Designing a Narrow Field of View, Low-Energy Gamma Ray Observatory

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Abstract

The goal of our project was to determine if it was possible to create a narrow field-of-view observatory for detecting cosmic gamma rays primarily in the regime between 10,000 KeV and one MeV, then build a functioning prototype. Cost, size, and complexity were major factors that we aimed to minimize in our designs. Candidate designs were also required to be able to be trained towards individual point-sources of celestial gamma rays, such as active galactic nuclei (AGNs), and collect data on the intensity of gamma radiation coming from the target, as well as the energy of individual gamma rays. Multiple designs were considered, and once one was selected, construction of a prototype began. Said prototype is mostly completed, and testing is currently underway.

I. Introduction

Just like visible light, gamma rays are a form of electromagnetic radiation. They have the highest energies and frequencies and shortest wavelengths of any form of EM radiation (Stark). Unlike visible light, gamma rays cannot be seen or detected without specialized equipment. Unfortunately, cosmic gamma rays are unable to fully penetrate Earth's atmosphere, being stopped around 10 kilometers above sea level (Fig. 1). Direct gamma ray astronomy must therefore be conducted from orbit, though indirect observation of cosmic gamma rays can be conducted by ground-based Cherenkov-effect observatories.

Indirect observation of celestial gamma rays is achieved using the Cherenkov effect. When a cosmic gamma ray enters Earth's atmosphere, it will inevitably hit an atom. This interaction can lead to the creation of subatomic particles, which produce a faint glow as they move through a material such as air or water that has a lower speed of light than the speed of the particle. This glow can be observed using large focusing mirrors (Fig. 2) or underground water tanks (Richmond). This kind of setup can scan large swathes of the sky at once and is more likely to detect high energy particles. However, it has large space requirements, cannot perform direct gamma ray astronomy, and can be subject to weather and light pollution issues, depending on location and setup.

Direct observation of celestial gamma rays is primarily done from high altitude platforms, usually an orbiting satellite (Fig. 3). These typically use arrays of scintillators and/or pair-production imagers (Dooling) to conduct direct gamma ray astronomy across all energies. However, satellites and launch infrastructure both have huge costs associated with them and are usually slow to design and build.

II. Problem and Goals

Our project was designed to address the fact that most, if not all, installations/equipment designed to observe the sky in gamma wavelengths, such as the Fermi Gamma-Ray Space Telescope (Kavli) have wide fields of view and focus solely on higher-energy gamma rays. We wished to address this by focusing on the lower end of the gamma ray spectrum, specifically the 10,000 KeV to 1 MeV range. This is a regime in which the sky is not being as actively studied and mapped as the 100+ MeV gamma spectrum. Though our observatory may have ancillary capabilities, such as detecting higher-energy gamma rays, x-rays, and particles such as muons, our primary goal remains targeting this overlooked area of gamma ray astronomy. Our observatory was also designed around the concept of a narrow field of view, giving it the capability to target and observe a single point-source of gamma radiation.

III. Preliminary Research

Before setting out to design and build our observatory, we had to ascertain whether celestial gamma rays were observable from ground level. It was rather quickly discovered that only indirect observation was possible from ground level, as celestial gamma rays are all but stopped before penetrating below 10 kilometers above sea level (L3Harris Geospatial). A decision then needed to be made on whether to build a direct or indirect observatory, and research turned towards figuring out how each worked and their pros and cons. As an indirect Cherenkov effect observatory would be expensive, take up space we did not have, and be subject to severe light pollution due to our proximity to Manhattan, we chose to go for a direct observatory. The downside to this is that any testing would have to be accomplished by lofting it to a proper altitude or carried out on the ground using radioactive sources.

IV. Evaluating Materials

Having made our decision to design a direct observatory, focus shifted towards figuring out how gamma rays could be detected, and which method would be used. We eventually settled on using some sort of scintillator, which is a material that produces light whenever radiation passes through it, as we had preexisting equipment and experience with using them. We considered many different types of scintillating crystals and plastics; unfortunately, none were found that were sensitive only to gamma rays. However, one of the plastics considered, BC-408, was highly sensitive to almost all forms of radiation, with gamma rays being the exception (Fig. 4). Additionally, one of the other materials being considered, thallium-doped sodium iodide crystals, heretofore referred to as NaI(Tl), had excellent gamma ray sensitivity (Fig. 5). NaI(Tl) also had many other desirable features, including low background radioactivity from trace contaminants, excellent signal response to 1 MeV and lower gamma rays, and signal strengths proportional to the energy of detected gamma ray photons. It also featured good resistance to radiation damage, which would be an asset in the high-radiation environment of space. It was decided to use NaI(Tl) to detect gamma rays and use a secondary BC-408 scintillator to veto detections not caused by gamma rays.

V. Considerations & Candidate Designs

A gamma observatory with a narrow field of view was one of the major stated goals of our project and became the main design focus after we had selected our detection materials. Gamma rays cannot be easily refracted, unlike normal light, as they have extremely good penetration capabilities through most materials and would prefer to punch through rather than be refracted. Therefore, we could not use conventional optics, and several options were considered. The first was an experimental gamma ray lens made from high density, high Z-number elements which would have a better chance of refracting gamma rays rather than letting them punch through (Fig. 6). However, suitable materials were often expensive and/or difficult to work with. Another option considered was an experimental multi-material layered refractor (Fig. 7) proposed in a paper by several Los Alamos researchers that would use thin alternating layers of high- and low-density materials to concentrate gamma rays (Shirazi et al., 2020). However, we did not have the ability to produce such a complicated design with the time and resources at our disposal. Therefore, we went with the third option under consideration, which was well within our means and used multiple stacked lead sheets with holes drilled through them and an enclosed, shielded housing to create a gamma ray “pinhole camera.” Having made this decision, design work began, of which several candidate designs are seen in Figures 8-12.

VI. Prototype Construction

As time was in short supply due to my schedule in the laboratory, we did not wait for all of the materials to arrive before beginning work. Construction of the prototype began as soon as a final design was selected, using materials and resources that were already available in the lab. Some structural brackets were fabricated using 3d modeling software and a 3D printer, and more equipment was obtained by recycling parts from old/damaged equipment, discontinued/failed experiments, and equipment in storage. At the same time, the following new equipment was being ordered:

- 2” NaI(Tl) crystal.
- Lead sheeting.
- Arduino Mega 2560, to be used as part of a data acquisition board.
- Electrical trough, to be shielded and used as the detector housing.
- Various electrical components needed for creating a data acquisition board.
- GPS and rotation tracking components, to be used in tracking the detector’s position and orientation.

