Pulse Shape Discrimination with BEGe Detectors in GERDA Phase I

Victoria Wagner

on behalf of the GERDA Collaboration

Max-Planck-Institut für Kernphysik

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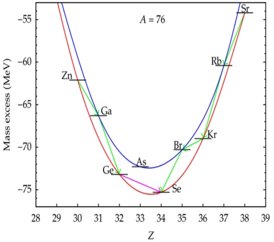
Double Beta Decay ($2\nu\beta\beta$)



The Rarest Decay Ever Observed

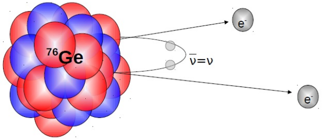
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}$$

- Can occur for even-even nuclei if single β-day is energetically forbidden
- 35 candidates such as: ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe
- The half live of $2\nu\beta\beta$ in ^{76}Ge as measured by GERDA is $T^{2\nu}_{1/2} = 1.84^{+0.14}_{-0.10} \times 10^{21} yr$

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

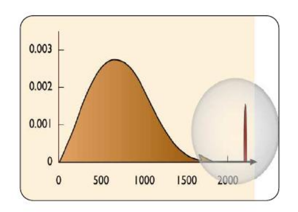
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

- In the standard interpretation the process is mediated by light massive Majorana neutrinos
- Forbidden in the standard model
- Observation would imply lepton number violation ($\Delta L = 2$)
- $0\nu\beta\beta$ decay has not been observed yet
- For ^{76}Ge $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr (90% C.L.)
  – Phys. Rev. Lett 111 (2013) 122503



Experimental Approach to $0\nu\beta\beta$

The Experimental Signature of $0\nu\beta\beta$



Energy sum spectrum of the two emitted e^-

The energy of the electrons in the final state is measured:

- $2\nu\beta\beta$ describes a continuous energy spectrum
- $0\nu\beta\beta$ would produce a full energy peak at the maximum energy, $Q_{\beta\beta}$
- For ^{76}Ge: $Q_{\beta\beta} = 2039\text{keV}$

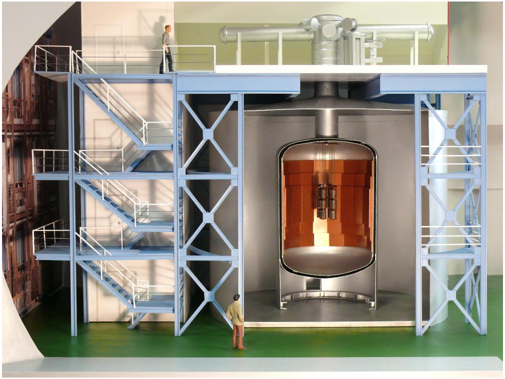
No background: $T_{1/2}^{0\nu} \propto \frac{1}{N^{0\nu}}$

How to Achieve a High Experimental Sensitivity on the Lower Limit of $T_{1/2}^{0\nu}$?

$$T_{1/2}^{0\nu}(90\%\text{C.L.}) \propto f \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

1. High abundance of the $\beta\beta$ isotope f
2. High signal detection efficiency ϵ
3. Large mass M
4. Long measurements time T
5. Excellent energy resolution ΔE, to avoid background from $2\nu\beta\beta$
6. Very low background B at $Q_{\beta\beta}$, $[\frac{cts}{keV \cdot kg \cdot yr}]$

The GERmanium Detector Array Experiment



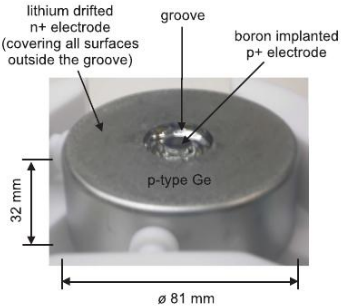
Searching for $0\nu\beta\beta$ of ^{76}Ge

