Characterization of BEGe detectors in GERDA

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for the BEGe GERDA WG

Outline

- Characterization of 3 Canberra BEGe detectors
  - The detectors
  - The depl BEGe detectors
  - Energy Resolution & Linearity
  - Count rate vs HV
  - The dead layer determination
  - Average pulses and RT distributions
  - Single Site Events/ Multi Site Events Pulse Shape Discrimination

- Comparison and discussion of the results of the 6 BEGe detectors tested so far in GERDA.
The detectors

- P-type HPGe
  - Li-drifted, n+, wrap around contact for HV+.
  - p+ B implanted at bottom center for Readout electrode.

- Diameter: Φ = 70 mm
- Native Ge (natGe)
- LNGS
- 32 mm

- Diameter: Φ = 74 mm
- Depleted Ge (deplGe)
- CC
- 33 mm

- Diameter: Φ = 74 mm
- Depleted Ge (deplGe)
- DD
- 23 mm

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Since 2009 GERDA is pursuing with Canberra an R&D for the production and characterization of BEGe detectors from $^{\text{depl}}\text{Ge}$ from ECP plant then refined & reduced to metal @ PPM (21.5 kg) $\rightarrow$ same origin and chemical purification “history” of 37.5 kg $^{\text{enr}}\text{Ge}$.

- Canberra Oak Ridge for x-tal pulling. Industrial process discussed and modified to minimize the Ge wastes
- Canberra Olen for detector production

- 4 p-type x-tal ingots pulled in 2009.
- 2 $^{\text{depl}}\text{BEGe}$ made out from the x-tals and then characterized by GERDA collaboration so far (in hands since april 2010)
- 2 -3 more detectors will be produced & tested

**Purpose of the R&D:**
- Demonstrate that the ECP/PPM material is good for Ge HP
- Qualify the industrial procedure, modified to maximize
HV scanning of the two \textsuperscript{depl}BEGe by \textsuperscript{60}Co source

\begin{enumerate}
  \item Count Rate vs bias
  \item Peak Position vs bias
  \item E. Res vs. bias
\end{enumerate}

→ Standard behaviour

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HV scanning of the $^{natBEGe}_{LNGS}$ by $^{137}$Cs source

- Peculiarity shows up $\sim 2000$ V, in CR curves.
- Not an artefact
- Studied carefully (explanation in extra slides, please ask question!)
Resolution & Linearity of the $^{\text{nat}}$BEGe$_{\text{LNGS}}$ detector

At the bias operational V (3500 V) Resolution and Linearity have been carefully studied irradiating with $^{241}$Am, $^{137}$Cs, $^{60}$Co, $^{228}$Th sources.

Unlinearity < 0.02%

$R(\text{FWHM}) = a + b\sqrt{E}$

$a = (0.18 \pm 0.01) \text{ keV}$

$b = (0.0393 \pm 0.0004)\sqrt{\text{keV}}$

$R = 500 \text{ eV @ 60 keV}$

$R = 1.56 \text{ keV @ 1.332 MeV (6 µs shaping time)}$

R (pulser) = Standard, excellent behaviour
Determination of the active volume of the \textsuperscript{nat}BEGe\textsubscript{LNGS} (70 x 32 mm)

- By top radial and lateral axial scanning with $^{241}$Am source (425 kBq)
- The estimated diameter of the active volume is ~ 69 mm.
- Height of the active volume is ~ 29 mm.
Dead Layer (DL) thickness determination for the BEGe

- The average thickness of the DL is derived by the ratio of the intensities of the 81 keV and 356 keV γ-lines of a $^{133}$Ba 125 kBq source.

- The DL thickness on the top of the detector, which is necessary to reproduce the experimental ratio $R = 1.07 \pm 0.01$

  is $(0.79 \pm 0.03 \text{ stat} \pm 0.9 \text{ syst}) \text{ mm}$

- The DL thickness on the side is $0.7 \text{ mm}$. 