Both scintillation detectors were assembled in the same way. The scintillators were cleaned and polished, if necessary, and then mated to the lens of a photomultiplier tube using an optically clear, soft silicone “cookie” to obtain a nearly seamless transition. The location where the scintillator was mated was then wrapped in reflective white tape, followed by the whole assembly being double wrapped in black EMF-blocking wrapping and black electrical tape to make the whole assembly light-tight. This ensured that the photomultiplier tube would see only the faint pulses coming from the scintillator, not external light sources. This process is shown in Figure 13.

VII. Initial Testing and Further Construction

Once assembled, both the NaI(Tl) and BC-408 detectors were individually powered up and tested with radioactive sources once installed into the housing to confirm their operation (Fig. 14). Work is currently focused on constructing the lead sheeting to go around the housing and the lead pinhole panels necessary for restricting observatory FoV and screening out background radiation. Work has just started as of this writing on calibrating the sensitivity of both detectors against natural background radiation levels and exposure to the radioactive sources at different levels and distances. Additionally, the data acquisition board PCB has been designed, ordered, and is currently on route to the lab for final assembly and usage. The design being used was intended for another project but is suitable for this project with only minimal modifications.

VIII. Current Results

So far, our observatory has excellent gamma ray detection capabilities. Directional capabilities exist but are less certain, as initial testing has revealed a potential need for thicker lead shielding or some different way of achieving a narrow field of view. Originally, we thought we were experiencing issues with low energy gamma rays being unable to propagate very far through the atmosphere to the point where a vacuum chamber might have been necessary; however, further tuning of both detectors suggests this is not the case. Instead, a different issue has cropped up with the detector perhaps being too sensitive, making detection of a radioactive source at distance hard to distinguish from normal background radiation levels. Hopefully, the planned future installation of lead shielding around the detector housing will mitigate this issue.

A full results page will not be available until construction is further along, any necessary modifications made, and more testing and calibration has been conducted with the completed prototype.

IX. Limitations Encountered

Although we can test the detector using radioactive sources, celestial gamma rays do not reach ground meaning we cannot yet test our prototype using them. During testing of sources, it was found that the distance falloff of radiation due to the inverse square law makes detecting sources at distance hard to distinguish from background radiation levels. Additionally, we are currently testing the detector with very old NIM crate electronics, which are touchy and occasionally prone to failure. Additionally, the prototype currently works off of an external power source, and we will need to find a way to make it self-sufficient if we want to loft it up to a proper testing altitude via, for example, a weather balloon.

During the materials acquisition process, we had several issues surrounding the acquisition of the NaI(Tl) crystal, mostly due to minimum purchase order thresholds that were not conveyed to us by the original supplier until payment was about to be made and the crystal shipped. Costs were an issue too, as the crystal was expensive for our budget. Additionally, we had attempted to order a Raspberry Pi miniature computer to control the data acquisition board, but chip shortages meant none were in stock through any supplier. We did eventually find one in storage, though.

We have since identified a design oversight; the current BC-408 veto setup only works in line with the device's field of view. We will eventually need to redesign the veto setup to cover 360 degrees to block muons, which are not stopped by any practical amount of lead shielding. As for the lead sheeting, it is toxic and requires special care to be worked safely, may not be thick enough as-is.

X. Future Work

Future work mainly consists of calibrating our current design and completing the lead shielding to go around the detector housing, as well as building and transitioning testing to the data acquisition board and other associated electronics. Further into the future, we have identified several potential design modifications that we would like to make, such as the previously mentioned redesign of the BC-408 veto or obtaining and nesting the NaI(Tl) crystals in such a way so as to obtain a narrow field of view without needing as much lead shielding. We would also like to revisit other, more complicated design options, such as the experimental gamma ray concentrator or gamma lenses.

XI. Conclusion

Although our current design is flawed and still needs more calibration and adjustment, it is possible to design and build a relatively small, narrow-FoV gamma ray observatory on a relatively modest budget. However, lead is probably not the best way to shield against background radiation and restrict FoV on such an observatory, as it is quite heavy and very toxic, and a large amount is needed for the pinhole to be truly effective based on initial testing. We have determined that our design can be scaled down even further, potentially to sizes that could be easily carried to altitude without needing a dedicated satellite or flight platform; however, more advanced designs will require much more time, money, and more advanced equipment than is currently available to us.

XII. References

Dooling, D. (2019, February 21). Fermi Gamma-ray Space Telescope. Encyclopedia Britannica. https://www.britannica.com/topic/Fermi-Gamma-ray-Space-Telescope

Habs, D., Günther, M. M., Jentschel, M., & Urban, W. (2012, May 1). *Refractive index of silicon at y-ray energies*. Physical Review Letters. Retrieved April 9, 2023, from https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.184802

Kavli Foundation | Stanford University. (n.d.). *Fermi gamma-ray space telescope*. Kavli Institute for Particle Astrophysics and Cosmology (KIPAC). https://kipac.stanford.edu/research/projects/fermi-gamma-ray-space-telescope

L3Harris Geospatial. (2014, August 25). *Atmospheric windows and optical sensors*. L3Harris Geospatial. Retrieved April 3, 2023, from https://www.l3harrisgeospatial.com/Support/Maintenance-Detail/ArtMID/13350/ArticleID/17333/Atmospheric-Windows-and-Optical-Sensors

Luxium Solutions. (2021). *Efficiency Calculations for Selected Scintillators*. Luxium Solutions. Retrieved April 9, 2023, from https://www.crystals.saint-gobain.com/sites/hps-mac3-cma-crystals/files/2021-09/Efficiency-Calculations-Brochure.pdf

Richmond, M. (n.d.). *Highest-energy gamma rays: ground based telescopes, sources*. Highest-energy gamma rays: Ground based telescopes, sources. Retrieved April 3, 2023, from http://spiff.rit.edu/classes/ast613/lectures/gamma_high/gamma_high.html

Shirazi, Farzane, Bloser, Peter Forbes, Legere, Jason S., & McConnell, Mark L. *Performance simulation of the soft gamma-ray concentrator.* United States. https://doi.org/10.1117/1.jatis.6.2.024001

