Third Guidance Committee Meeting

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25 February 2025

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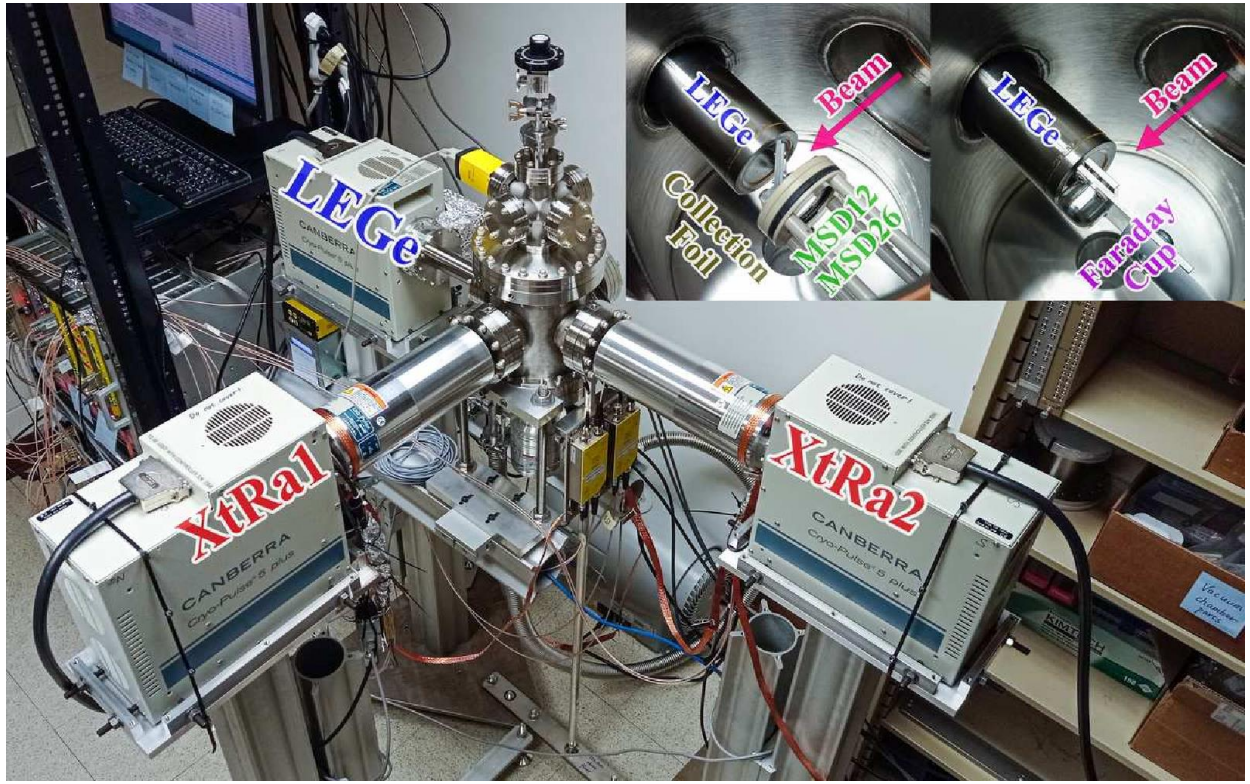
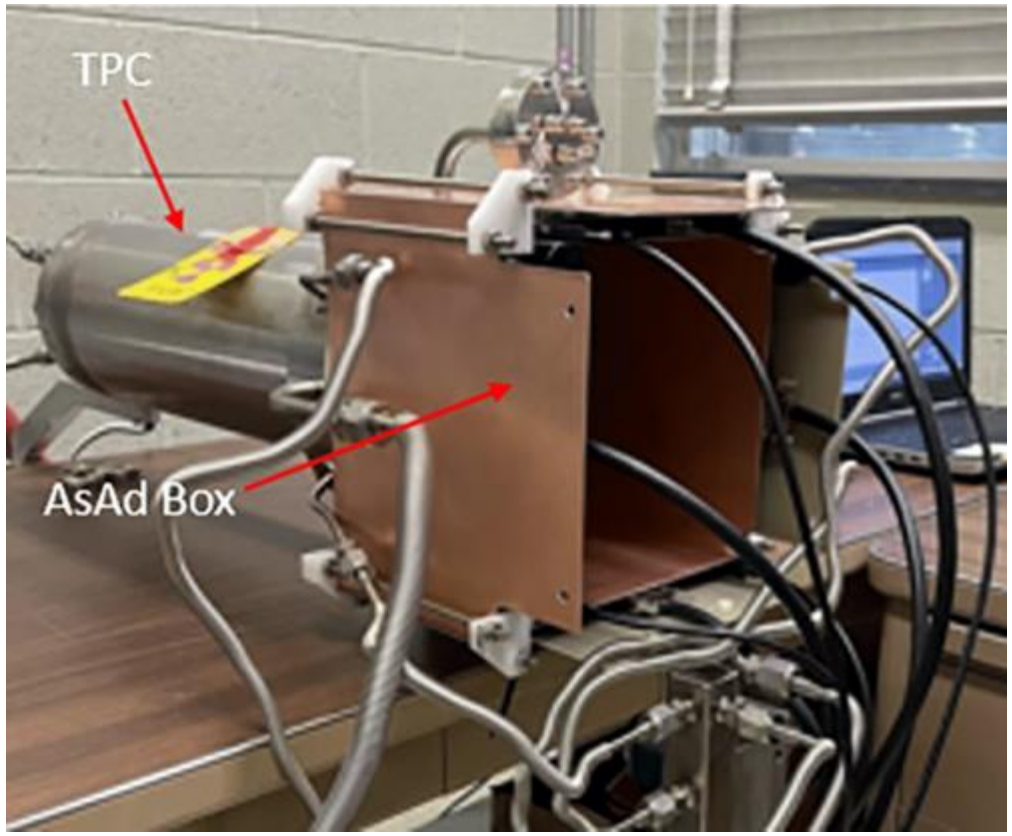
Two Part Thesis

- LIBRA (formerly PXCT) development -- HEP Instrumentation Fellowship Project

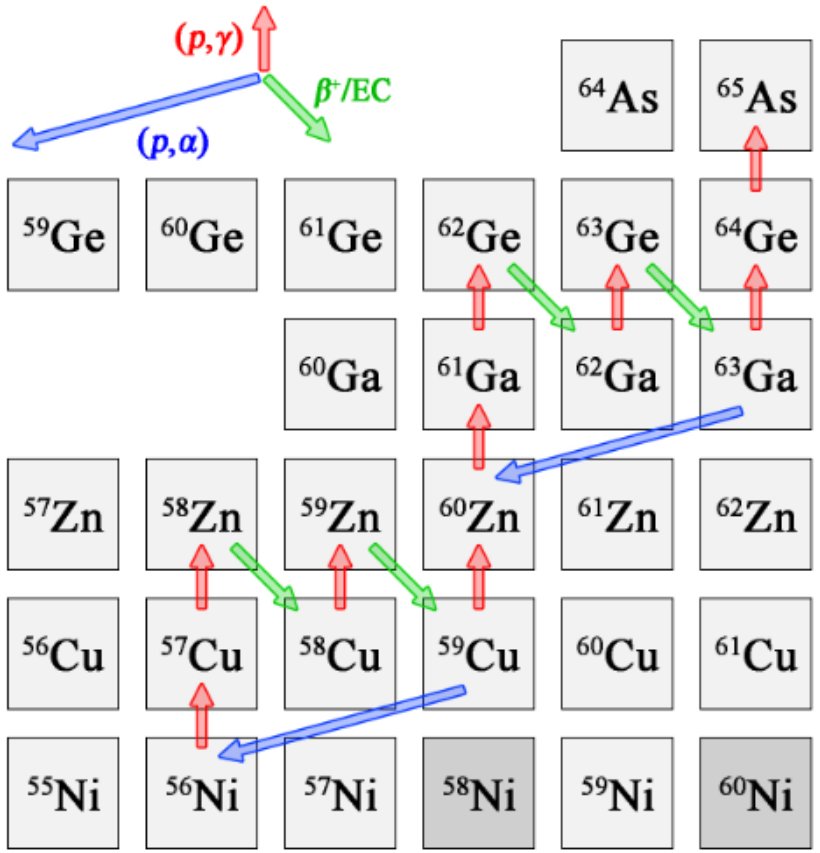


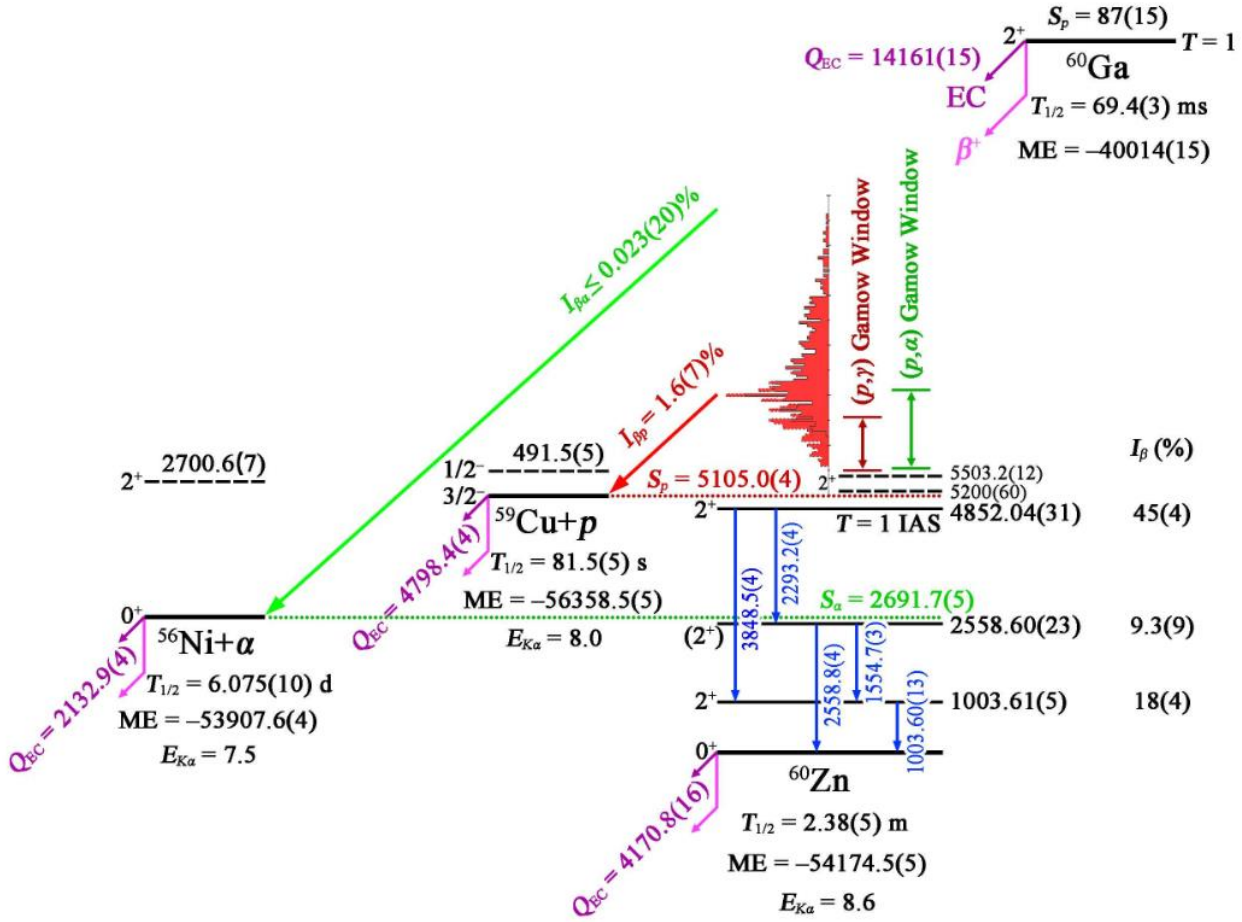
- Double Alpha Search w/ GADGET II TPC



LIBRA Paper: Case Study NiCu Cycle

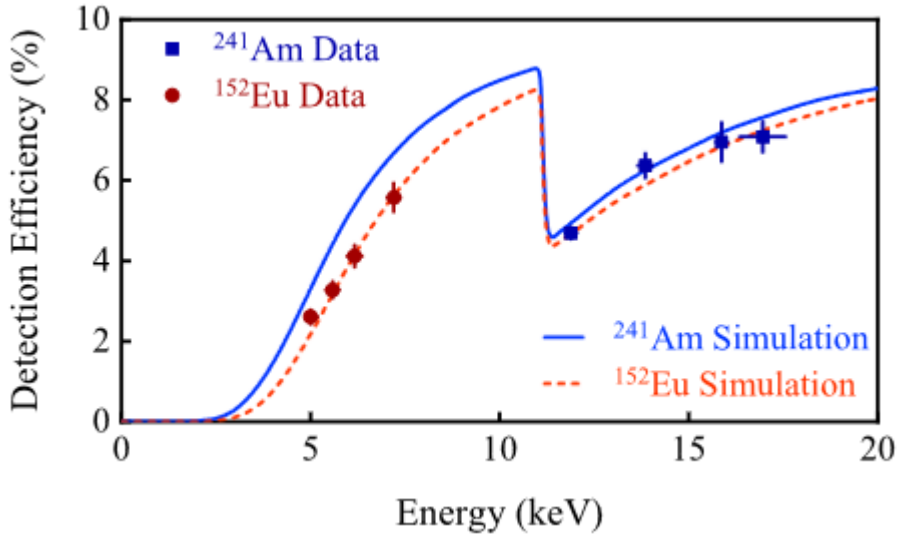
- NiCu Cycle and ZnGa Cycle portion of the rp-process

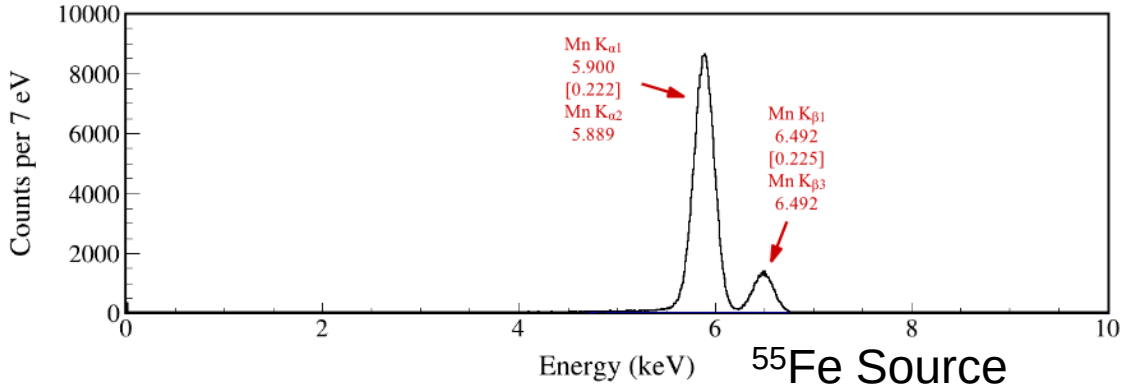




Characterizing each Ge detector

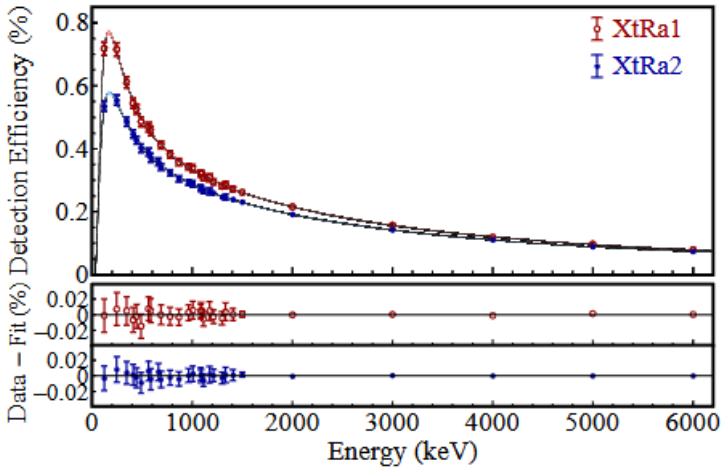
- LEGe Planar Detector

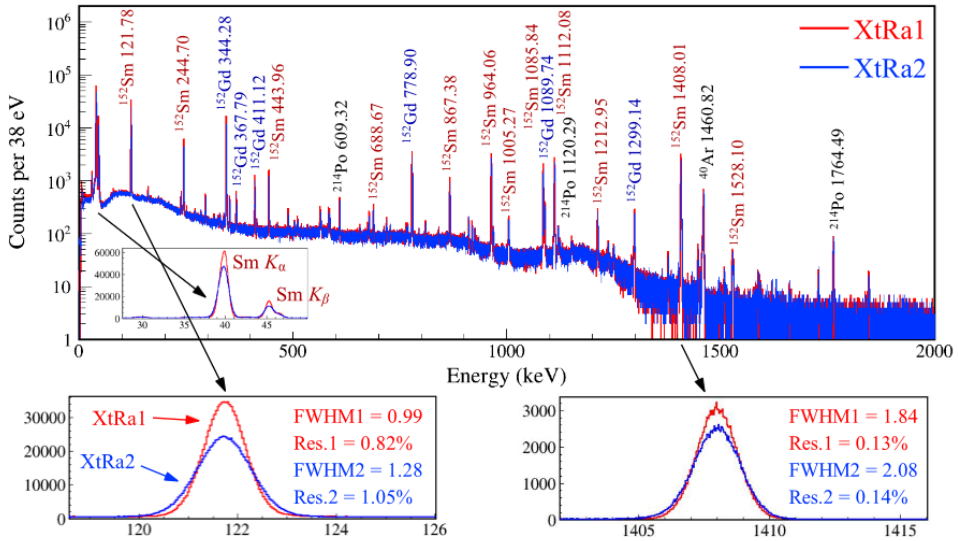




55Fe Source

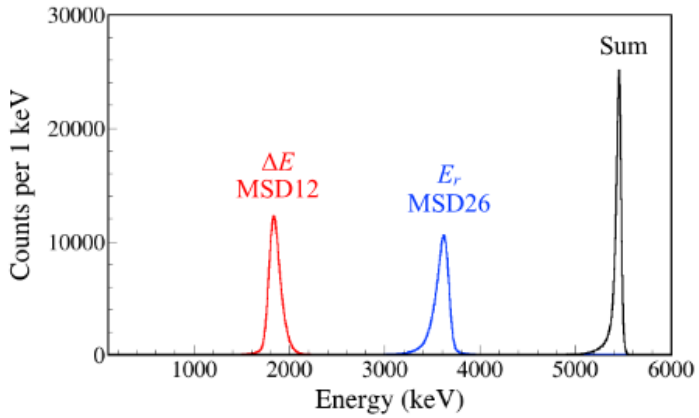
- XtRa Coaxial Ge Detector

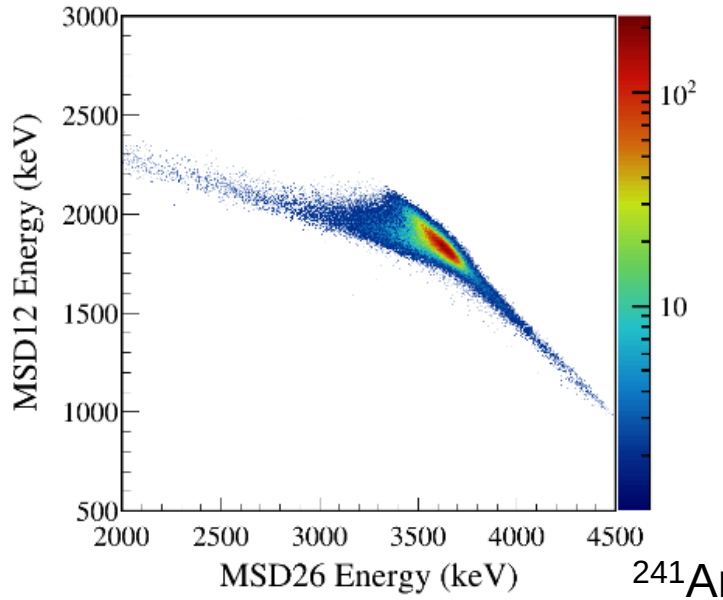


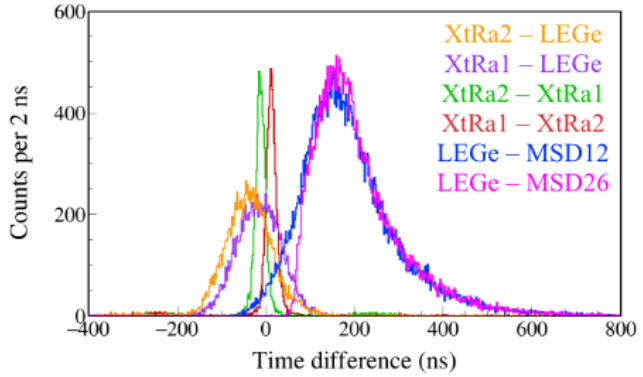


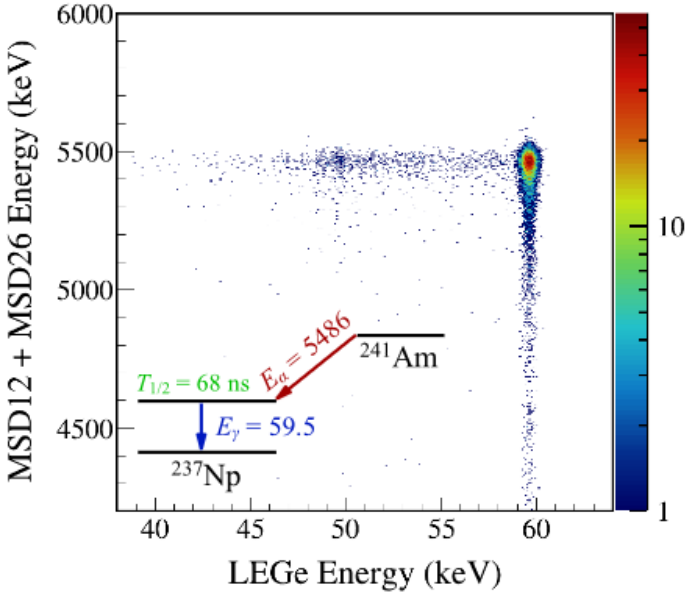
152Eu Source

Characterizing Si telescope detector & coincidences









^{241}Am Source

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Second Author Paper Summary

- Our set up that uses the Particle X-ray Coincidence Technique (PXCT) to measure lifetimes and branching ratios is fully completed and benchmarked (called LIBRA: Lifetimes and Branching Ratios Apparatus)
  - A technical paper has been submitted to PRC (https://doi.org/10.48550/arXiv.2410.16446) and we have received positive referee comments that we are in the process of responding to

