Study of the Energy Dependence of the LEGEND-200 Pulse Shape Discrimination Parameters Using ^{56}Co

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LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

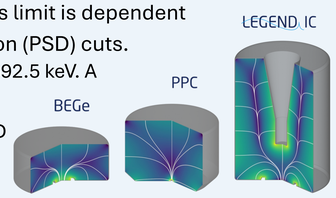
The University of North Carolina at Chapel Hill | TUNL Triangle Universities Nuclear Laboratory

Introduction and Background

The LEGEND-200 (L-200) experiment is searching for $0\nu\beta\beta$ in ^{76}Ge at $T_{1/2}^{0\nu\beta\beta} > 10^{27}$ years. This limit is dependent on the efficiency, of which one contribution is the efficiency of the pulse shape discrimination (PSD) cuts.

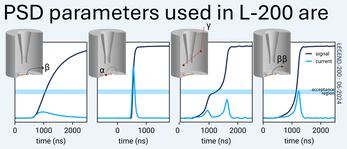
Goal: The PSD efficiency contribution is calculated using the ^{208}Tl double escape peak (DEP) at 1592.5 keV. A correction must be applied to determine the efficiency at $Q_{\beta\beta}$ = 2039.1 keV.

Method: ^{56}Co DEPs between 1-2.5 MeV were used to study the energy dependence of the LEGEND PSD cuts and apply a correction. Short lived ^{56}Co sources were created and deployed for the first in-situ measurement of this dependence in three detector types: ICs, BEGes, and PPCs.



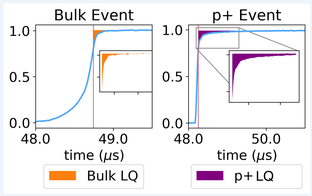
Pulse Shape Discrimination

Pulse shape discrimination utilizes differences in waveform shapes to differentiate backgrounds from potential signal events, which are single site bulk events. The main PSD parameters used in L-200 are A/E and LQ.



A/E

- Calculated from the ratio of the maximum current and the energy of an event
- Used to distinguish between multisite events (low A/E), surface events near the point contact (high A/E), and bulk events
- Applied to PPCs, BEGes, and all ICs



LQ (Late Charge)

- The "slowness" of the final 20% of an event waveform
- Used to distinguish between bulk events and surface events
- Applied to PPCs and some ICs

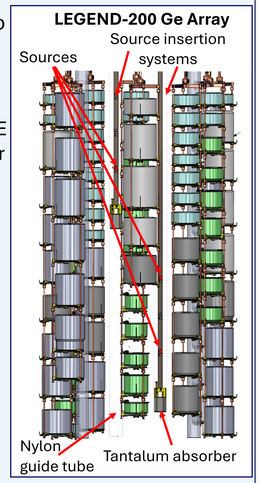
^{228}Th Calibrations

^{228}Th sources are lowered into the array weekly to calibrate the energy scale, resolution, and PSD performance.

- The centroid and width of A/E are tracked and corrected for using the single Compton scattered population in the range 900 to 2300 keV

PSD Cut Tuning:

- Low A/E: set to a 90% survival fraction of ^{208}Tl DEP events to reject multisite events
- High side A/E and LQ: set at three standard deviations above the mean to reject surface events



Energy Dependence and the ^{56}Co Calibration

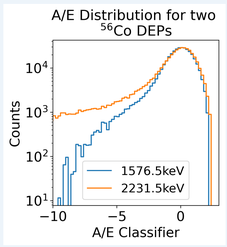
The signal efficiency of the A/E cut varies with energy due to:

- Collective charge effects and electronic noise, accounted for in ^{228}Th calibrations
- Absorption of bremsstrahlung photons, corrected by ^{56}Co calibrations

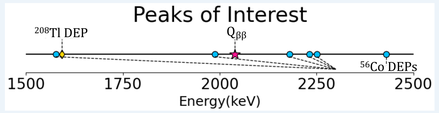
Bremsstrahlung photons production is more probable at higher energies, and results in an increase in the number of events in the low A/E tail.