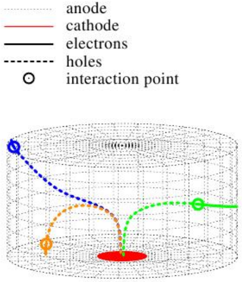
- GERDA searches for the $0\nu\beta\beta$ of ^{76}Ge
- The detector are arranged in an array which is merged into a liquid argon (LAr) cryostat
- The LAr serves as shielding and cooling material
- Germanium diodes are used as source and detector to maximize the detection efficiency
- The diodes are isotopically enriched in ^{76}Ge to about $f_{76} \approx 86\%$ (natural abundance $\approx 8\%$)
- Germanium detectors have an excellent energy resolution $\Delta E \approx 0.2\%$ at $Q_{\beta\beta}$

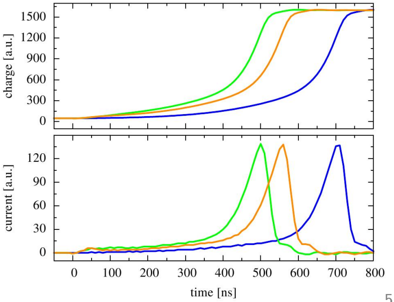
The GERDA Phase I

- Nov '11 - May '13: 8 detectors from former Heidelberg-Moscow and IGEX experiment with $M = 17.67$kg
- July '12 - May '13: 5 new BEGe detectors with 3.63kg were inserted as a test

Broad Energy Germanium Detectors

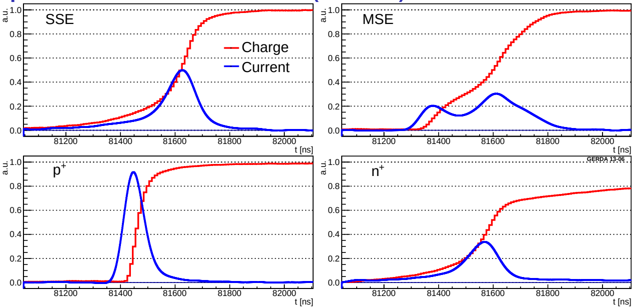




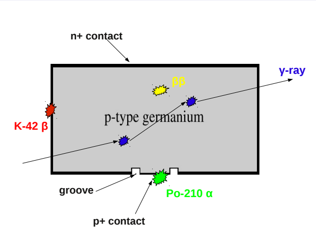


from JINST 6 P03005

Pulse Shapes Discrimination (PSD)

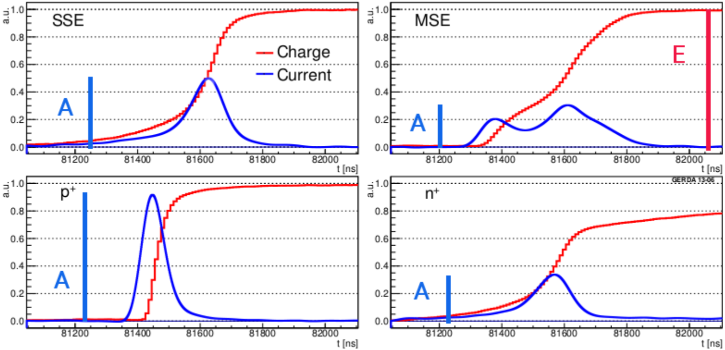


Which Events Can Be Distinguished?



- $\beta\beta$-events are single site events (SSE), i.e. the energy deposition happens locally
- SSE by γ-rays are signal like and cannot be rejected
- γ- rays depositing energy in different locations of the crystal are so-called multi-site event (MSE)
- α-particles enter the detector through the region of the p^+ contact
- β-particles enter the detector via the n^+ surface and produce slow pulses

The Pulse Shape Analysis Method

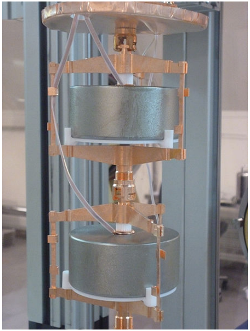


The A/E Parameter

- **A/E**: The ratio of the maximum amplitude of the current pulse A and the energy E
- For a given energy
  - MSE has lower A/E values;
  - α (p^+ contact) event has larger A/E;
  - β (n^+ contact) event has lower A/E;

in comparison to a signal like SSE event.