Lifetimes and Branching Ratios Apparatus (LIBRA)

L. J. Sun[1],* J. Dopfer[2,1], A. Adams[2,1], C. Wrede[2,1],† A. Banerjee[3,4], B. A. Brown[2,1], J. Chen[1], E. A. M. Jensen[5], R. Mahajan[1], T. Rauscher[6,7], C. Sumithrarachchi[1], L. E. Weghorn[2,1], D. Weisshaar[1], and T. Wheeler[2,1,8]

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(Dated: October 23, 2024)

History of Double Decays

- Single Decay Modes
  - α – E. Rutherford (**1899**)
  - β – H. Becquerel (**1896**)
  - γ – P. Villard (**1900**)
- Double Decay
  - $2\nu\beta\beta$ - M. K. Moe, D. D. Lowenthal (**1980**)
  - $\gamma\gamma$ - J. Kramp, et al.(**1987**)
  - αα – Undiscovered (**????**)

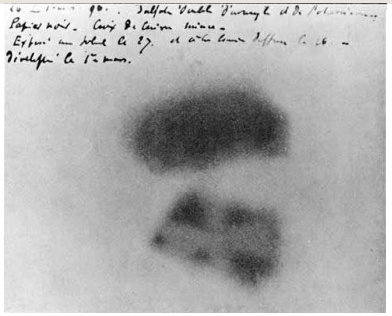
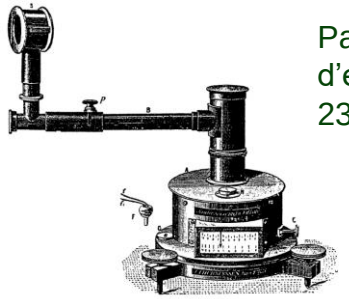
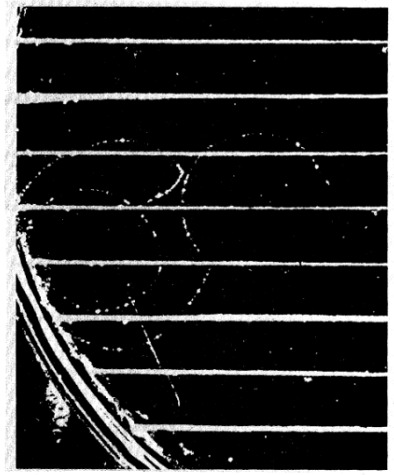
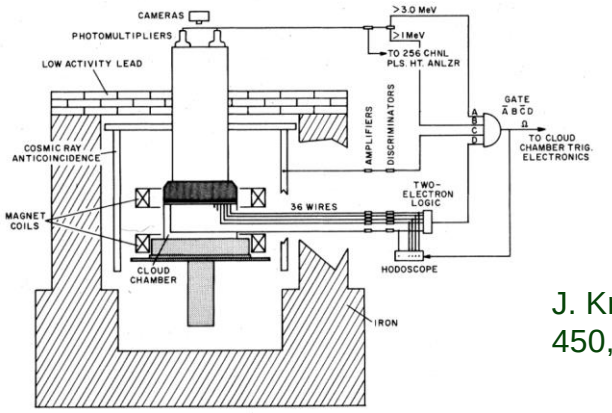


Image Credit: CERN

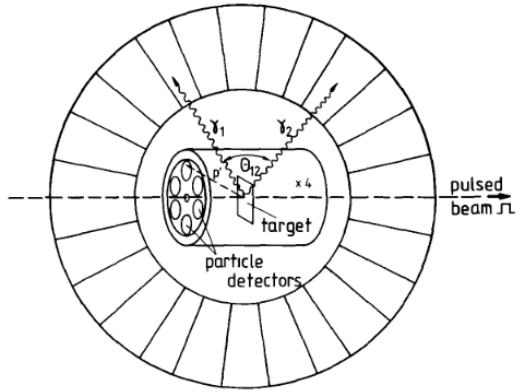


Paul Villard, Archives d'électricité médicale, 16, 236–238, (1908).





M. K. Moe *et al.*, Phys. Rev. C, 22, 2186, (1980).



J. Kramp et al., Nuclear Phys. A, 474, 2, 412-450, (1987).

Double Alpha Decay Theory

ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА / NUCL. PHYS. AT. ENERGY 22 (2021) 121-126

ЯДЕРНА ФІЗИКА
NUCLEAR PHYSICS

УДК 539.164 https://doi.

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SPONTANEOUS DOUBLE ALPHA DECAY: FIRST EXPERIMENTAL LIMIT AND PROSPECTS OF INV

Nuclear decays with simultaneous emission of two alpha particles are energetic nuclides. Prospects of searching for such kind of decay for nuclides present in the elements are discussed here. The first experimental limit on half-life for 2α decay is se 90 % C.L., using the data of work [P. de Marcillac et al. Nature 422 (2003) 876]. The process are also given. Using these values, which are on the level of 10^{33} y or more, one of experimental observation of 2α decay are very pessimistic.

Keywords: double alpha decay, low background experiments, theoretical and experin

PHYSICAL REVIEW LETTERS **127,** 01

PHYSICAL REVIEW C **104**, 064604 (2021)

Theoretical investigation on double-α decay from radioactive nuclei

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(Received 31 July 2021; revised 26 October 2021; accepted 24 November 2021; published 8 December 2021; corrected 25 February 2022)

Theoretical investigation on the concept of double-α (2α) decay is studied in the framework of the modified generalized liquid drop model with different preformation parameters. Comparison of 2α and ^{8}Be emission from various nuclei reveals that 2α emission is more probable than ^{8}Be emission, and ^{8}Be emission does not occur due to its highly unstable nature. Probable 2α emitters are investigated for nuclei in the natural isotopic compositions of elements with atomic numbers varying from 60 to 92 and our predictions on half-lives are in agreement with the values reported by Tretyak [Nucl. Phys. At. Energy. **22**, 121 (2021)] using the semiempirical formula for cluster decays. The computed 2α half-life of ^{209}Bi using the SemFIS formula is found to be 1.926×10^{15} yr and is compared with the first reported experimental limit ($T_{1/2} > 2.9 \times 10^{20}$ yr) estimated from the experimental data of de Marcillac *et al.* [Nature (London) **422**, 876 (2003)]; and this observation demonstrates the possibility of the detection of 2α decay from the ^{209}Bi isotope. We have also predicted 2α half-lives for various isotopes $^{191-226}$At, $^{193-228}$Rn, $^{197-232}$Fr, $^{201-235}$Ra, $^{205-237}$Ac, $^{208,211-239}$Th, $^{212-241}$Pa, $^{215-243}$U, and $^{219-245}$Np, and most of the decay half-lives are below the measurable upper limit thereby promising chances to enhance experimental investigations on 2α decay in the future.

DOI: 10.1103/PhysRevC.104.064604

PHYSICAL REVIEW C **107**, 024614 (2023)

α and 2α decay of nuclei in the region $94 \leqslant Z \leqslant 101$ using the modified generalized liquid drop model

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[2]*School of Pure and Applied Physics, Kannur University, Swami Anandatheertha Campus, Payyanur, Kerala 670327, India*

(Received 23 December 2022; revised 1 February 2023; accepted 9 February 2023; published 22 February 2023)

The α decay and 2α decay of various isotopes of Pu, Am, Cm, Bk, Cf, Es, Fm, and Md in the mass region $A = 218$ to 273 are investigated using the modified generalized liquid drop model (MGLDM) and universal decay law. The comparison of experimental alpha decay half-lives with the predicted half-lives proves the consistency of our calculations. As a result we broadened our investigation to also include a study of double alpha decay of these isotopes. There is a considerable interest in performing research on double alpha decay, as seen by the proposal submitted at CERN to investigate the double alpha radioactivity of ^{224}Ra. In view of this, the decay half-lives of most probable 2α emitters, calculated using MGLDM by employing different preformation factors, are presented which can be beneficial for upcoming experimental investigations on this topic. A peak or dip in α and 2α decay half-life is witnessed which indicates the stability of parent or daughter isotopes correspondingly. Minimum and maximum half-lives for decay are observed when the daughter and parent nuclei, respectively, contain a magic number of neutrons. From our study, 126 and 162 are found as magic/semimagic numbers. A linear plot is obtained while plotting $\log_{10}T_{1/2}$ of all the isotopes against $ZQ^{-1/2}$, which emphasizes that our estimations are reliable.

DOI: 10.1103/PhysRevC.107.024614

Microscopic Description of 2α Decay in ^{212}Po and ^{224}Ra Isotopes

F. Mercier,[1] J. Zhao,[2] J.-P. Ebran,[3,4] E. Khan,[1] T. Nikšić,[5] and D. Vretenar[5]

[1]*IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405 Orsay Cedex, France*

[2]*Center for Circuits and Systems, Peng C*

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[5]*Physics Department, Faculty of Science, U*

(Received 2 April 2021; revised 11 May 20

A microscopic calculation of half-lives for both t using a self-consistent framework based on energy de a separable pairing interaction of finite range are us surfaces as functions of quadrupole, octupole, and h action paths are determined, that trace the α and 2α e of scission. The calculated half-lives for the α decay A new decay mode, the symmetric 2α emission, is p for cluster emission.

DOI: 10.1103/PhysRevLett.127.012501

PHYSICAL REVIEW C **107**, 034311 (2023)

Microscopic description of α, 2α, and cluster decays of $^{216-220}$Rn and $^{220-224}$Ra

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[1]*Center for Circuits and Systems, Peng Cheng Laboratory, Shenzhen 518055, China*

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(Received 25 November 2022; revised 3 January 2023; accepted 1 March 2023; published 17 March 2023)

α and cluster decays are analyzed for heavy nuclei located above ^{208}Pb on the chart of nuclides: $^{216-220}$Rn and $^{220-224}$Ra, which are also candidates for observing the 2α decay mode. A microscopic theoretical approach based on relativistic energy density functionals (EDF), is used to compute axially symmetric deformation-energy surfaces as functions of quadrupole, octupole, and hexadecupole collective coordinates. Dynamical least-action paths for specific decay modes are calculated on the corresponding potential-energy surfaces. The effective collective inertia is determined using the perturbative cranking approximation, and zero-point and rotational energy corrections are included in the model. The predicted half-lives for α decay are within one order of magnitude of the experimental values. In the case of single-α emission, the nuclei considered in the present study exhibit least-action paths that differ significantly up to the scission point. The differences in α-decay lifetimes are not only driven by Q values, but also by variances of the least-action paths prior to scission. In contrast, the 2α decay mode presents very similar paths from equilibrium to scission, and the differences in lifetimes are mainly driven by the corresponding Q values. The predicted ^{14}C cluster decay half-lives are within three orders of magnitudes of the empirical values, and point to a much more complex pattern compared with the α-decay mode.

DOI: 10.1103/PhysRevC.107.034311

Estimation of the double alpha-decay half-life

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[b] *Institute for Nuclear Research, Prospect Nauki 47, 03028 Kiev, Ukraine*

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Alpha decay
Cluster emission

ABSTRACT

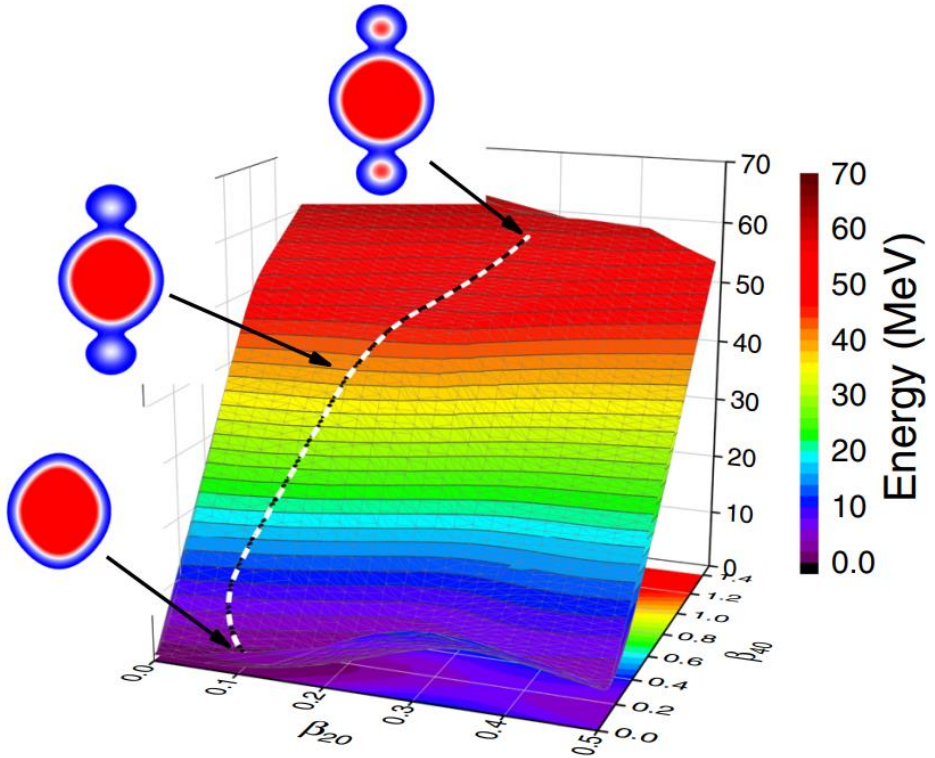
The model for the description of the simultaneous emission of two α-particles from the opposite sides of the nucleus (the double α-decay) is discussed in detail. The 32 smallest values of the half-lives of the double α-decay of nuclei are calculated. The daughter nuclei formed after the double α-decay are even-even and spherical in the ground state in the model. It is shown that the half-lives of the double α-decay are much smaller than the emission of ^{8}Be cluster with sequential decay of ^{8}Be into two α-particles. The calculated values of the double α-decay half-lives show that measuring this decay is possible in the accelerator experiments by forming the proton-rich nuclei. A detailed comparison of the characteristics of the single and double α-decays as well as the emission of ^{8}Be cluster is presented.

Double Alpha Decay Theory: ^{220}Rn

- The branching ratio of double alpha decay varies widely depending on the theoretical model
- Our goal with this experiment is to measure past the microscopic limit
- Single alpha decay of ^{220}Rn $t_{1/2}$=55.6 s

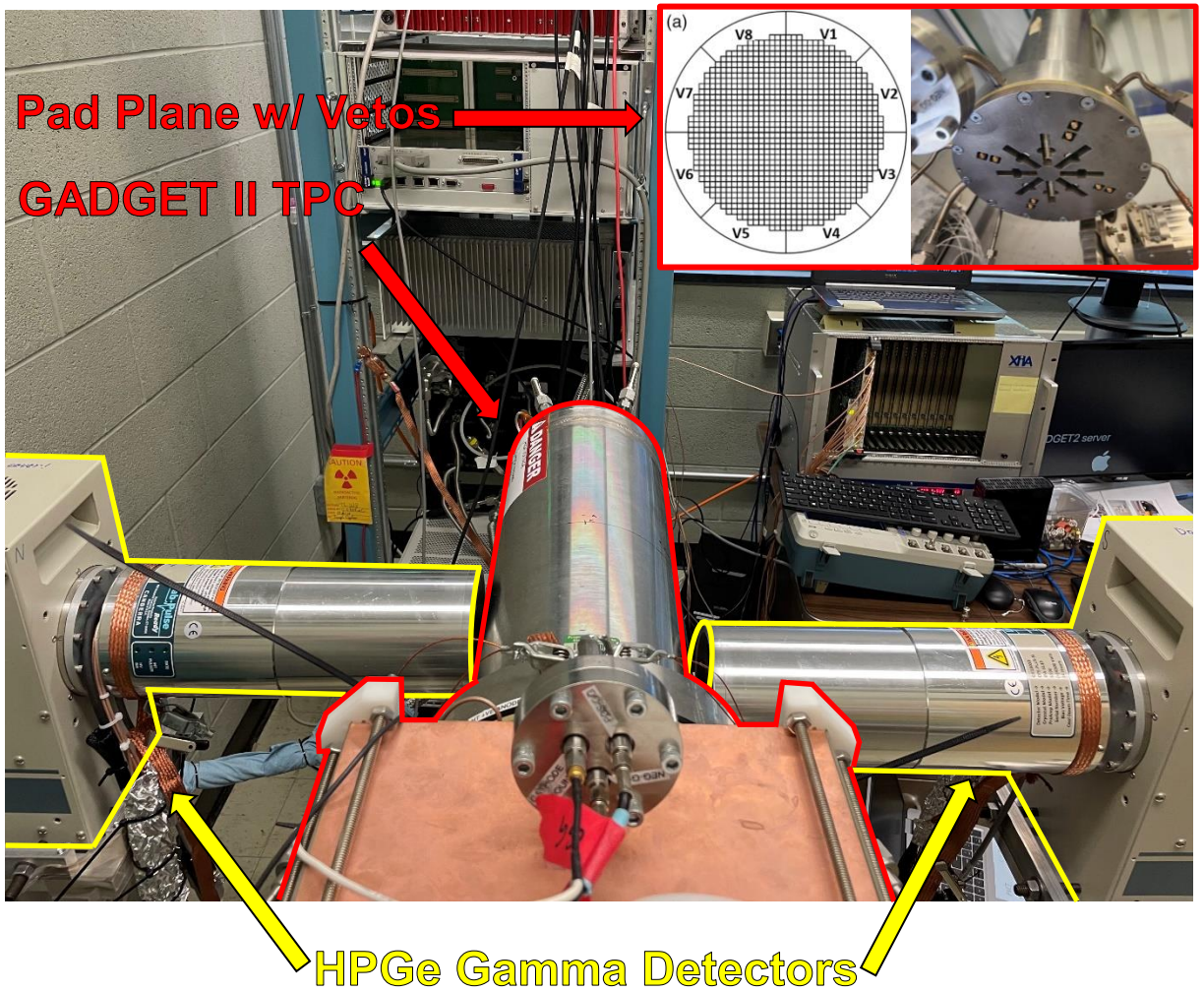
Theory	Branching Ratio	Half Life
UMADAC [1]	8.51×10^{-3}	6532 s
Microscopic [2]	3.98×10^{-7}	1.1×10^{8} s
MGLDM [3]	$\sim 10^{-20}$	$\sim 5.6 \times 10^{21}$ s

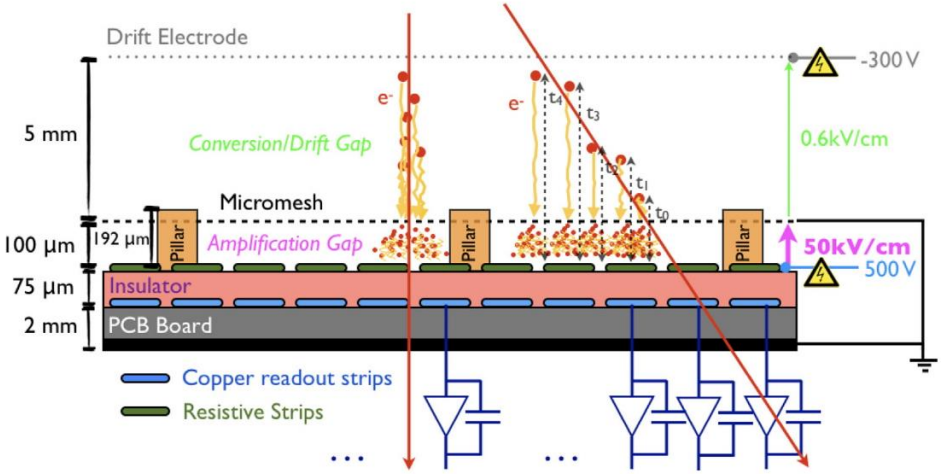
[1] V.Yu. Denisov, Phys. Lett. B, 835, 137569, (2022).
[2] J. Zhao *et al.*, Phys. Rev. C, 107, 034311, (2023).
[3] K. P. Santhosh *et al.*, Phys. Rev. C, 104, 064604, (2021).