^{56}Co Source Production:

- Oct. 2023 : custom ^{56}Co foils created at Berkeley National Laboratory
- Feb 2024: assembled into six sources at Los Alamos National Laboratory
- Apr. 2024: first L-200 in-situ ^{56}Co calibration



Single Site Proxies for $0\nu\beta\beta$	
Proxy	Use in LEGEND-200
Single Compton Scatter	Calibrate A/E
$2\nu\beta\beta$	Characterize topological difference between DEP and $\beta\beta$ events
^{208}Tl DEP	Tune cut level for A/E and LQ
^{56}Co DEP	Study energy dependence of PSD



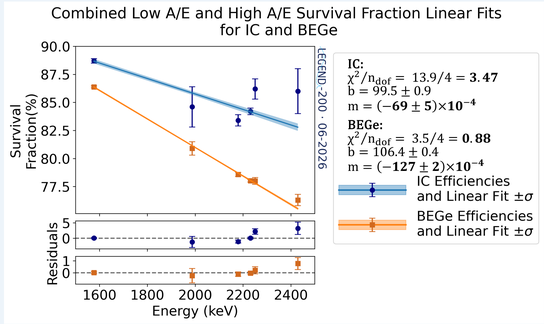
PRL Cut Analysis

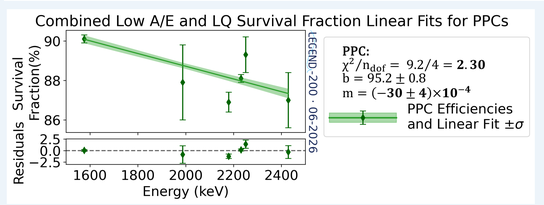
Methodology: A multipeak fitter is used to simultaneously fit all peaks in spectra passing and failing the cuts to determine the amplitudes A_{pass} and A_{fail}.

- The efficiency is defined as: $\epsilon = \frac{A_{pass}}{A_{pass}+A_{fail}}$
- And the statistical uncertainty as:

$$\sigma_\epsilon = \epsilon(1-\epsilon)\sqrt{(\frac{\sigma_{pass}}{A_{pass}})^2+(\frac{\sigma_{fail}}{A_{fail}})^2}$$

A linear model, motivated by simulations, is then fit to the DEPs efficiencies as shown below.



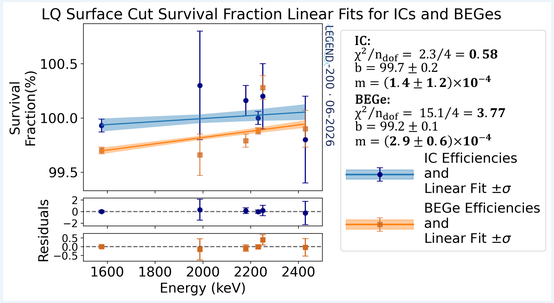


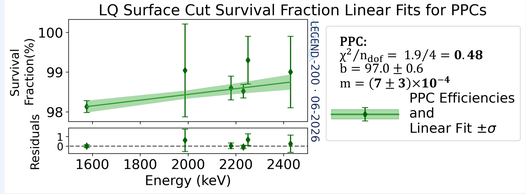
Exploratory Cut Analysis

Motivation: While LQ is presently only used on a subset of detectors, ongoing work may result in its application to additional detector types in the future. Thus, we investigated the energy dependence in LQ to guide future use.

Methodology: As the efficiency of LQ is set to over 99%, the efficiency could not be calculated as in the main analysis. Thus the efficiency is calculated as:

- $\epsilon = \frac{A_{pass}}{A_{total}}$, with the statistical uncertainty calculated using bootstrapping





Conclusions

Results:

The PSD efficiency at $Q_{\beta\beta}$ is:

- $\epsilon_{Q_{\beta\beta}} = \epsilon_{Tl\ DEP} + \Delta\epsilon_{Co}$ + other corrections
- Where $\Delta\epsilon_{Co} = (2039.1 - 1592.5) \times m_{fit}$, and m_{fit} is the fitted slope acquired from the linear fit to the ^{56}Co DEP efficiencies

^{56}Co Efficiency Corrections and Resulting Efficiency at $Q_{\beta\beta}$			
	IC	BEGe	PPC
$\Delta\epsilon_{Co_{PRL}}$(%)	-3.0 ± 0.6	-5.7 ± 0.3	-1.4 ± 2.4
$\Delta\epsilon_{Co_{Exp}}$(%)	-3.0 ± 2.7	-5.6 ± 0.7	-1.2 ± 3.7
$\epsilon_{Q_{\beta\beta}}$(%)	84.85 ± 2.96	81.07 ± 3.78	85.00 ± 4.49

Conclusions:

^{56}Co was used to show the energy-dependence of the PSD cut efficiencies in L-200 detectors, and provide a correction to those found using the Tl DEP (additional corrections are also applied). The total efficiency shifts are given in the table.

- ^{56}Co correction is the largest contributor to efficiency corrections at $Q_{\beta\beta}$ for most detectors
- We recommend follow-up ^{56}Co calibrations for each HPGe array deployment
- This work is expected for publication in 2026 (currently under internal review)

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