Energy calibration for the GERDA experiment

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Outline

- Detecting neutrinoless double-beta decay ($0\nu\beta\beta$)
- GERDA and the calibration procedure
- Energy scale calibration and stability
- Determining resolution at $Q_{\beta\beta}$
- Future developments
- Conclusion
Detecting $0\nu\beta\beta$

- Can explain mass of neutrino with small Majorana mass component
- Allows for $0\nu\beta\beta$ decay: hypothetical lepton number violating process
- Signature would be monoenergetic line, $Q_{\beta\beta}$, in energy spectrum of emitted electrons, 2039 keV for $^{76}\text{Ge}$
- Sensitivity to half-life of decay:

$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{Mt}{BI \cdot \Delta E}}$$

where $\epsilon$: efficiency; $Mt$: exposure; $BI$: background events per kg·yr·keV; $\Delta E$: resolution
GERDA and the calibration procedure

- Knowledge of energy scale, resolution vital for all physics analyses
- Detectors calibrated by $^{228}$Th sources ea. 7-10 days
- Three sources lowered to three positions from above cryostat for $\approx 2h$
  $\rightarrow$ all detectors exposed
- Source Insertion System (SIS) built in Zurich
  - Operating reliably since 2011
  - Two independent measurement systems determine position of source to $\pm 1$ mm
GERDA and the calibration procedure (cont.)

- 40 detectors, two main types: Semi-coaxial (Coax) and Broad Energy Germanium (BEGe)
- Germanium detectors have excellent resolution (∼3 keV for Coax, ∼4 keV for BEGe)

![Graph showing calibrated energy vs. events]

Coax BEGe
Energy scale calibration

- GERDA calibration software identifies, fits peaks in spectra for each detector
- Calibration curves are linear fit between reconstructed and physical energy
- Range of peaks fitted between 583 keV and 2.6 MeV

Calibrated energy: 860 keV

Detector: GD91A, Date: 20180224
Stability monitoring

- Energy scale stability required for combining of data between calibrations → stability should not limit resolution
- Stability of position, resolution of 2.6 MeV $^{228}$Th peak monitored calibration to calibration
- Shifts of 2.6 MeV peak usually $\lesssim 0.5$ keV

**Energy scale stability**

**Resolution stability**

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Resolution at $Q_{\beta\beta}$

- Recall:
  \[
  T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{Mt}{BI \cdot \Delta E}}
  \]

- Sensitivity depends strongly on resolution
- Poor resolution would leak to $2\nu\beta\beta$ events leaking towards $Q_{\beta\beta}$

- Want to know resolution at $Q_{\beta\beta}$ in physics spectrum

- Procedure:
  - Combine many calibration spectra for each detector
  - Fit peaks, find resolution at each peak
  - Combine resolutions for each dataset, weighting by exposure
  - Fit resolution curve, interpolate to $Q_{\beta\beta}$

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[Graph showing energy calibration with counts per 25 keV for different isotopes and conditions like prior liquid argon (LAr) veto and PSD, after LAr veto, after LAr veto and PSD, and 50 keV blinding.]
Resolution at $Q_{\beta\beta}$ (cont.)

- Step 1: Combine calibration spectra for each detector
  - Easy! Simply add up all calibration spectra!
Resolution at $Q_{\beta\beta}$ (cont.)

- Step 1: Combine calibration spectra for each detector ✓
- Step 2: Fit peaks, find resolution at each peak
  - Easy! Use existing calibration software, apply to combined spectra.
Resolution at $Q_{\beta\beta}$ (cont.)

- Step 1: Combine calibration spectra for each detector ✓
- Step 2: Fit peaks, find resolution at each peak ✓
- Step 3: Combine resolutions for each dataset
  - Weight by exposure: how much a single detector contributes to physics spectrum for each dataset
  - Not so easy...
Resolution at $Q_{\beta\beta}$: Combining detector resolutions

- Combination of many Gaussians is a Gaussian mixture, so:
  \[
  \sigma^2 = \sum_i w_i \left( \sigma_i^2 + \mu_i^2 \right) - \sum_i (w_i \cdot \mu_i)^2
  \]

- Assume all means are equal (correctly calibrated peaks!):
  \[
  \sigma^2 = \sum_i w_i \, \sigma_i^2
  \]

where $\sum_i$ is sum over detectors, $w_i$ is detector exposure, $\sigma_i$, $\mu_i$ are the resolutions / mean positions for each detector.

\[\text{Example gamma line}\]
Resolution at $Q_{\beta\beta}$ (cont.)

- Step 1: Combine calibration spectra for each detector ✓
- Step 2: Fit peaks, find resolution at each peak ✓
- Step 3: Combine resolutions for each dataset, weighting by exposure

  - Use Gaussian mixture equation
Resolution at $Q_{\beta\beta}$ (cont.)

- Step 1: Combine calibration spectra for each detector ✓
- Step 2: Fit peaks, find resolution at each peak ✓
- Step 3: Combine resolutions for each dataset, weighting by exposure ✓
- Step 4: Fit resolution curve, interpolate to $Q_{\beta\beta}$
  - Empirically, fit equation: $\text{FWHM}(E) = \sqrt{aE + b}$
  - Doppler broadened single-escape peak is excluded

At $Q_{\beta\beta} = 2039$ keV

Coax FWHM: $3.55 \pm 0.02$ keV

BEGe FWHM: $2.94 \pm 0.01$ keV
Future developments

- Current method of simply adding spectra is not perfectly representative of physics data
  - Some calibrations are longer than others, exposure is not identical for each calibration
  - Calibrations are not applied for the same period of time
- New method (in development)

<table>
<thead>
<tr>
<th>Raw calibration spectra, different exposures</th>
<th>Normalise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>Weight by calibration validity</td>
</tr>
<tr>
<td>Sum</td>
<td>Sum</td>
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</tbody>
</table>

Simple summed spectra  
Representative spectra
Future developments (cont.)

- Some complications:
  - Not trivial to normalise
  - Detectors are different distances from sources
  - (Position of sources not perfectly reproduced each calibration)
  - Ratio of gamma line strengths will be different for each detector/calibration
  - One solution: create different normalised spectra for each gamma line?
- Not trivial to sum and fit
  - Poisson statistics must be treated correctly when adding events
- In future, could event combine spectra for multiple detectors for form dataset spectra
Conclusion

- GERDA searches for $0\nu\beta\beta$ of $^{76}$Ge
- Regular calibrations are made with $^{228}$Th sources
- Energy scale and resolution of detectors monitored
- Resolution at $Q_{\beta\beta}$ is determined by combining calibration spectra and detectors
- New method will produce more representative spectra