BEGe Detectors in GERDA Phase I



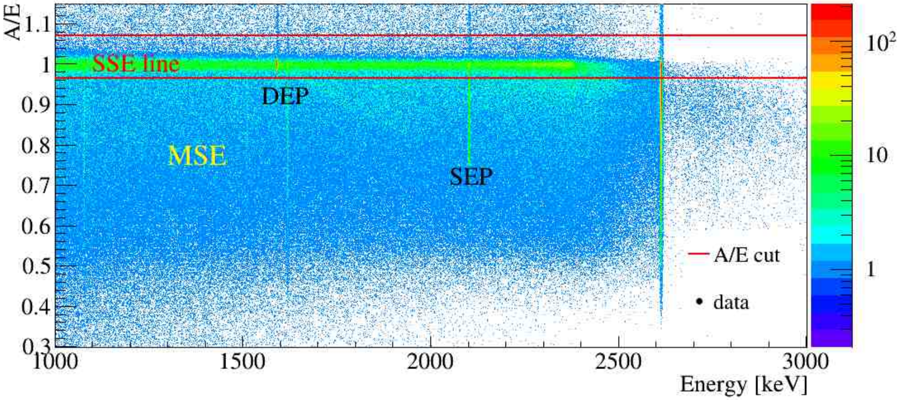
BEGe Diodes in GERDA Phase I

In July 2012 five new enriched BEGe diodes were installed in the GERDA LAr cryostat. The goal of this test was to prove that BEGe's

- can be operated stable in LAr over a long period;
- have an enhanced pulse shape discrimination (PSD) against background events.

- Additional mass for $0\nu\beta\beta$ analysis

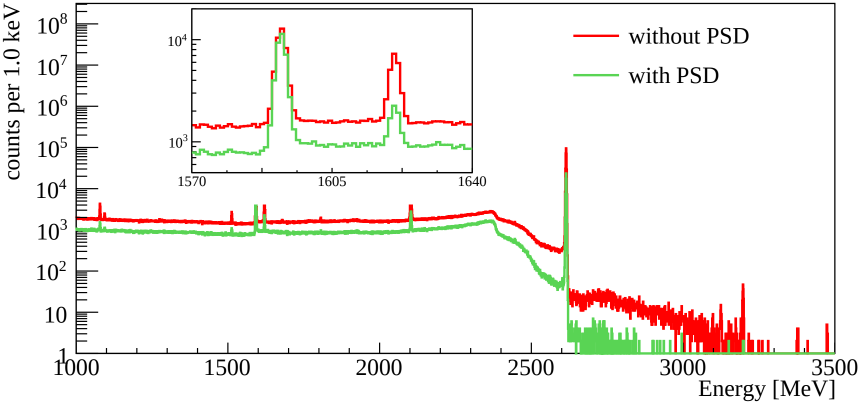
Calibration of A/E Cut



^{228}Th Spectrum: SSE vs MSE

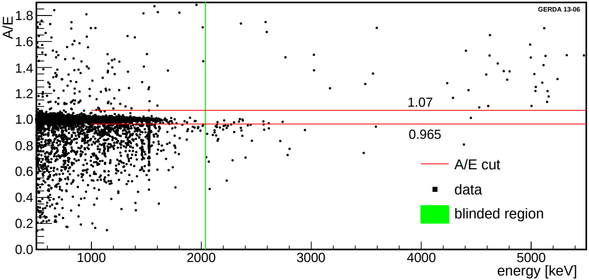
- SSE lie on a horizontal line at $A/E = 1$
- MSE are below SSE line
- Events above SSE line are close to the read-out electrode
- The double escape peak (DEP)at 2.6 MeV - 2· 511keV are signal-like events

