Characterization of a Candidate Electron Detector for the KATRIN Experiment

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BE BOUNDLESS

Outline

Background

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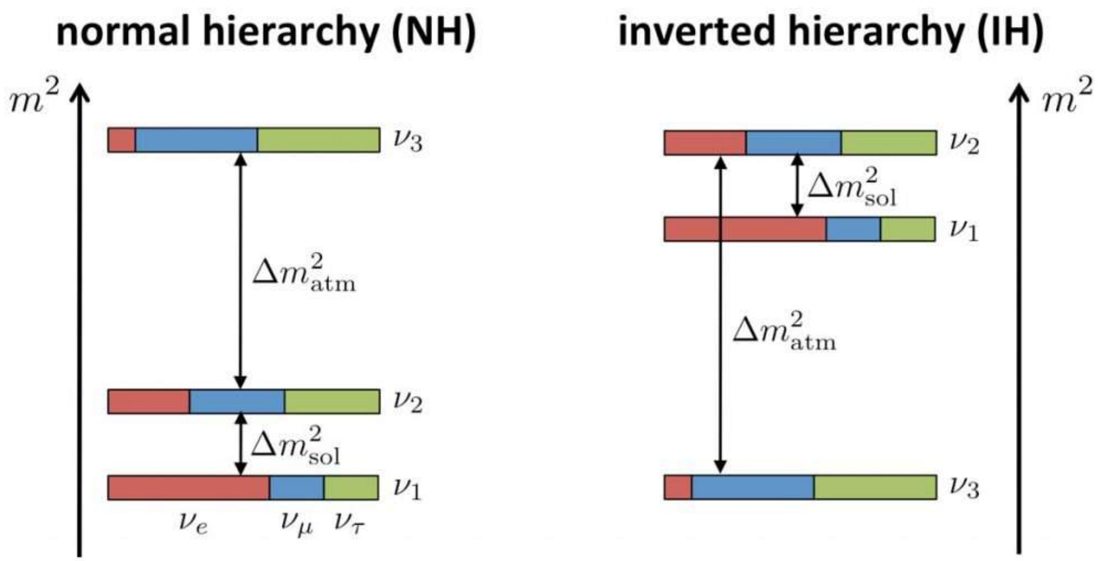
Neutrino Mass

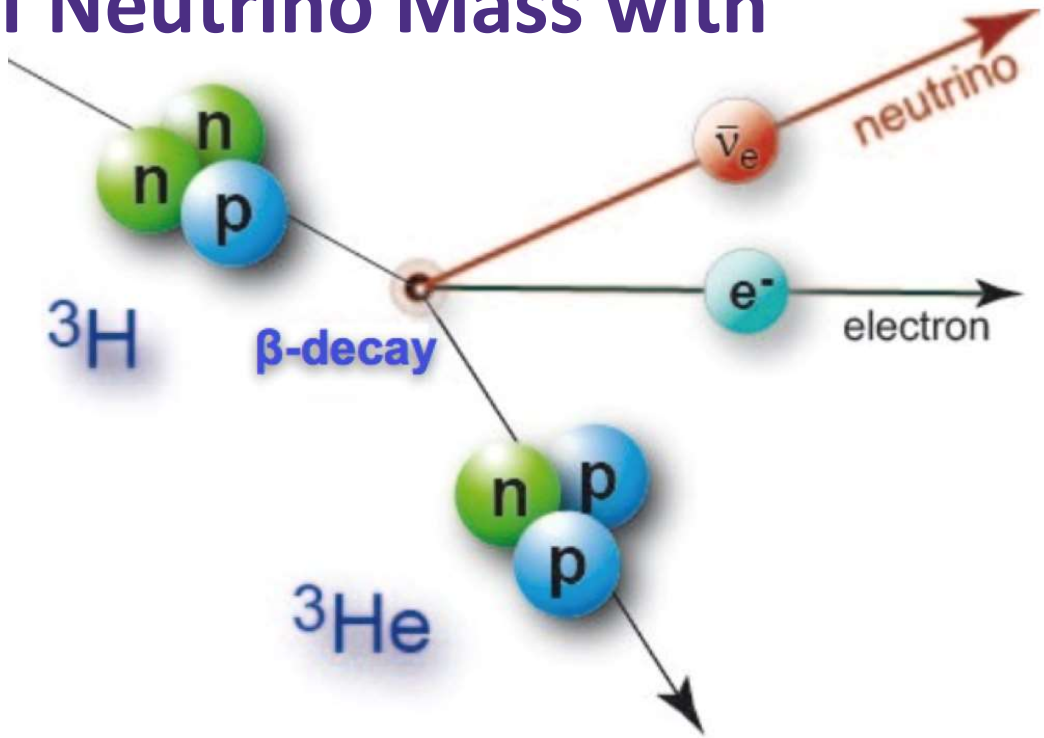
- Standard Model predicts no mass
- Observed oscillations require a superposition of mass eigenstates
- There is a difference between these masses, so they cannot all be zero
- The mass is still at least 10^6 times smaller than an electron



JUNO Collaboration, Two Potential Mass Orderings, *Fermilab* (2023). https://neutrinos.fnal.gov/mysteries/mass-ordering/#moreinfo

Direct Measurement of Neutrino Mass with Electron Beta Decay

- Tritium beta decays into
  - Helium-3
  - Electron
  - Electron anti-neutrino
- The electron energy spectrum is affected by neutrino mass



$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot P \cdot (E + m_e) \cdot (E_0 - E)\sqrt{(E_0 - E)^2 - m_\beta^2}$$

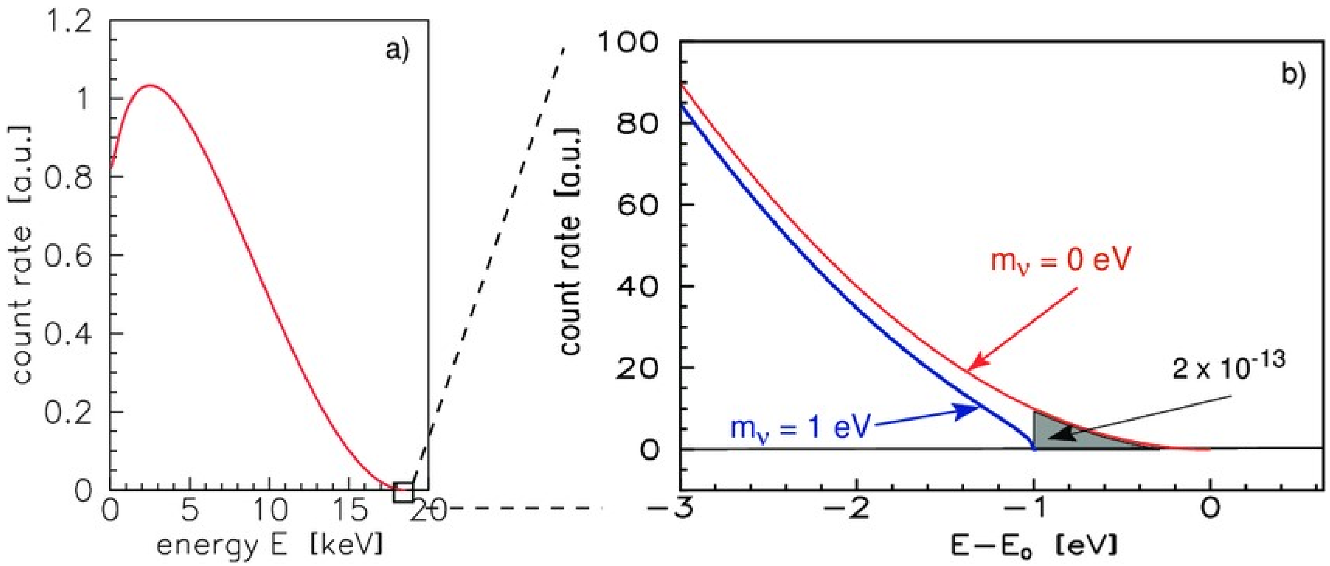
Neutrino mass

(some details/corrections not included here)

A cartoon of tritium (hydrogen-3) decay, *Project-8*(2023). https://www.project8.org/about
Enomoto, Direct Measurement of Neutrino Mass with Sub-eV Sensitivity by KATRIN, *UW Colloquium*(2022).

High Pass Electron Energy Filter

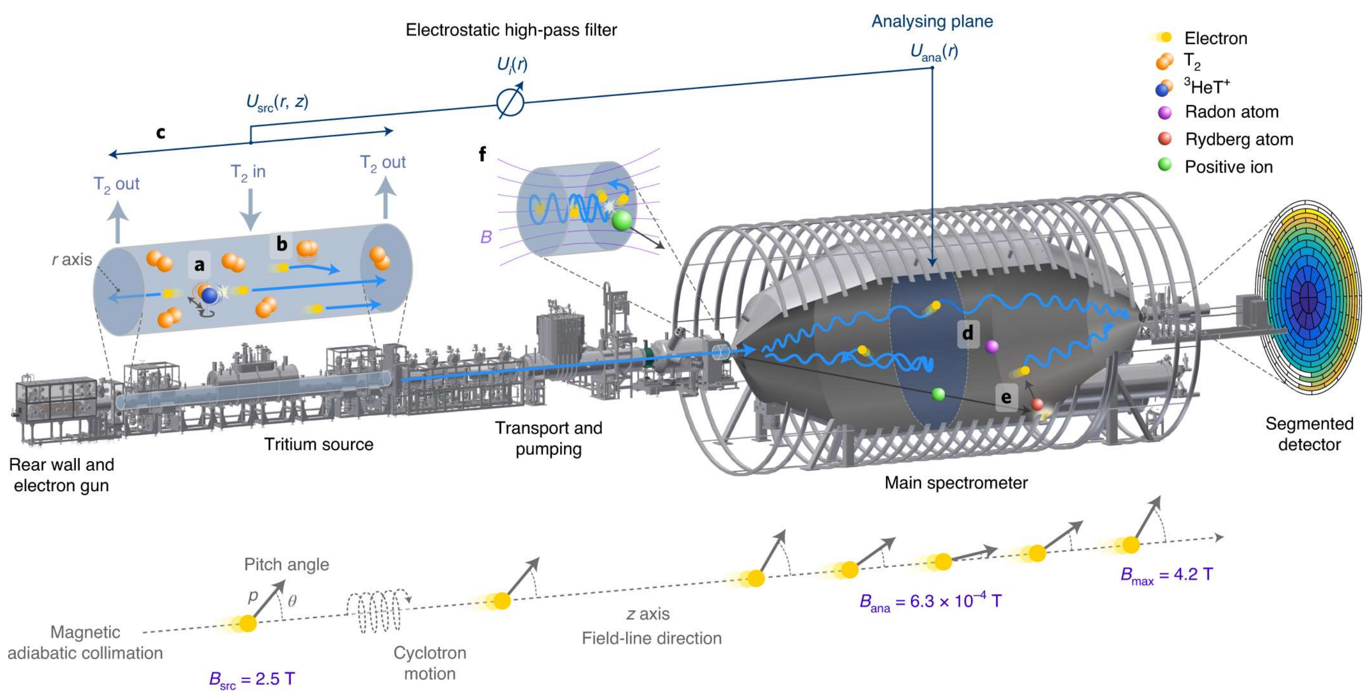
- Clear decrease in electron energy, depending on neutrino mass
- Electric potential in the main spectrometer selects electron energies higher than a certain threshold
- Detector resolution is relevant in eliminating noise



Ubieto Diaz, Marta. (2011). Off-line commissioning of a non-destructive FT-ICR detection system for monitoring the ion concentration in the KATRIN beamline.

Karlsruhe Tritium Neutrino (KATRIN) Experiment

- Tritium source undergoes beta decay
- Main spectrometer imposes high pass filter
- Segmented detector detects beta electrons
- Upper limit of 0.8 eV at 90% Confidence Level



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KATRIN, *Nat. Phys.* (2022).