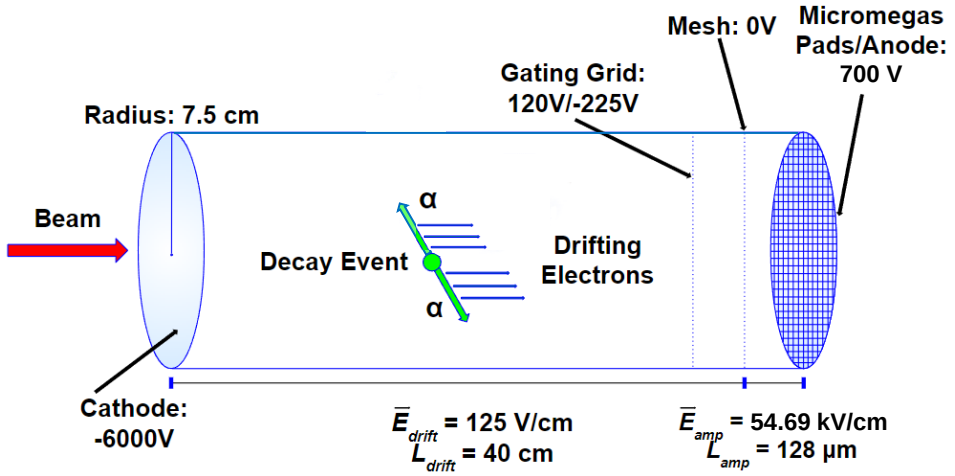
F. Mercier *et al.*, Phys. Rev. Lett., 127, 012501, (2021).

Using the GADGET II TPC to search for ^{220}Rn double alpha



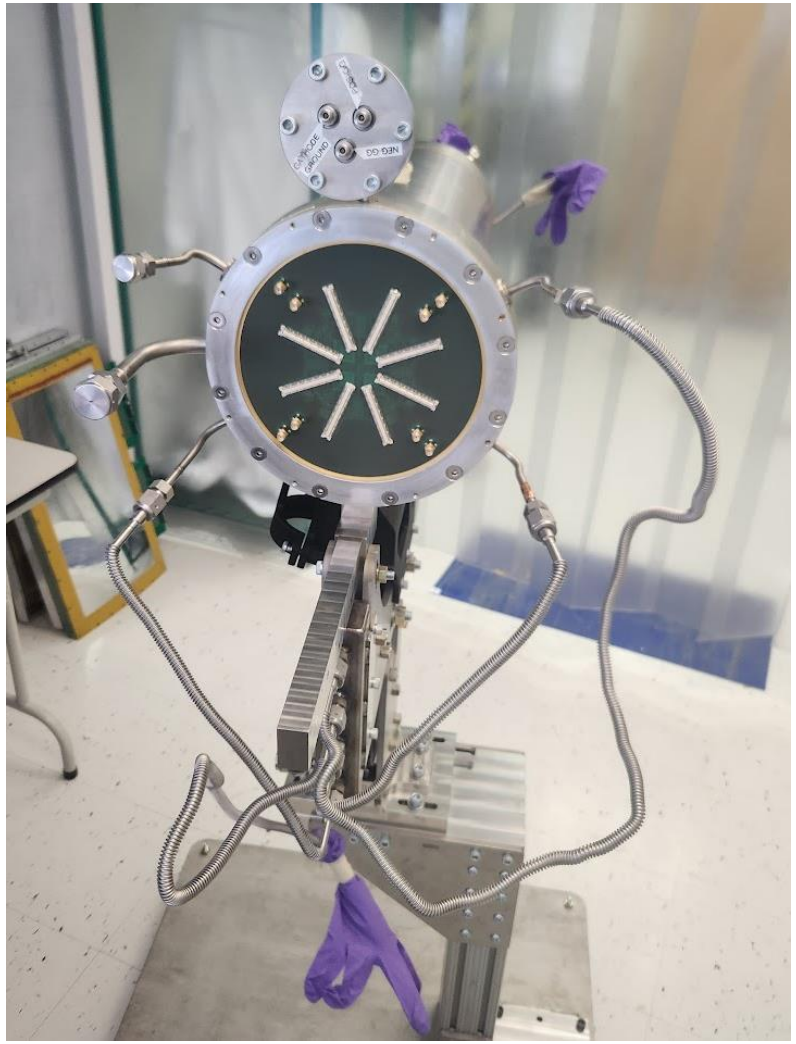


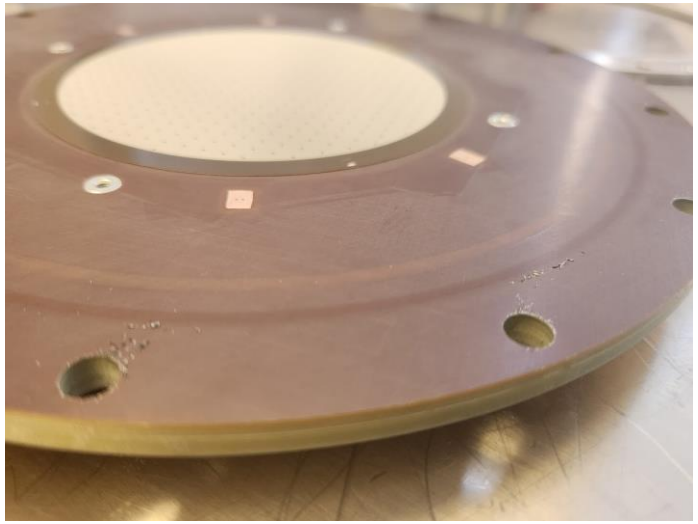
F. Kruger, Nucl. Instr. Meth., A845, 248, (2017).