Stark, G. (2021, October 22). *gamma ray*. *Encyclopedia Brittanica.* https://www.britannica.com/science/gamma-ray

VERITAS. (n.d.). *VERITAS (Very Energetic Radiation Imaging Telescope Array System)*. VERITAS. Retrieved April 3, 2023, from https://veritas.sao.arizona.edu/

XIII. Figures

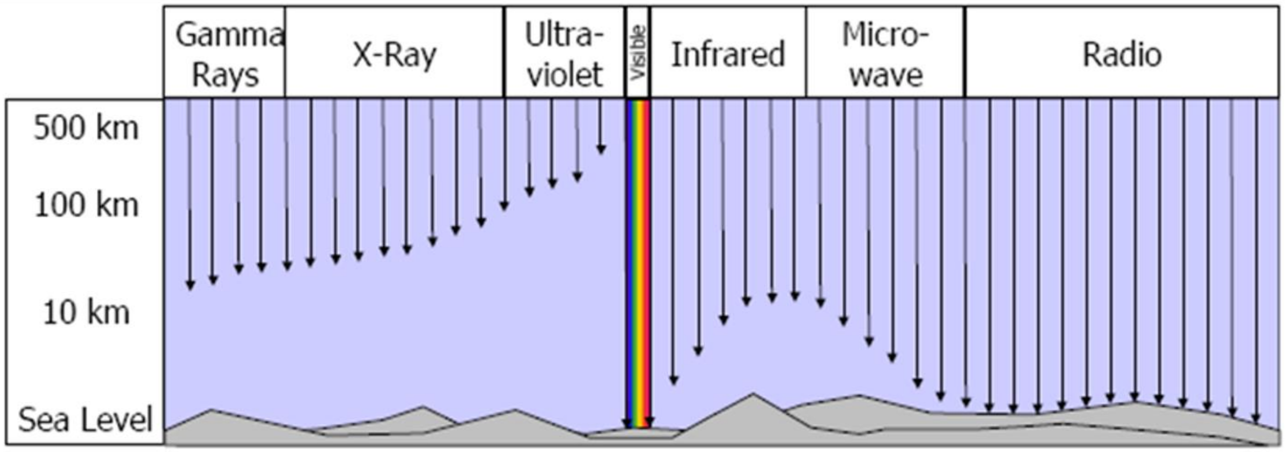

Figure 1. Diagram showing atmospheric penetration across the electromagnetic spectrum (L3Harris Geospatial).

Figure 2. Veritas Cherenkov effect observatory (VERITAS).

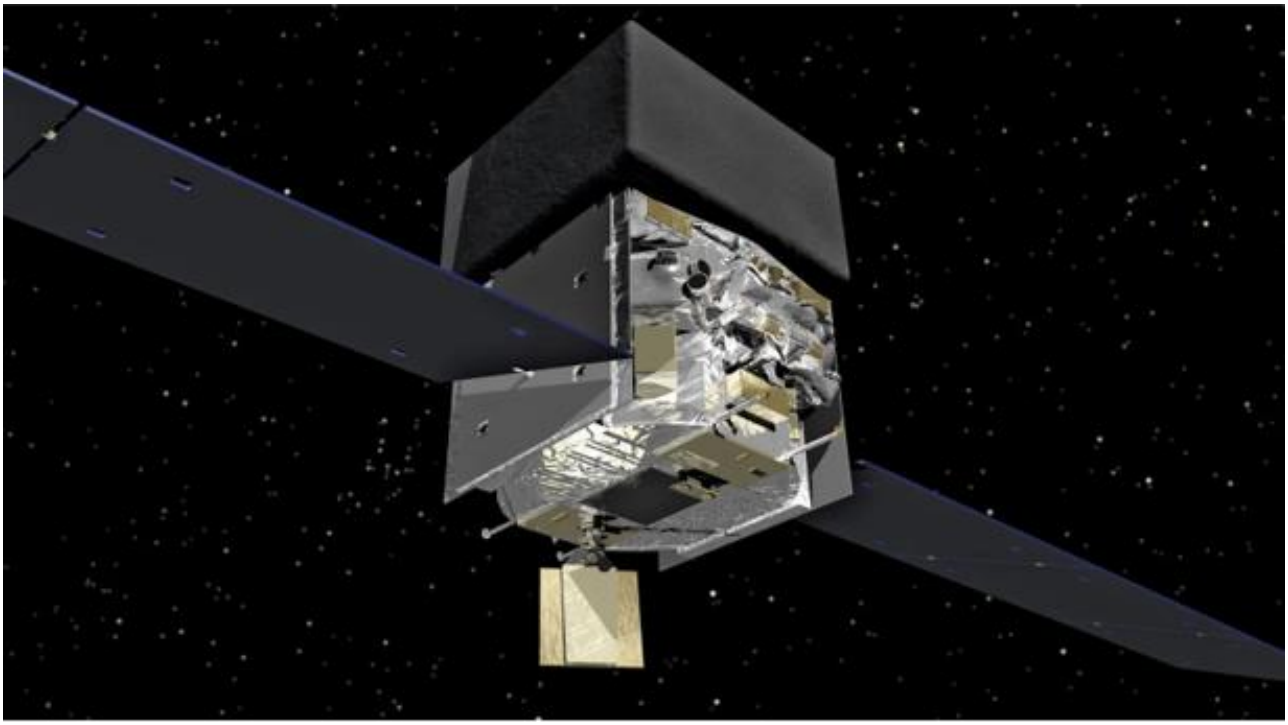

Figure 3. FERMI gamma-ray observatory (Dooling).

