Characterizing Inverted Coaxial Detectors' Low-Energy Performance in the MAJORANA DEMONSTRATOR

Jason Chapman *on behalf of the MAJORANA DEMONSTRATOR Collaboration*

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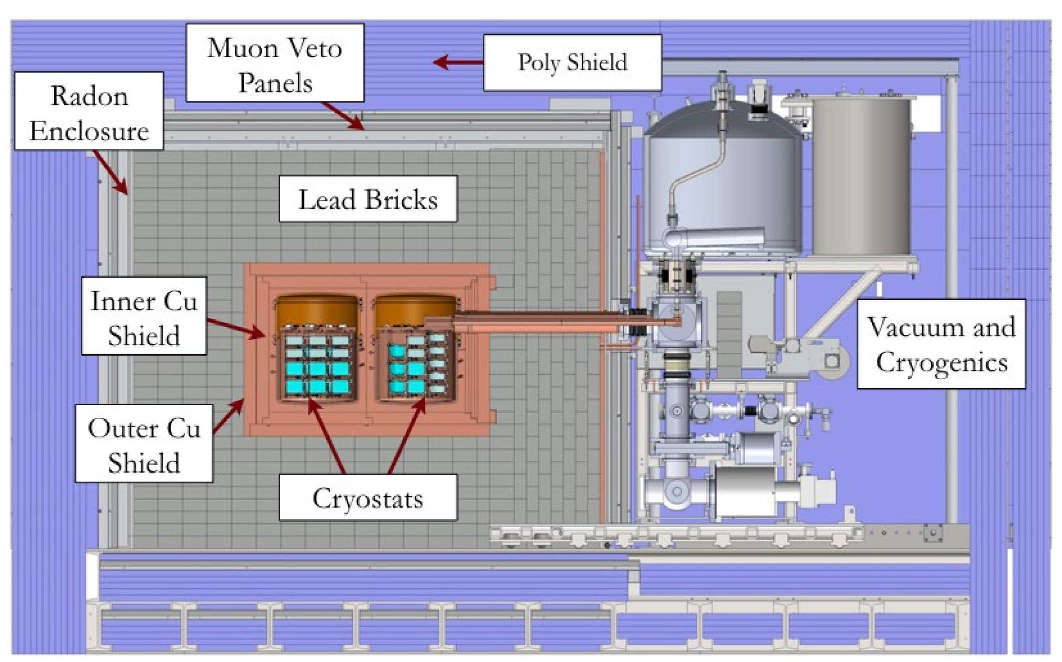
Introduction

The MAJORANA DEMONSTRATOR (MJD)

- Searched for neutrinoless double-beta decay (**$0\nu\beta\beta$**) in **^{76}Ge** [1]
  - Operated 2015-2025
  - Final result: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.L.)
- Sanford Underground Research Facility (SURF)
  - **4850 ft** level (4300 m.w.e.)
- Primarily utilized enriched p-type point contact (**PPC**) detectors

Goals

1. Evaluate the **low-energy** (<100 keV) performance of inverted coaxial (**IC**) detectors
2. Verify usability for beyond Standard Model (**BSM**) searches in LEGEND-200 and LEGEND-1000
   - Including fundamental symmetries, dark matter, trinucleon decay, quantum mechanical wavefunction collapse
3. Identify signatures in the low-energy spectrum to assist in **data cleaning** and pulse-shape discrimination (**PSD**) efforts



MAJORANA DEMONSTRATOR experimental design.

Data

- **Four ICs** operated for 2.82 kg·yr exposure in MJD.
- **Vacuum cryostat**
  - Largest **low-background**, **low-threshold** dataset currently available for ICs
- **Minimized cuts** to improve statistics and demonstrate ICs fundamental capabilities
  - Applied cuts remove rapid bursts of non-physical events (~25 events within several seconds)
  - Survival fraction = 96%

Parameter Estimation

- Energy (**E**)
  - Trapezoid filter with **4 μs** integration time, **2.5 μs** gap time
  - Fixed-time pickoff
- Maximum current (**T**)
  - Measures **max charge collection speed**, indicative of event topology
  - **Maximum value** of triangle filter convolution with 100 ns integration time, 10 ns gap time
  - Normalized by total energy to produce T/E