KATRIN Detector

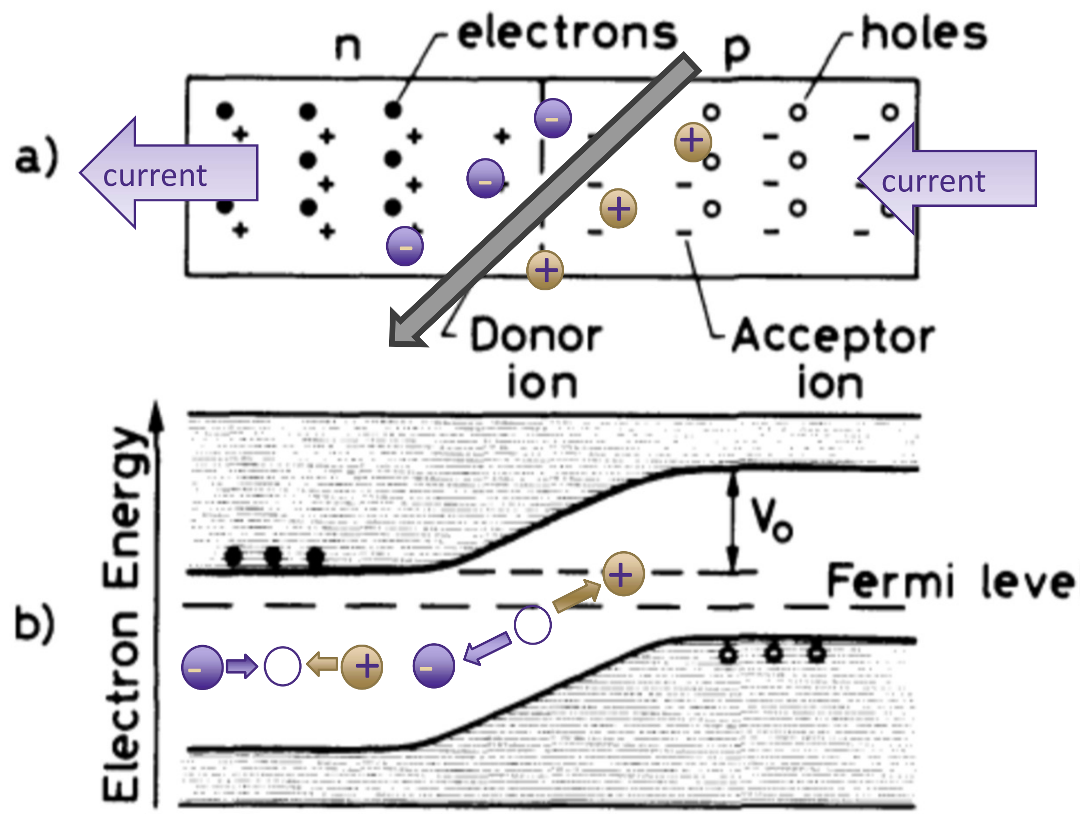
- 148-pixel silicon-PIN-diode focal-plane detectors (FPD)
- The mean dead layer, based on previous performance of the KATRIN experiment, is 155.4 +/- 0.5 +/- 0.2 nm

Mounted wafer with unsegmented front side, *KATRIN*(2023). https://www.katrin.kit.edu/84.php

The KATRIN Collaboration. Direct neutrino-mass measurement with sub-electronvolt sensitivity. *Nat. Phys.* 18, 160–166 (2022). https://doi.org/10.1038/s41567-021-01463-1
B.L. Wall, et al, Dead layer on silicon p–i–n diode charged-particle detectors, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 744, 73-79 (2014)., https://doi.org/10.1016/j.nima.2013.12.048

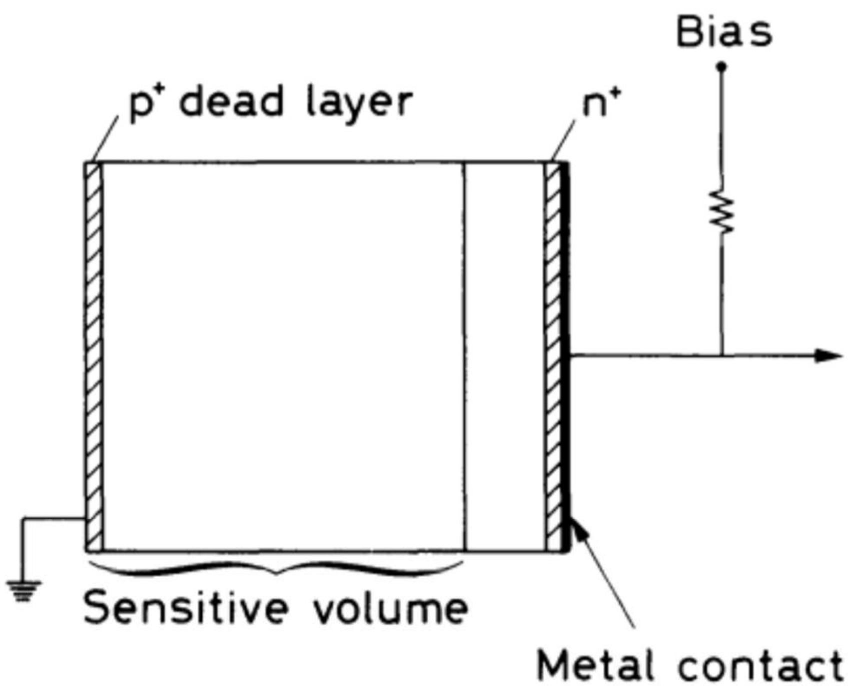
Silicon-PIN-Diode Focal-Plane Detectors (FPD)

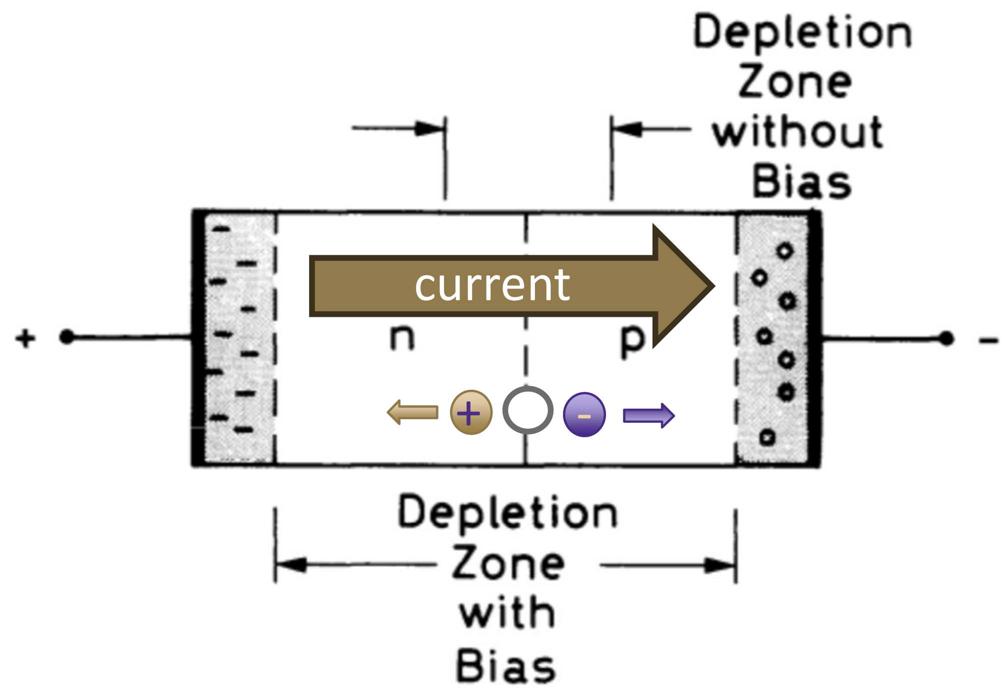
- Semiconductor
- Reverse biased
- Charge separation
- Ionization of particles passing through the detector
- Creates current, which is recorded



Leo, William R., *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag, Heidelberg, 1994; (Second Revised Edition, 223)

Dead Layer Thickness





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Leo, William R., *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag, Heidelberg, 1994; (Second Revised Edition, 223)

Experimental Set-Up

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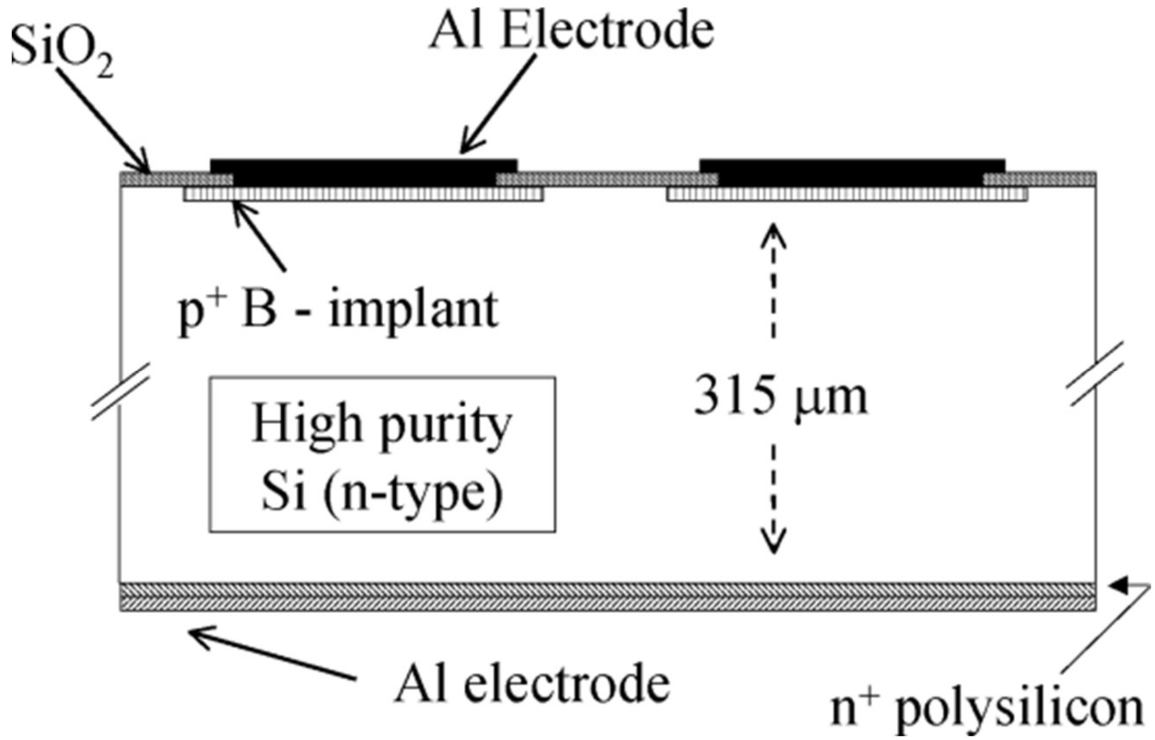
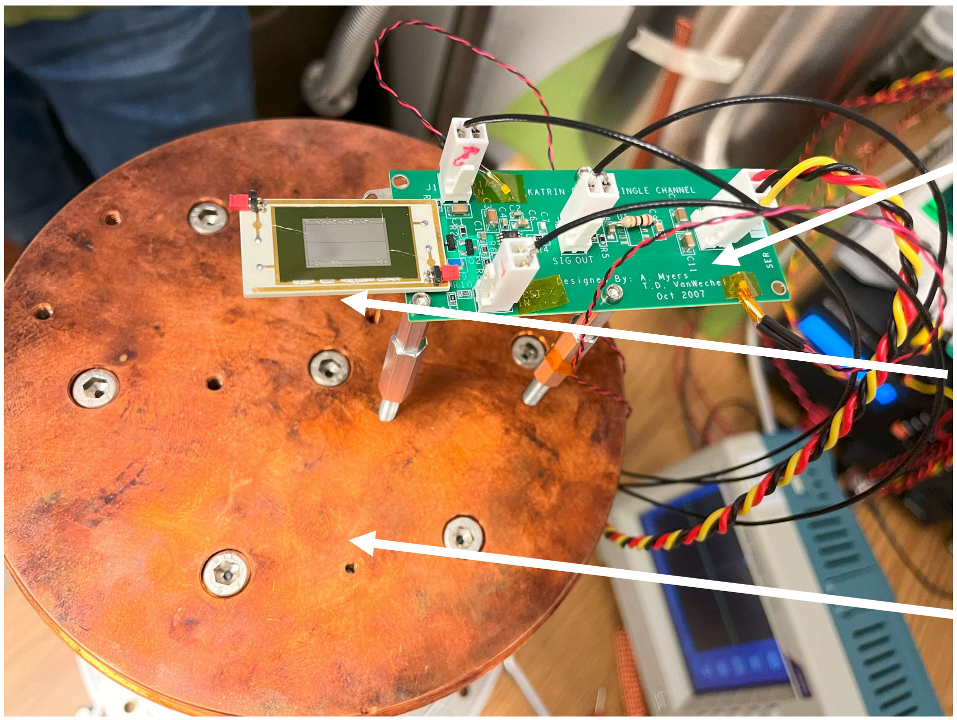
Candidate Detector from LBNL

- Expected dead layer thickness of 35 nm (currently 155.4 nm)
- Aluminum coating to reduce noise
- Thin contacts
- 0.944 cm^2 surface area
- Good candidate!



C. S. Tindall *et al.*, "Silicon Detectors for Low Energy Particle Detection," in *IEEE Transactions on Nuclear Science*, vol. 55, no. 2, pp. 797-801, April 2008, doi: 10.1109/TNS.2008.918527.

