The GERDA Experiment and the Search for Neutrinoless Double Beta Decay

Björn Lehnert
(on behalf of the GERDA Collaboration)

Moriond, La Thuille,
17/03/2014
Double Beta Decay

\[ 2\nu\beta\beta : (Z, A) \rightarrow (Z + 2, A) + 2e^- + 2\bar{\nu}_e \]

\[ 0\nu\beta\beta : (Z, A) \rightarrow (Z + 2, A) + 2e^- \]

Schechter-Valle theorem:
If \(0\nu\beta\beta\) exists, it can always be interpreted as a neutrino Majorana mass term

- Lepton number violation

Effective neutrino mass:
(only for dominant light Majorana neutrino exchange)

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = F^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2
\]

\( F^{0\nu} \): phase space factor
\( \mathcal{M}^{0\nu} \): nuclear matrix element
\( m_{ee} \): effective neutrino mass

Double Beta Decay Experiments

**Sensitivity:** (for gaussian background)

\[ T_{1/2}^{\text{limit}} \propto \alpha \cdot \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}} \]

- \( \alpha \): isotopic abundance
- \( \eta \): active volume fraction
- \( \epsilon \): detection efficiency
- \( M \cdot T \): exposure
- \( B \): background index
- \( \Delta E \): energy resolution

- Many DBD experiments using various nuclides and experimental techniques
- Recent results from EXO, KamLAND-ZEN and GERDA
- \(^{136}\text{Xe} \) combined

\[ T_{1/2}^{0\nu} > 3.4 \times 10^{25} \text{ yr at 90\% C.L.} \]

- Claim of observation of 0\( \nu \beta\beta \) in \(^{76}\text{Ge} \) by subgroup of Heidelberg-Moscow experiment

\[ T_{1/2}^{0\nu} = 1.19 \times 10^{25} \text{ yr} \]

- Best previous \(^{76}\text{Ge} \) limits:

\[ \text{IGEX} : T_{1/2}^{0\nu} \geq 1.6 \times 10^{25} \text{ yr (90\% C.L.)} \]

\[ \text{HdM} : T_{1/2}^{0\nu} \geq 1.9 \times 10^{25} \text{ yr (90\% C.L.)} \]
The GERDA Collaboration

http://www.mpi-hd.mpg.de/gerda/

16 institutions
~100 members
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GERDA: Search for $0\nu\beta\beta$
Idea: Operate HPGe detectors naked in liquid argon (LAr)
• Liquid argon serves as cooling, shielding and active veto
Phase I: Nov 12 - May 13
- 8 coaxial detectors from Heidelberg, Moscow, and IGEX
- ~18 kg enriched germanium (86%)
- $\Delta E \sim 4.5$ keV @2.6 MeV
- 5 BEGe’s deployed in Phase I since June 2012
- Exposure 21.6 kg yr
- Blind analysis

Phase II: Start during 2014
- 30 additional enriched BEGe Detectors
- Additional ~20 kg enriched germanium
- Enhanced pulse-shape properties and $\Delta E$ (FWHM ~3 keV @2.6 MeV)
- Background aim: $10^{-3}$ cts/(keV kg yr)
- Exposure aim >100 kg yr to explore $10^{26}$ yr range
Background sources

- Natural radioactivity ($^{232}$Th, $^{238}$U chains)
- $\gamma$-rays (e.g. $^{208}$Tl, $^{214}$Bi)
- alpha-emitters on surface ($^{210}$Po, $^{222}$Rn)
- Cosmogenic isotopes ($^{68}$Ge, $^{60}$Co)
- Long-lived cosmogenic Ar isotopes ($^{42}$Ar, $^{39}$Ar)

Mitigation strategies

- Underground location: muons, cosmogenic isotopes
- Water tank and Cherenkov-veto: neutrons, muons
- Detector anti-coincidence: $\gamma$-rays
- Time-coincidence: BiPo, $^{68}$Ge
- Pulse-shape discrimination: surface events and $\gamma$-rays
- LAr scintillation veto [Phase II]
Duty Cycle and Data Sets for Phase I

Phase I data taking:
- Start: Nov 9 2011
- End: May 21 2013
- 556 calendar days
- Duty cycle: 88%

3 independent data sets:
Splitting according to detectors class and run performance

<table>
<thead>
<tr>
<th>Data set</th>
<th>Detectors</th>
<th>Exposure [kg yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden</td>
<td>Coaxial detectors</td>
<td>17.9</td>
</tr>
<tr>
<td>Silver</td>
<td>Coaxial det. in runs with large background</td>
<td>1.3</td>
</tr>
<tr>
<td>BEGe</td>
<td>BEGe detectors</td>
<td>2.4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>21.6</td>
</tr>
</tbody>
</table>
Main features:

