Germanium Detectors in $0\nu\beta\beta$ Decay

Roger Huang

April 25, 2018

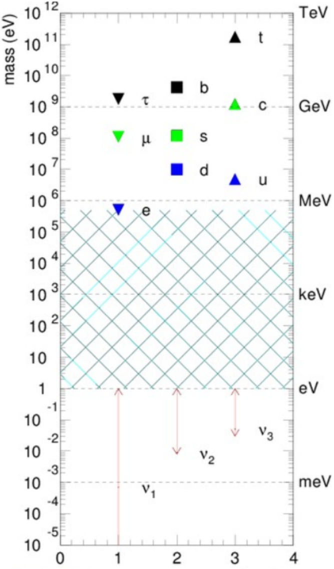
Outline

- $0\nu\beta\beta$ decay
- Principles of germanium detectors
- The GERDA experiment
  - BEGe detectors in GERDA
  - Background rejection with pulse shape discrimination

Motivation for $0\nu\beta\beta$ Decay

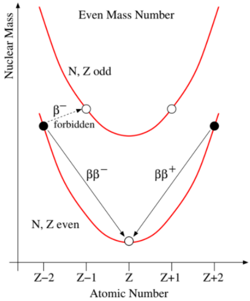
- Neutrino oscillations have been observed → neutrinos are not massless as the Standard Model predicted
- Mechanism for neutrino mass?
    - Seesaw mechanism - but requires that neutrinos be Majorana particles

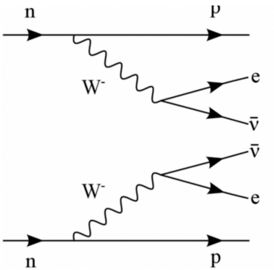
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}\nu_1 \\ e^{i\alpha_2/2}\nu_2 \\ \nu_3 \end{pmatrix}$$

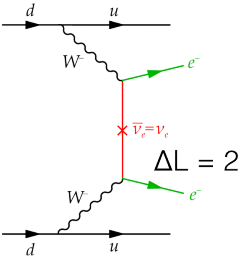


Double Beta Decay

- $2\nu\beta\beta$ decay is a rare but permitted process in the Standard Model
- $0\nu\beta\beta$ decay becomes possible if the neutrino is a Majorana particle







Experimental Requirements for $0\nu\beta\beta$ Detection

- Sensitivity to $0\nu\beta\beta$ requires
  - Large mass
  - Long exposure
  - Low background
  - High energy resolution

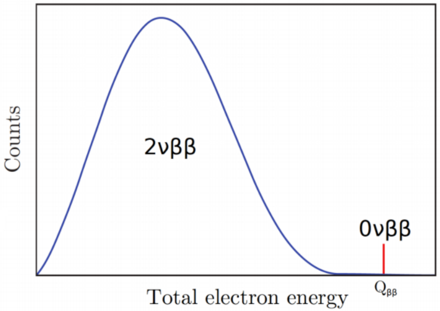
Background Limited

$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} \sqrt{\frac{MT}{b\Delta E}}$$

Background Free

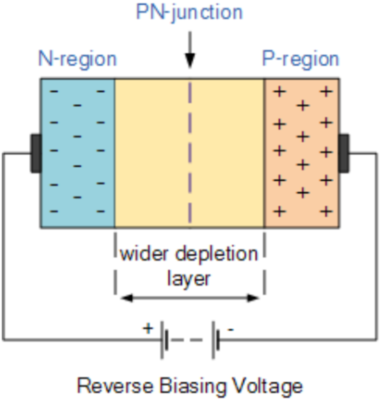
$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} MT$$

a = isotopic abundance
η = stoichiometric coefficient
ε = detector efficiency
b = background index
ΔE = energy resolution
M = target mass
T = livetime



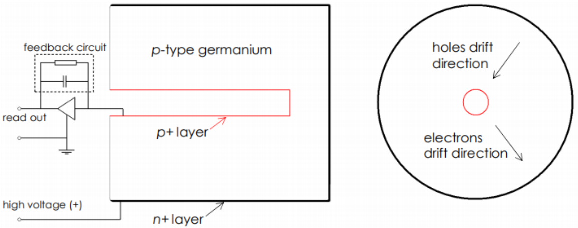
Germanium Detectors - Basic Principles

- Semiconductors with impurities can be p-type or n-type, giving additional holes or electrons to serve as charge carriers
- *Depletion regions*, where there are no free charge carriers, occur at pn junctions
- Semiconductor detectors use this depletion region as the sensitive volume, and can expand its size with a large reverse-biased voltage