Vacuum Cavity and Electronics



Vacuum Cavity

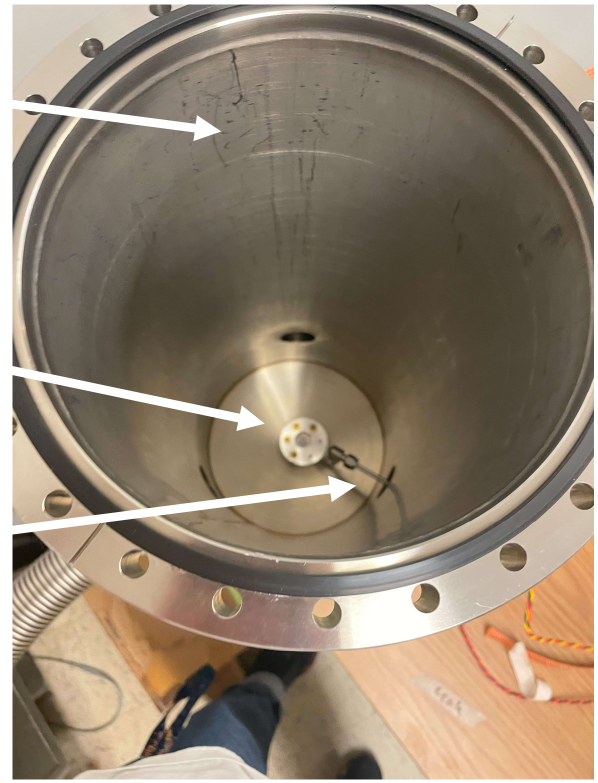
Preamplifier

Source

Detector

Pivot

Cooling Plate



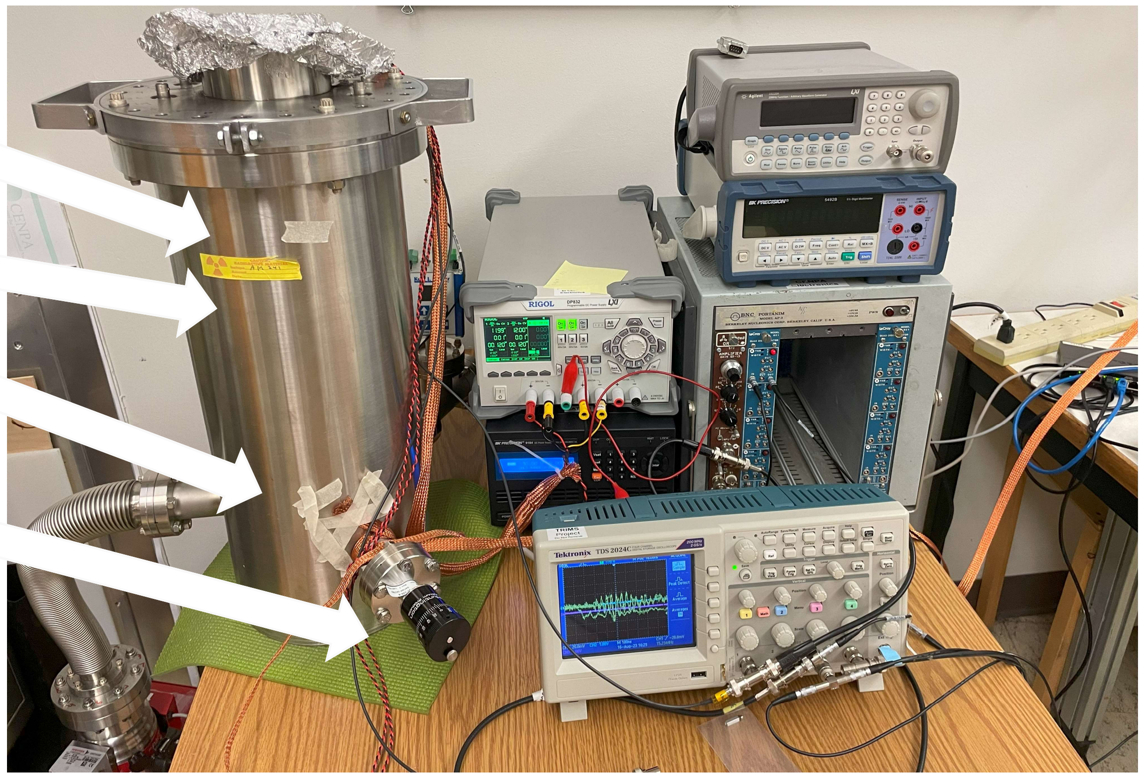
The Running Set-Up

Liquid Nitrogen

Detector

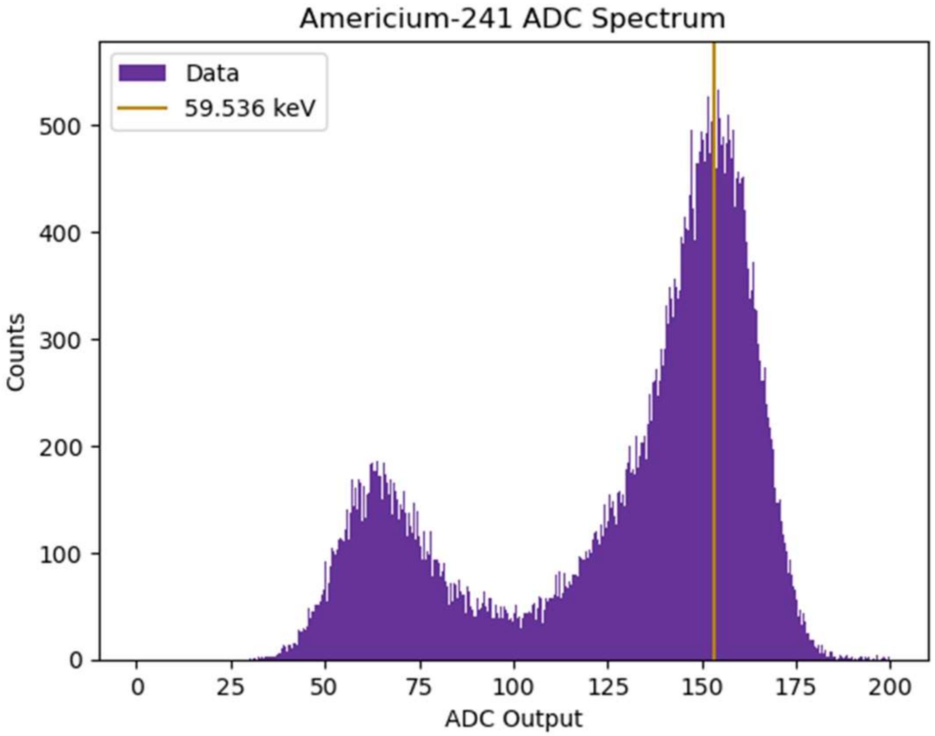
Source

Pivot Angle Knob



Energy Calibration with an Am-241 Spectrum

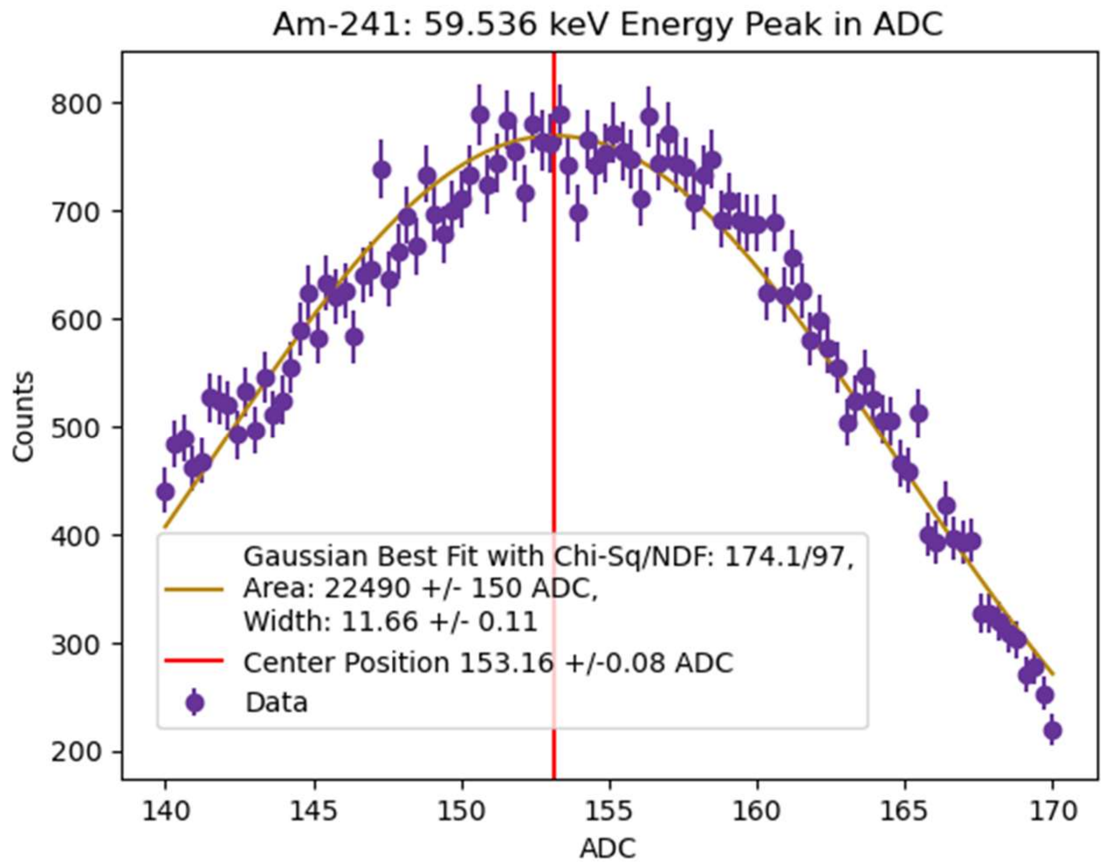
- ADC: Analog to Digital Converter
- 59.536 keV peak
- Gamma particles unaffected by dead layer energy loss
- Gaussian broadening due to instrumental noise
- Fitted with a Gaussian



Conversion from ADC to Energy (keV)

- Centered on 59.536 keV/(153.16 +/-0.08 ADC)
  - 0.05% error
- Conversion factor of:

0.38892 +/- 0.00020 keV/ADC



Dead Layer Thickness

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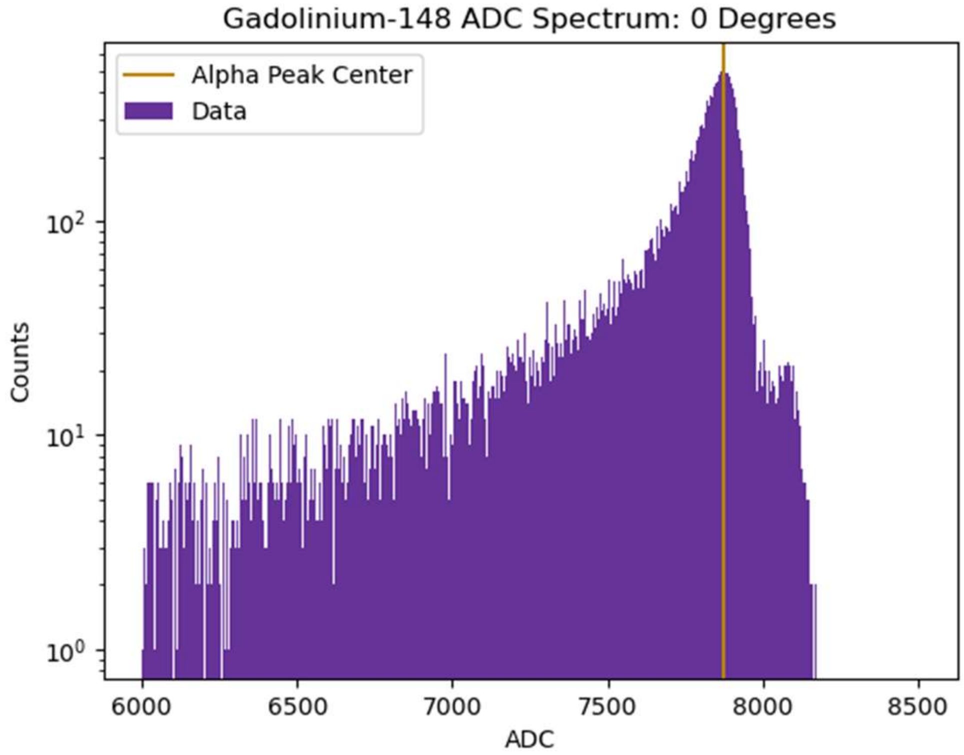
Spectrum of Gd-148 Alpha Source

- Initial energy of an alpha particle emitted from this source: 3182.8 keV
- Alpha particles lose energy in all media
- Useful for calculating dead layer but not calibration
- Gaussian behavior on the right slope
- Exponential energy loss on the left slope



