Energy calibration for the GERDA experiment

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Outline

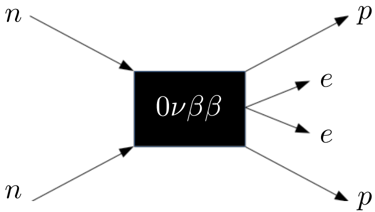
- Detecting neutrinoless double-beta decay ($0\nu\beta\beta$)
- GERDA and the calibration procedure
- Energy scale calibration and stability
- Determining resolution at $Q_{\beta\beta}$
- Future developments
- Conclusion

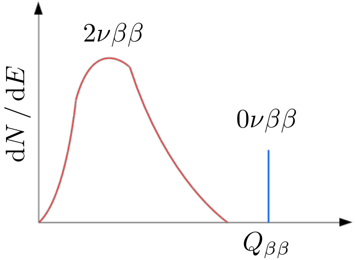
Detecting $0\nu\beta\beta$

- 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}Ge
- Sensitivity to half-life of decay:

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

where ϵ: efficiency; Mt: exposure; BI: background events per kg·yr·keV; ΔE: resolution

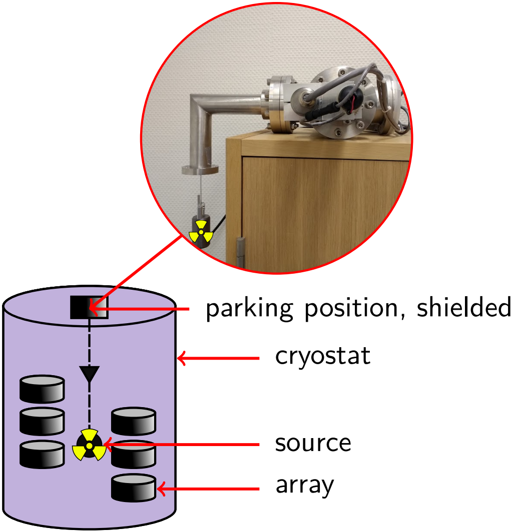




GERDA and the calibration procedure

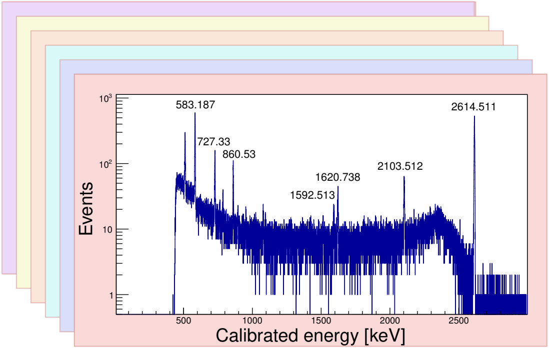
- Knowledge of energy scale, resolution vital for all physics analyses
- Detectors calibrated by ^{228}Th sources ea. 7-10 days
- Three sources lowered to three positions from above cryostat for $\approx$ 2h

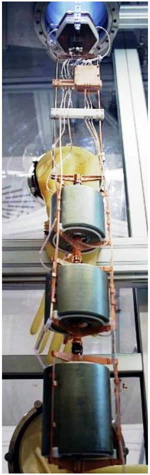
  $\rightarrow$ all detectors exposed
- Source Insertion System (SIS) built in Zurich
  - Operating reliably since 2011
  - Two independent measurement systems determine position of source to ± 1 mm



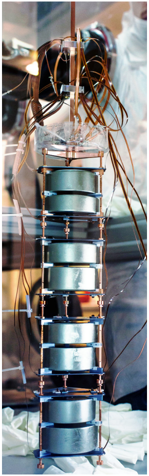
GERDA and the calibration procedure (cont.)

- 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)





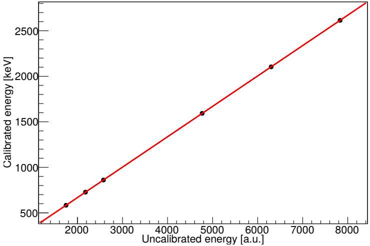
Coax

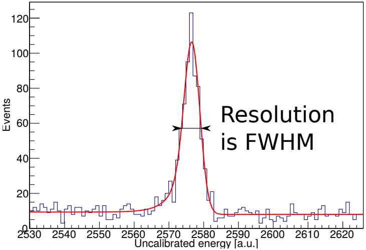


BEGe

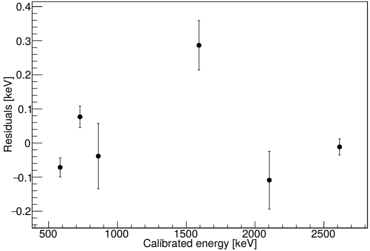
Energy scale calibration

- 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





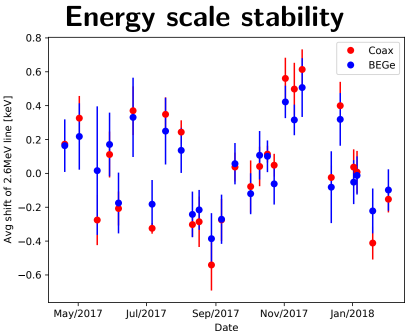
Calibrated energy: 860 keV

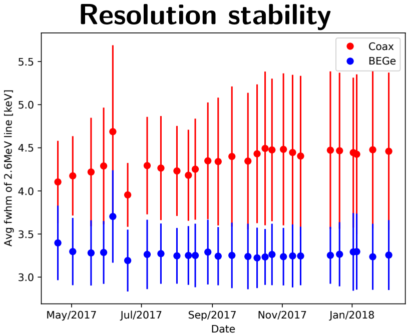


Detector: GD91A, Date: 20180224

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



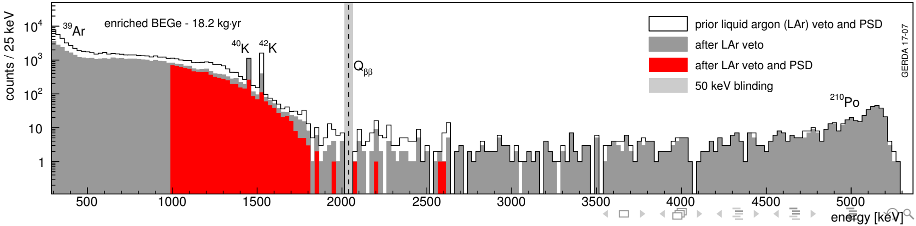


Resolution at $Q_{\beta\beta}$

- Recall:

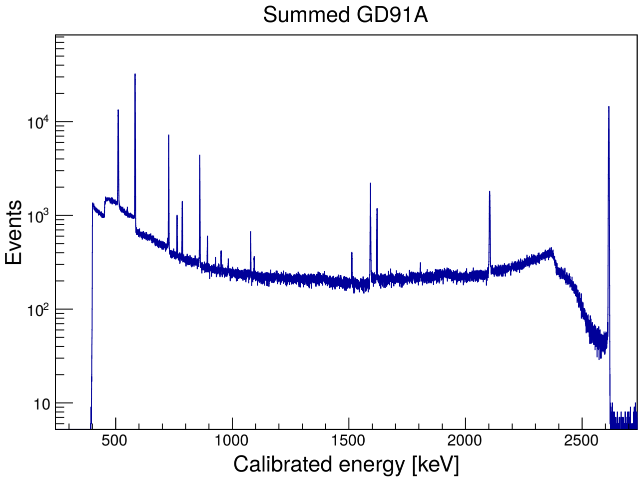
$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{Mt}{BI \cdot \Delta E}}$$

  - 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 $Q_{\beta\beta}$



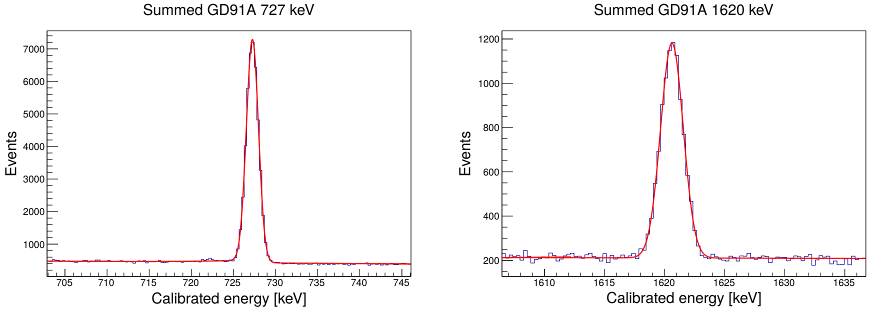
Resolution at $Q_{\beta\beta}$ (cont.)

- 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

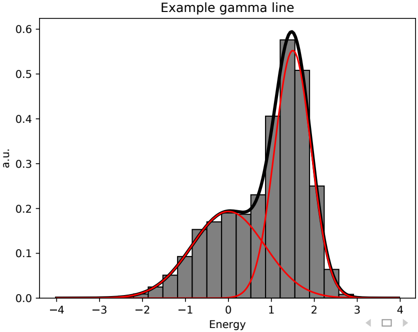
- Combination of many Gaussians is a Gaussian mixture, so:

$$\sigma^2 = \Sigma_i w_i \left(\sigma_i^2 + \mu_i^2\right) - \Sigma_i \left(w_i \cdot \mu_i\right)^2$$

- Assume all means are equal (correctly calibrated peaks!):

$$\sigma^2 = \Sigma_i w_i \ \sigma_i^2$$

where Σ_i is sum over detectors, w_i is detector exposure, σ_i, μ_i are the resolutions / mean positions for each detector



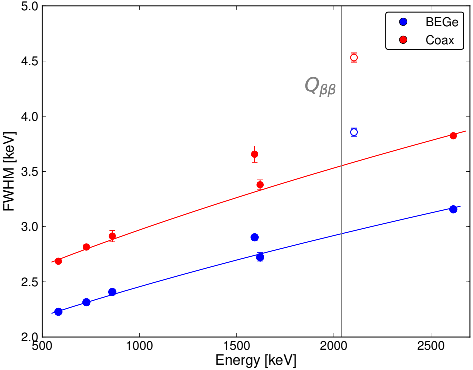
Resolution at $Q_{\beta\beta}$ (cont.)

- 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: $\mathrm{FWHM}(E) = \sqrt{aE + b}$
  - Doppler broadened single-escape peak is excluded



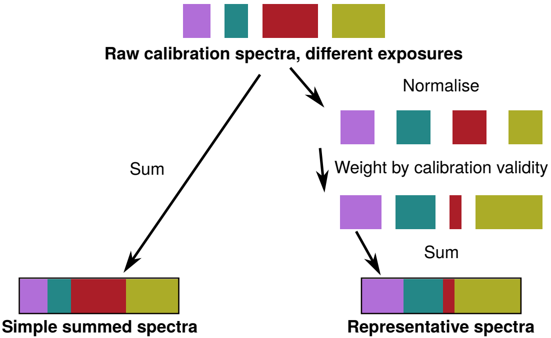
At $Q_{\beta\beta} = 2039\,\mathrm{keV}$

Coax FWHM:
$3.55 \pm 0.02\,\mathrm{keV}$

BEGe FWHM:
$2.94 \pm 0.01\,\mathrm{keV}$

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)



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