The ^{228}Th Calibration Spectrum



- DEP events: Survival efficiency 93%
- Single escape peak (SEP) events are mostly MSE: Survival efficiency 16.5%
- Compton region suppressed by a factor of 2

Application of Pulse Shape Discrimination (PSD) to the Physics Data

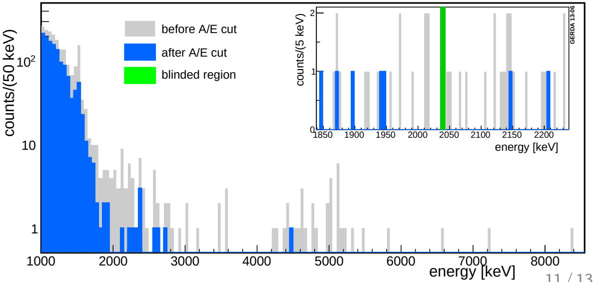


The PSD Cut

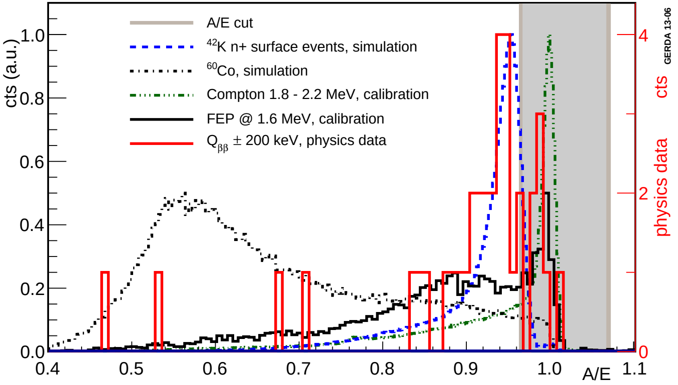
- The cut rejects events with $A/E < 0.965$ ("low A/E cut") and $A/E > 1.07$ ("high A/E cut")
- The cut was chosen to have a high probability of no events around $Q_{\beta\beta} = 2039$ keV, but maintain a high signal efficiency of 92%

80% of Events Rejected in ROI

- In the 400 keV region around $Q_{\beta\beta}$ 40 events are observed
- The PSD cut rejects 33 out of 40 events the ROI



Surface Events



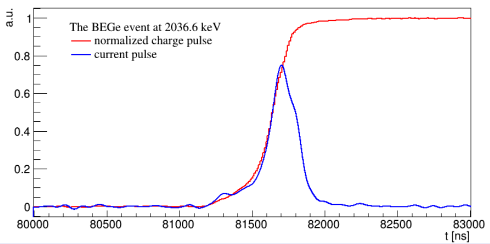
Rejection of β Events on the Detector Surface in GERDA

- ^{42}Ar decays into ^{42}K via β^-, Q-value is 600 keV
- ^{42}K decays into ^{42}Ca via β^-, Q-value of 3525 keV
- About half of the events in the $Q_{\beta\beta}$-region are from ^{42}K decays on the n$^+$ surface
- n$^+$ surface events are slow pulses, thus have a significantly lower A/E

$\rightarrow$ β events on the detector surface are efficiently rejected by the low A/E cut even when the cut is loose