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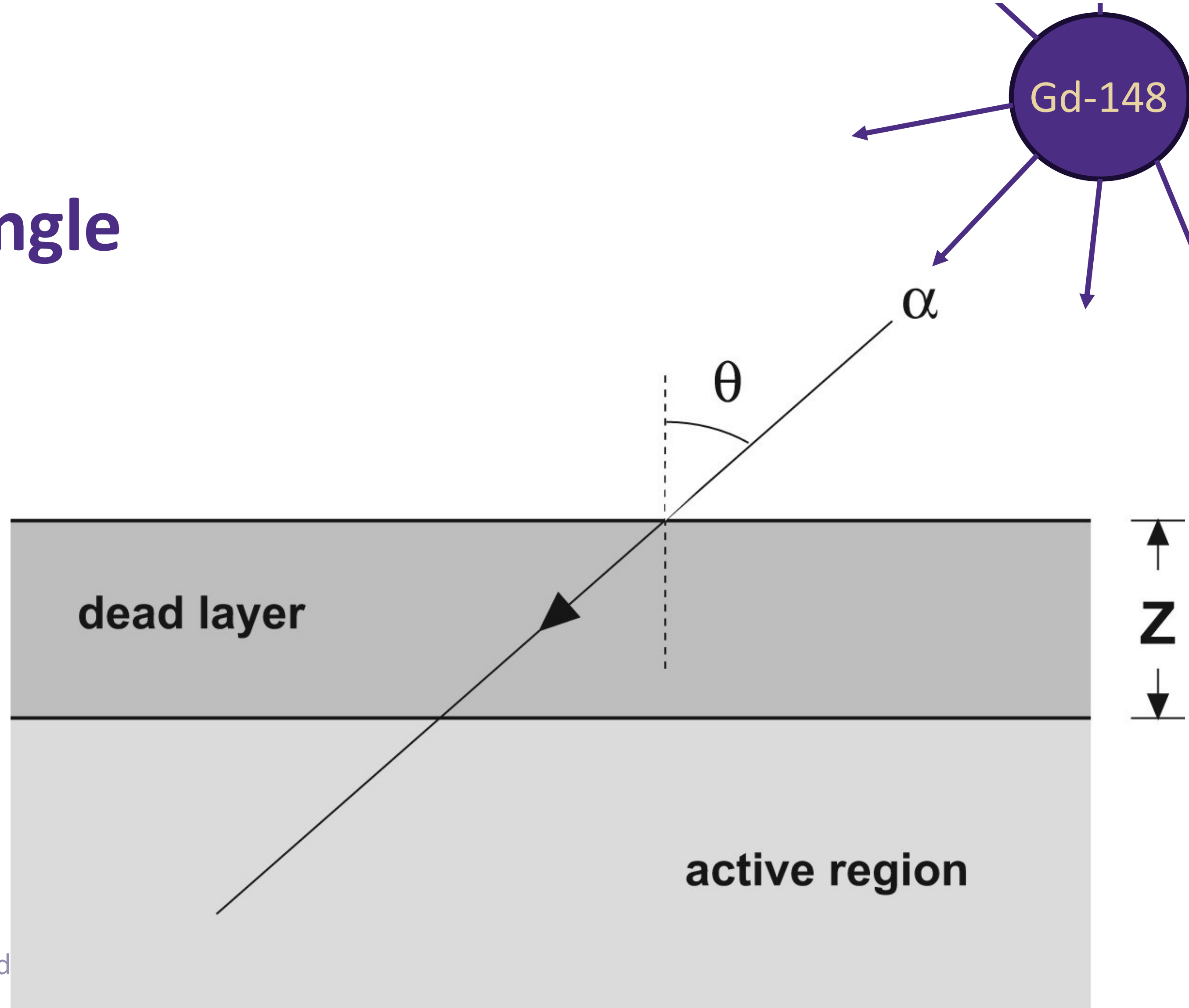
Nadine M. Chiera, et al, Determination of the half-life of gadolinium-148, Applied Radiation and Isotopes, Volume 194, 2023, 110708, ISSN 0969-8043, https://doi.org/10.1016/j.apradiso.2023.110708. (https://www.sciencedirect.com/science/article/pii/S0969804323000611)

Varying Source Angle

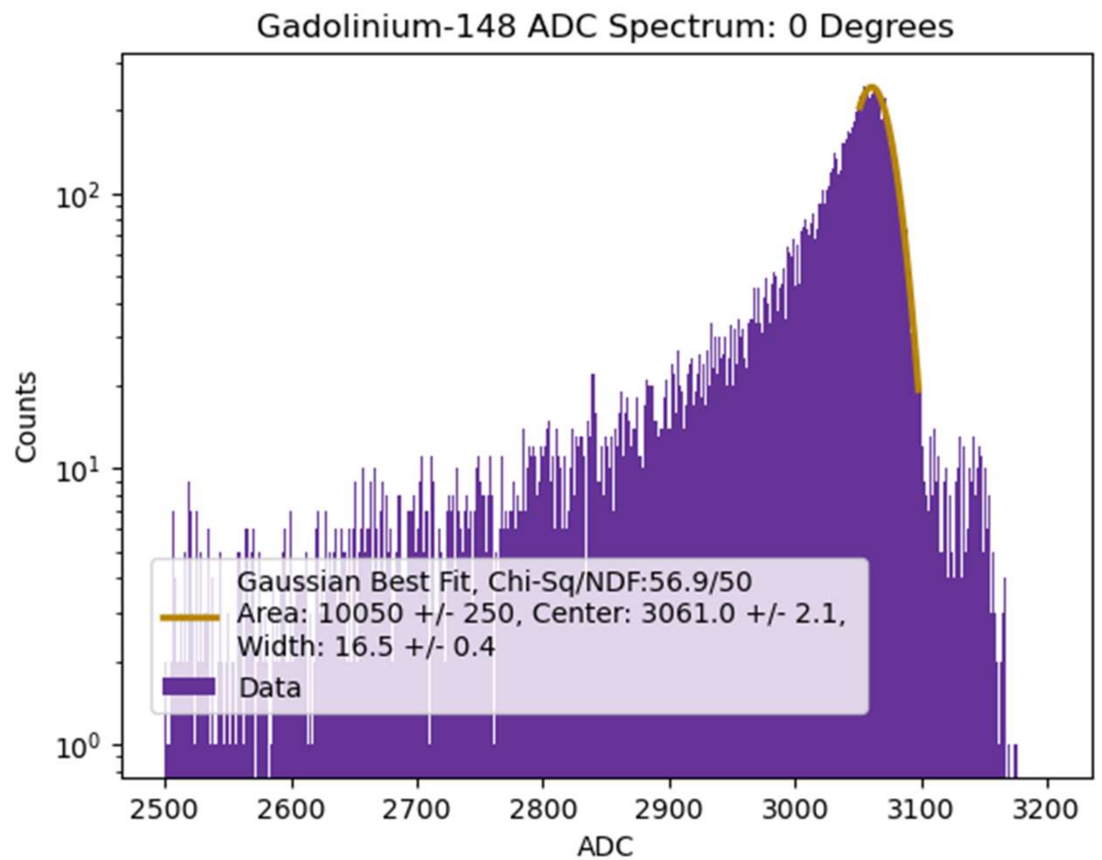
- Z: dead layer thickness
- Θ: angle of the source relative to vertical
- α: emitted alpha particle incident on the detector
- Path length through dead layer: Z/cos(Θ)
- Robust against absolute energy scale errors and dE/dx low energy uncertainty



B.L. Wall,, *Nuclear Instruments* (2014).

Fitting a Gaussian to the Right Side

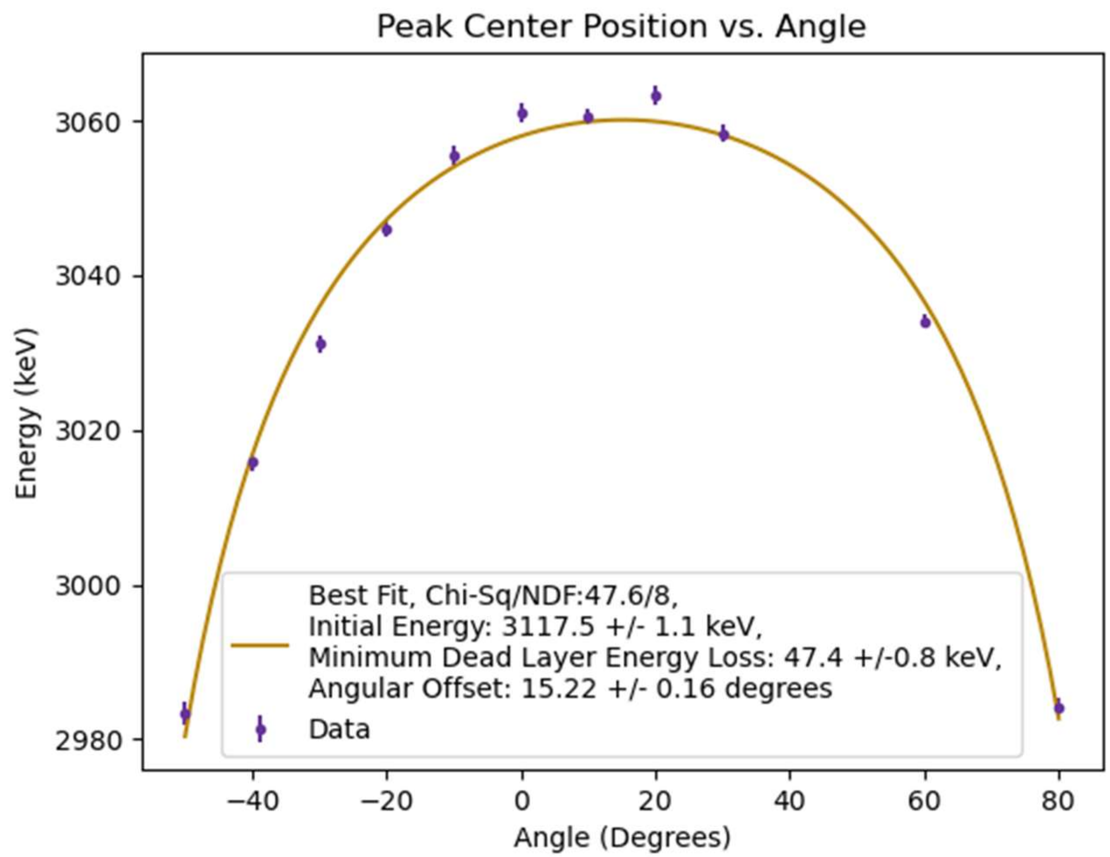
- Manually choose the Gaussian portion of the histogram
- Assess the quality of fit
- Record the center peak energy for each source angle
- Note: center position error impacted by conversion factor error



Results of Alpha Peak

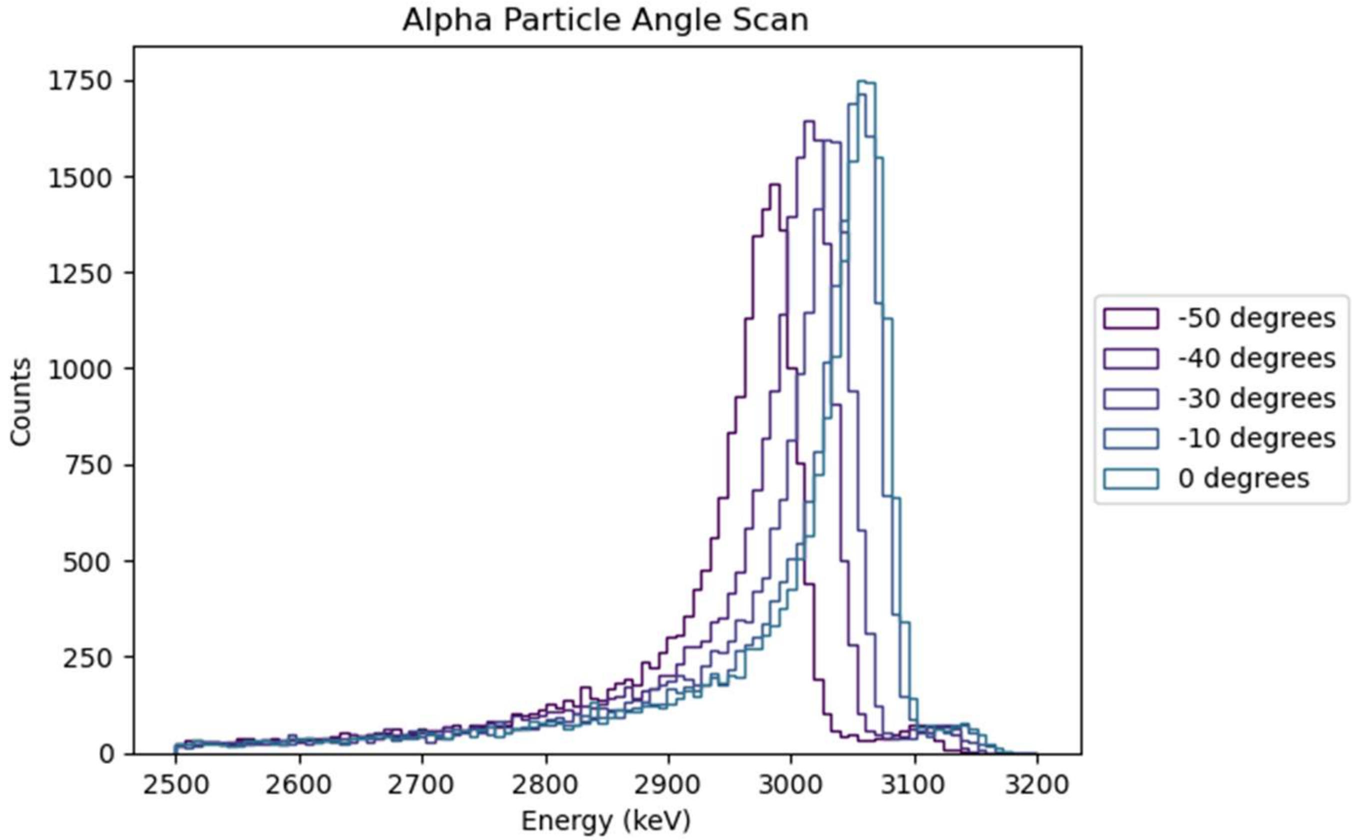
- Fitted to $y = a - \frac{b}{\cos(x-c)}$
- Minimum Dead Layer Energy Loss: 57.4 +/- 0.8 keV
- Energy loss coefficient for alpha particles in silicon: 170 +/- 10 keV/micrometer
- Dead layer thickness:

338 +/- 25 nm



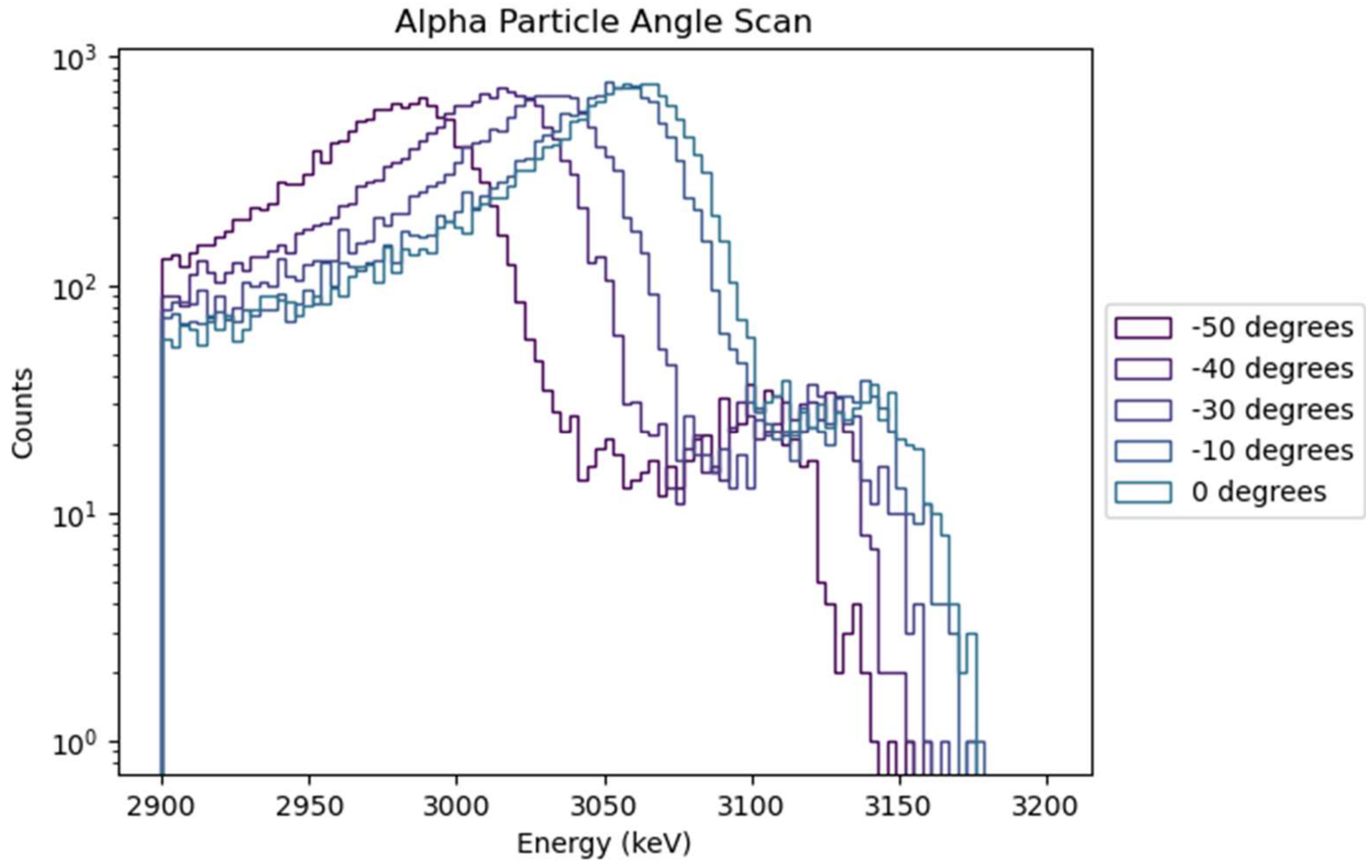
Angular Displacement Effect on Gd-148 Spectrum

- Decreasing angular displacement
- Decreases path length through the dead layer
- Shifts energy peaks to the right



Twin Alpha Peaks

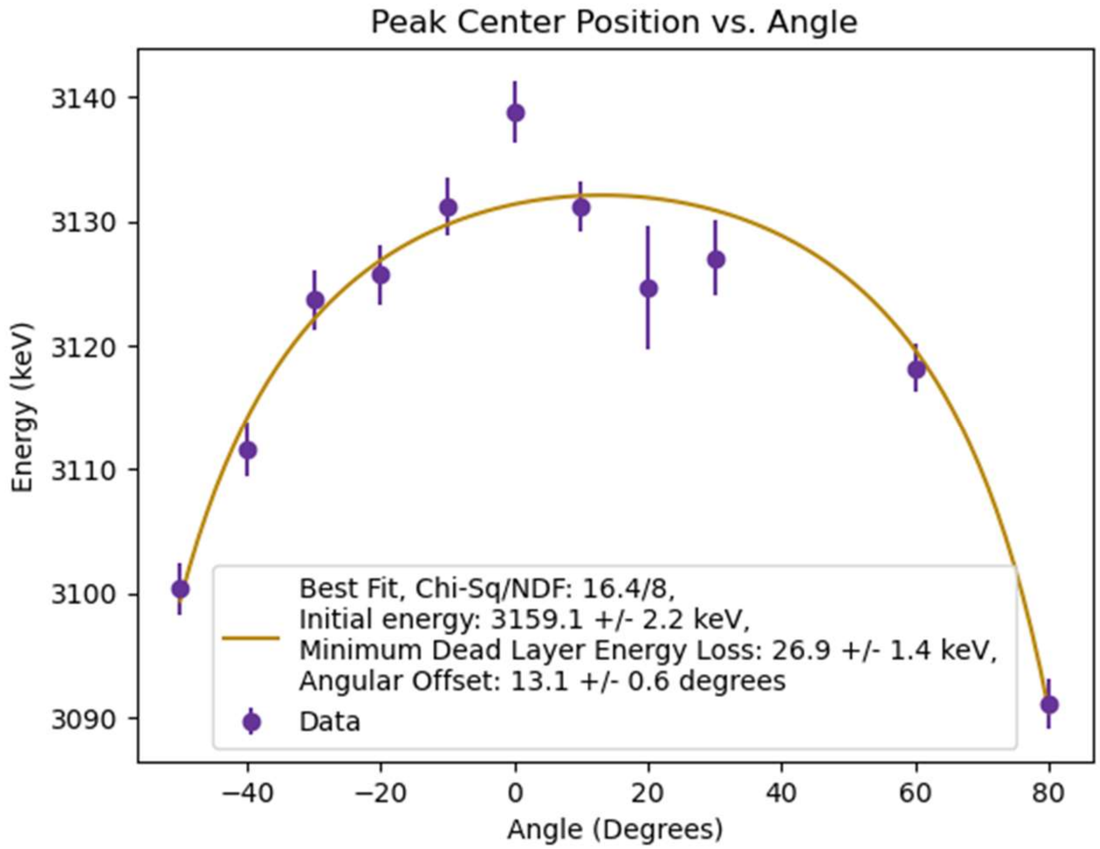
- Angular dependence
- Second smaller peak which behaves similarly



Results of Second Alpha Peak

- Fitted to $y = a - \frac{b}{\cos(x-c)}$
- Minimum Dead Layer Energy Loss: 26.9 +/- 1.4 keV
- Energy loss coefficient for alpha particles in silicon: 170+/- 10 keV/micrometer
- Dead layer thickness:

158 +/- 18 nm



Systematics Investigation

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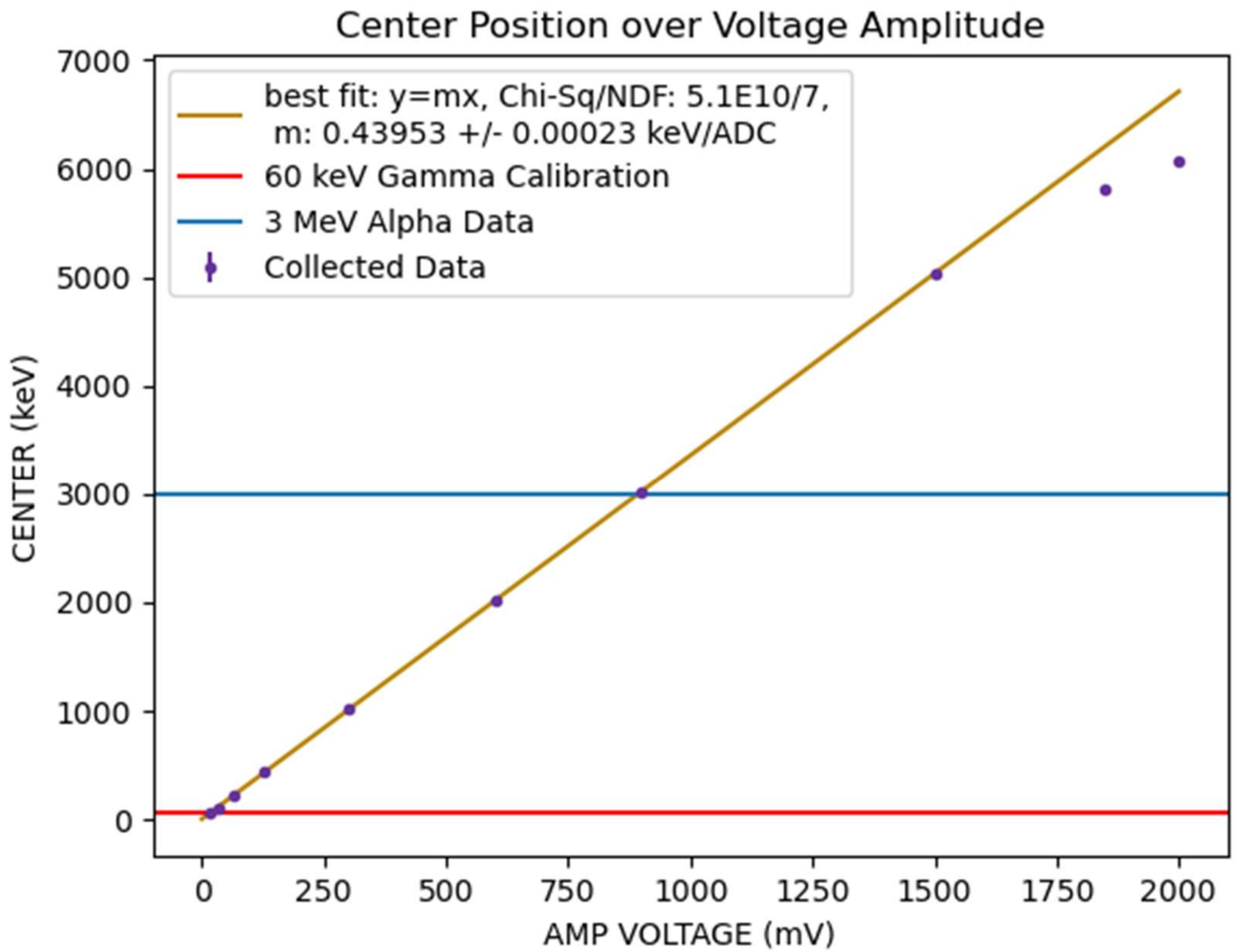
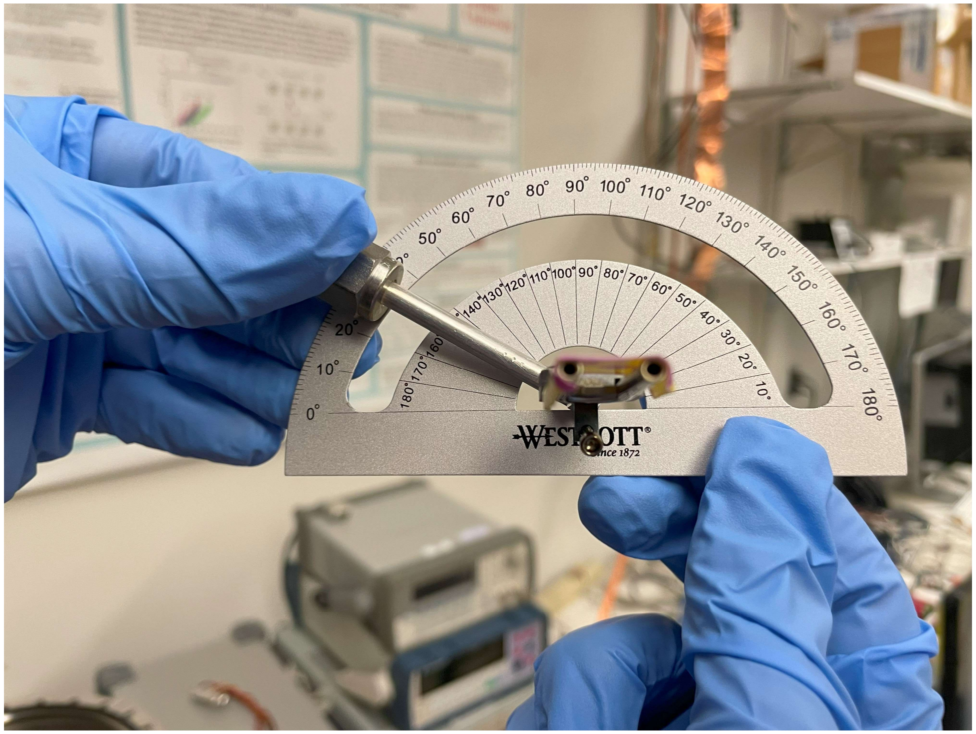
Linearity Scan