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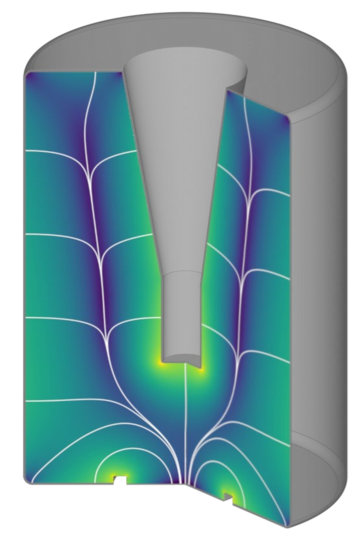
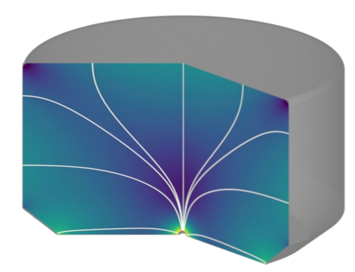
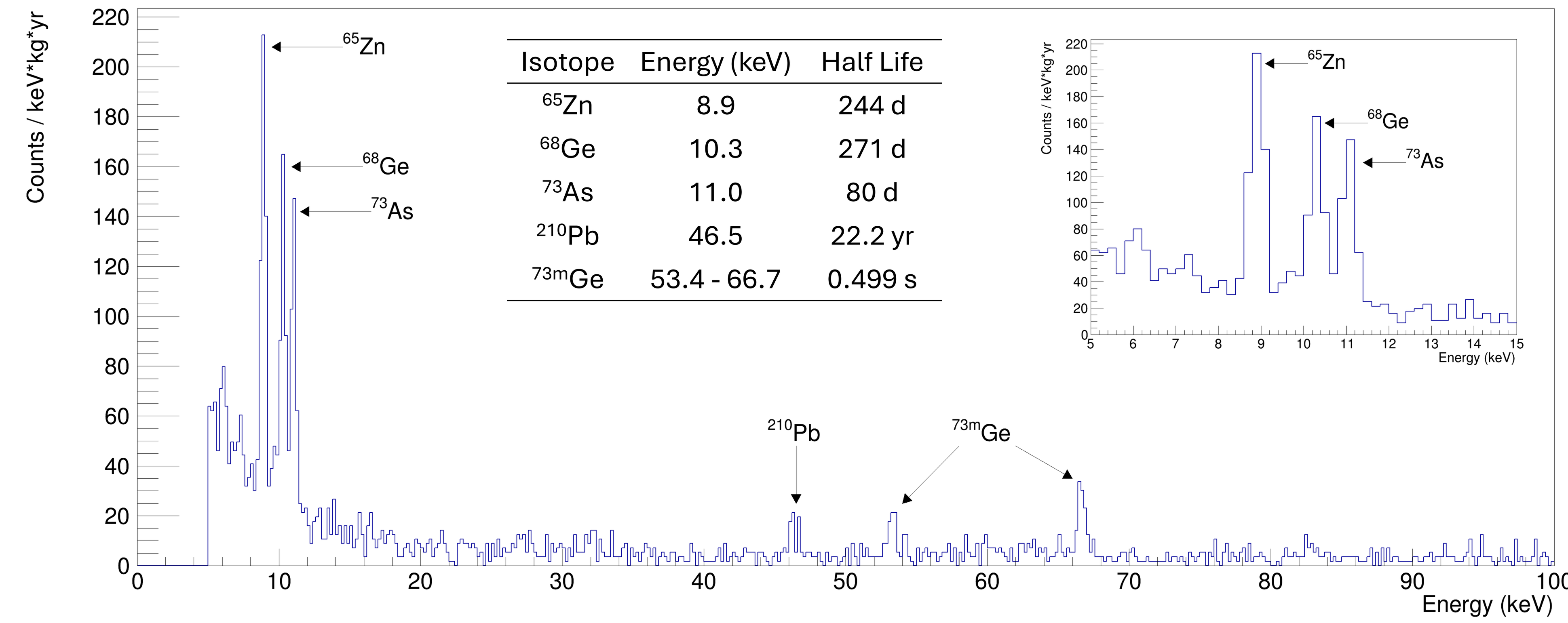


IC detector geometry



PPC detector geometry



Isotope	Energy (keV)	Half Life
^{65}Zn	8.9	244 d
^{68}Ge	10.3	271 d
^{73}As	11.0	80 d
^{210}Pb	46.5	22.2 yr
^{73m}Ge	53.4 - 66.7	0.499 s

Full IC low-energy dataset.