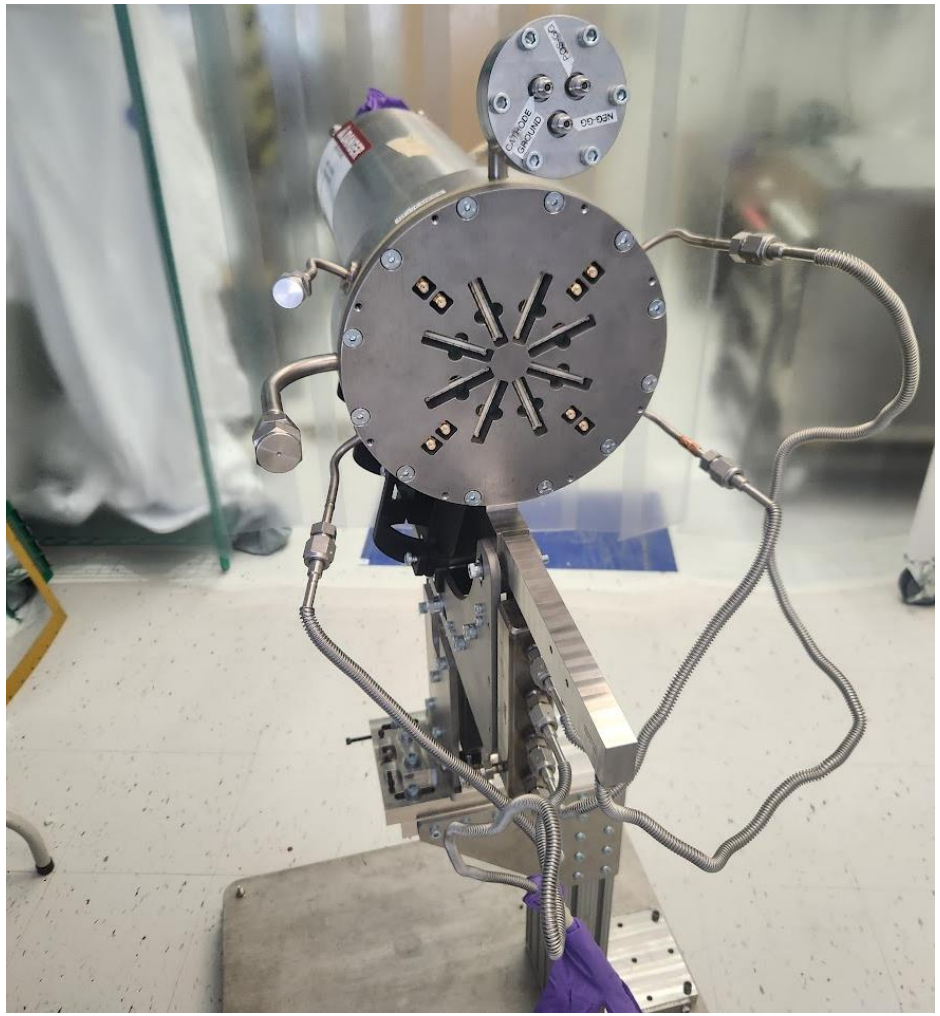


R. Mahajan, et al., Phys. Rev. C, 110, 035807, (2024).

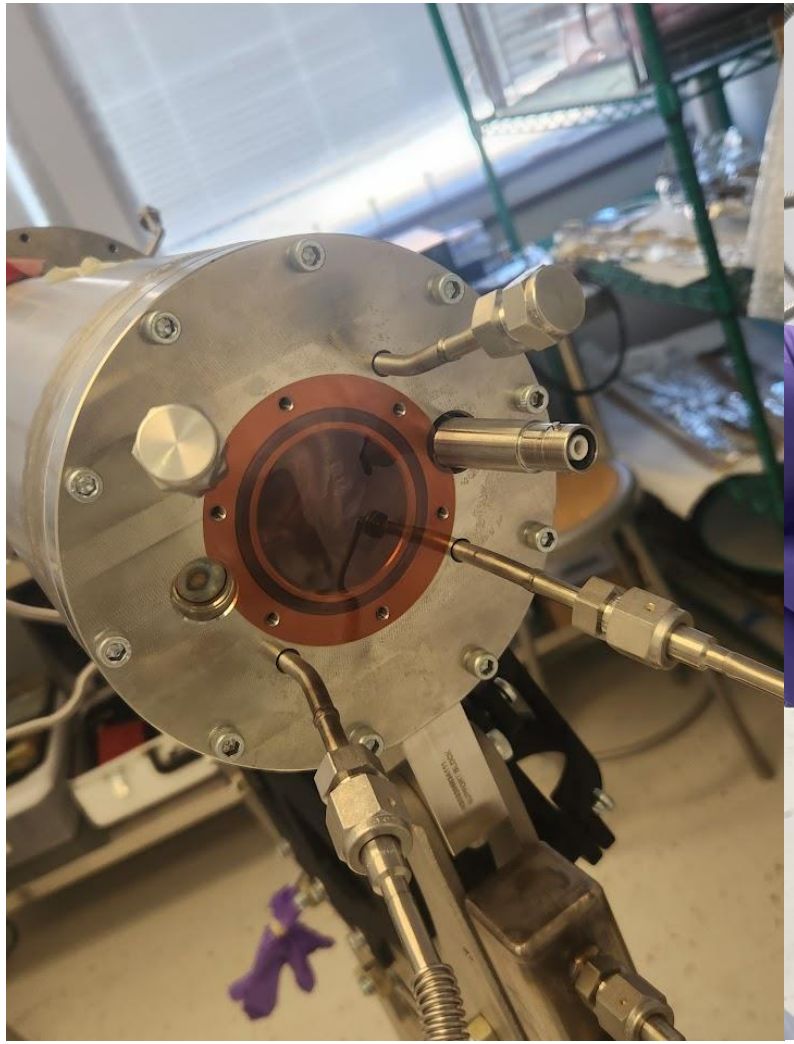
Pressure Upgrade: 800 torr → 2,000 torr

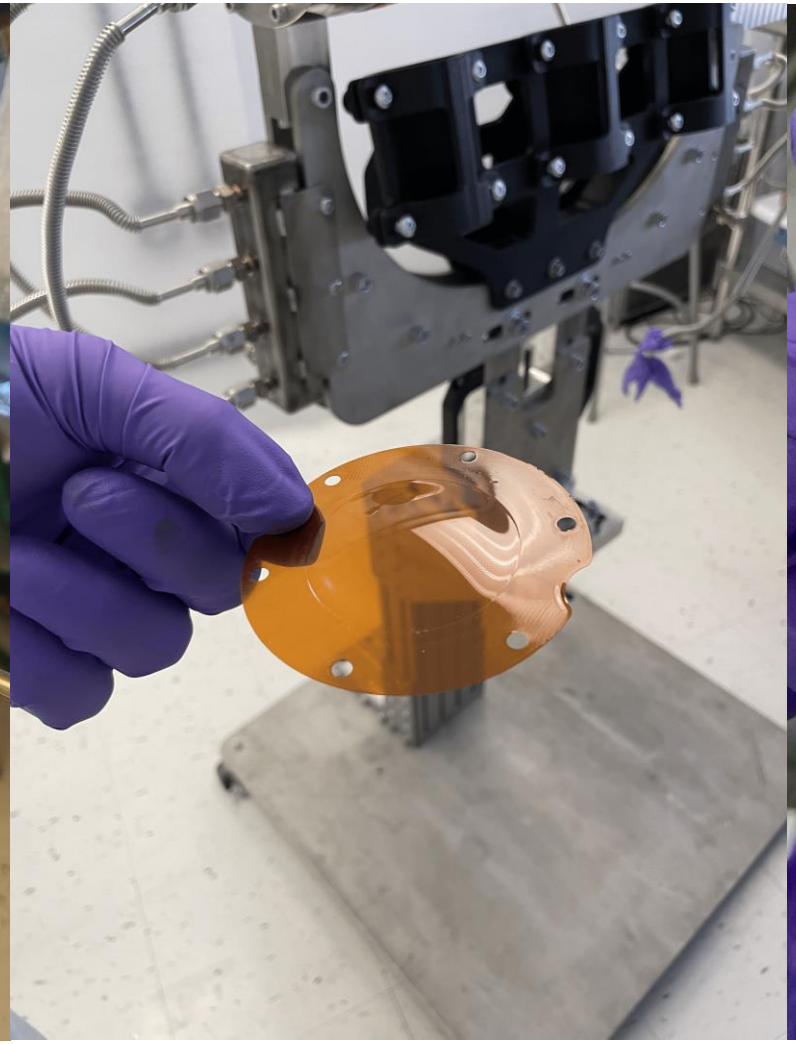


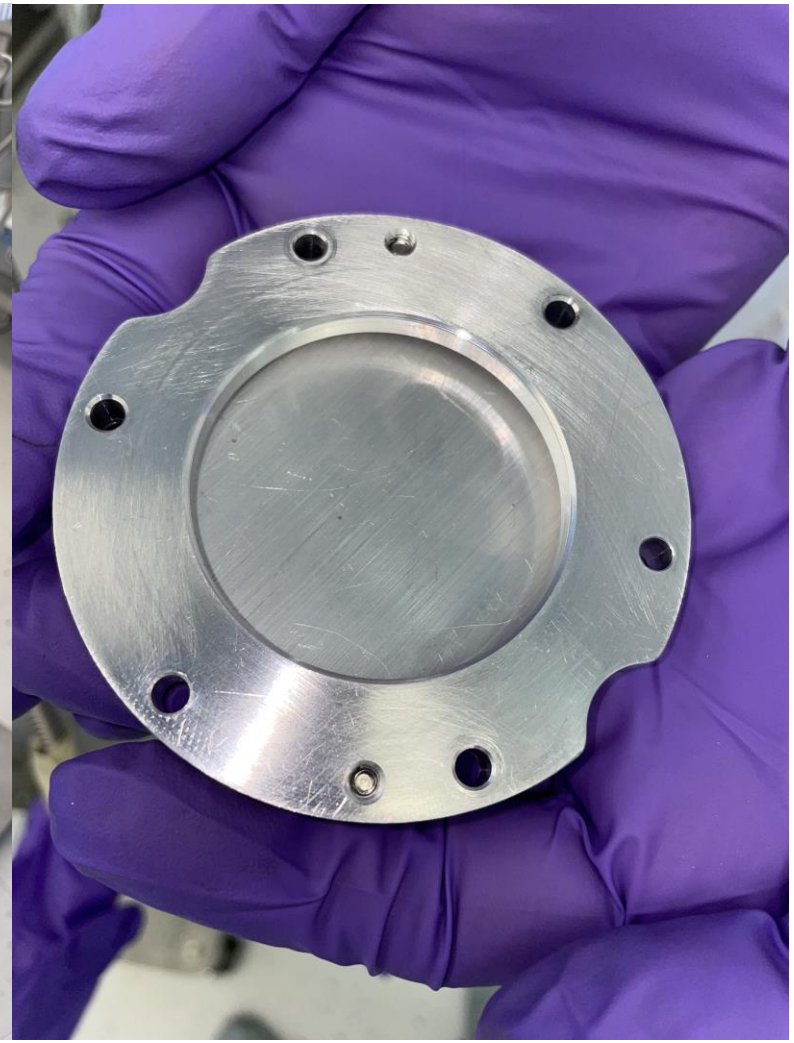




Pressure Upgrade

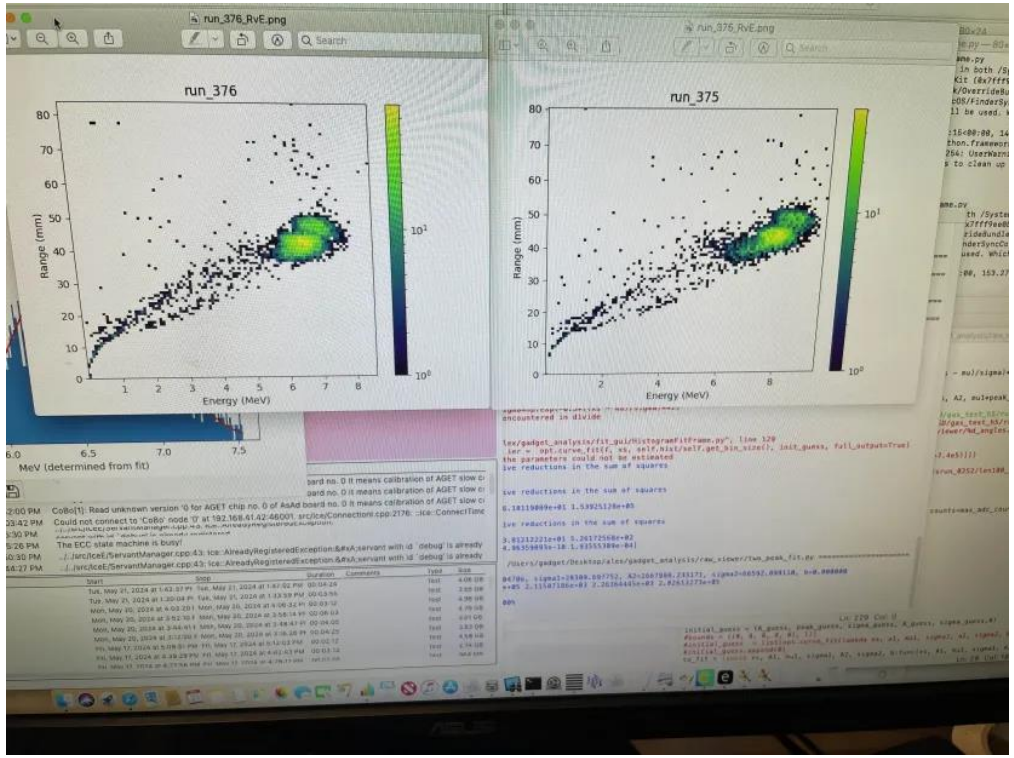


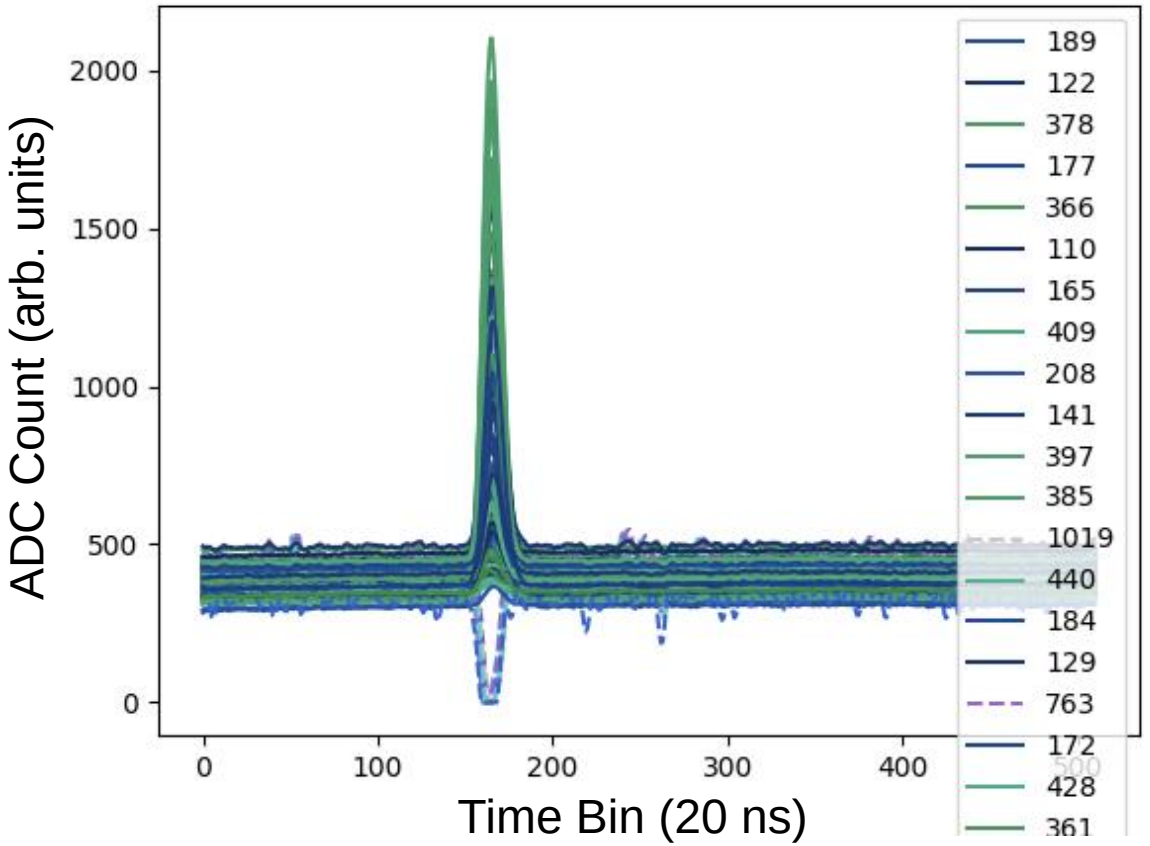




Optimizing Settings for Double Alpha and General TPC Operation

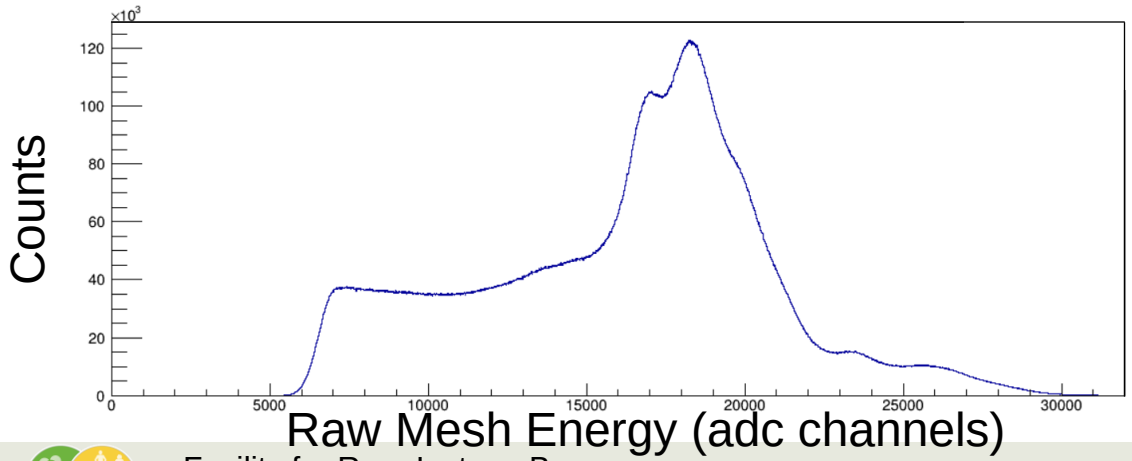
- Increasing pressure inside the TPC means that the settings in software, as well as set voltages, needed to be re-optimized

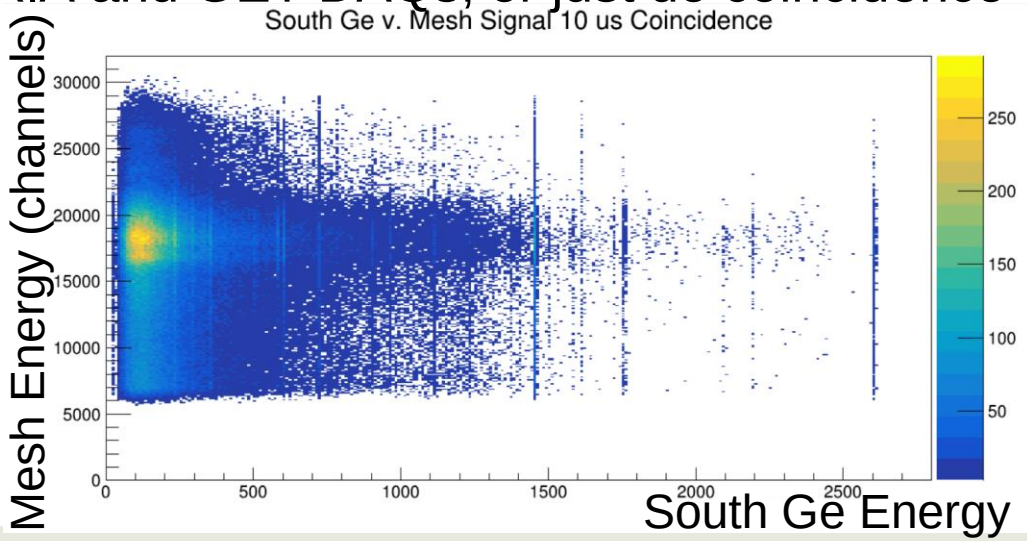




Coupling the DAQs

- Passed raw mesh & logic signal from GADGET to the XIA DAQ that recorded 4 total channels
  - North Ge Signal
  - South Ge Signal
  - Raw Mesh Signal
  - Logic Signal
- The logic signal is the trigger for the GET DAQ, which combines a threshold for the mesh signal and a busy signal for the GET DAQ
  - This means that we can compare event-to-event between XIA and GET DAQs, or just do coincidence entirely using the root files generated from the XIA data





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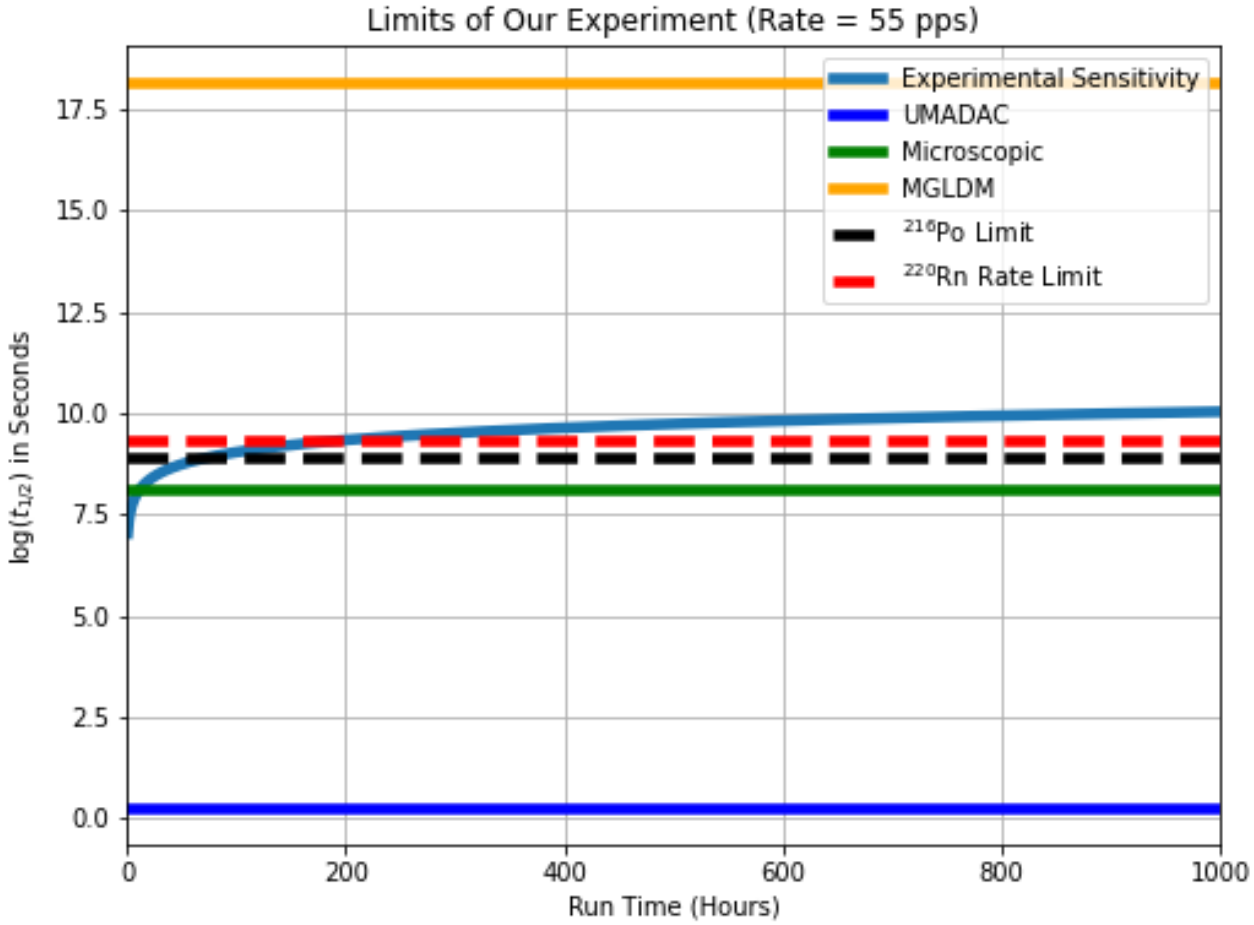
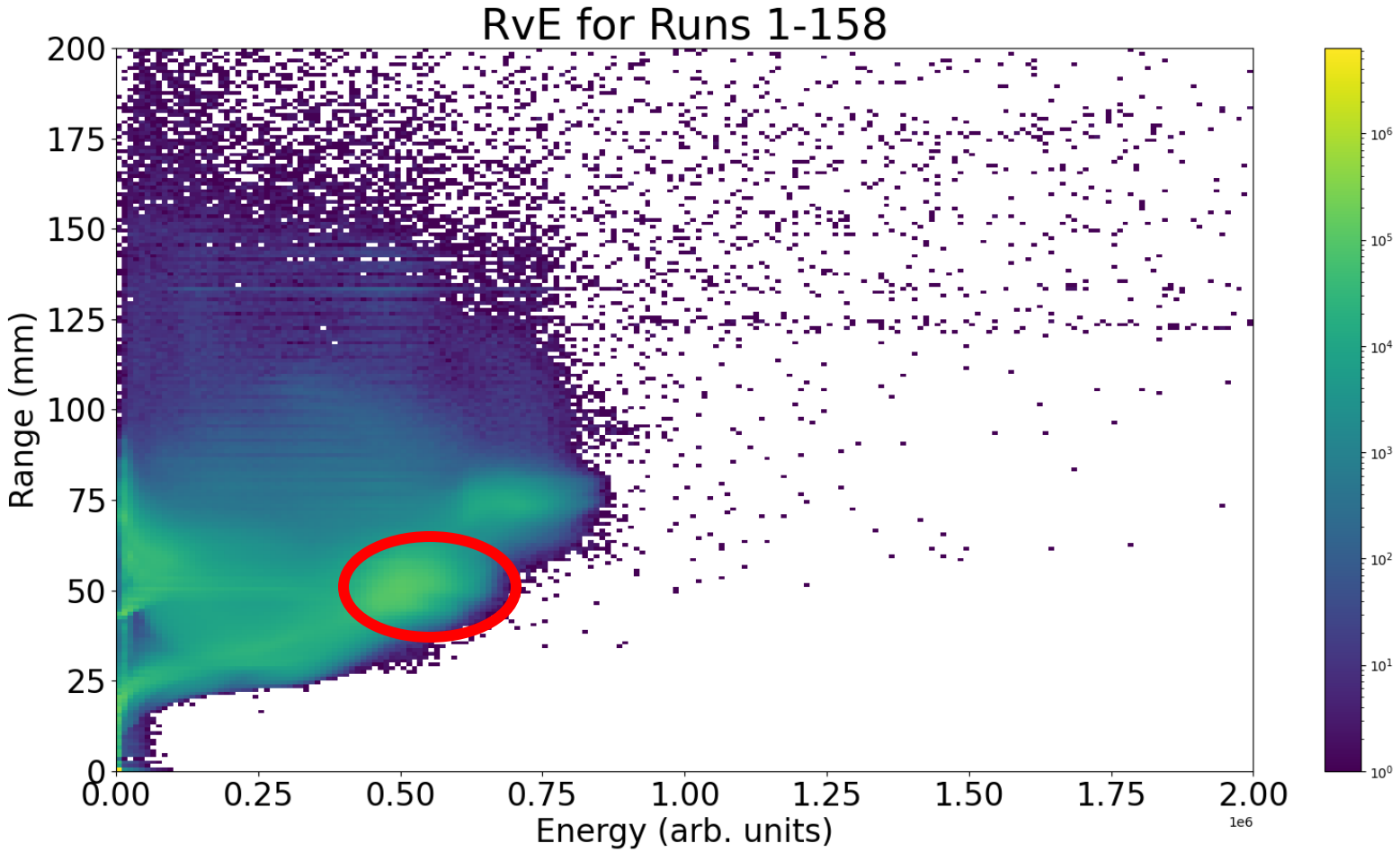
frib.msu.edu

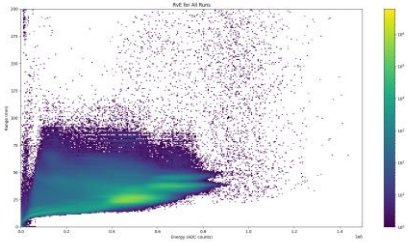
Experimental Sensitivity



Identifying Candidate Double Alpha Events

- These initial runs provide enough data to rule out the Denisov prediction of 1/100 decays being double alphas





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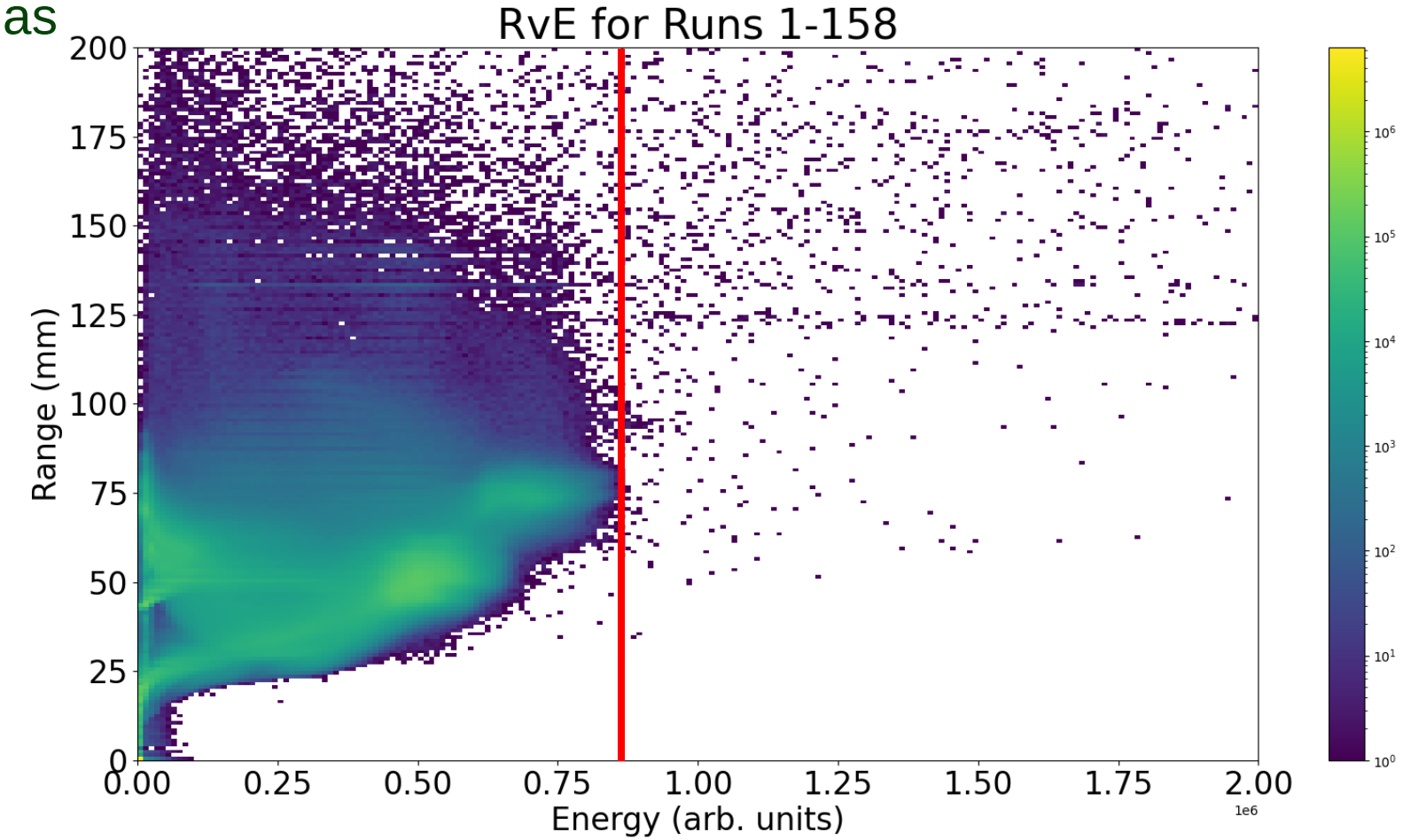
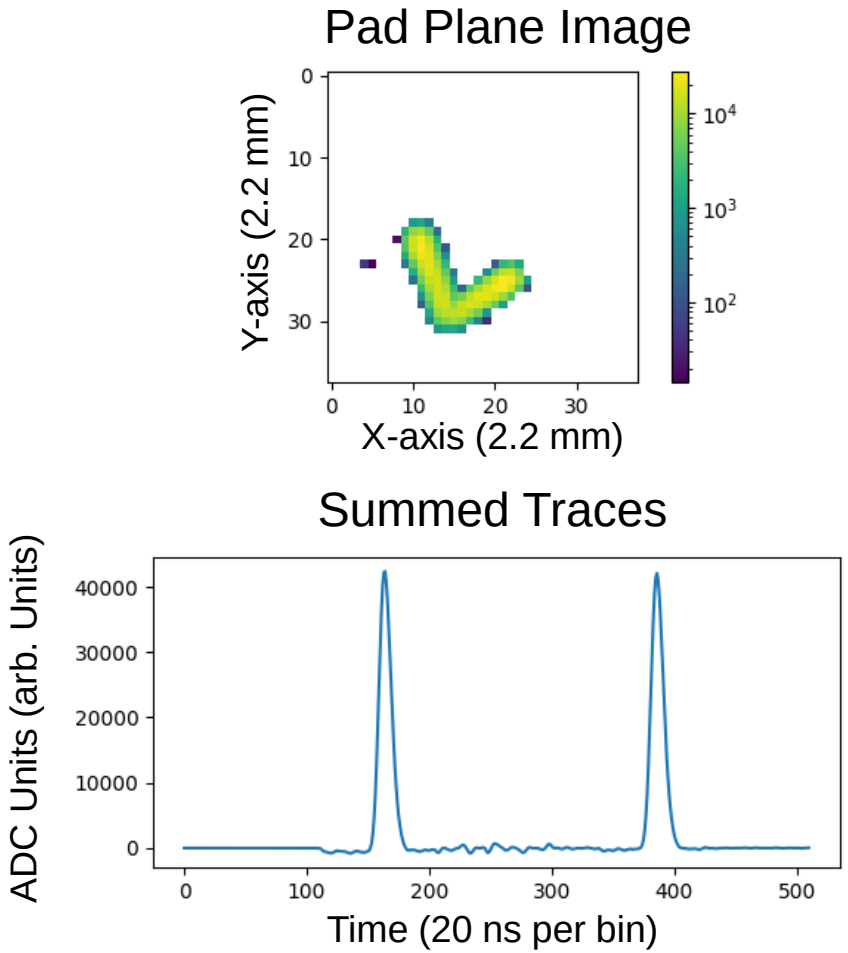
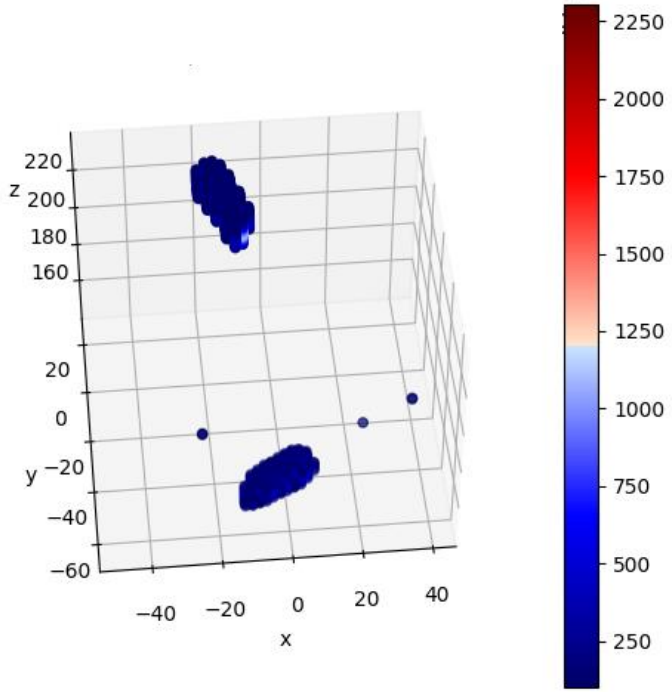