- Linearity of conversion factor holds for up to 5000 keV
- 0.05% error up to about 5000 keV



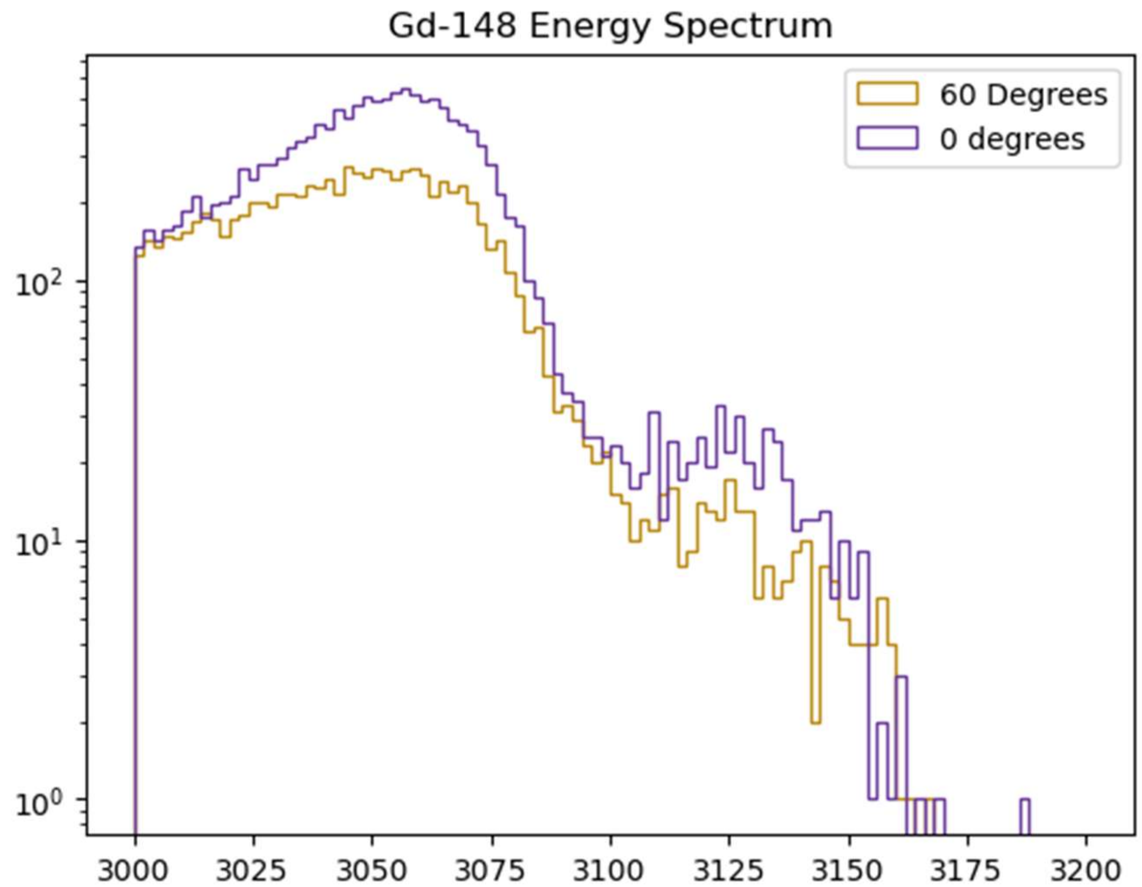
Potential Surface Irregularities

- Coating on source surface, with scratches
- Twin peaks with different initial energies
- Test by varying source “tilt” and path length through source coating



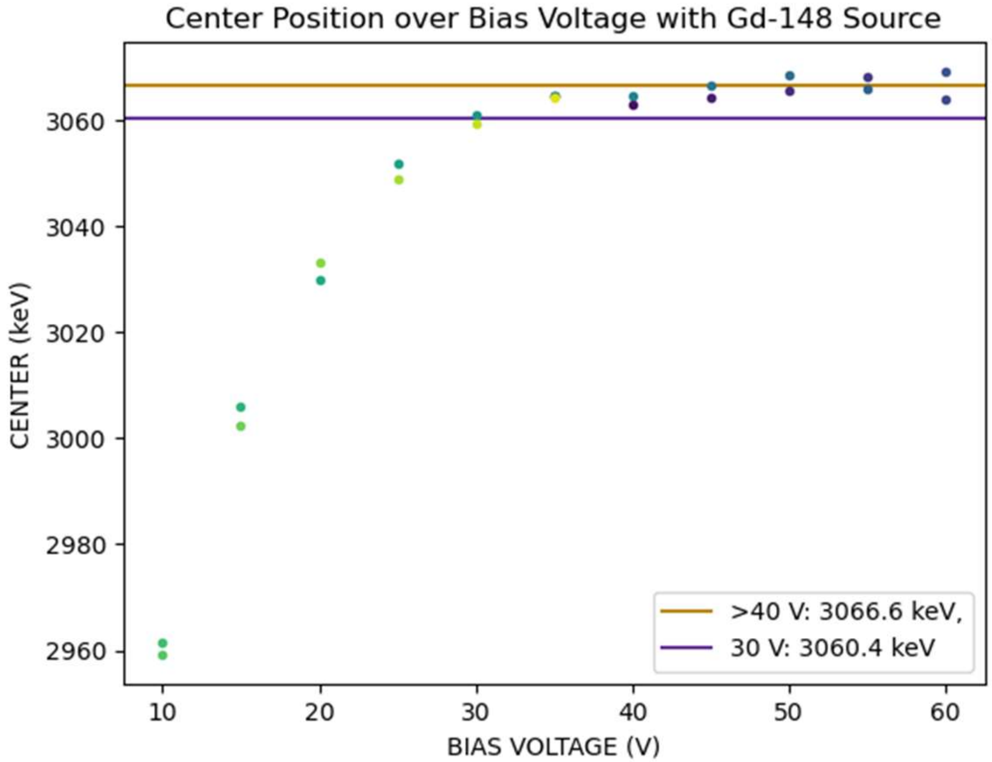
“Tilt” of the Source

- Each run’s energy scale independently calibrated with Americium-241 peak
- No change in peak position
- No coating on the source



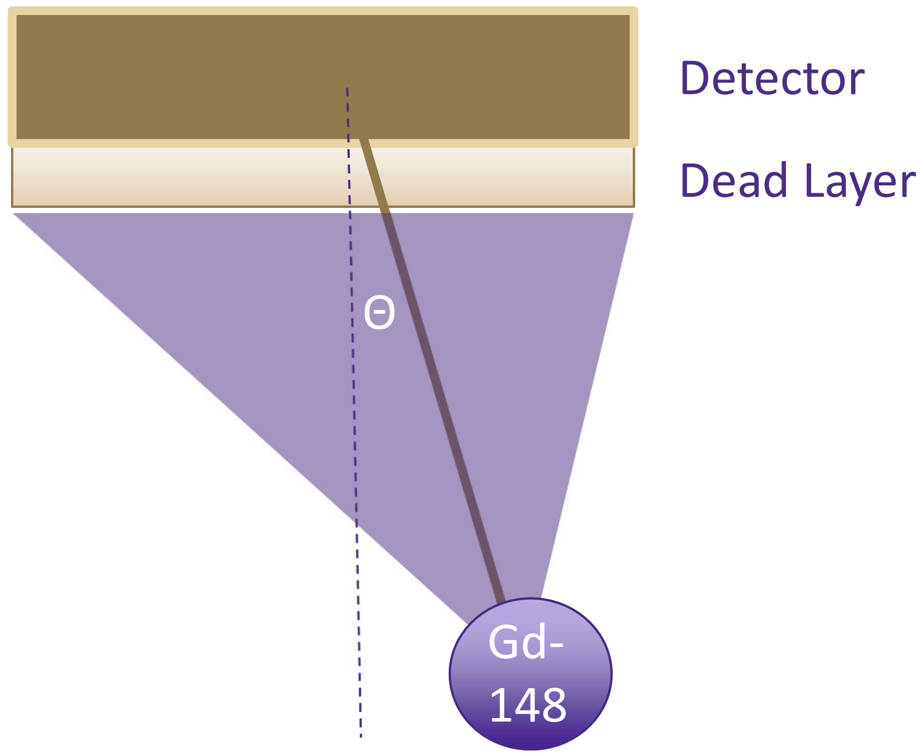
Bias Voltage Dependence

- 30 V bias used for angle scan
- 0.2% reduction in peak energy between 30 V and voltages above 30 V
- Additional 6.156 +/- 0.009 keV energy loss at 30 V
- 36.4 +/- 2.2 nm added to the dead layer



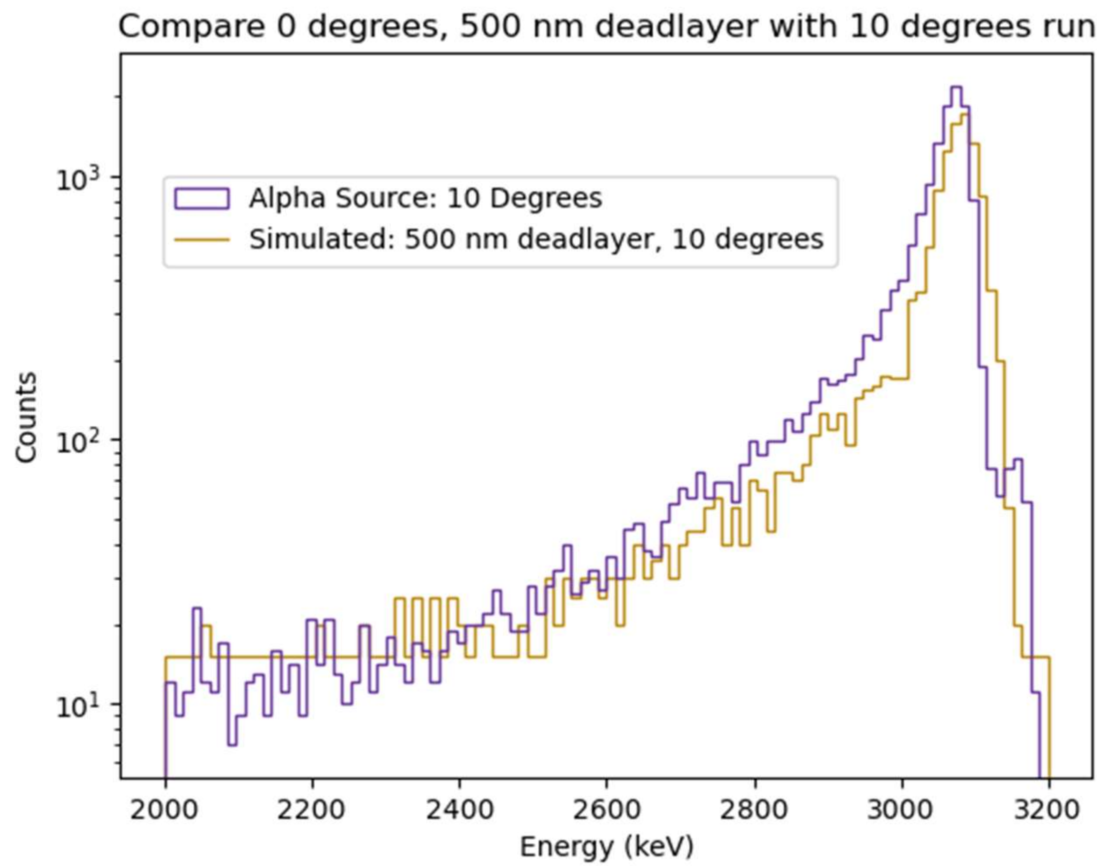
Monte Carlo Simulation in Python

- Emission from a spherical source
- Selecting which particles impact a detector of surface area 70 mm^2
- Energy loss in the dead layer, impacted by the source angle, and the emission angle
- Two rounds of exponential energy loss
- Gaussian broadening