Energy Spectrum

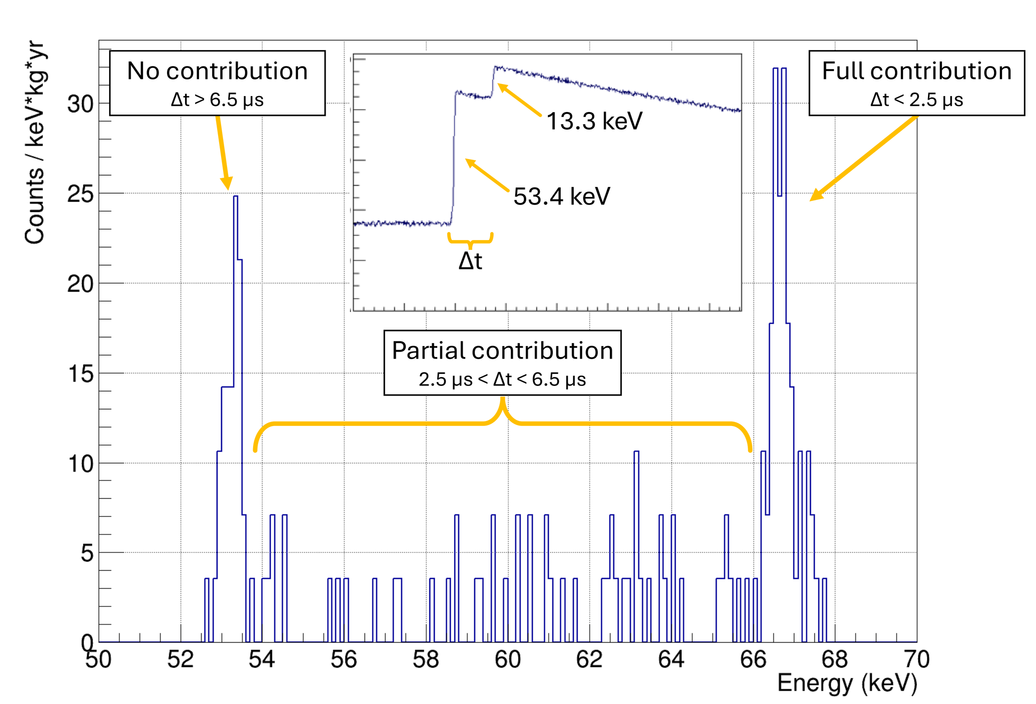
The energy spectrum (*above*) features several notable signals. The most prominent are peaks from **cosmogenic isotopes** produced in the bulk of the detector during surface exposure.

^{73}As → ^{73m}Ge → ^{73}Ge (*right*) produces distinct spectral signatures.

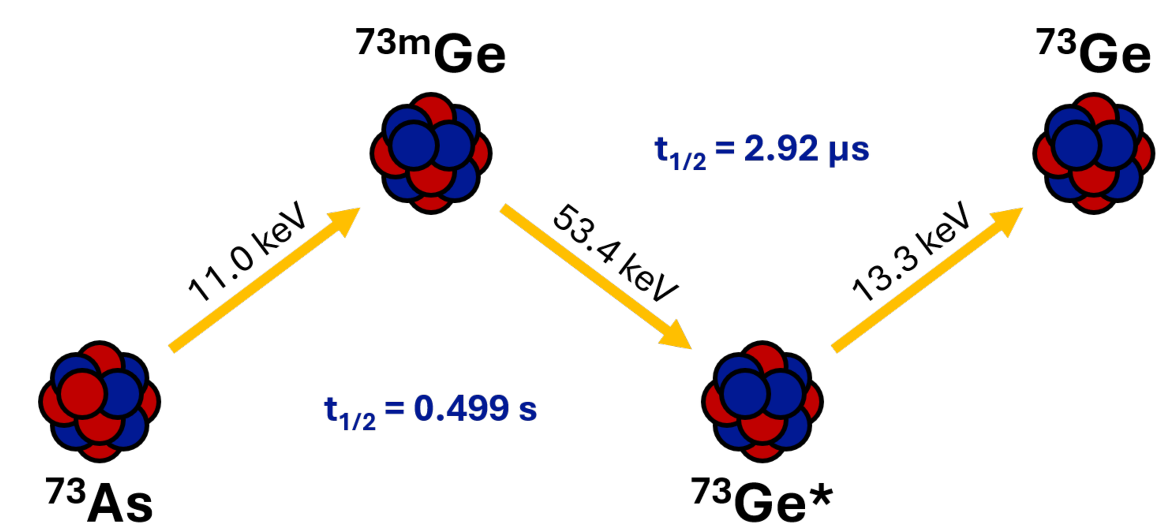
- MJD's low event rate allows a 5-second **time-coincidence** cut to isolate this population
- ^{73m}Ge de-excitations separated by a half-life of 2.92 μs
  - On the order of the trapezoid filter timescale (4 – 2.5 – 4 μs)
- 13.3 keV signal's energy contribution depends on **Δt** (*below*)
  - **Full contribution** (Δt < 2.5 μs): peak at sum energy (66.7 keV)
  - **Partial contribution** (2.5 μs < Δt < 6.5 μs): near-flat continuum [2]
  - **No contribution** (Δt > 6.5 μs): peak at first signal energy (53.4 keV)