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Active volume determination of $^{\text{depl}}\text{BEGe}_{cc}$

Radial & axial scanning by $^{241}\text{Am}$ source

For DL determination need to go through MC

DL values not yet available
Active volume determination of $^{\text{depl}}\text{BEGe}_{\text{DD}}$

Radial & axial scanning by $^{241}\text{Am}$ source

For DL determination need to go through MC

DL values not yet available
Comparison of exp data with the detector modeling

- Model ingredients: actual geometry, impurity density profile, E field
- Output: $V_{\text{depl}}$ & pulse simulation

Comparison of exp vs simulated pulses for the LNGS BEGe scanning the top surface with $^{241}\text{Am}$

Excellent agreement

Preliminary presented at NSS09
Preliminary: Pulse RT & search of Slow pulses

- To study the “slow pulses” we have irradiated the detectors with an uncollimated $^{241}$Am source placed on the top surface.

- Questions: Are the slow pulses (RT > 500 ns) related to the detector DL thickness?
  - Observation: SP number increases at decreasing of energy $\Rightarrow$ slow pulses from $\gamma$s interaction at the border of Active Volume and the DL. ($\mu_{60\text{keV}} = 1 \text{ mm}$)
  - Is the SP number related to the thickness of the DL?

Msmnt performed in over ground lab

Msmnt performed in shallow lab
Pulse RT & search of Slow pulses in $\text{deplBEGe}_{\text{DD}}$ & $\text{deplBEGe}_{\text{CC}}$

CC
DL~0.4 mm

DD
DL~0.4 mm

E=241Am peak
2 keV<E<30 keV
Slow Pulses (cont’d)

- **Work in progress** as DL not yet derived from data for CC and DD $^{\text{depl}}$BEGe

- Investigate SP in data collected irradiating with sources of different energies (if Slow Pulses related to DL should be less increasing the energy of $\gamma$)
The PSD to identify SSE & MSE

- **Charge pulse**
  - $\tau_{\text{rise}} = 141 \text{ ns}$
  - $E = 846 \text{ keV}$

- **Current pulse**
  - Typical SSE
  - $A/E = 0.723 \text{ a.u.}$

- **Charge pulse**
  - $\tau_{\text{rise}} = 262 \text{ ns}$
  - $E = 726 \text{ keV}$

- **Current pulse**
  - MSE
  - $A/E = 0.448 \text{ a.u.}$
Example: Definition of the PSD cuts on the $^{228}$Th data for the BEGe$_{\text{LNGS}}$

- The detector is irradiated with 95 kBq $^{228}$Th source
- Events are plotted in A/E vs E
- Select $\Delta E$ (DEP,FEP,CC) \( \rightarrow \) projected on A/E axis
Acceptance as a function of A/E cut

Define cut requiring an acceptance of 90% of the DEP peak \( \rightarrow \)

\(~10\%\) acceptance of the 1620 keV FEP

![Graph showing the acceptance as a function of A/E cut](image)
Energy spectra when applying the PSD cut

- When applying the PSD cut
  - the DEP peak (SSE) survive at 90% while the FEP @ 1620 keV ($^{212}\text{Bi}$ line) is reduced at ~10%
  - The Compton Continuum is reduced of a factor ~ 2
# PSD: comparison of results from all the BEGe tested in GERDA