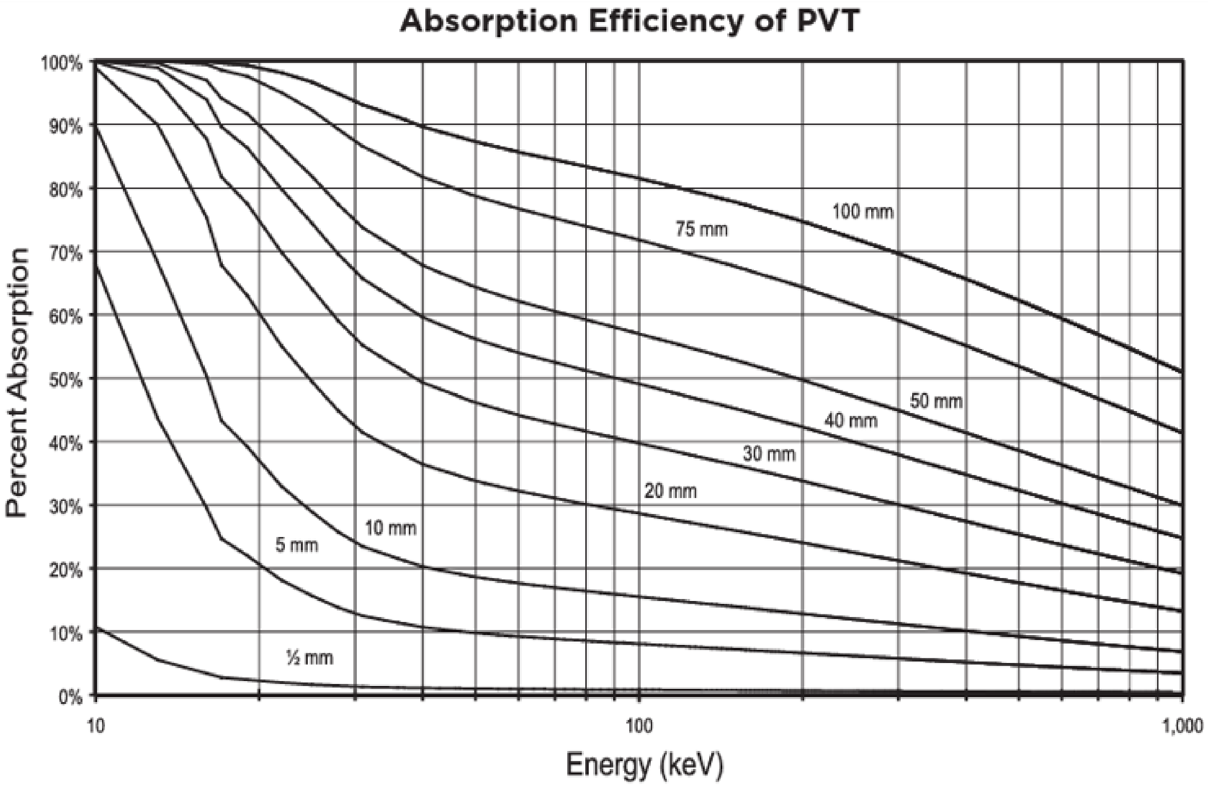

Figure 4. Gamma absorption efficiency of PVT plastic scintillators such as BC-408 (Luxium).

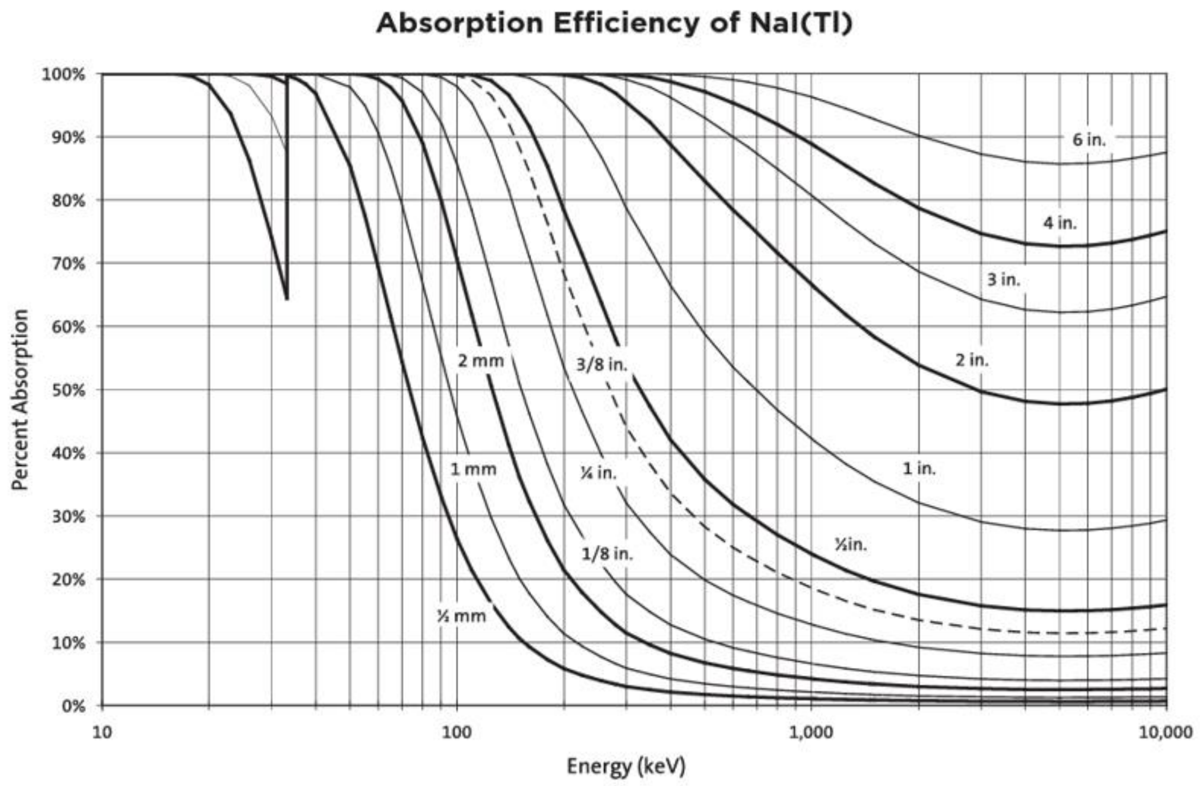

Figure 5. Gamma absorption efficiency of NaI(Tl) crystal scintillators (Luxium).