Summary and Conclusion

Finally Opening the Box

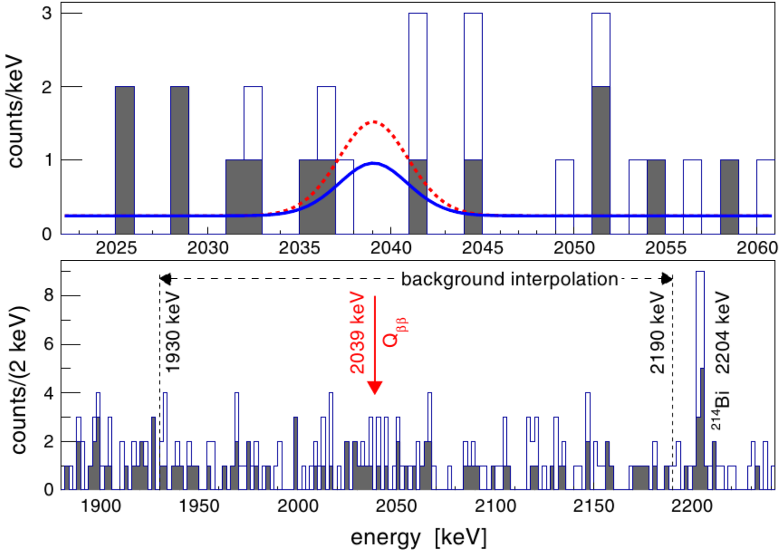


- Unblinding the region from 2036 - 2043 keV region revealed one event in the BEGe channels
- The pulse shape analysis characterizes this event clearly as background
- $A/E = 0.75$, well below the cut at 0.965

- The BEGe detectors, with their special geometry allow for a powerful pulse shape analysis based on a single parameter A/E. (see Eur. Phys. J. C 73 (2013) 2330)

Bonus Slides

Opening the Box



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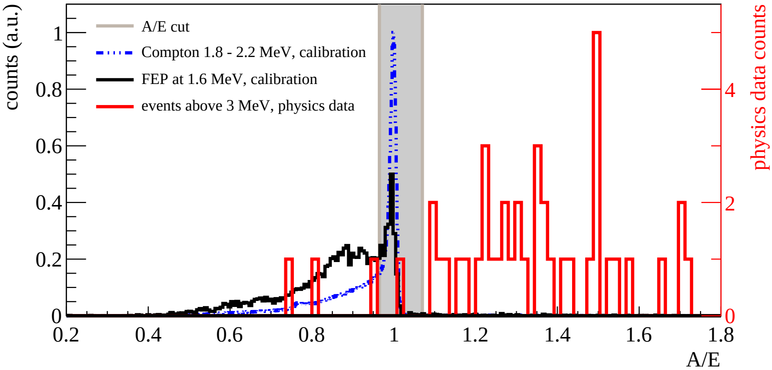
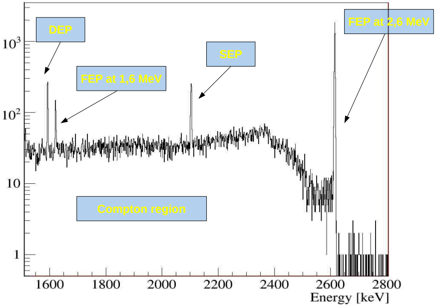
Rejection of p^+ Events

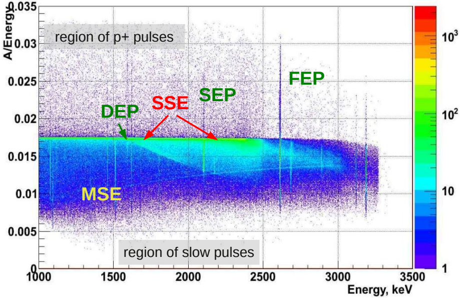


p^+ Surface Events

- α's cannot penetrate the dead layer, they enter the detector through the p^+ contact
- As both charge carrier types contribute to the signal A/E is significantly larger compared to bulk events
- Nearly all events above 3 MeV show a high A/E value
- The four events below the high A/E cut are inconsistent with α events according to their pulse shape

