installed on the three faces of the detector visible in this image. The other three sides are currently empty.

IV. MOVING LED CALIBRATION APPARATUS

The basic design of the device that will be used to calibrated the NuLat detector consists of a fast LED that can mimic a scintillation event mounted on three linear actuators run by stepper motors, as seen in figure 3, to allow for travel in two dimensions. Two of the linear actuators are parallel to each other, for travel in the x-direction, and a third is mounted in between them for travel in the y-direction. In our design, we used FUYU FSL30 linear actuators with 300 mm of total travel distance that are run by NEMA 11 stepper motors powered with a 5 V power supply. A 300 mm length was chosen to ensure that the LED would be able to reach the center of each 2.5 inch (63.5 mm) cube[1] on one face of the detector without needing to move the entire apparatus. One of the faces of the detector that the device will be mounted on is shown in figure 2. Stepper motors allow for a high degree of accuracy when traveling; on our chosen linear actuators, 1 mm of travel is equivalent to about 100 steps of the stepper motor, giving a total of about 30000 steps for a travel car to run its full distance. The stepper motors are controlled by two Adafruit DC and Stepper Motor HAT drivers[6] stacked on a 3B+ Raspberry Pi computer[7], as seen in figure 4. Each driver has the ability to control two stepper motors, so the two motors that run in the x-direction are controlled by one of the drivers and the one motor that runs in the y-direction is controlled by the other.

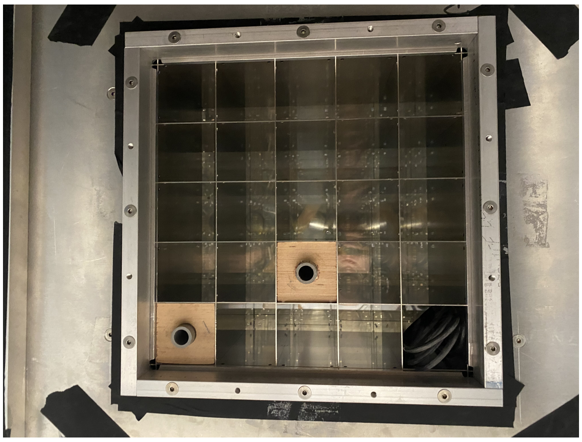

FIG. 2: Interior of the NuLat detector, as viewed from the bottom face of the detector. This is one of the faces where the calibration device will be used. Two of the cubes have light collimators directed into them.

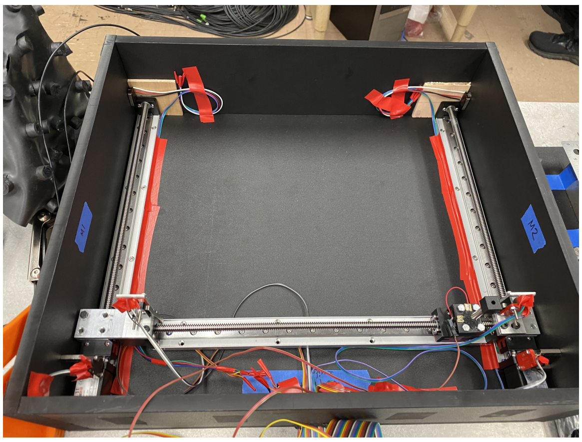

FIG. 3: The moving LED device, designed to move an LED in two dimensions. The linear actuator for moving in the y-direction is mounted between two parallel linear actuators for moving in the x-direction. Limit switches are installed on all ends of travel. The whole apparatus is inside of a light-tight box. In this image, the x-direction is in near its full travel position and the y-direction is near its zero position.

All code for programming the stepper motors is written in the CircuitPython programming language, which

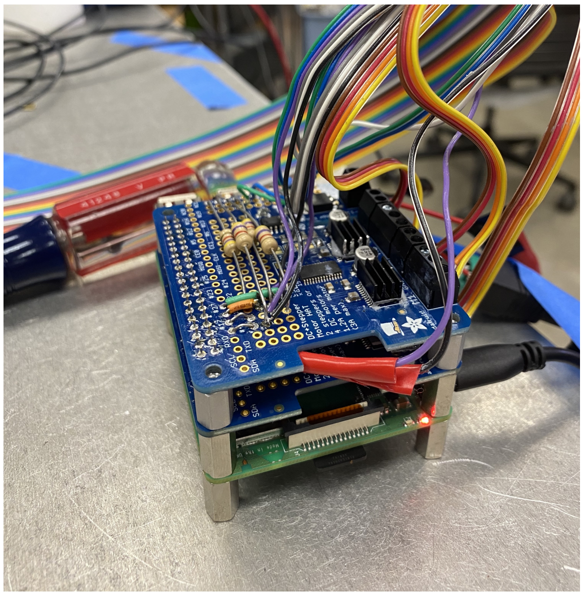

FIG. 4: The Raspberry Pi computer with two Adafruit Stepper Motor HATs stacked to control the stepper motors. The pull-down resistors visible on the top board are for operating the limit switches.

is based on the high-level programming language Python and designed for use with microcontroller boards, such as the Adafruit drivers used in our setup[?] . For controlling our stepper motors, we downloaded the Adafruit CircuitPython MotorKit library, which contains the appropriate features for operation of our apparatus[9], and enabled I2C (Inter-Integrated Circuit) support on the Raspberry Pi so that the driver HATs can communicate with the computer. Using the MotorKit library, we can choose whether to run the travel car “forward,” away from the motor, or “backward,” toward the motor, as well as choose the style of steps, from single steps, double steps, or interleaved steps. Single steps power one coil of the stepper motor at a time, double steps power two coils to create more torque, and interleaved steps are a combination of single and double stepping, making the motor appear to have twice as many steps. We chose to use double steps as the default for our apparatus, as double steps provided smoother and more accurate travel than single steps, and were much faster than interleaved steps with a negligible difference in accuracy between the two.