^{210}Pb decay produces 46.5 keV γ and **10.8 keV x-ray** photons

- Using time-coincidence, the overlapping ^{73}As peak is removed
- The resulting spectrum is **consistent with background** at 10.8 keV while retaining the 46.5 keV γ signal
  - A peak fit on the remaining spectrum sets a limit of < 4 cts/kg·yr
- Contamination on detector **surface** or in **nearby material**
  - γ **penetrates** dead layer and is detected
  - X-ray interacts in dead layer or transition layer, degrading signal



^{73m}Ge de-excitation pile-up spectrum.



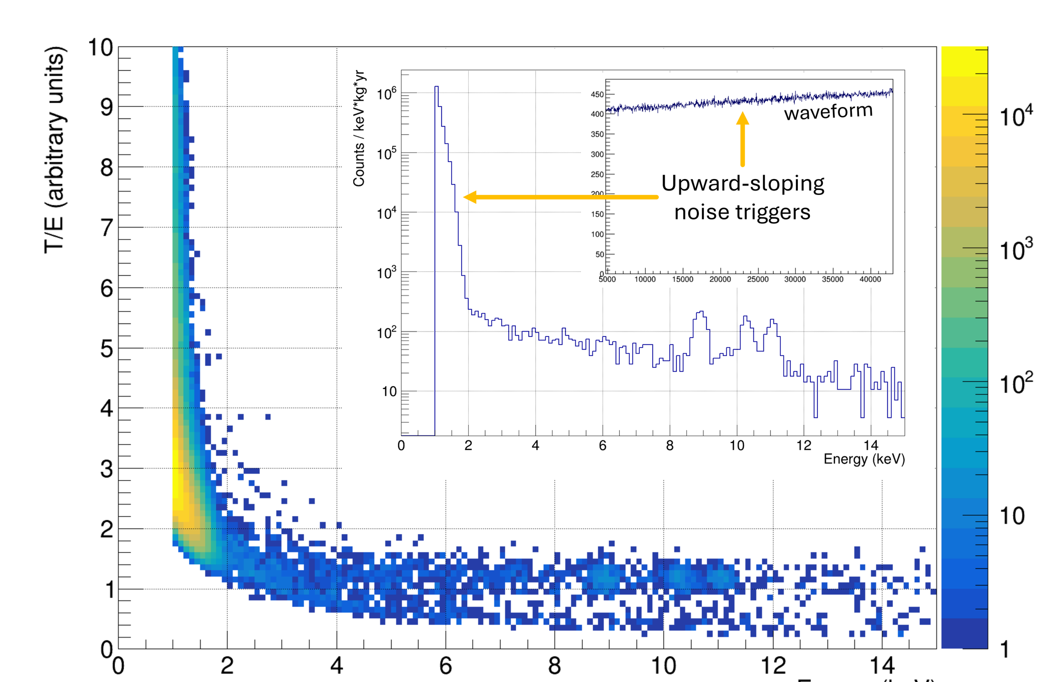
Backgrounds

Below 20 keV

- Cosmogenic **tritium β-decays** in the detector bulk
- Large cosmogenic peaks (^{65}Zn, ^{68}Ge, and ^{73}As) will decay after three years of underground cool-down
- Noise triggers on slowly rising waveforms dominant below 2 keV
  - Noise fluctuations produce constant T values, forming a reciprocal-shaped population in the T/E plot (*below*)