Germanium Detectors - Basic Principles

- Radiation depositing energy in the active volume creates electron-hole pairs, inducing a current in the external electrodes
  - Total charge collected at signal electrode $\propto$ absorbed energy for β, α, γ particles
  - Leakage current can occur from thermal excitation of charge carriers, but can be reduced to almost 0 with cryogenic temperatures
- HPGe crystals for γ-ray spectroscopy are normally in a closed-end coaxial geometry



Germanium Detectors for $0\nu\beta\beta$ Decay

- Advantages
  - Source = detector
  - HPGe crystals are some of the purest solid materials available
  - Very good energy resolution (order of 0.1% at Q-value)
  - Already a well-developed technology
- Disadvantages
  - ^{76}Ge has low Q-value of 2039 keV
  - Cost

The GERDA Experiment

- GERDA (GERmanium Detector Array) is located at underground laboratory LNGS in Italy and is searching for $0\nu\beta\beta$ decay of ^{76}Ge
- Enriched Germanium detectors (87% ^{76}Ge) submerged in a 64 m^3 liquid argon cryostat, which is submerged in a 590 m^3 water tank
- 66 PMTs located in the water tank and 16 low-background cryogenic PMTs in the cryostat allow active rejection of background events

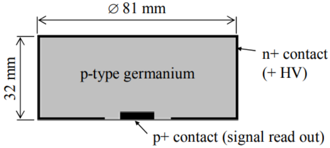
The GERDA Experiment

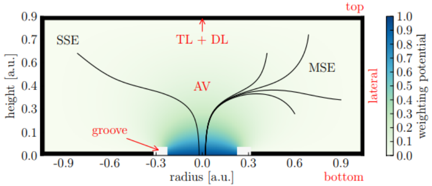
SSE and MSE Events

- At greater than a few hundred keV, Compton scattering dominates γ interactions with the detector
  - Energy is deposited at multiple sites (Multi-Site Event)
- β and α particles have very short stopping distances in the detector
  - Energy is deposited in one place (Single-Site Event)
- Being able to discriminate between SSE and MSE allows rejection of γ backgrounds
- Differences are subtle in coaxial detectors, but Pulse Shape Discrimination (PSD) was doable with neural networks

Broad Energy Germanium (BEGe) Detectors

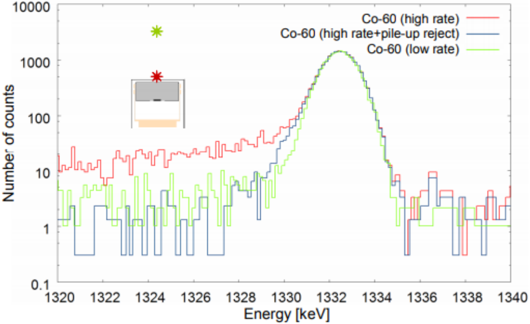
- BEGe detectors give lower noise, better energy resolution, and better pulse-shape discrimination
- 1 mm thick surface electrode blocks most external β and α praticles
- Induced charge at electrode $Q(x)^{e,h} = -q^{e,h} \cdot W(x)$
    - q = charge of charge carrier cluster, $W(x)$ = weighting potential at position x





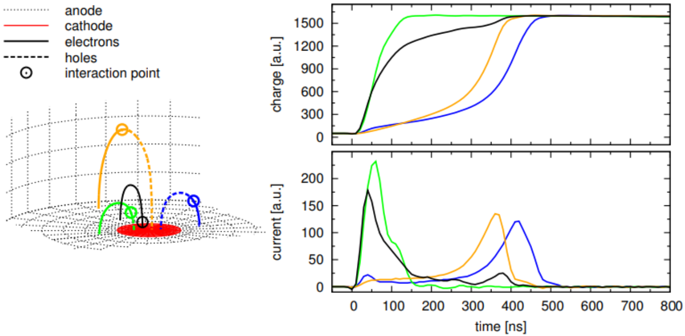
Charge Trapping and Pileup in BEGe Detectors

- BEGe detectors have charge collection times up to 1 μs instead of 100's of ns like in coaxial detectors
  - Charge trapping and recombination losses are potentially a concern
  - If present, these effects show up as shifts in peak positions and low energy tails of full energy peaks
  - These effects are not present for the BEGe detectors being used (tails are seen, but can be attributed to pileup)