Two Alpha Events in the Cut Region

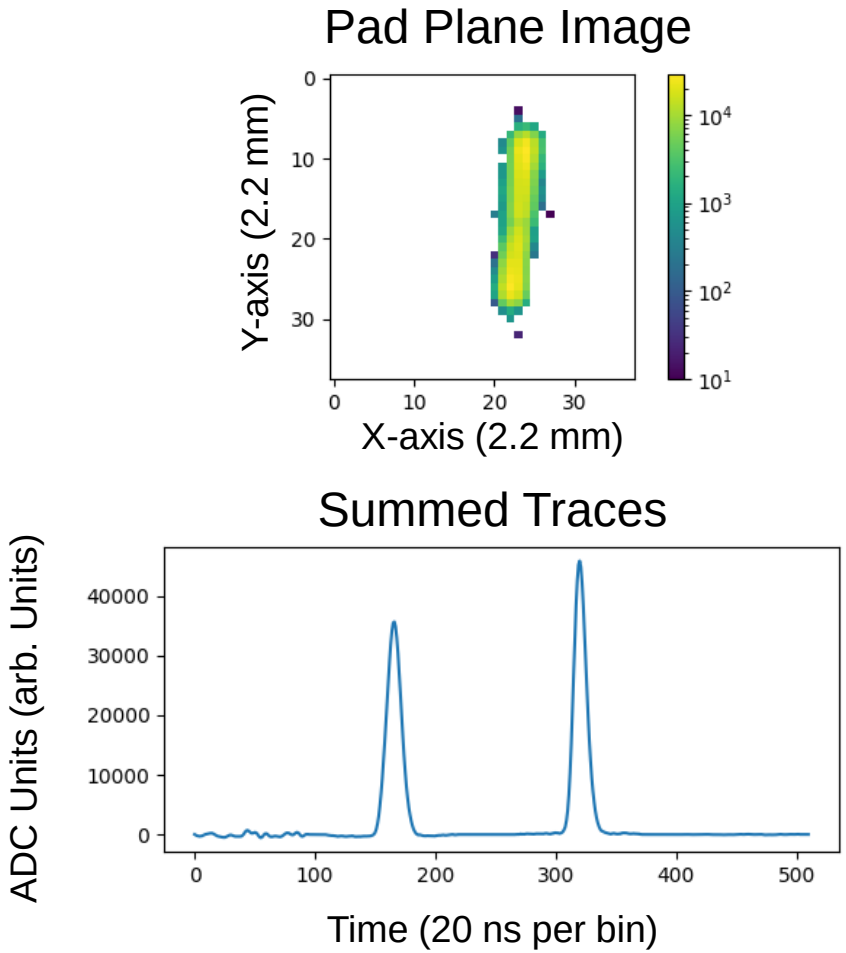
- Run 77 Event 487347 – Sequential single-alpha decays of ^{220}Rn and ^{216}Po

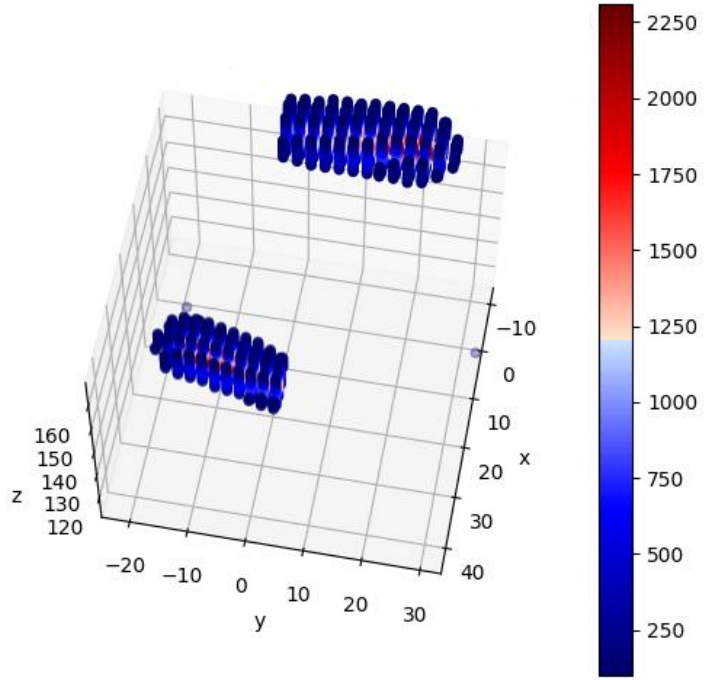




Two Alpha Events in the Cut Region

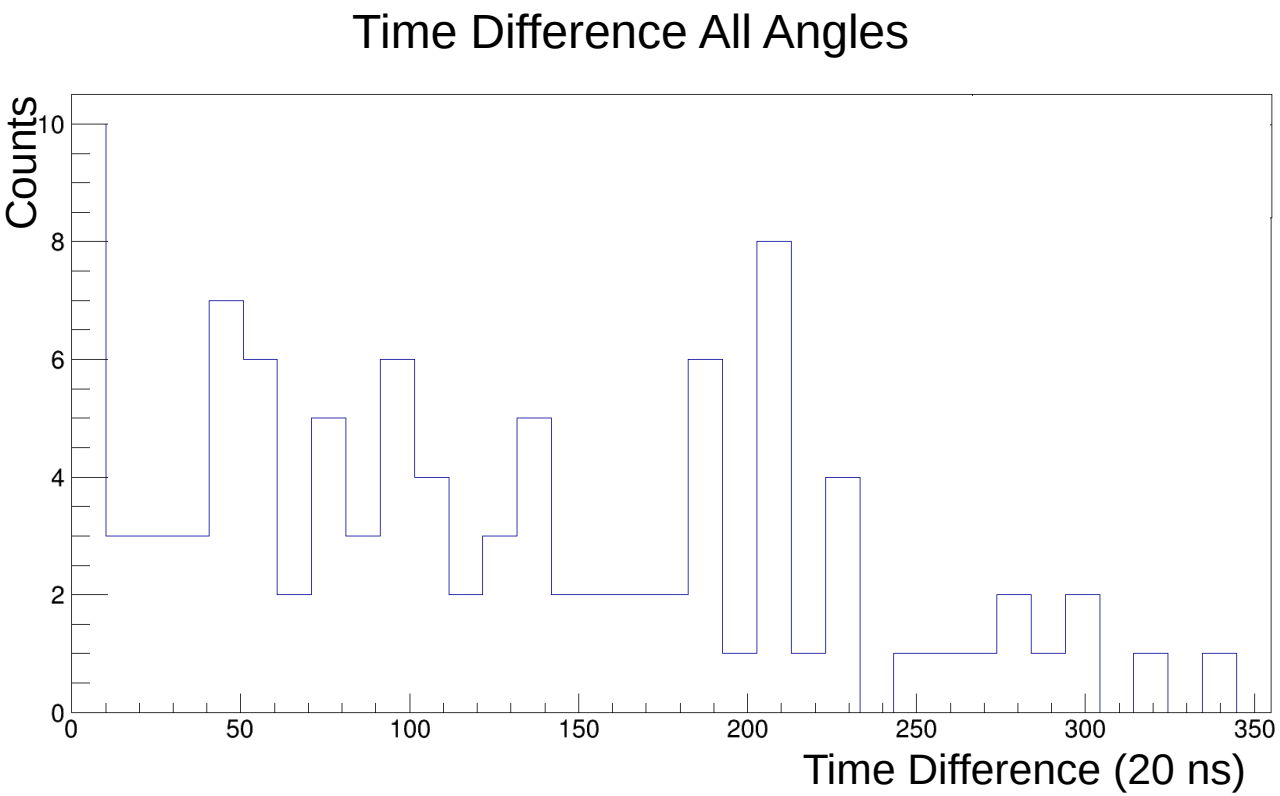
- Run 12 Event 176748 – Sequential single-alpha decays of ^{220}Rn and ^{216}Po

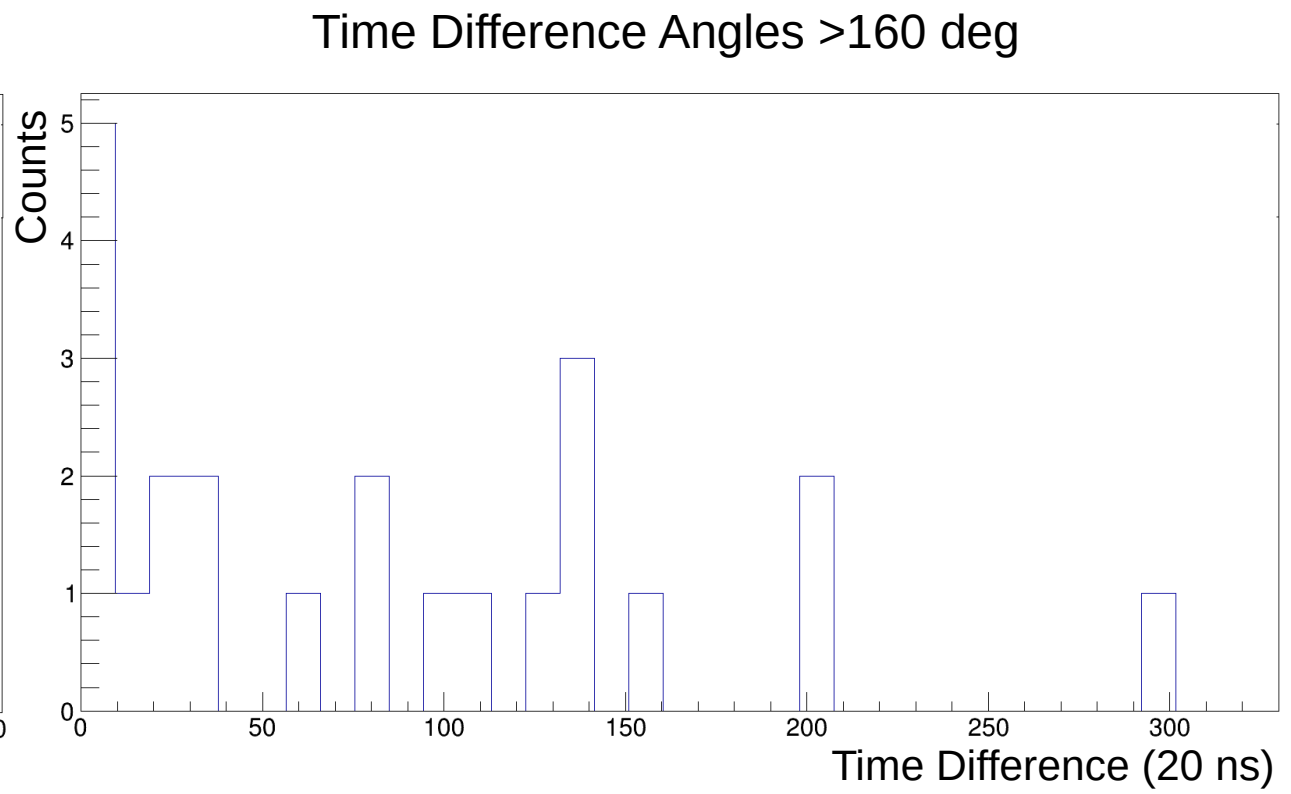




Looking for Evidence of Double Alpha Decay

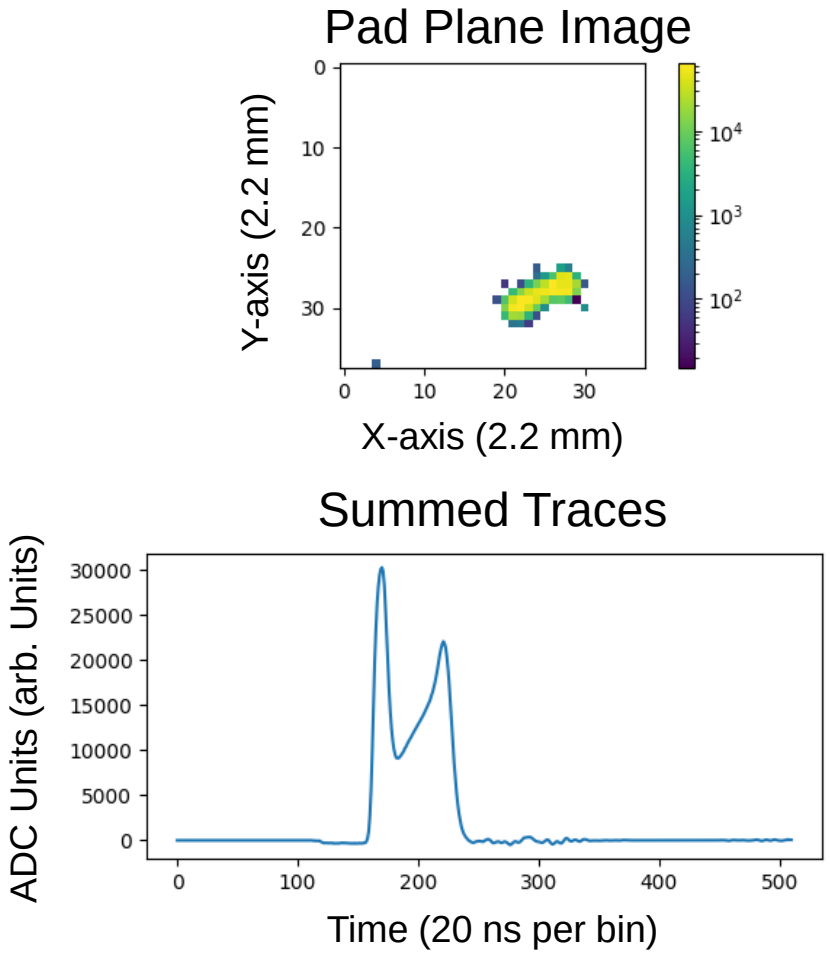
- Time difference between two alpha events histogram

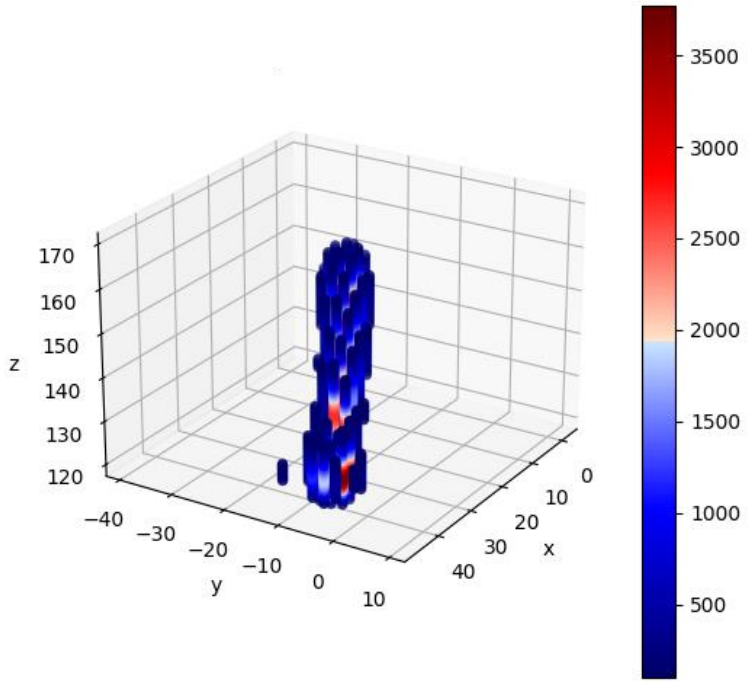




Preliminary Double Alpha Candidates

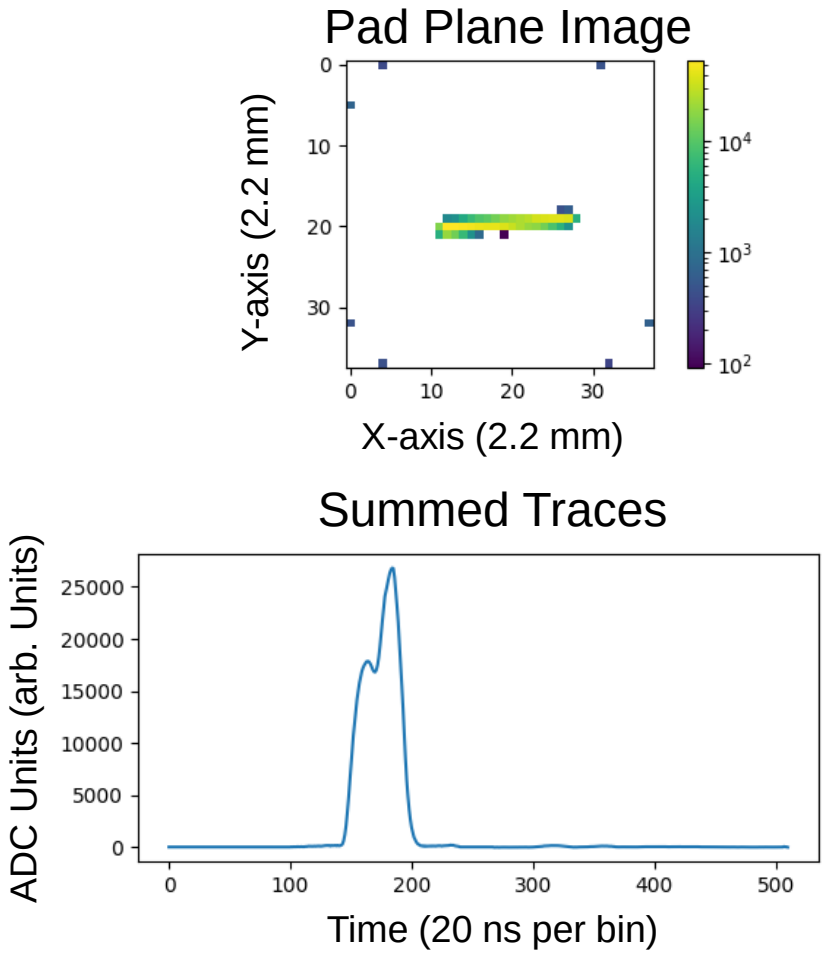
- Run 10 Event 160001 – Double Alpha Candidate