Calibration of A/E Using the ^{228}Th spectrum





The ^{228}Th Spectrum: MSE vs SSE

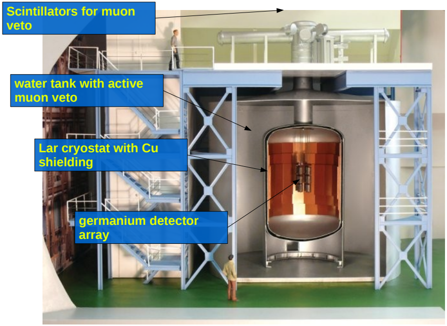
- SSE are located on a horizontal line: Single Compton events
- MSE are found below the SSE-line
- Full energy peaks (FEP) contains a high fraction of MSE. E.g. γ rays that are fully absorbed by multiple Compton scattering
- Single escape peak (SEP) events are mostly MSE, since an electron and an annihilation photon pair is detected $\rightarrow$ the SEP contains a high fraction of MSE,
- In the double escape peak (DEP) events only the electron from the annihilation is detected $\rightarrow$ DEP events are SSE
- The DEP is used as a proxy for $0\nu\beta\beta$

How to Achieve a Low Background in GERDA?

- The goal is to avoid any background in the ROI
- The most dangerous contribution for the identification of $0\nu\beta\beta$ events are decays with Q values above 2039 keV

Passive Background Suppression

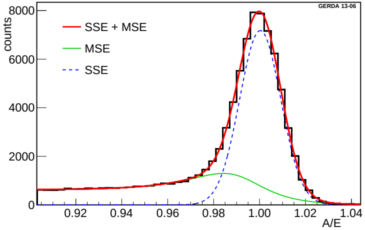
- GERDA is located deep underground at LNGS where the overburden reduces the muon induced neutron flux to a negligible level
- All built-in materials are of (a known) low activity
- The liquid argon (LAr) serves both as cooling and shielding material
- The LAr cryostat has an additional cupper shielding
- The surrounding water tank moderates and absorbs neutrons



Active Background Suppression

- The water tank is equipped with PMT to detect muons via Cherenkov light
- Muons are also detected by the plastic scintillators on the top
- In Phase II the LAr will be used as a scintillation medium to detect γ-rays
- Analysis of the signals pulse shape helps to discriminate background from signal-like events
- In Phase II new detector design will be used with enhanced energy resolution and pulse shape discrimination: **B**road **E**nergy **Ge**rmanium detectors

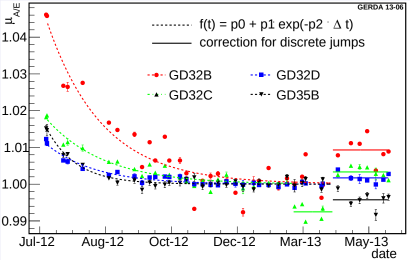
Calibration of E/A Cut



The A/E Distribution

- Compton continuum and DEP events from ^{228}Th calibrations have an A/E distribution which is described by
  - a Gaussian part from SSE and
  - a low side tail from MSE
- The same is true for events in the $2\nu\beta\beta$ region in physics data
- The Gaussian mean $\mu_{A/E}$ of the DEP A/E distribution is used to monitor the stability of the pulse shape parameter

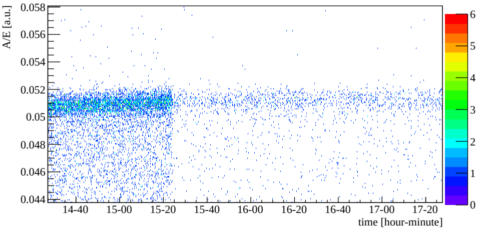
A/E Long Term Behavior



- The weekly ^{228}Th calibrations are used to monitor the stability of A/E
- The $\mu_{A/E}$ of the DEP describes an exponential decay with a time constant of about a month
- The total change was between 1 and 5%
- Additional jumps in A/E occurred e.g. after a power failure
- Simulation show that collected charges on the detectors surface shift $\mu_{A/E}$ to lower values

The correction is applied as $A/E_{corr} = \frac{A/E}{f(t)}$ to calibration and physics data