Simulation Results

- Replicated spectrum shape
- Small effect of angular spread
- Can use simulated spectrum for future peak fitting



Conclusions and Future Steps

- Two dead layers:
  - 302 +/- 5 nm
  - 122 +/- 8 nm
- Detector performance is comparable with the current detector, but further testing is needed
  - Conduct future measurements with a bias voltage above 30 V
  - Further systematic error analysis
    - Fit with non-Gaussian model

Institutional Acknowledgements

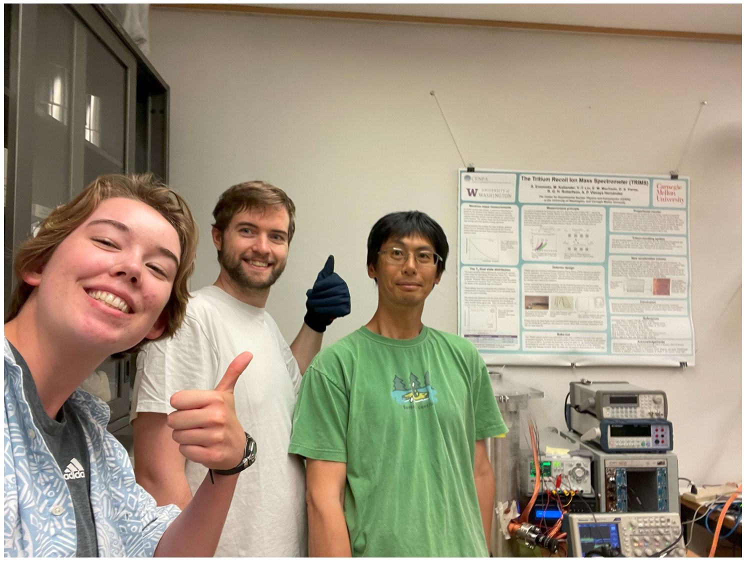
A big thank you to the following organizations for supporting me in this research experience:

CENPA
Center for Experimental Nuclear Physics and Astrophysics
UNIVERSITY *of* WASHINGTON

INSTITUTE for NUCLEAR THEORY

Acknowledgments

- Thank you to the REU organizers!
- Thank you to my fellow REU interns for a great summer!
- Thank you to Sanshiro and Alexander for their support and guidance !
- Thank you to Matt for getting things to work!
- And thank you to the entire UW KATRIN group and CENPA!



Outline

Appendix

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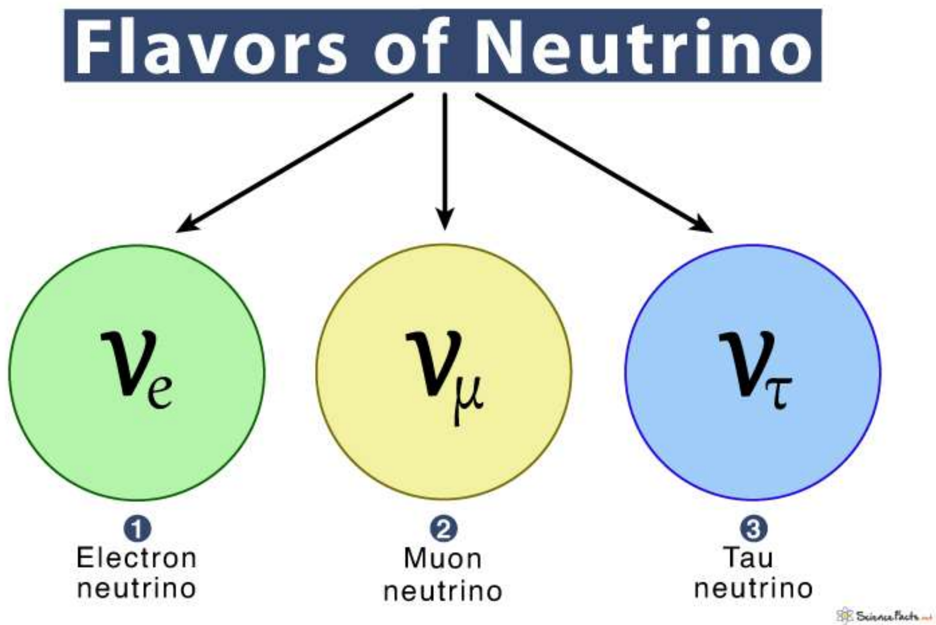
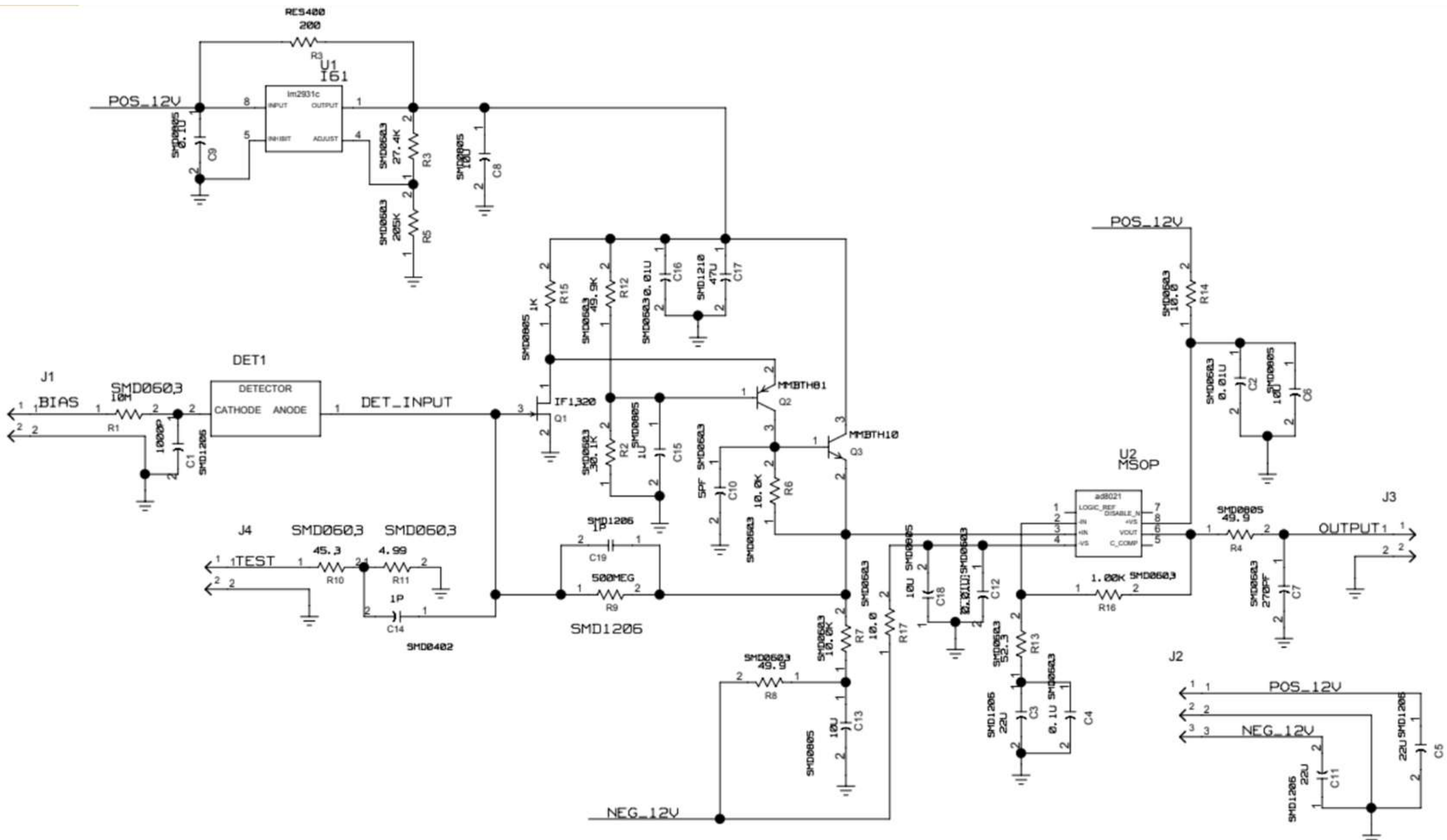
What kinds of neutrinos are there?



There Are Three Types or Flavors of Neutrino, Each Relating to a Charged Particle. Science Facts .net. Science Facts, 2023. https://www.sciencefacts.net/neutrino.html.

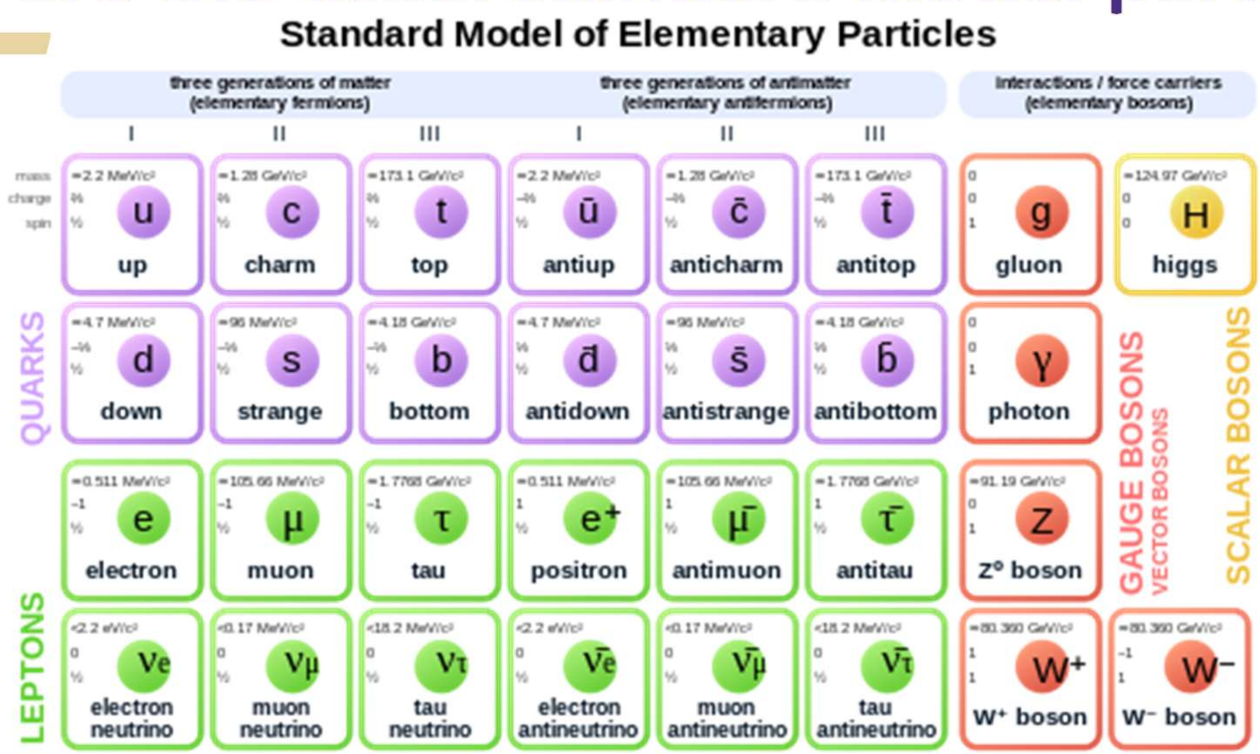
Do you have a schematic for the pre-amplifier?