To prevent the motors from stalling when travel cars reach the ends of their travel, limit switches are installed on both ends of the linear actuators that are programmed to stop the stepper motors if they are activated. The switches are wired so a voltage can be read across the switch when it is triggered by one of the travel cars, so the code is written such that when this voltage is read, the motors will release and not move any further in the direction they were moving in. In our setup, the ends of the linear actuators with bearings are the “zero” position of the travel cars, where x = 0 and y = 0, and the end with the motors attached are where the cars are at full travel. To place a car in its "zero" position, a program is written to run the motor until the car activates the limit switch at the end of its travel, then pause and run the motor in the opposite direction for a given number of steps until the switch is no longer activated. The limit switches are controlled from general purpose input-output (GPIO) pins on the Raspberry Pi.

The detector will be calibrated with a LED that will be mounted on the travel car running in the y-direction, which will be powered using a pulse generator so that the LED can pulse on the order of nanoseconds, which is much faster than is possible with the Raspberry Pi, to mimic a scintillation event. The LED will be at the base of a tube with a small aperture, shown in figure 5, to collimate the light so that it is focused when sent into the center of a cube. Tests will be run with an LED with a wavelength of 430 nm, which is in the blue range of visible light, as this will attain a high spectral response from the PMTs[5]. A UV-range LED may also be used for tests and calibration in order to scintillate the cubes; however, the acrylic box that the scintillating cube lattice is inside of in the detector blocks most UV light, so there won't be as much of a signal to detect.

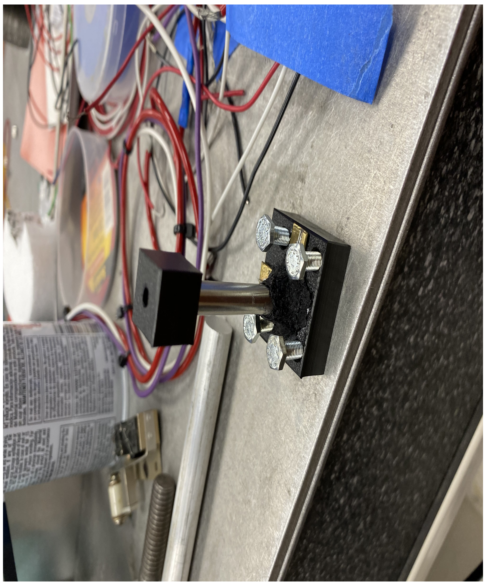

FIG. 5: A close-up image of the light collimator that is be mounted onto the y-direction travel car. The collimator will focus the light from the LED at its base into the center of the cubes.

The whole apparatus is inside of a light-tight box to prevent any light leakage from sources other than the LED from reaching the inside of the detector and causing background to show up in measurements from the PMTs. The box has an open face so that it can be mounted on an available face of the detector, and a hole for the ribbon cable to be pulled through so that the Raspberry Pi can be detached as a precaution when moving the apparatus, and so the Raspberry Pi can be operated separate from the apparatus.

V. CONCLUSIONS AND NEXT STEPS

Currently, the device is fully assembled and operational, so we have the ability to program the stepper motors to run the linear actuators to any x-y position of our choosing. We are also able to "zero" the cars to either side of its total available travel length by using the limit switches. However, before it can be used for calibrating the detector, it will next be necessary to run some preliminary tests to ensure that it will be able to accurately calibrate the detector. One such test includes situating a single PMT in the center of the apparatus while it is covered to prevent light leakage and lying flat on the table, as in figure 6, so that we can scan the LED across the PMT to test its responsiveness when the LED is positioned in multiple x-y locations with respect to the photocathode. This test can then be repeated with plastic scintillating cubes, like the cubes used in the NuLat detector, stacked between the LED and the PMT so that we can figure out how much light from the LED signal is lost after traveling through multiple cubes as it will be within the the detector.

FIG. 6: An image of the setup for preliminary tests that we can run with the moving LED device before using it to calibrate the detector. The PMT and the device are inside of a light-tight box to prevent light leakage, and the PMT is positioned in the center of the apparatus. This allows us to scan the LED across the photocathode of the PMT and find its responsiveness at multiple x-y locations.

In designing and assembling the calibration device, we had to take many details of the NuLat detector into account along with making sure to consider ease of operation and accuracy of positioning. Once the device is fully tested and ready for use with the NuLat detector, it will be useful in calibrating the gains of the PMTs due to its ability to send an identical signal into each cube. First, the device will be mounted onto one face of the detector without PMTs installed. Next, the motors will be zeroed in both the x-direction and y-direction so that we know that starting location of the LED. Then, the LED will be moved to the center of each of the 25 cubes on the one face of the detector pulse an identical signal that mimics a scintillation event. Each signal will propagate through the detector using the total internal reflection process so that it will be caught and amplified by the PMTs directly across from and orthogonal to the the cube where the signal was sent. We can then use the detector's data acquisition system to read the strength of the signals from each PMT. This will have to be repeated on all three faces of the detector without PMTs, which will allow us to set the voltages for the gains of the PMTs so that we will be able to get a consistent signal from each. At this time, further testing is required before the device can confidently be used as a way to calibrate the detector before taking data.

VI. ACKNOWLEDGMENTS

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