<table>
<thead>
<tr>
<th>Dim.sns</th>
<th>Contact dim [mm]</th>
<th>Mass [g]</th>
<th>$V_{\text{depl}}$ [V]</th>
<th>Compton @Qbb</th>
<th>DEP 1592 keV</th>
<th>FEP 1621 keV</th>
<th>SEP 2103 keV</th>
<th>FEP 2614 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>81 x 32</td>
<td>15</td>
<td>868</td>
<td>4000</td>
<td>39 ± 2</td>
<td>90±1.6</td>
<td>9.5±1.5</td>
<td>5.8 ± 0.6</td>
<td>7.7 ± 0.7</td>
</tr>
<tr>
<td>70 x 32</td>
<td>15</td>
<td>632</td>
<td>3000</td>
<td>37.5±0.5</td>
<td>90±0.6</td>
<td>11.5±0.1</td>
<td>6.2±0.4</td>
<td>6.4±0.1</td>
</tr>
<tr>
<td>60 x 26</td>
<td>15</td>
<td>390</td>
<td>3000</td>
<td>45 ± 2</td>
<td>90 ± 3</td>
<td>18 ± 3</td>
<td>6.8±1.7</td>
<td>14 ± 3</td>
</tr>
<tr>
<td>80 x 30</td>
<td>15</td>
<td>825</td>
<td>3500</td>
<td>49 ± 2</td>
<td>90 ± 3</td>
<td>29 ± 2</td>
<td>23 ± 2</td>
<td>Not avlbl</td>
</tr>
<tr>
<td>74 x 33</td>
<td>9</td>
<td>752</td>
<td>3500</td>
<td>38.3 ± 0.3</td>
<td>90 ±1.1</td>
<td>10 ± 0.6</td>
<td>5.4±0.3</td>
<td>8.3 ± 0.1</td>
</tr>
<tr>
<td>74 x 32</td>
<td>22</td>
<td>~750</td>
<td>3500</td>
<td>39.8±0.3</td>
<td>90±1.1</td>
<td>11.3±0.6</td>
<td>5.8±0.4</td>
<td>8.8±0.1</td>
</tr>
</tbody>
</table>

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Conclusions

- In the GERDA collaboration 6 BEGe (3 commercial, two from depl Ge GERDA-custom Canberra production run ) detectors have been tested until now.

- All of them show superior En Res and no charge collection inefficiencies, extra dead-layers etc.

- The PSD applying the A/E cuts originally developed in GERDA collaboration (D. Budjas et al., JINST 4 (2009) P10007 ), acts as follows in all detectors:
  - When Single Site Events $\beta\beta$-like (i.e. DEP @ 1.593 keV) are accepted with 90% efficiency
  - ~ 6-8% of the MSE from $\gamma$s interactions are accepted at the $^{208}$Tl SEP (2.103 MeV) and $^{208}$Tl (2.614 MeV) lines
  - The acceptance of events at Compton Continuum is $\leq$40% as expected from physics of Compton interactions (SSE)

- Two detectors show some deviations on PSD of $\gamma$-like events: further investigation.
Conclusions

- The exp.data together with the detector modeling show that:
  - Bckgrd from $^{68}$Ge ($\beta^+ Q_\beta=1.8$ MeV + $2\gamma$ 511) keV, will be rejected as $^{208}$Tl SEP $\gamma$-like events at ~ 94% level
  - Bckgrd from external $^{60}$Co ($\gamma$s 1.17 MeV keV & 1.332 MeV) i.e. $\gamma$-like, will be rejected at ~1% (0.10 x 0.10) level
  - Bckgrd from internal $^{60}$Co ($\beta^-$ $Q_\beta$=2.8 MeV + $\gamma$s 1.17 MeV keV & 1.332 MeV) will be also rejected at 99%

- Slow Pulses: work in progress.
  - Some indications from (70 x 30 mm) that pulses with RT > 700 ns related to DL thickness, but not fully consistent with all the detectors tested so far \(\rightarrow\) repeat msrmnts/analysis
  - Possible correlation with readout contact/insulating groove dimensions
  - Need further study

- The detector modeling (E field and pulse shapes in the full detector volume) is very advanced and is a powerful tool!
Satellite peaks in $^{137}$Cs spectra

Effects related to:
- Readout Electrode dimension
- Impurity profile impact Efield
The bubble-locking interpretation and experimental evidences

with $^{137}\text{Cs}$ @ $V_{\text{bias}} = 2010$ V

radial scanning from the top

vertical scanning

E-field in the detector at $V_{\text{bias}} = 2400$ V

Average pulses
Specifications for GERDA Phase I FE electronic:

- **Charge Sensitive Amplifier**
  - Sensitivity: ~ 150 mV / MeV
  - Range Dynamic: > 5-6 MeV (now 8-9 MeV)
  - Working @ Cryogenic T
  - Large Open loop gain (~ $10^5$) to guarantee stability (but cryogenics helps)
  - Noise: <1 keV in Ge (< 150 e·r.m.s) @ 1 MeV, $\tau = 8 - 10$ µs, at T= 77°K
  - Rise time: < 30 ns to allow PSD of ionization events in Ge detectors
  - Compact / integrated as possible
  - Drive 50 Ω load through 6 m (later 10 m and then 20 m) long cables
  - Power dissipation: < 50 mW /ch (as low as possible)
  - Output stage: Better differential (later single ended)