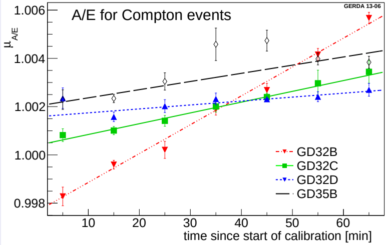
A/E Drift during Calibration



Calibration $A/E \neq$ Physics A/E

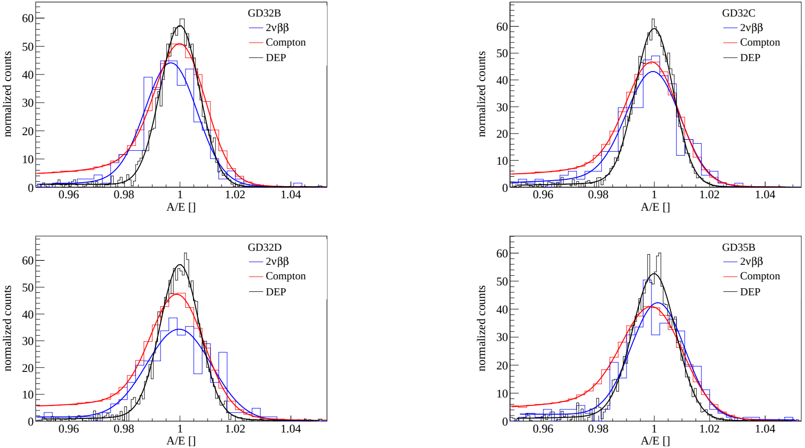
- A/E is increasing during calibrations
- This increase leads to a higher A/E value of Compton events from calibration than of the $2\nu\beta\beta$ events in physics runs
- As a consequence, a correction has to be applied to the calibration data

Correction of A/E Drift during Calibrations



- For the correction the drift was averaged over the first 70 minutes
- The drift is approximated with a linear function $f(t) = b0 + b1 \cdot t$
- The correction to calibration data is applied as $A/E_{corr} = \frac{A/E \cdot b0}{f(t)}$
- After calibration A/E decreases again to the starting value within one day

A/E Distribution after Corrections



- After all corrections the difference between $2\nu\beta\beta$ (1.-1.3 MeV) and DEP $\mu_{A/E}$ is very small ($< \sigma(A/E)$)
- This shows the validity of the applied corrections

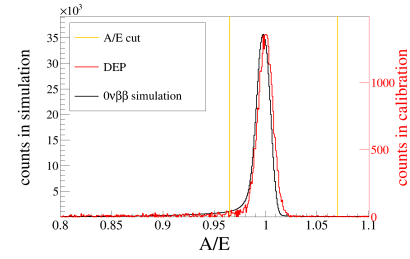
Comparison of Survival Fractions in Calibration and Bck

region	low cut	high cut	surviving fraction
^{228}Th calibration			
DEP 1592.5 keV	0.054 ± 0.003	0.015 ± 0.001	0.931 ± 0.003
FEP 1620.7 keV	0.771 ± 0.008	0.009 ± 0.002	0.220 ± 0.008
SEP 2103.5 keV	0.825 ± 0.005	0.011 ± 0.001	0.165 ± 0.005
1839 - 2239 keV	0.463 ± 0.001	0.0152 ± 0.0001	0.540 ± 0.001
background data			
FEP 1524.7 keV	0.69 ± 0.05	0.027 ± 0.015	0.29 ± 0.05
1.-1.45 MeV	0.230 ± 0.011	0.022 ± 0.004	0.748 ± 0.011
1839 - 2239 keV	30/40	3/40	7/40
$>$ 4 keV (α at p+)	1/35	33/35	1/35

Signal Efficiency

$0\nu\beta\beta$ Survival Efficiency

DEP is a proxy for $0\nu\beta\beta$ survival of the low A/E cut because MSE fraction in DEP is equivalent to the MSE fraction in $0\nu\beta\beta$