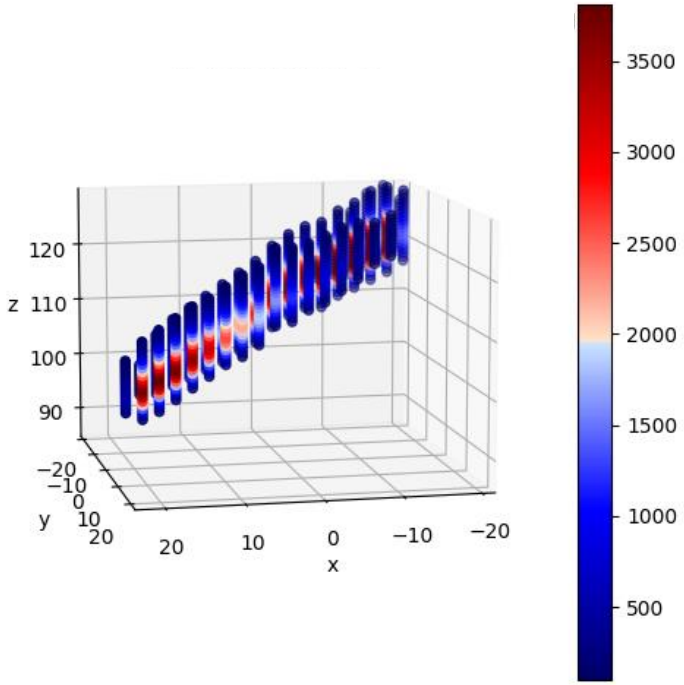




Preliminary Double Alpha Candidates

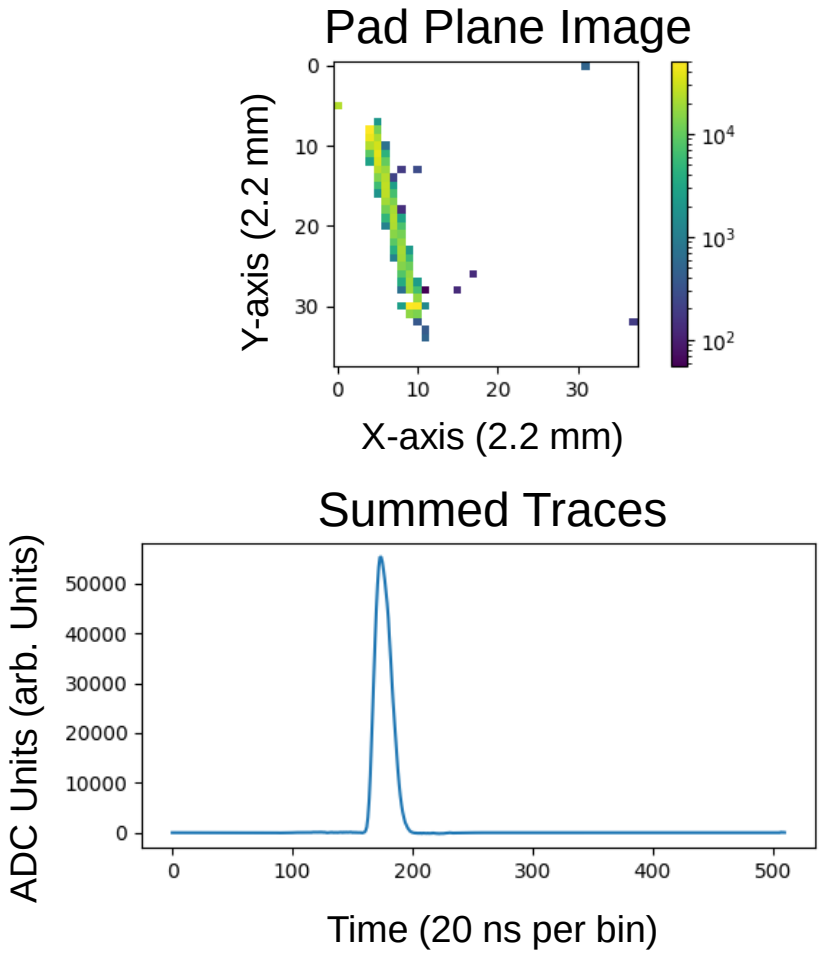
- Run 86 Event 136154 – Double Alpha Candidate

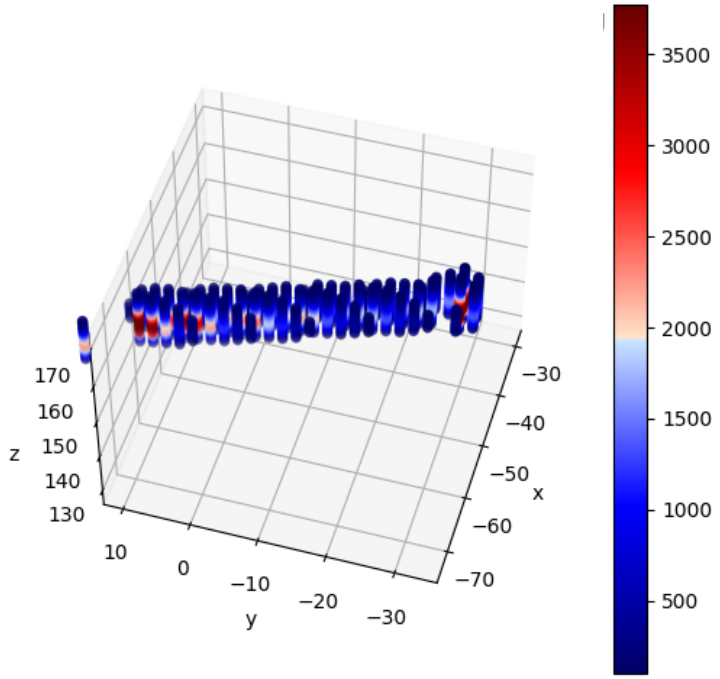




Preliminary Double Alpha Candidates

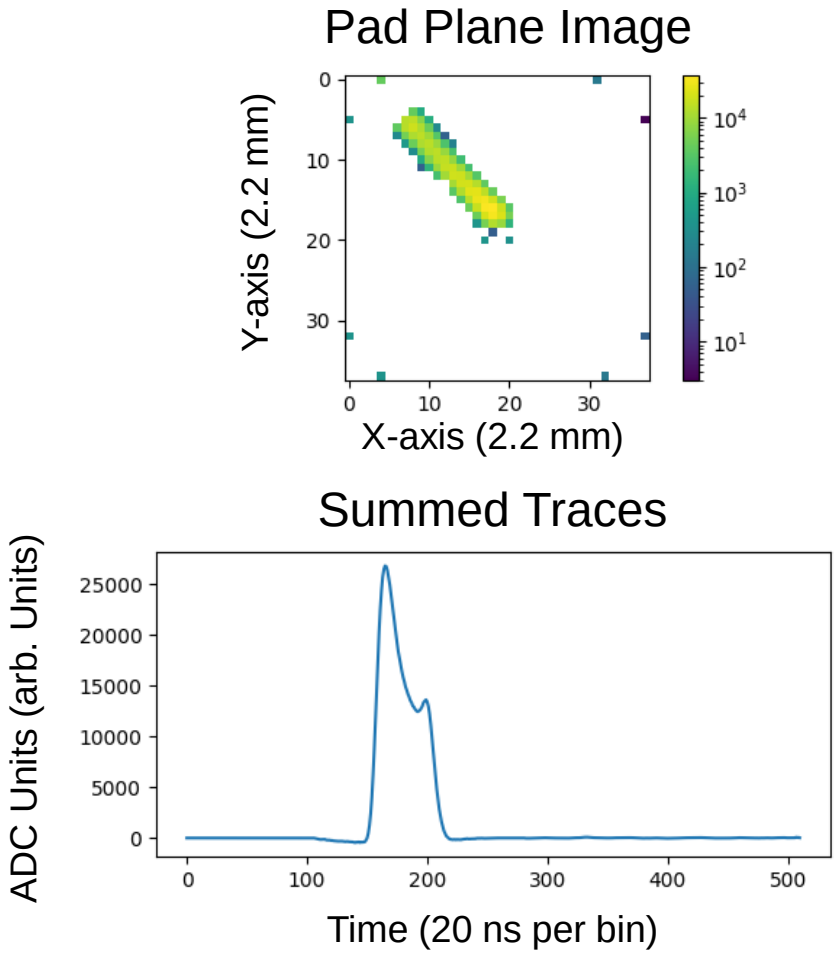
- Run 92 Event 242519 – Double Alpha Candidate

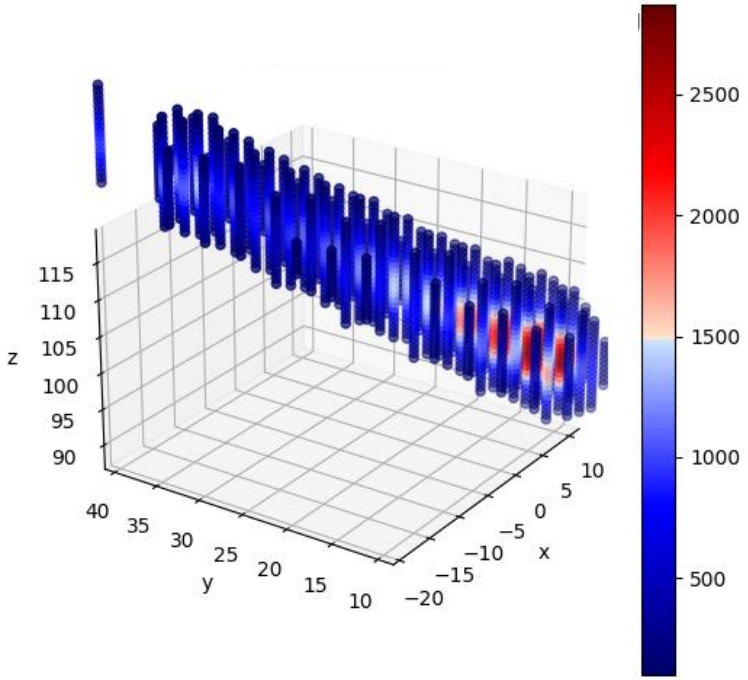




Preliminary Double Alpha Candidates

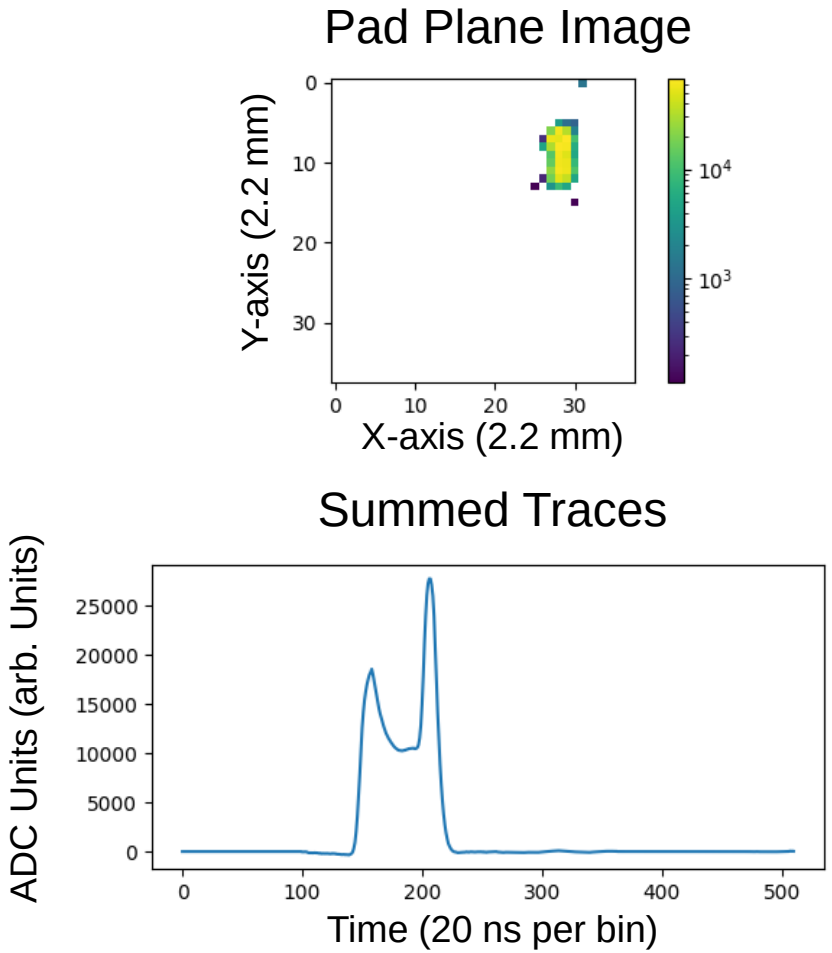
- Run 95 Event 68242 – Double Alpha Candidate

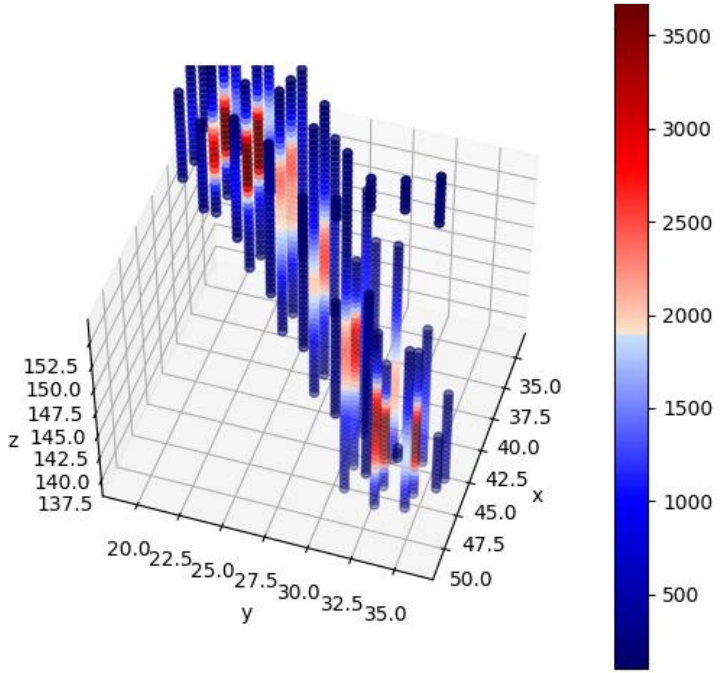




Preliminary Double Alpha Candidates

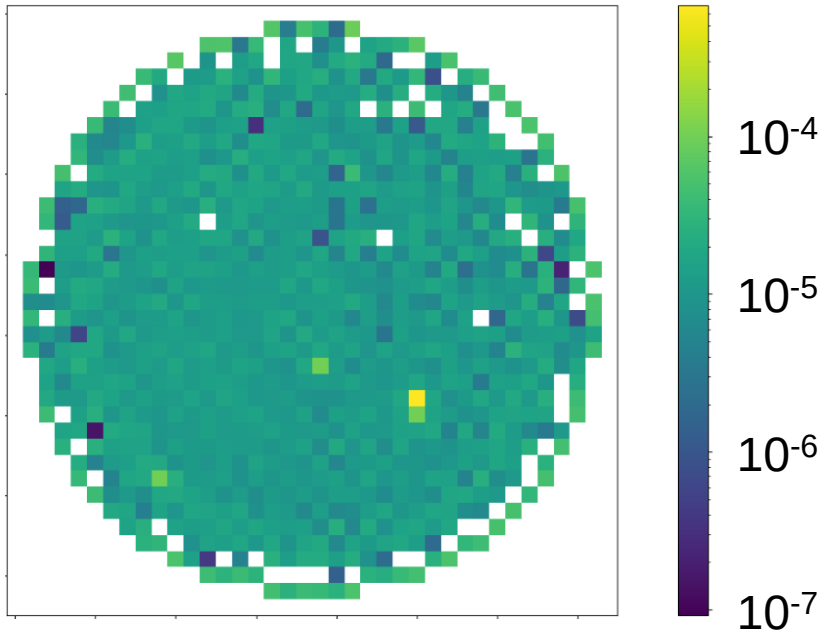
- Run 101 Event 14362 – Double Alpha Candidate





Pad Gain Matching

- Running a minimization code on 100,000 events of data from the double alpha runs to simultaneously gain match and energy calibrate the ^{212}Po alpha events
- Work in progress: constrain gains and see if gain matched data improves energy resolution
- If we get a good enough handle on the energy resolution, we may be able to distinguish between a true double alpha event versus an accidental coincidence



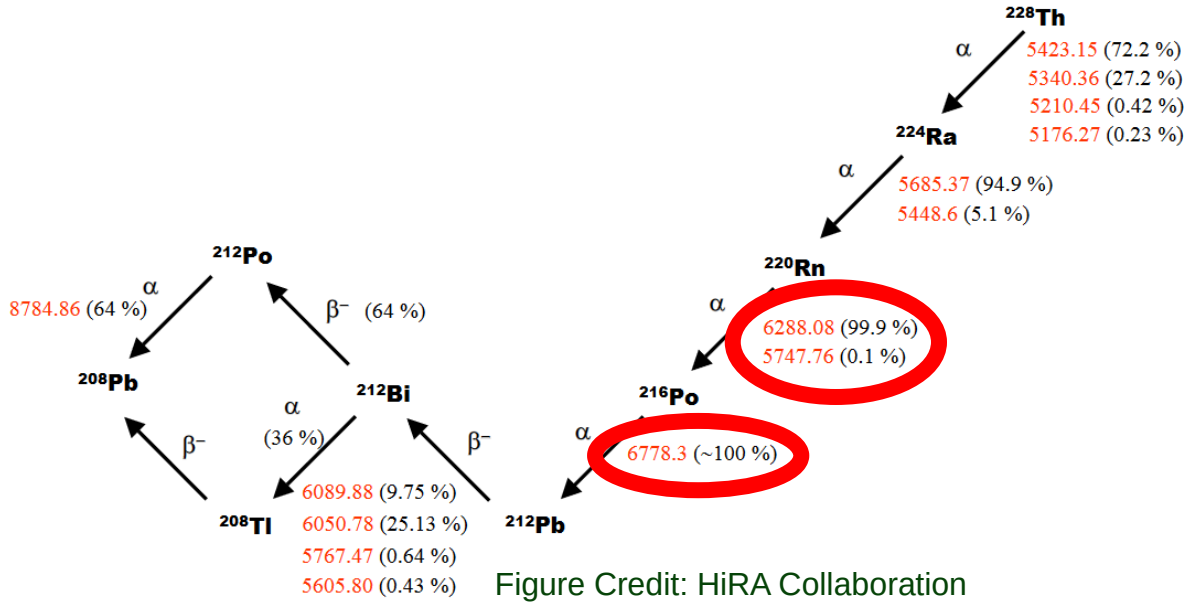
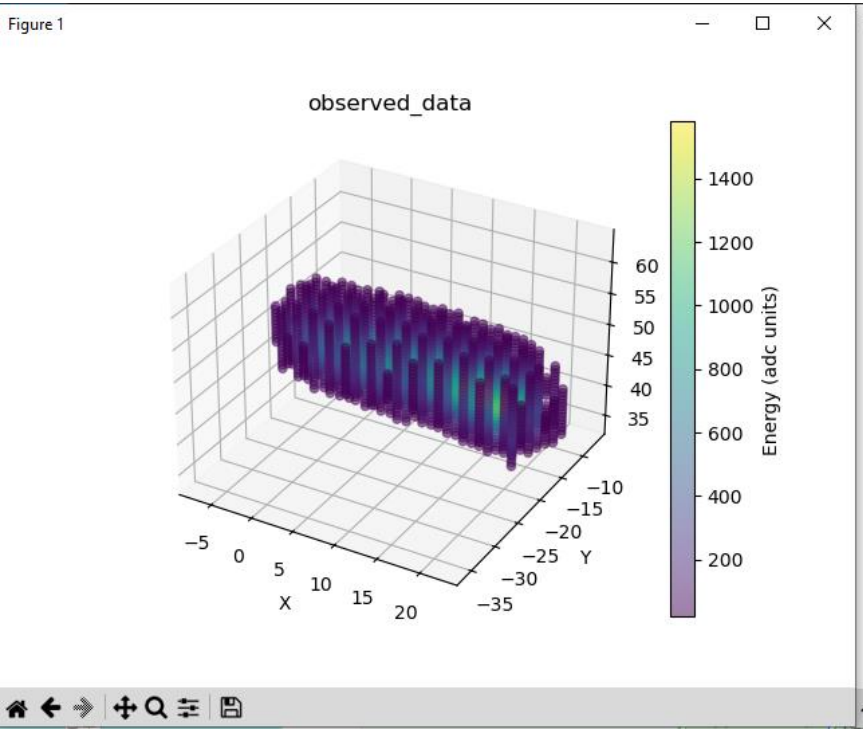
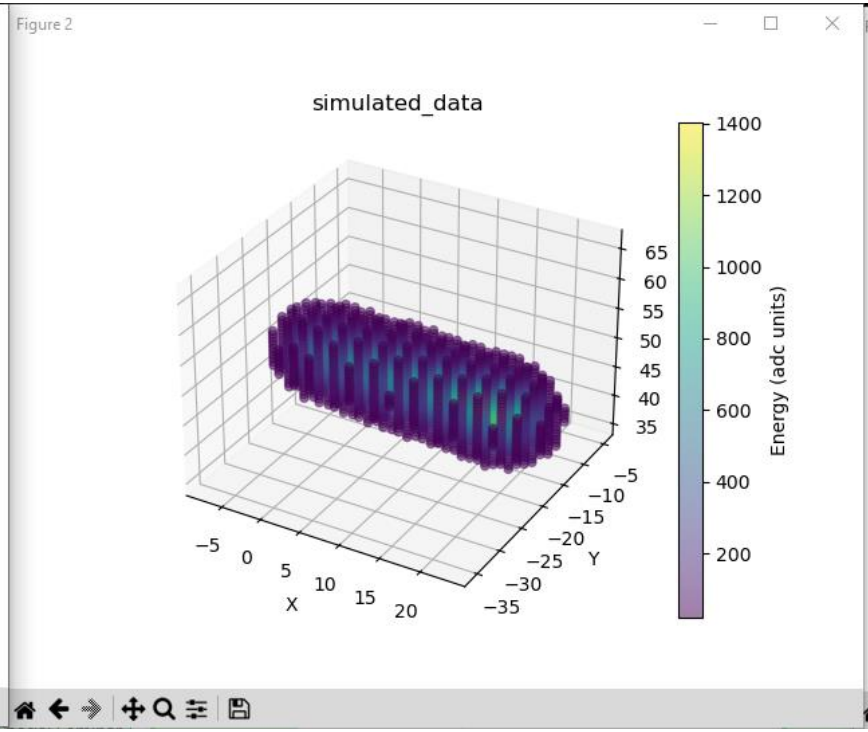