- **PCB requirements**
  - 3ch modularity to serve 1 string
  - Radiopurity: as low as possible later set limit < 500 µBq $^{232}$Th and 2.5 mBq $^{238}$U for distance
  - Interconnection with input detector and output/LV cables by pins
  - Cryogenic (stable vs deformations for thermal cycles etc.)
The recentest results with bare BEGe (80 x 40 mm) & cold FE in LARGE setup (@GDL):

![BEGe detector](image)

![LAr scintillation light readout implemented](image)
CSA Intrinsic Energy Resolution: $C_{\text{det}} = 33$ pF

![Graph showing energy resolution vs. shaping time for different temperature conditions.](image)

**Room Temperature**

Circle : 6 V JFET Power Supply

**LN Temperature**

Triangle : 12 V JFET Power Supply

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CSA Rise Time

- Blue line: CSA + 10 m long output cables (50 Ohm terminated)
- Red line: CSA + 1 m long output cables (50 Ohm terminated)
- Pulser signal 5 ns rise time
- Rise time defined as time interval between 10% and 90% of CSA output signal
Spectroscopy with CC2 CSA + encapsulated detector

- Analog Amplifier (10 us Shaping Time)
- MCA
- Reproducible Energy Resolution
  \( \sigma = 0.03 \text{ kev over 20 short measurements} \)
- Rate 2 kHz

Irradiation with \(^{22}\text{Na}\) source.
FWHM = 2.15 kev
Spectroscopy with CC2 CSA + encapsulated detector

- Analog Amplifier (10 us Shaping Time)
- MCA
- Background long acquisition (over the night)

\[ \text{FWHM} = 2.75 \text{ keV} \left( ^{232}\text{Th} \right) \]

\[ \text{FWHM} = 2.28 \text{ keV} \left( ^{40}\text{K} \right) \]
Digital Spectroscopy with CC2 CSA

- CAEN FADC
- Off-line processing
- Digital FIR filtering with symmetric weighting function for baseline
- CSA output signals with 700 us decaying time (from 10% to 90%)
- Good agreement with single-pole exponentially decaying pulse model

FWHM = 2.27 keV
Crosstalk between Channels

• Between Ch2 (detector) and Ch1

• Same procedure as for PZ0:
  Ch1 and Ch2 through analog shaper (10us)
  Gain amplification for Ch2 = 200
  Gain amplification for Ch1 = 1000

• Experimental Result:
  \[ \frac{\Delta Ch1}{\Delta Ch2} = \frac{15 \text{ mV}}{5 \text{ V}} / 5 = 0.06 \% \]

• Very similar results for cross-talk measurement between Ch2 and Ch3

• Because cross-talk is low, it is also difficult to estimate because of the electronic noise

• As a conservative assumption:
  Cross-talk < 0.1%

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Summary of CC2 measured characteristics

• Best energy resolution @ LNT : 0.7 keV FWHM (0 pF Cdet)
  1.1 keV FWHM (33 pF Cdet)
  (with 1 Mev pulser signal, \(\tau=12\ \mu s\))

• Best energy resolution @ LNT : 1.96 kev FWHM for \(^{22}\text{Na}\)
  \((\tau = 12\ \text{us shaping time, 5k counts acquisition})\)

• 15 MeV guaranteed energy dynamic range

• 50 \(\Omega\) drive capability with 10 m long cables

• Power consumption < 140 mW (down to 100 mW for 10 Mev dyn. range)

• Rise time : less then 55 ns with 50 Ohm terminated, long cables and energy up to 15 Mev

• Cross-talk : < 0.1%

• Power Supply Rejection Ratio : OK

• Expected CSA radio-activity <= 150 \(\mu\text{Bq}\) for 3ch PCB for both \(^{232}\text{Th} & ^{238}\text{U}\)
Stability in an underground thermostatized lab