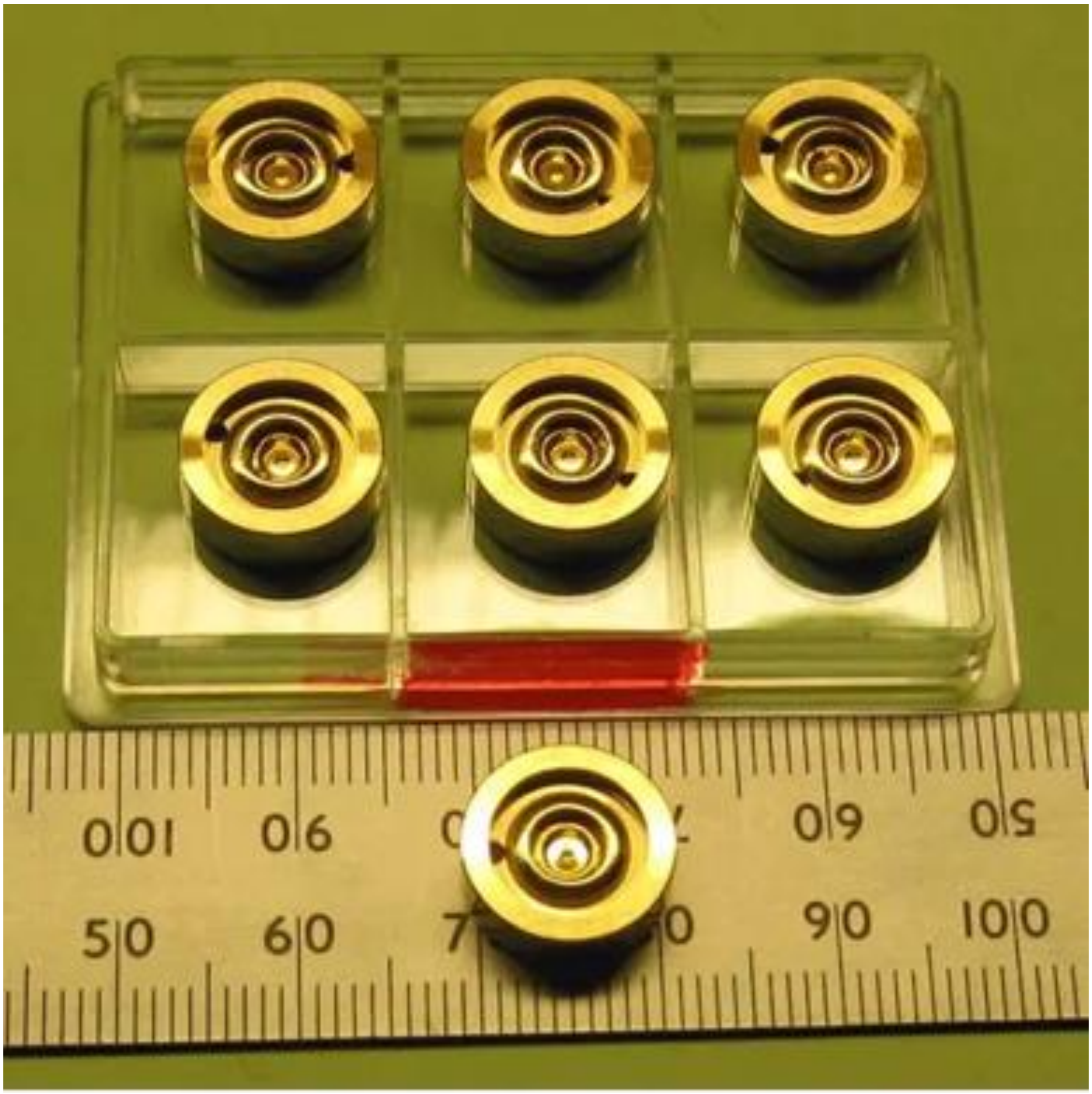

Figure 6. Experimental gamma ray lenses made from gold. (Habs et al., 2012)

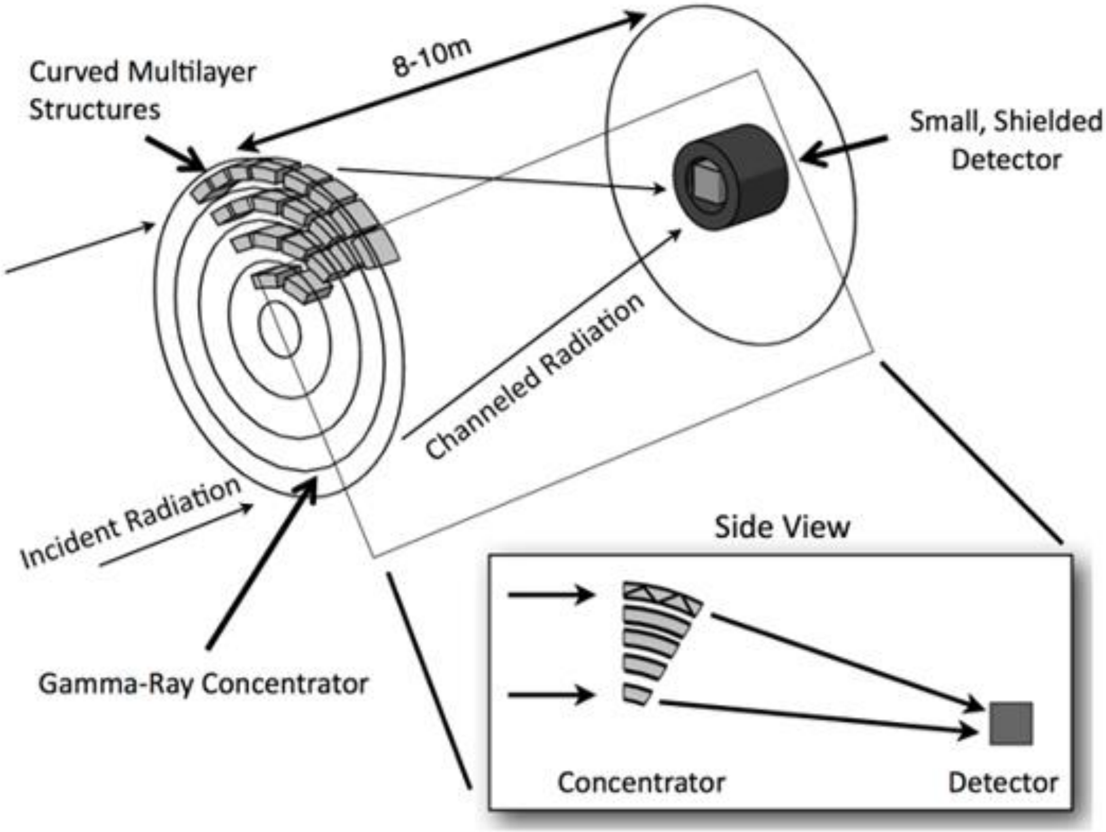

Figure 7. Experimental gamma ray concentrator proposed at Los Alamos (Shirazi et al., 2020).