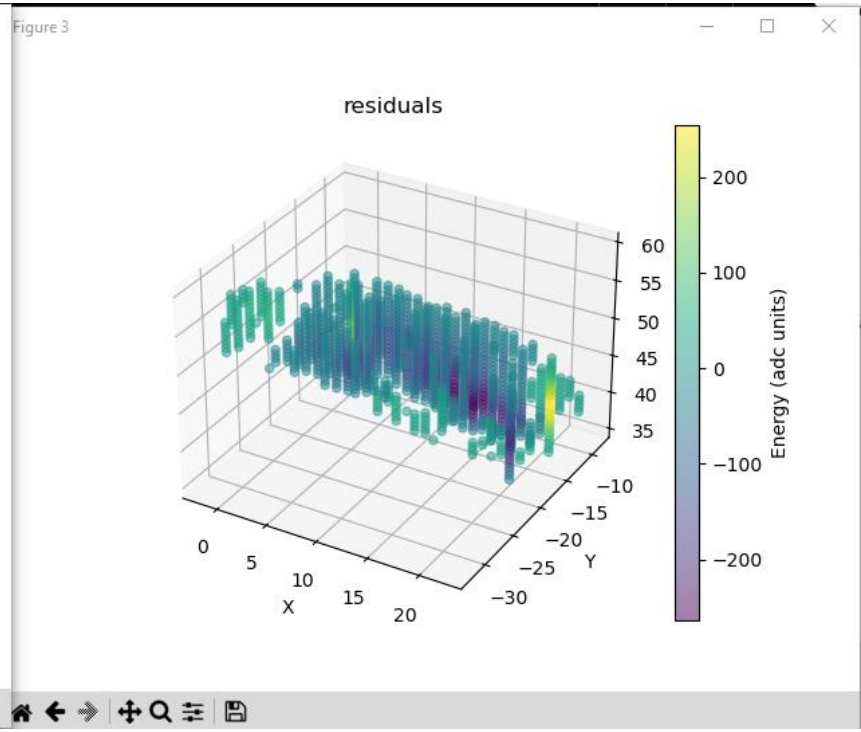
Figure Credit: HiRA Collaboration

Fitting 3D Events

- Code written by Alex Adams simulates data with a few different parameters and maximizes likelihood by adjusting alpha origin, energy, and angles
- Systematic way to extract information needed to create timing and angle plots

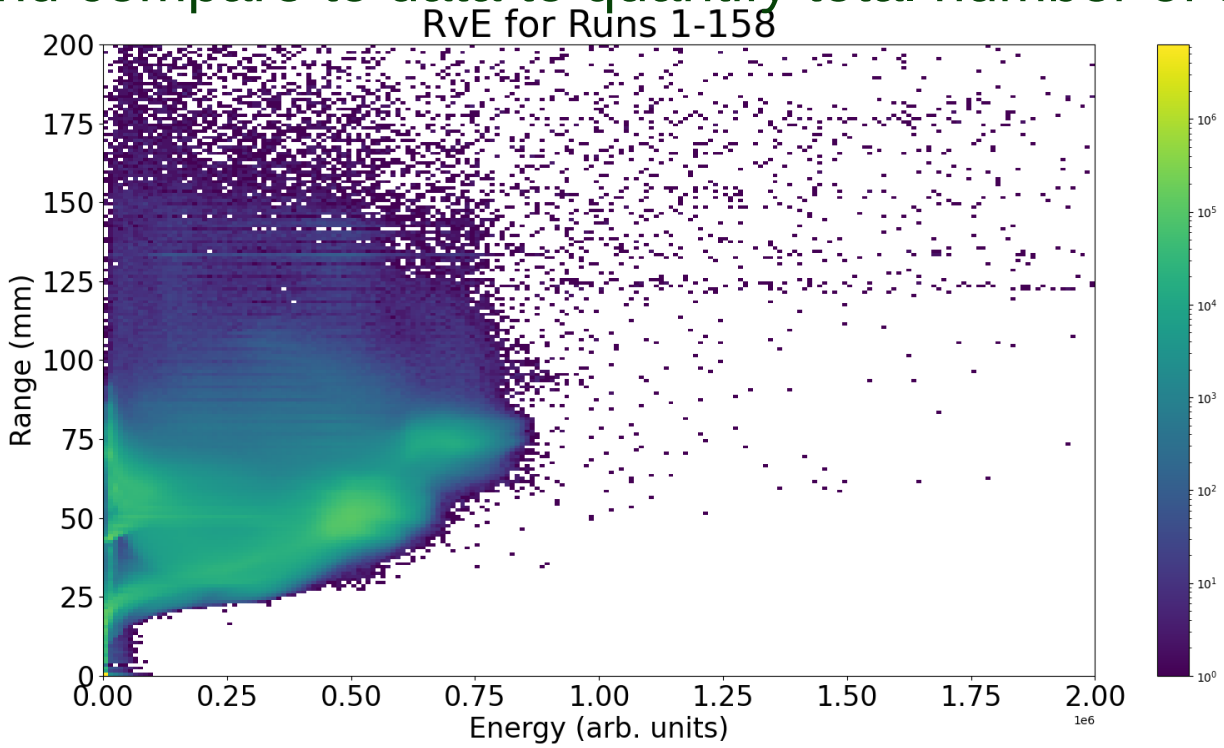


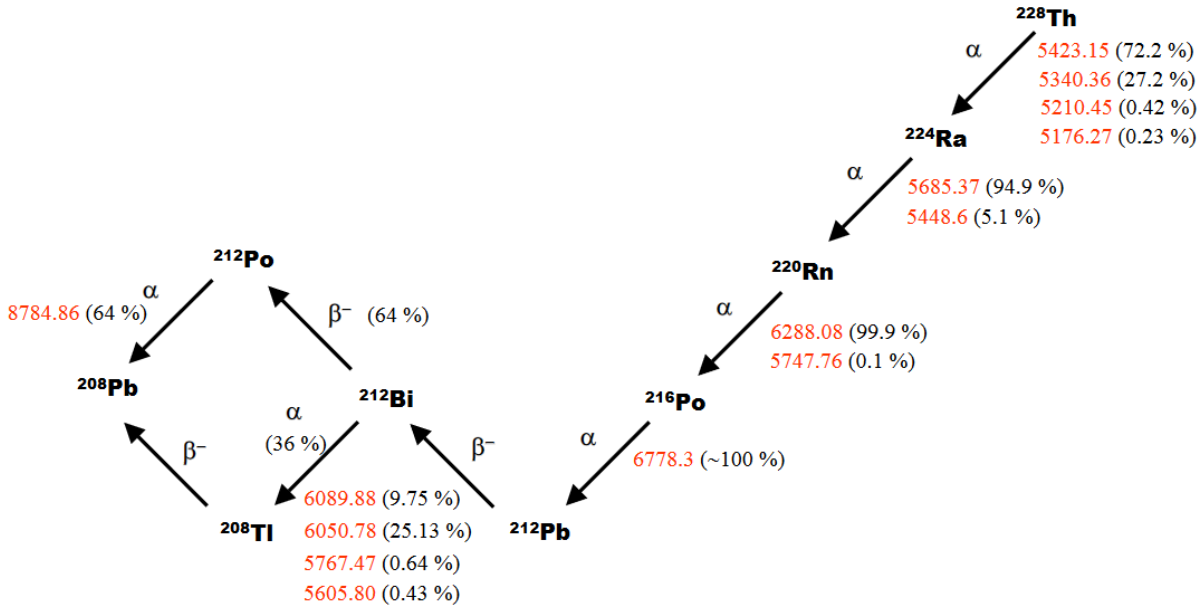




What Method Best Gives Total Number of Radon Decays?

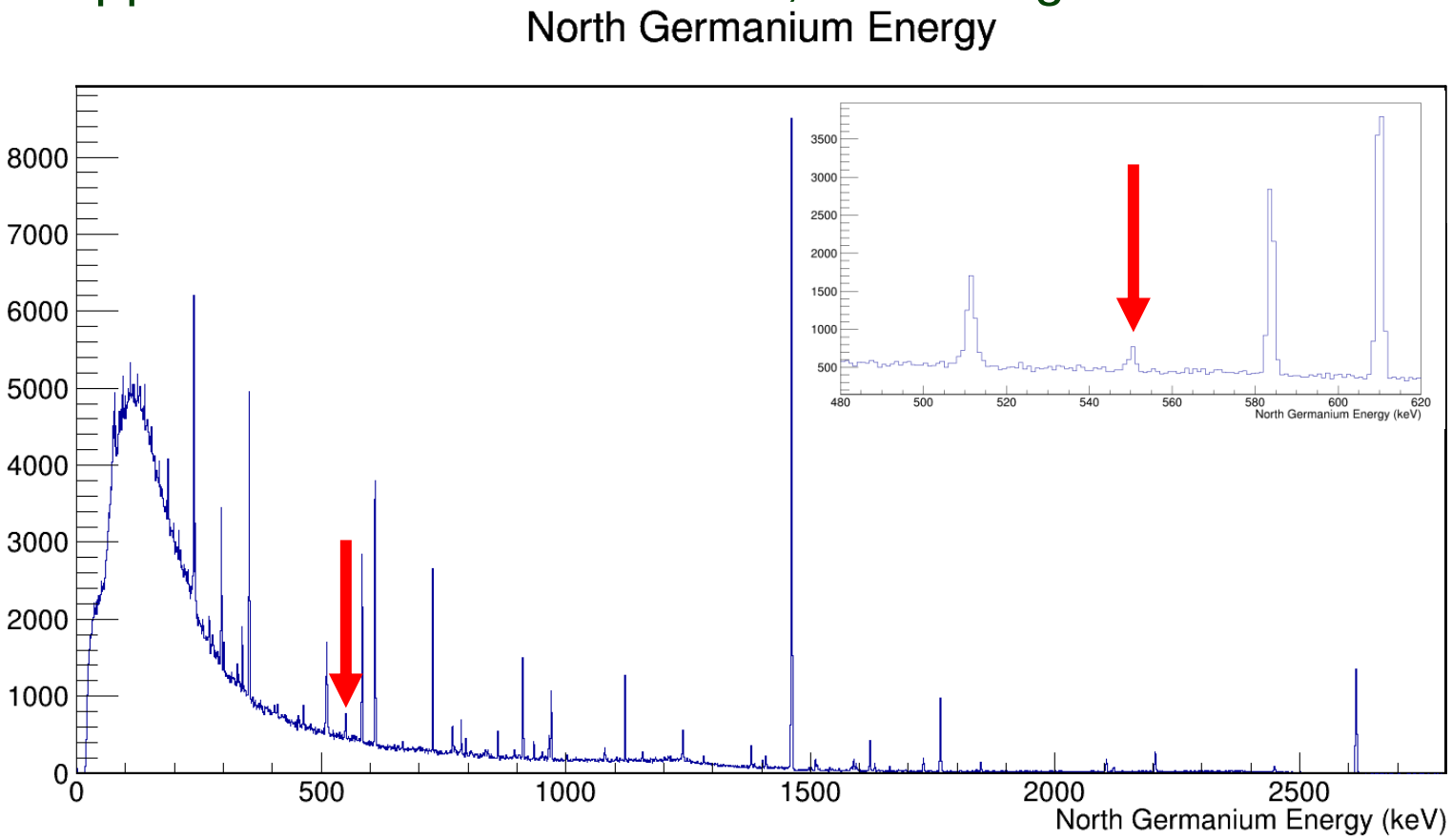
- Because of wall effect and the products from the full decay scheme, there is not a clean separation of single alphas from ^{220}Rn decay
- We will need to simulate this decay chain & add wall effect to our existing Geant4 simulation and compare to data to quantify total number of decays from ^{220}Rn nuclei

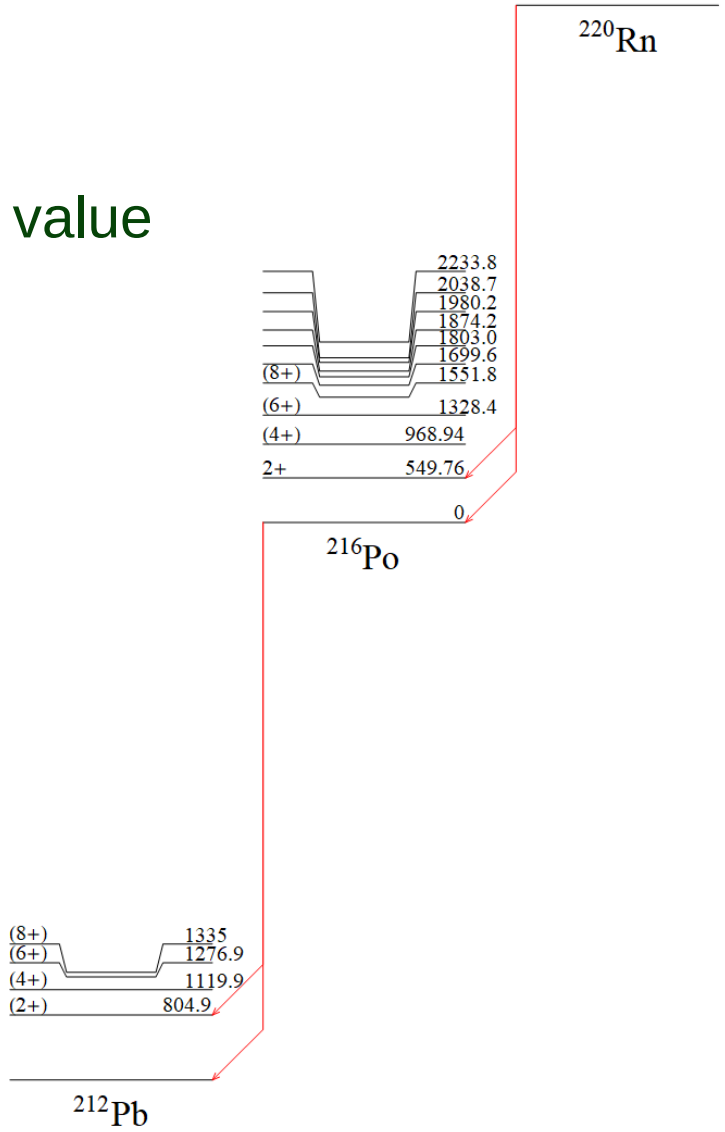




Gamma Data

- Gated on Mesh Trigger
- Set upper limit with data we have; not enough statistics for a finite value





What is on the Docket?

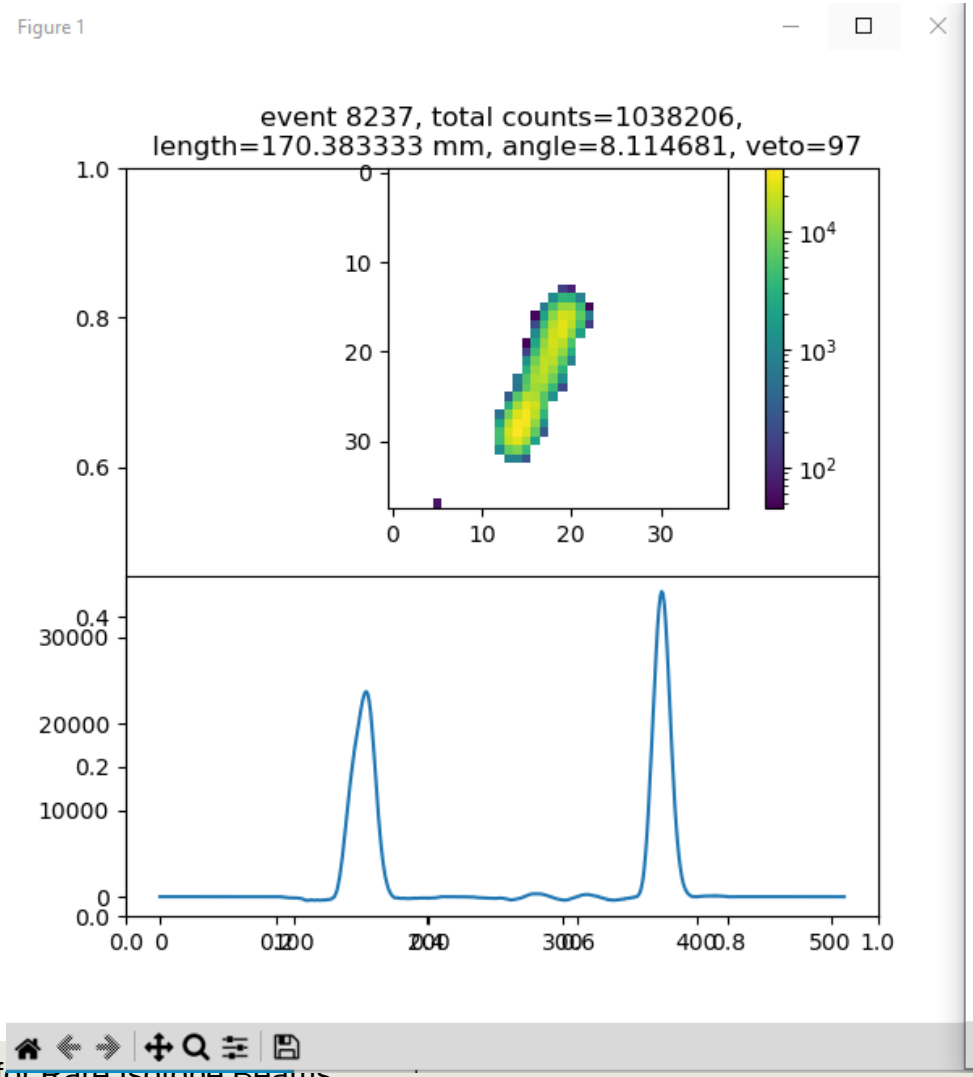
- Fit all events of interest (~3,000 events) using ‘fast’ 3D method
- Fit the double alpha candidates with MCMC routine to quantify uncertainties
- Double check our sensitivities to the two sources of background (sequential and accidental decays)
- Establish normalization, so we can accurately report a measured branching ratio
- Obtain upper limits on decays to excited states by fitting gamma spectra
- Write the rest of the thesis
- Write paper on the double alpha experiment
- GranPlan still needs to be approved!