What are the ADC specifications

- ADC output range: 0 to 16,000
- 150 megasamples per second
- Caen Model 725

What are the usual standard model particles?



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https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles_Anti.svg

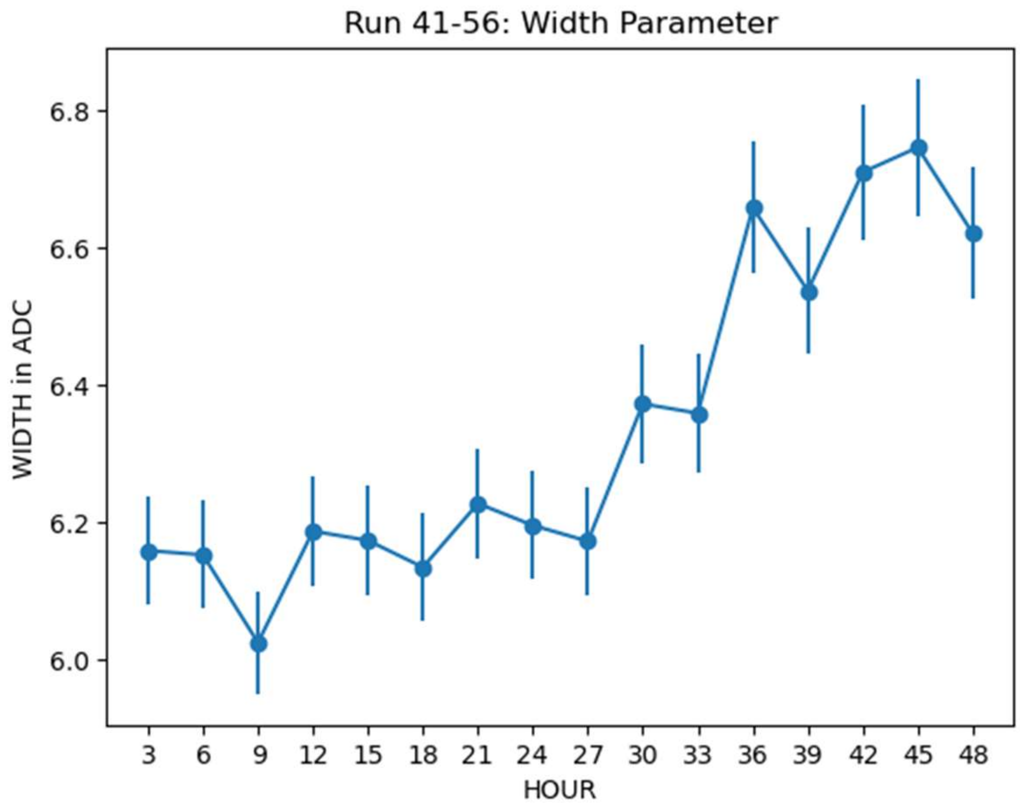
Why is KATRIN getting replaced by Project-8?

- KATRIN's resolution limit is determined by the size of the main spectrometer
- KATRIN's size limit is determined by the size of the main street in Karlsruhe
- It has hit that size limit

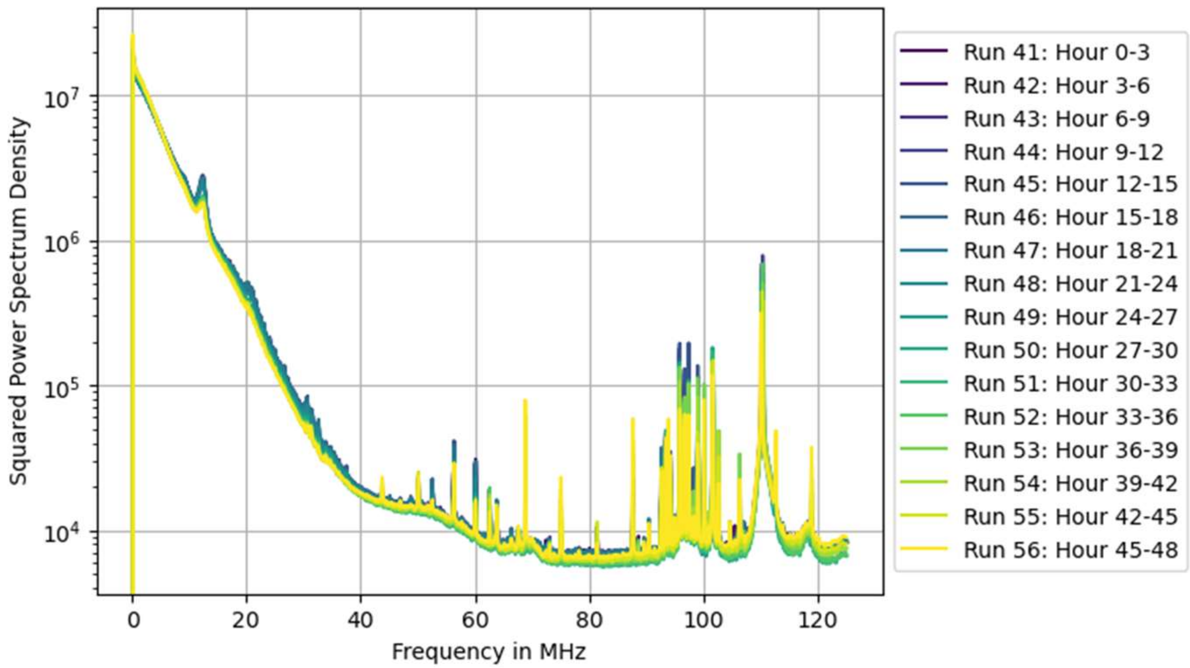
Chu, Jennifer, KATRIN experiment investigates neutrino mass, *Phys.org,* (2018). https://phys.org/news/2018-06-katrin-neutrino-mass.html

~10% Energy Resolution Drop in Response to Temperature Increase

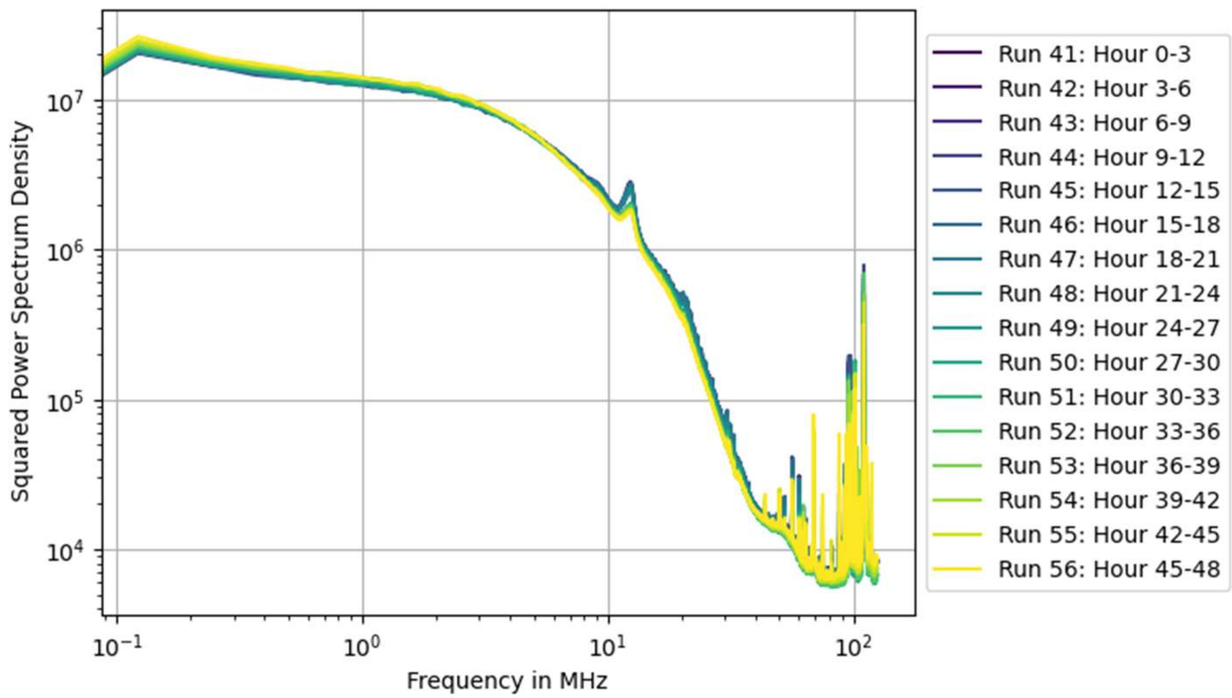
- Allowed liquid Nitrogen to boil off over 48 hours
- Not indicative of leakage current as a prominent noise source



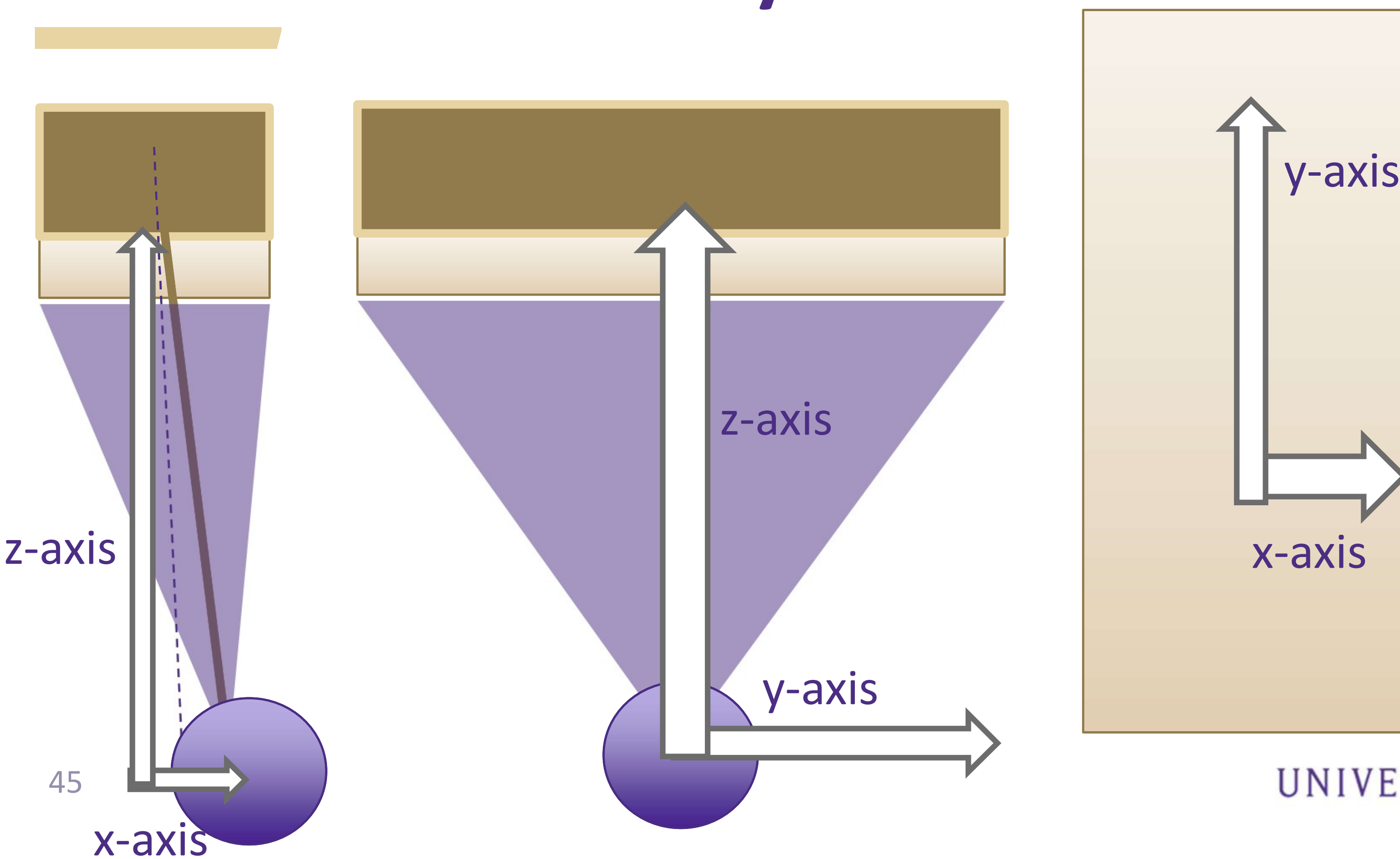
Fourier Frequency Analysis: Linear



Fourier Frequency Analysis: Logarithmic



Simulation Geometry



- Spherical emission from source
- X-position of hits varies with angle theta
- Y-position is randomly scattered about zero
- Pivot length of 2.75 in