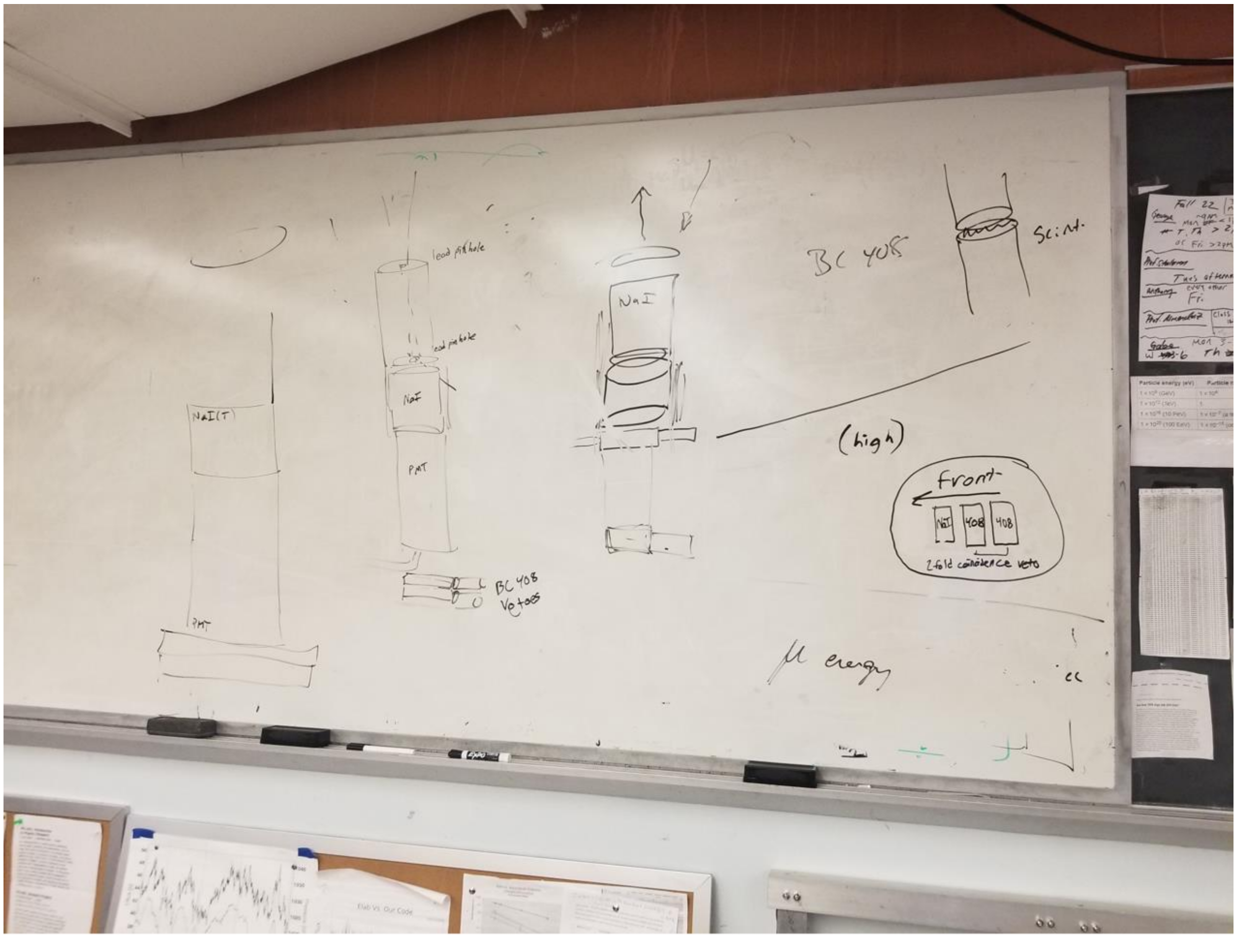

Figure 8. First rough sketches and design concepts.