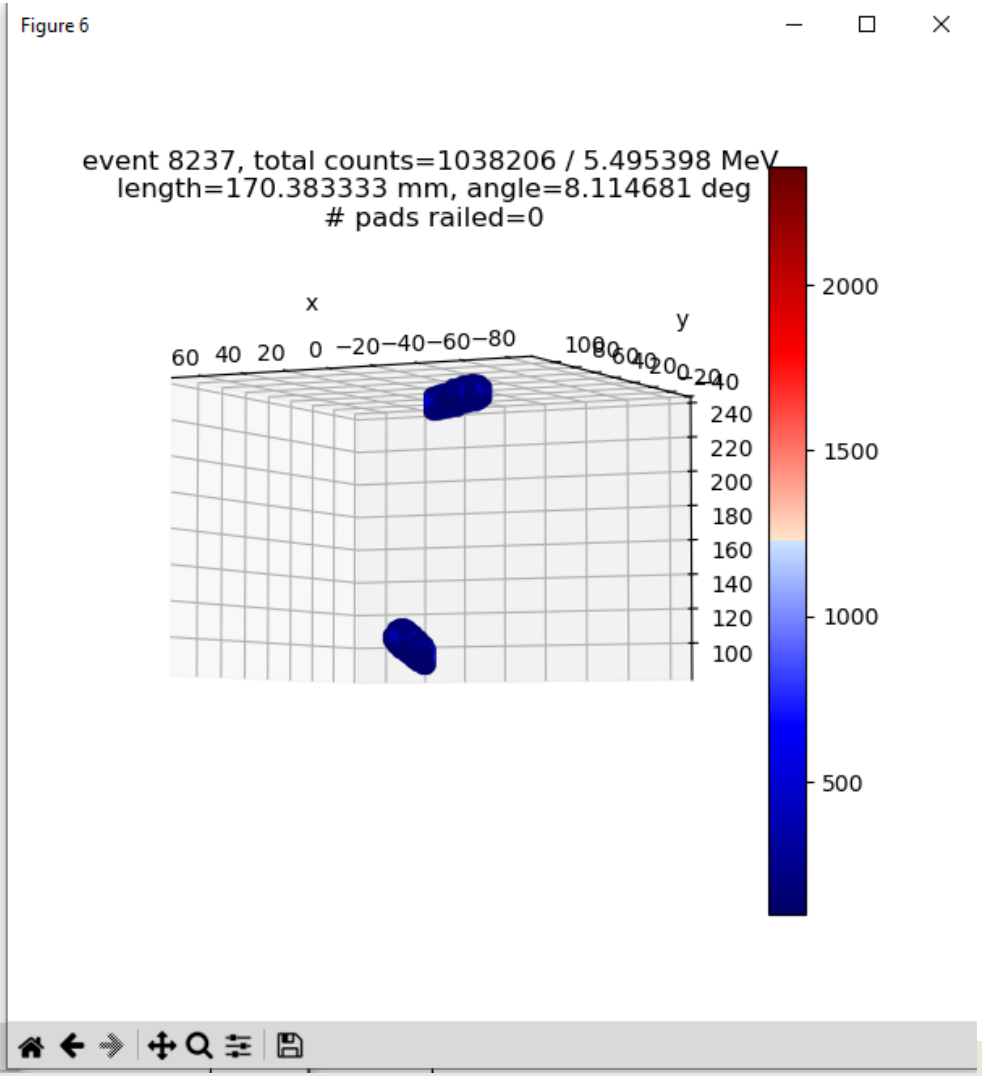
Summary

- Include a chapter in my thesis about developing the LIBRA set up
- Upgraded GADGET II TPC to operate at higher pressures, up to 2,000 torr
- We took enough data so that if we assume the middle theory prediction is correct, we should see about 10 double alpha events
- Extrapolating from the data I examined by hand, we should have about 30 double alpha candidates
- Finish analysis on alpha data to quantify for the branching ratio of double alpha decay in ^{220}Rn
- Analyze gamma data and give an upper limit on the alpha decays to excited states we do not observe

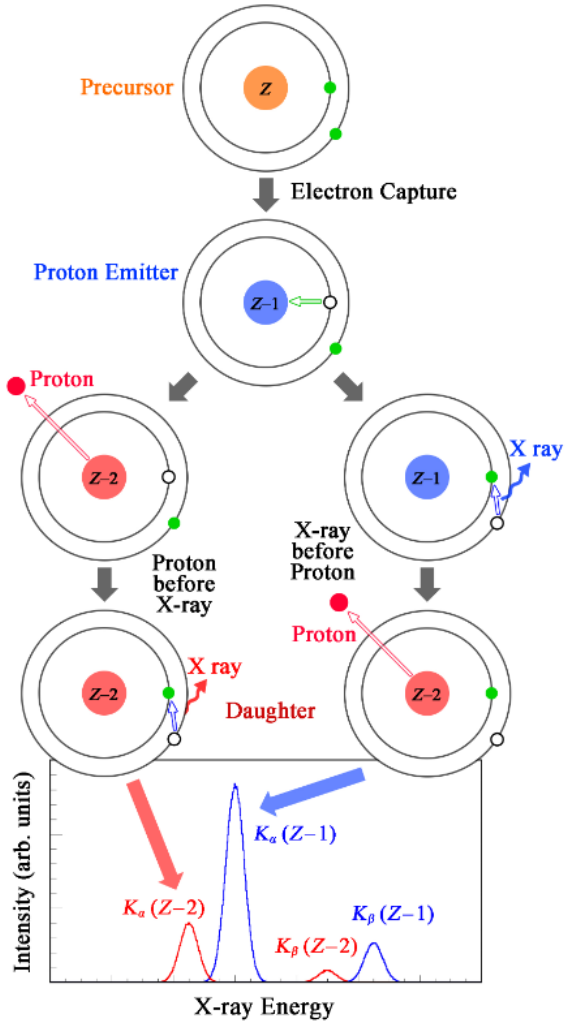
Supplemental Slides

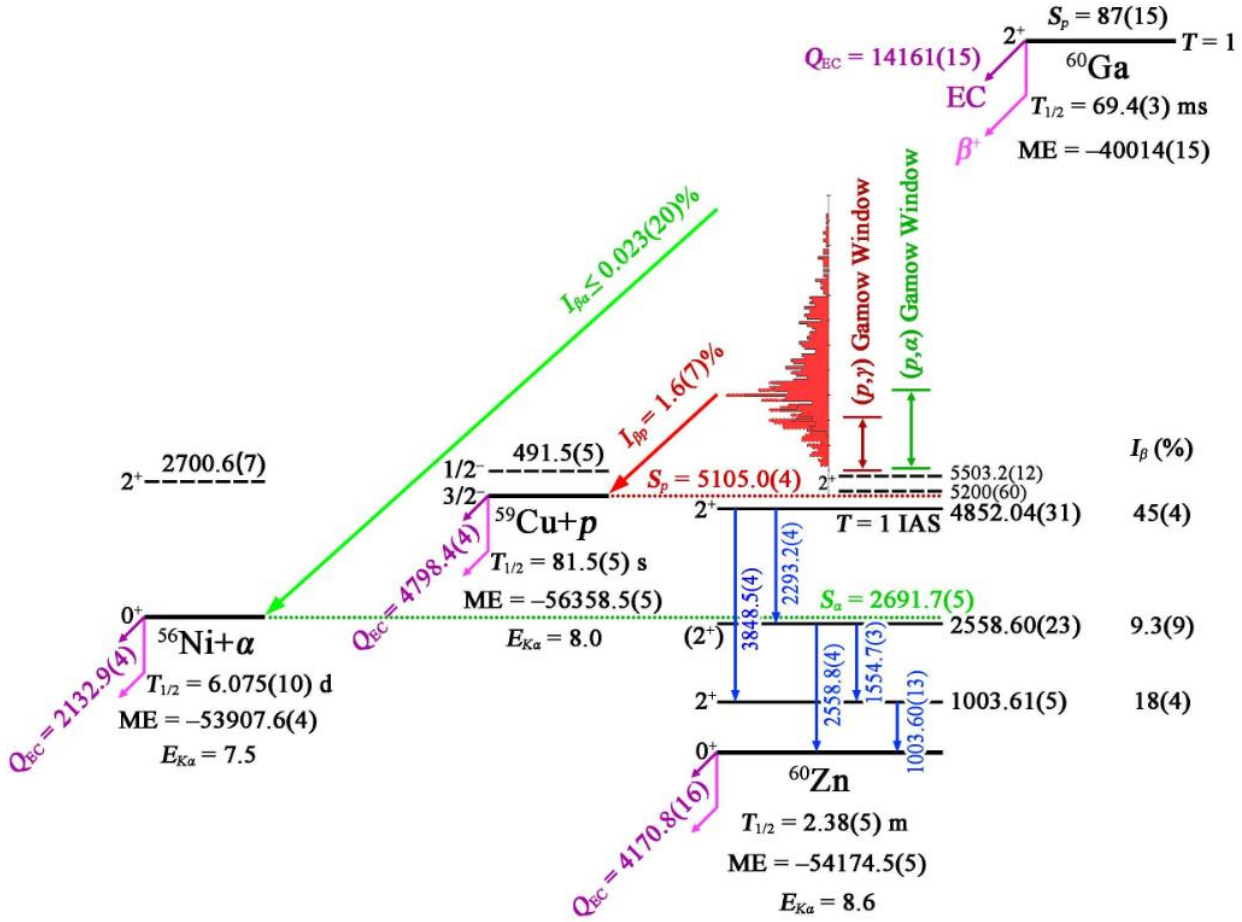
Good example of the utility of 3d reconstruction





Theory Behind PXCT





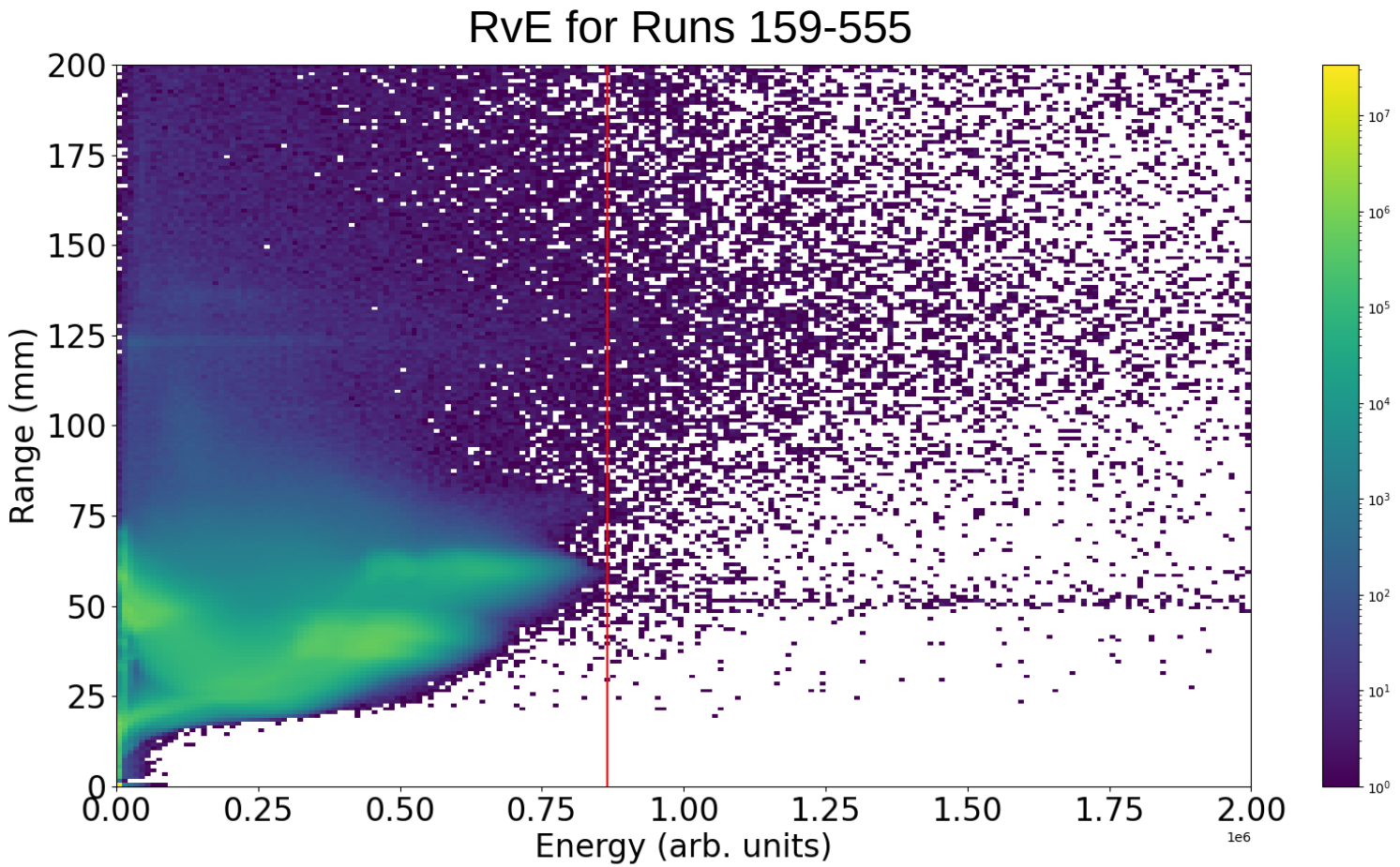
Courses (as they will be by the end of Spring 2025)

- PHY 820 – Classical Mechanics
- PHY 851 – Quantum Mechanics I
- PHY 802 – Survey of Nuclear Physics
- PHY 841 – Classical Electrodynamics I
- PHY 852 – Quantum Mechanics II
- CEM 985 – Selected Topics in Nuclear Chemistry (both hardware and software)
- PHY 831 – Statistical Mechanics
- PHY 982 – Nuclear Dynamics
- CMSE 801 – Intro Coml Model & Data Anyl
- PHY 855 – Quantum Field Theory
- PHY 981 – Nuclear Structure
- PHY 905 – Special Problems
- PHY 800 – Research Methods (6 credits)
- PHY 999 – Doctoral Dissertation Research (24 credits)

- Current RCR Requirements: Up to date through year 5, still have RCR Rigor and Reproducibility on April 8th

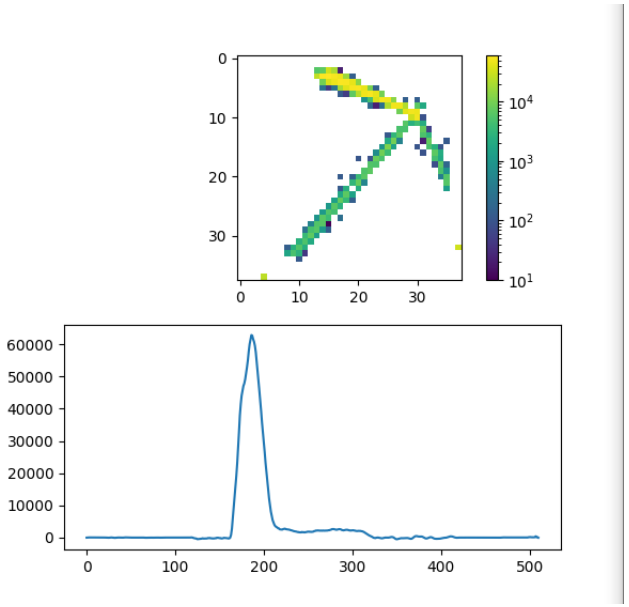
Identifying Candidate Double Alpha Events

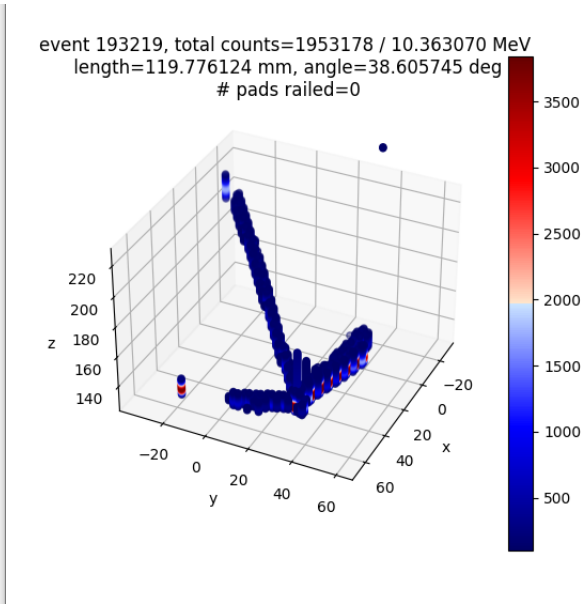
- These initial runs provide enough data to rule out the Denisov prediction of 1/100 decays being double alphas

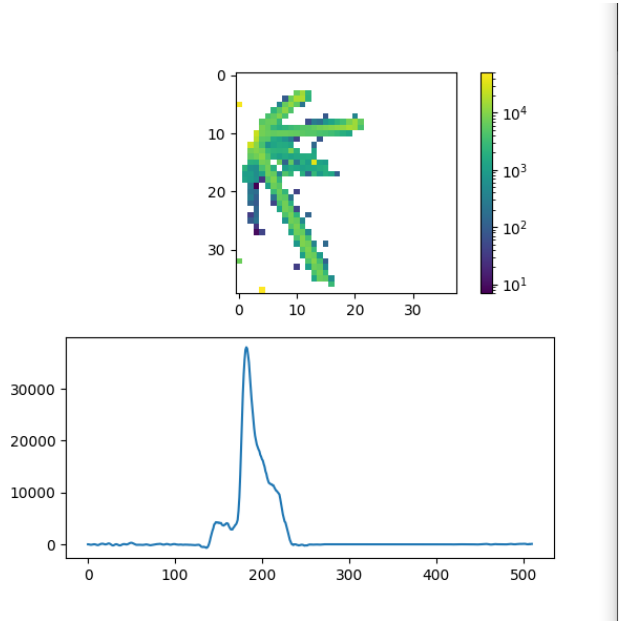


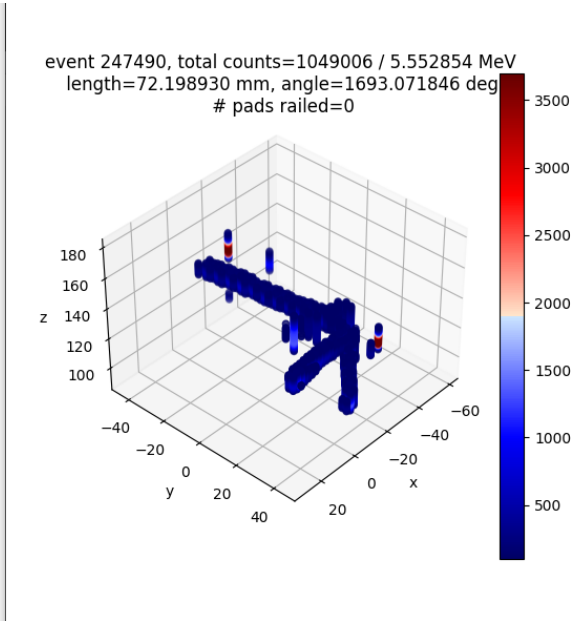
Preliminary Data

- Disintegration Events – We've seen ~5 of these types of events so far









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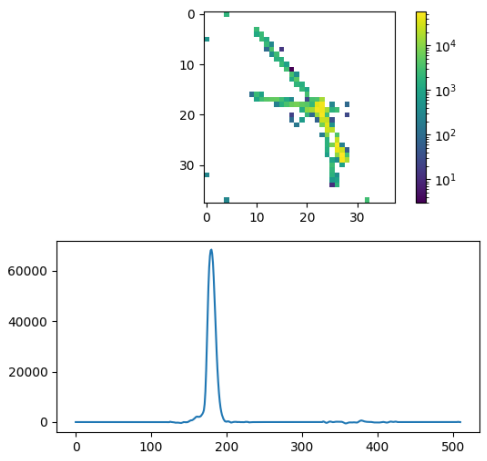

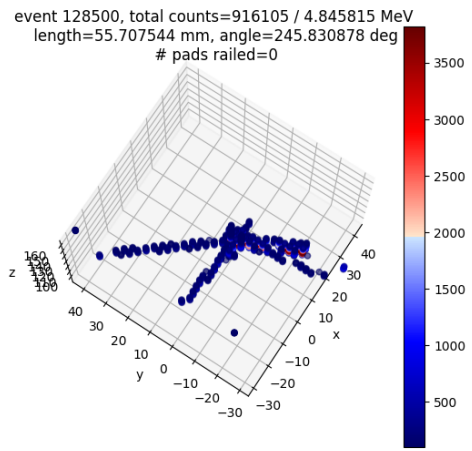

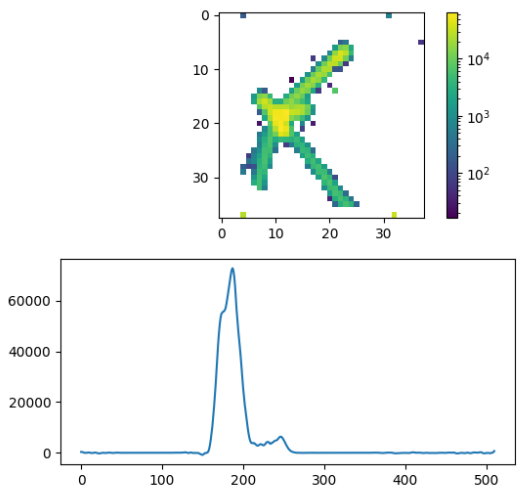

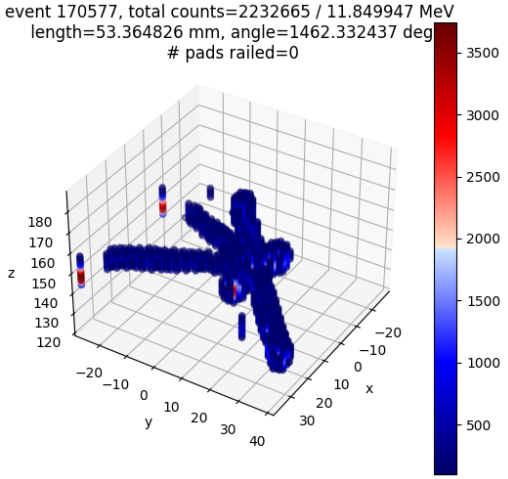

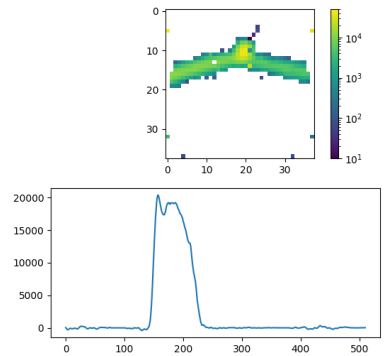

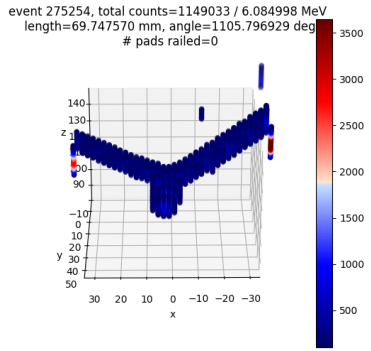

Update

- Our set up that uses the Particle X-ray Coincidence Technique (PXCT) to measure lifetimes and branching ratios is fully completed and benchmarked (and called LIBRA: Lifetimes and Branching Ratios Apparatus)
  - A technical paper has been submitted to PRC (https://doi.org/10.48550/arXiv.2410.16446)
- My thesis experiment uses the GADGET II TPC to look for double alpha decays of ^{220}Rn
- This required some adjustments to GADGET II, mainly a pressure upgrade that allowed us to run at 2000 torr for better double alpha efficiency
- We also coupled the TPC with the HPGe detectors from our LIBRA set up for the first time
- Data was taken offline with a source of ^{228}Th placed in the gas handling system over the course of 6 months
  - A total of ~50 TB of data was generated, compressed to about 25 TB and stored on fishtank for data analysis