- Fraction of events removed in DEP by low A/E cut: 0.054
- To determine the $0\nu\beta\beta$ survival fraction of the high A/E simulation data are used since the volume distribution of DEP and $0\nu\beta\beta$ events is different:
  - DEP events occur predominantly in the detector corners
  - $0\nu\beta\beta$ events are homogeneously distributed in the detector volume
- Fraction of events removed in simulated $0\nu\beta\beta$ by high A/E cut: 0.025

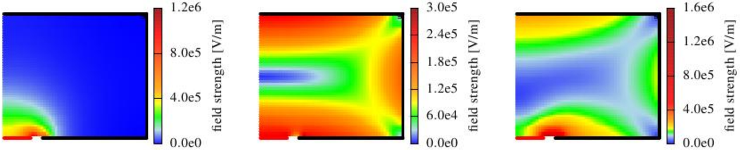
Cut survival efficiency of the $0\nu\beta\beta$ signal: 0.921 ± 0.019

Cross Check: The $2\nu\beta\beta$ Efficiency

- The survival fraction of events in the $2\nu\beta\beta$ region from 1.-1.45 MeV can be used as a cross check of the $0\nu\beta\beta$ signal efficiency when taking into account the different background components and their survival fractions
- Events in the transition layer (TL) of the detector are slow pulses and a smaller energy is seen at the read-out electrode. Thus, TL events are rejected by the A/E cut.
- Since the $0\nu\beta\beta$ events in the TL would not be seen at $Q_{\beta\beta}$ but the corresponding $2\nu\beta\beta$ events, the $2\nu\beta\beta$ efficiency is reduced by a factor of 0.985 electrode

Cut survival efficiency of the $2\nu\beta\beta$ events is 0.913 ± 0.054 and in good agreement with $0\nu\beta\beta$ efficiency

The Electrical Field inside Diodes



(b) $||\vec{E}_0(\vec{r})||$ (d) $||\vec{E}_\rho(\vec{r})||$ (f) $||\vec{E}(\vec{r})||$

The Funneling Effect from JINST 6 P03005

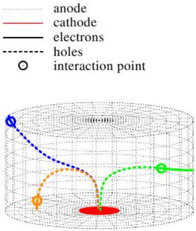
The internal electrical field $\vec{E}$ can be understood as a superposition of the potential created by the space charge distributions in the active volume, $\vec{E}_\rho$, and the electric field generated by the electrode potential only, $\vec{E}_0$:

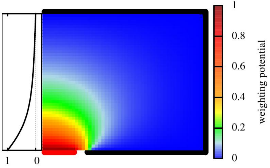
$$\vec{E}(\vec{r}) = \vec{E}_0(\vec{r}) + \vec{E}_\rho(\vec{r})$$

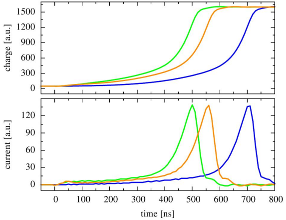
- The electric field created by the electrodes only, $\vec{E}_0$, is weak in the detector but in the vicinity of the small read-out electrode
- whereas $\vec{E}_\rho$ is strongest at the surface and weak in the middle slice of the diode

As the charge clusters follow the electrical field, the holes are collected in the middle slice of the detector, mainly by the contribution from $\vec{E}_\rho$, and finally funneled towards the read-out electrode by $\vec{E}_0$.

Signal Developing in the Diodes







Signal Development from JINST 6 P03005

The charge Q induced by a charge carrier q in the active detector volume at the read-out electrode is described by the Shockley-Ramo theorem:
$Q = -q \cdot W(x)$
$W(x)$ is the so-called *weighting potential* for the charge q at the position x. The signal development in time, i.e. the pulse shape, is given by the weighting potential $W(x)$. The signal increases as the charge cluster reaches a position of strong weighting potential within the diode.