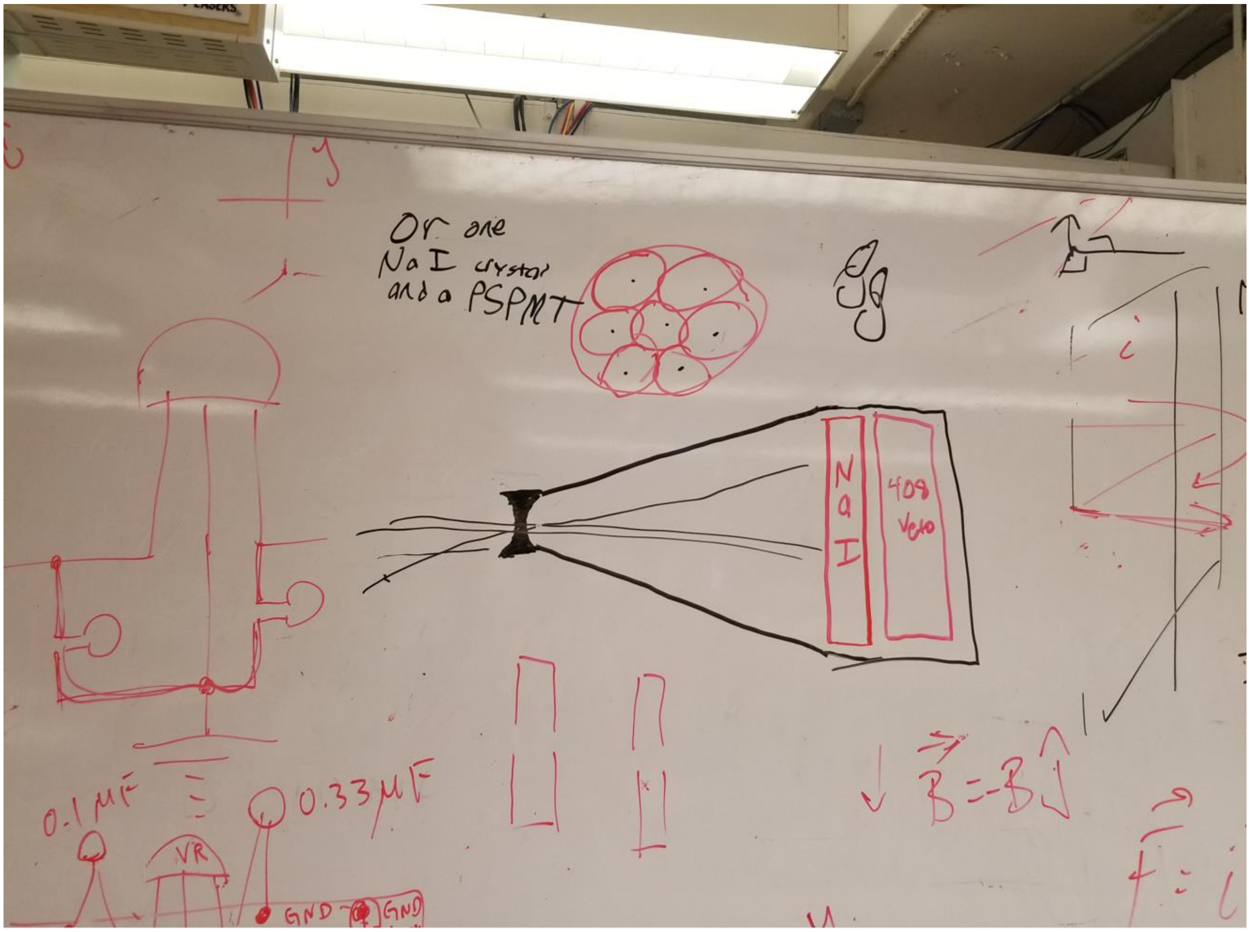

Figure 9. A design concept that would have used an experimental lens and either position-sensitive photomultiplier tubes or multiple individual photomultiplier tubes attached to the scintillators to create a gamma ray imager.

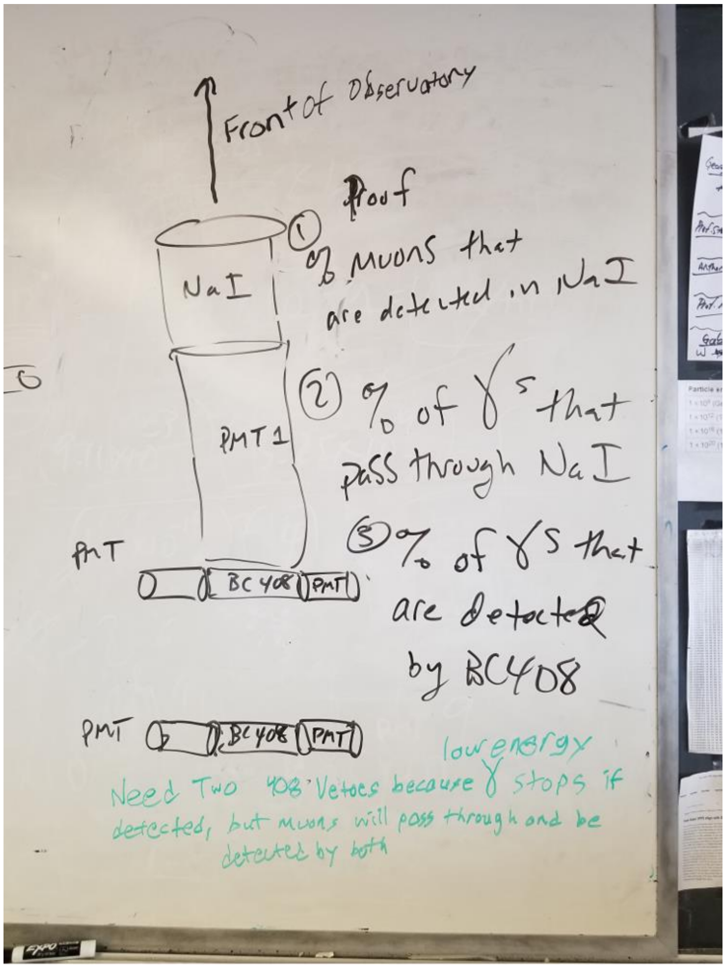

Figure 10. Early design candidate for a simplistic NaI(Tl)/BC-408 detector and veto setup.