Above 20 keV

- Dominated by **2νββ** and **Compton scatters** from natural radiation in nearby materials



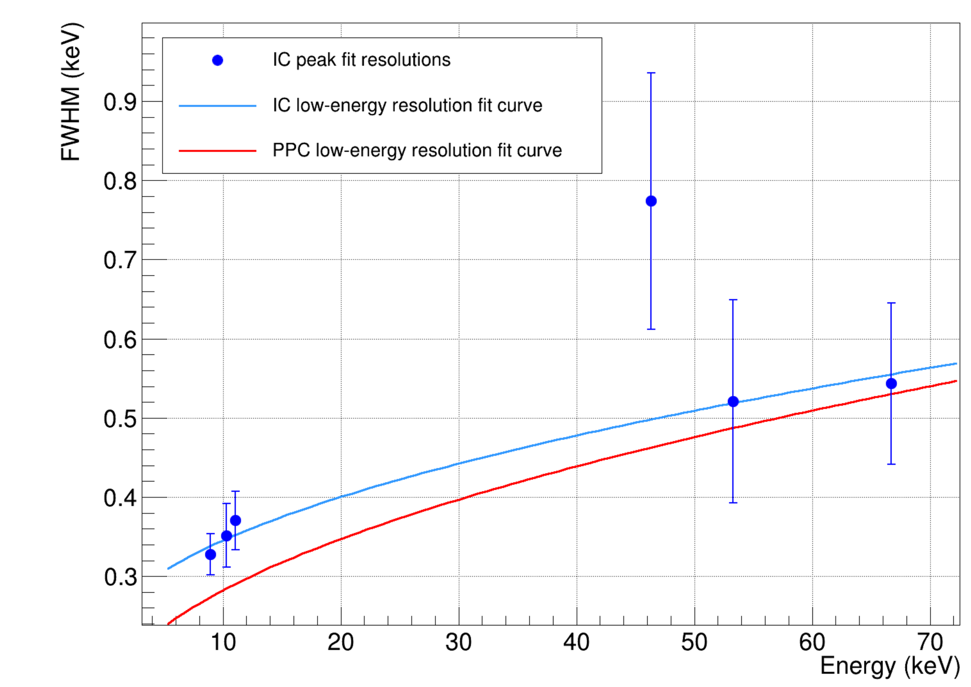
Low-threshold T/E with inset energy spectrum and sample waveform.

Energy Resolution

- ^{65}Zn, ^{68}Ge, and ^{73}As peaks **20-27% larger FWHM** compared to PPCs
- ^{73m}Ge no- and full-contribution peak resolutions higher, but **near consistent** with PPCs

IC resolution expected to be worse compared to PPCs.

- ICs has 2-3x higher capacitance than PPCs
- **Simplified data selection** process to preserve statistics
- Lacking optimization by **energy corrections**



Energy resolution comparison.

Note: ^{210}Pb peak at 46.5 keV omitted from both resolution curves.

Conclusions

IC detectors **performed well** in the low-energy region and are **suitable for BSM searches**.

- Predictable **energy spectrum**
- Low **backgrounds**
- Excellent **energy resolution**

These detectors were deployed in LEGEND-200 and contributed to LEGEND's first $0\nu\beta\beta$ result. [3]

Following internal review, this work will be published alongside the $0\nu\beta\beta$ analysis for IC detectors.

Future work

- Cosmogenic signatures may be useful as markers for further low-energy characterization, data cleaning, and PSD
- Reduced cosmic ray exposure and underground cool-down time will limit cosmogenic backgrounds
- This analysis on ^{73m}Ge has already proved useful to LEGEND trinucleon decay studies

^{39}Ar dominates the low-energy background in LEGEND-200

- Gathering low-threshold data will enable background mitigation efforts
- LEGEND-1000 will utilize **underground-sourced liquid argon** to dramatically reduce low-energy backgrounds

References:
[1] I.J. Arnquist et al., PRL 130, 062501 (2023)
[2] T. Ahsan et al., Plasma 6, 58 (2023)
[3] H. Acharya et al., PRL 136, 022701 (2026)