Signals in BEGe Detectors

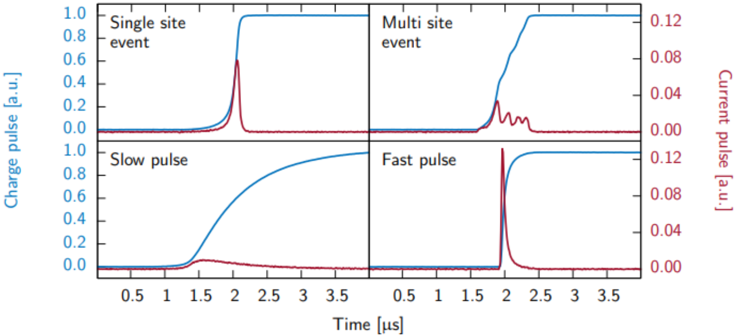
- Weighting potential distribution in BEGe detectors means most of the charge pulse comes from holes hitting the p+ electrode



(a) Trajectories (b) Charge and current pulses

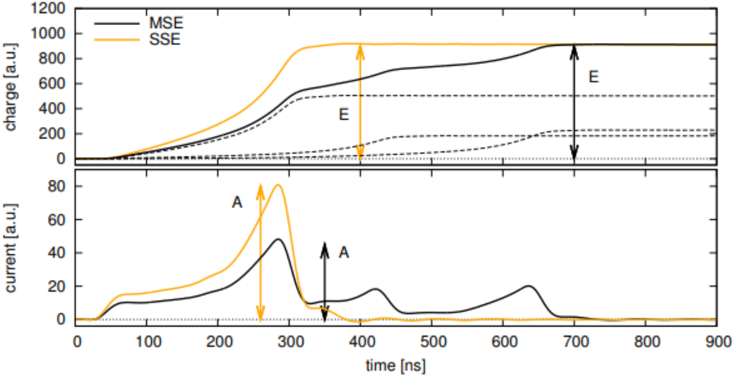
Pulse Shape Discrimination in BEGe Detectors

- Slow pulses occur for events near the lithium contact at the detector surface
- Fast pulses occur for events near the p+ point contact



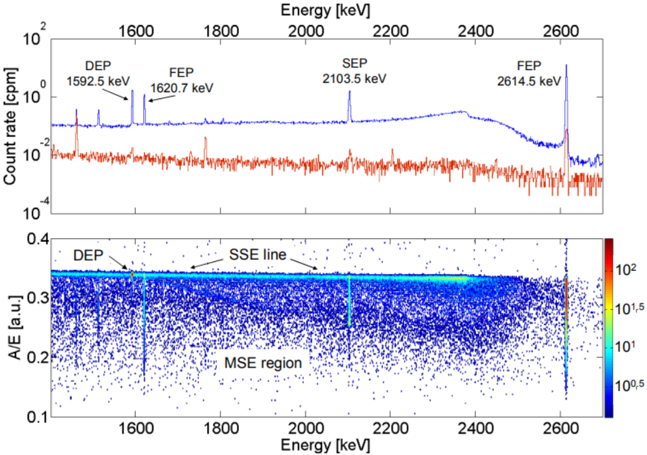
Pulse Shape Discrimination Parameters

- Simple A/E parameter used to discriminate between SSE and MSE
- A = maximum current pulse amplitude, E = total event energy



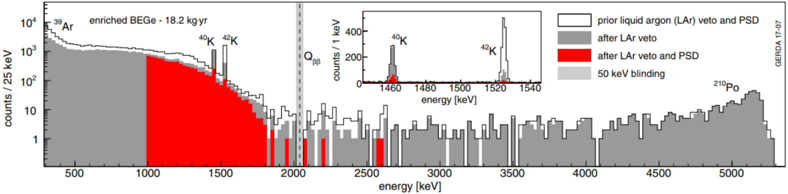
A/E Distributions

- SSE should have a flat A/E, while MSE have lower A/E
- Double-escape peak (DEP) in ^{208}Tl spectrum provides near-pure population of SSE



GERDA Results

- 90% CL limit: $T_{1/2}^{0\nu} > 8.0 \cdot 10^{25}$ yr
- Estimated background of $1.0^{+0.6}_{-0.4} \times 10^{-3}$ counts / (keV kg yr)
  - "Background-free": < 1 expected background counts in FWHM energy interval at Q-value over total design exposure of 100 kg yr



Summary

- Germanium detectors are a widely-used technology with many appealing features for $0\nu\beta\beta$ experiments
  - High purity, high energy resolution, and industrial support
  - Additional background rejection with pulse-shape discrimination
- GERDA currently has the best $0\nu\beta\beta$ half-life limit for ^{76}Ge, and is competitive with searches with ^{130}Te by CUORE and with ^{136}Xe by KamLAND-Zen

References

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