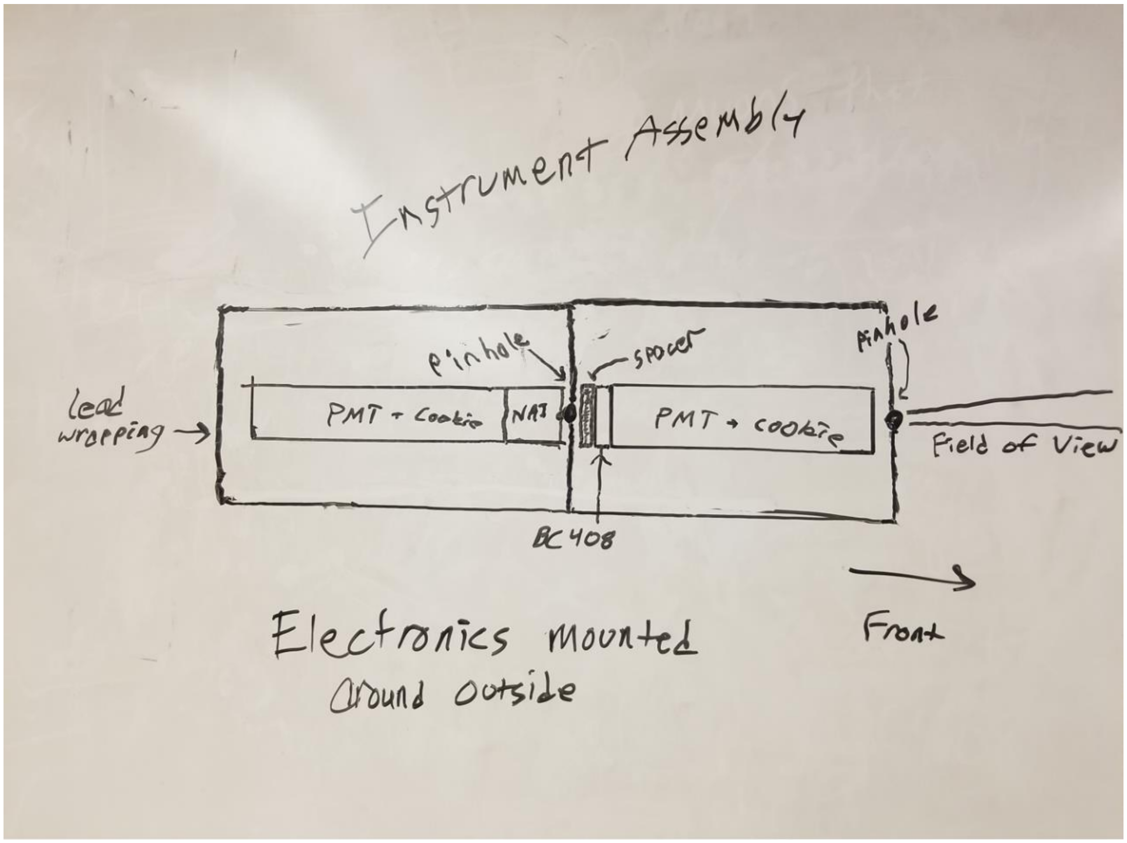

Figure 11. Final detector and veto setup, to be refined and prototyped.

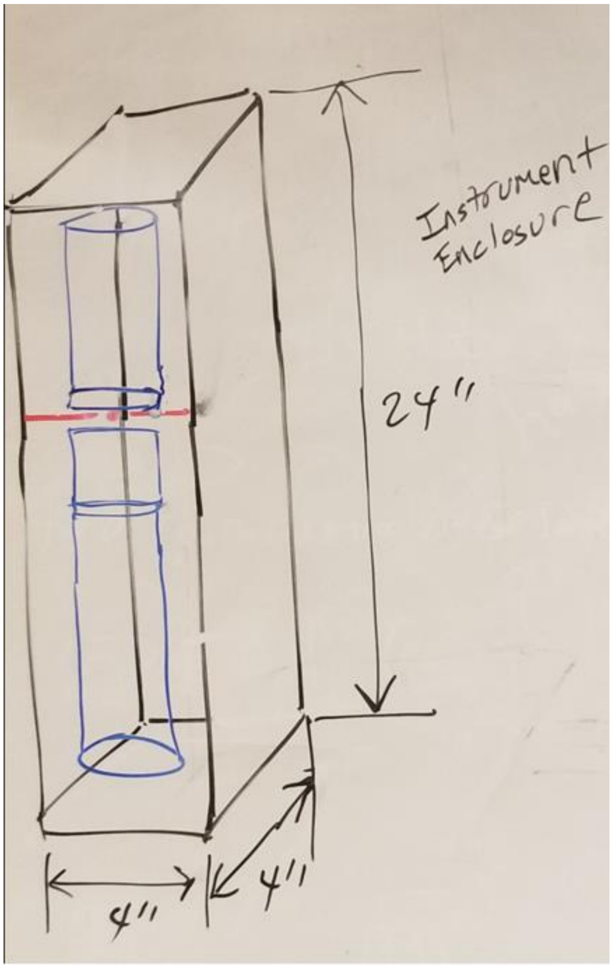

Figure 12. Sorting out minimum dimensions for detector housing.

Figure 13. Top left to bottom right: Assembling the BC-408 scintillation counter and installing it into the prototype housing. The NaI(Tl) scintillation counter was assembled in a similar process. Both are shown in the housing at bottom right. Brackets were custom-designed and 3d printed.

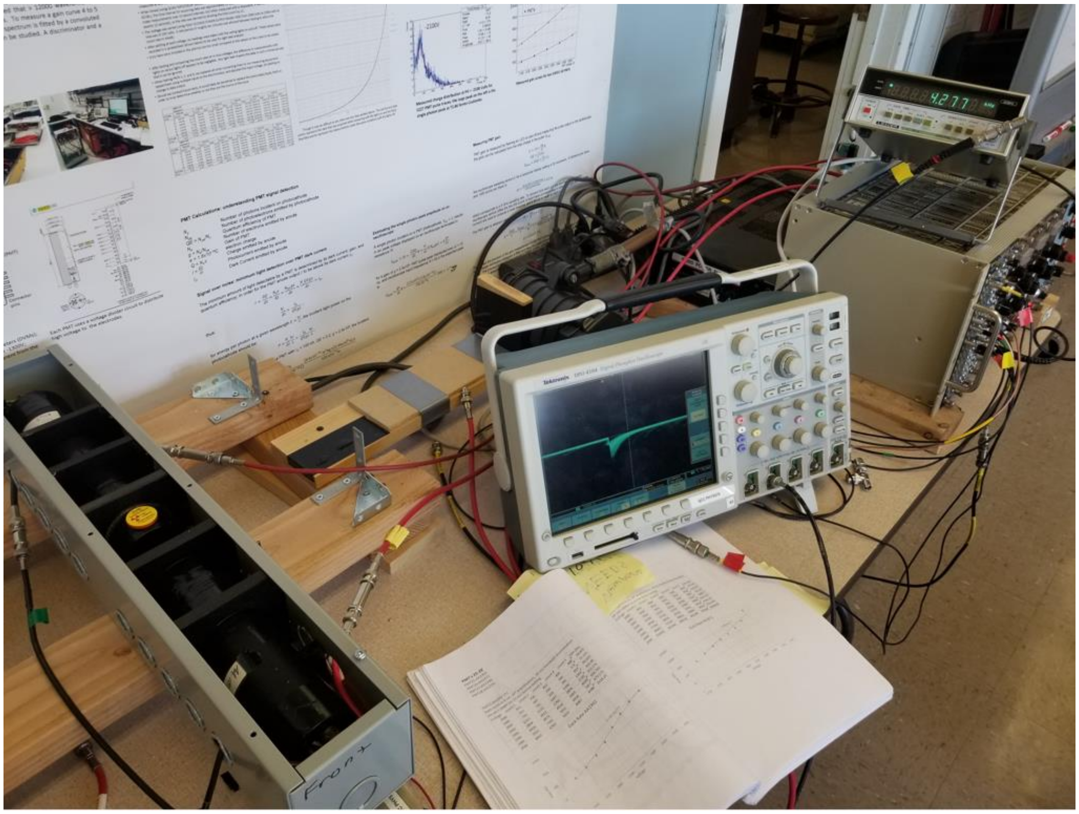

Figure 14. NaI(Tl) radiation detector powered up and exposed to Co-60 test source for the first time.