- $^{39}\text{Ar}$ (565 keV $\beta$, 1 Bq/l LAr)
- $2\nu\beta\beta$ (GERDA measurement):
  \[T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08} \text{ fit}^{0.11}_{-0.06} \text{ syst}) \cdot 10^{21} \text{ yr}\]
  

- $^{42}\text{Ar}, ^{42}\text{K}$ decay chain from inside LAr
- Alphas on surface of p$^+$ contact
- Decay chain $\gamma$-lines: reduced by factor 10 compared to Heidelberg-Moscow experiment
Phase I Spectrum and Background Model

- MC of known (screening) and observed (gamma lines) background and fit to data 570 - 7500 keV
- Different combinations and positions tested
- Dominant: $^{214}$Bi, $^{228}$Th on detector holders, $^{42}$K in LAr

**Conclusion:** No gamma lines in ROI; background flat between 1930 - 2190 keV
Pulse Shape Discrimination

1: single site
2: multi site
3: p^+
4: n^+

BEGe detectors:
Amplitude / Energy

Coaxial detectors:
Neural network

BEGe:
Background Rejection: 80%
$0\nu\beta\beta$ efficiency: $92\pm2\%$

Coaxial detectors:
Background Rejection: 45%
$0\nu\beta\beta$ efficiency: $90^{+5.9}_{-9}\%$
GERDA $0\nu\beta\beta$ Results

- Analysis cuts applied (Survival fraction around $Q_{\beta\beta}$)
  1. Quality cuts (≈ 99%)
  2. Detector anti-coincidence (≈ ??%)
  3. Muon-veto (≈ 60%)
  4. Time coincidence (≈ 100%)
  5. Pulse Shape cut (≈ 50%)

- No peak in spectrum observed
- GERDA improves limit

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<table>
<thead>
<tr>
<th>Data set</th>
<th>Exposure [kg yr]</th>
<th>background index $[10^{-2}$ cts/(keV kg yr)]</th>
<th>expected counts $(Q_{\beta\beta} \pm 5$ keV)</th>
<th>observed counts $(Q_{\beta\beta} \pm 5$ keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden</td>
<td>17.3</td>
<td>1.8</td>
<td>3.3</td>
<td>5</td>
</tr>
<tr>
<td>Silver</td>
<td>1.3</td>
<td>6.3</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
<td>3.6</td>
<td>1.0</td>
<td>1</td>
</tr>
</tbody>
</table>

w/o PSD w PSD
Frequentist analysis (baseline result)

- Maximum likelihood spectral fit on 3 subsets with common \( (T_{1/2})^{-1} \): Best fit \( n=0 \)
- Median sensitivity:
  \[ T_{1/2}^{0\nu} > 2.4 \times 10^{25} \text{ yr at 90\% C.L.} \]
- Profile likelihood result:
  \[ T_{1/2}^{0\nu} > 2.1 \times 10^{25} \text{ yr at 90\% C.L.} \]

Combination \( ^{76}\text{Ge} \):

\((\text{GERDA } + \text{ HdM } + \text{ IGEX})\)

\[ T_{1/2}^{0\nu} > 3.0 \times 10^{25} \text{ yr at 90\% C.L.} \]
Comparing two hypotheses:

\[ \mathcal{H}_1: T_{1/2}^{0\nu} = 1.19 \cdot 10^{25} \text{ yr} \]

\[ \mathcal{H}_0: \text{background only} \]

GERDA only (best fit 0 events)

- \( P(n=0|\mathcal{H}_1) = 0.01 \)
- Bayes factor: \( P(n=0|\mathcal{H}_1)/P(n=0|\mathcal{H}_0) = 0.024 \)
- 5.9 \((\pm 2.0)\) expected events in \(\pm 2\ \sigma_E\) from claim (\(+background\) after PSD. 3 observed

Not comparing to \(T_{1/2}\) claim in Mod. Phys. Lett. 21 (2006) 157 because of inconsistencies in analysis (missing efficiencies) as pointed out in Ann. Phys. 525 (2013) 259
GERDA $0\nu\beta\beta$ Results: Comparing with Claim

Combined $^{76}\text{Ge}$:
- Bayes factor:
  \[ P(H_1)/P(H_0) = 2 \cdot 10^{-4} \]

Combined $^{76}\text{Ge} + ^{136}\text{Xe}$:
- Comparison via matrix elements
- Bayes factor (EXO old):
  \[ P(H_1)/P(H_0) = 2.2 \cdot 10^{-3} \]
Conclusion

- GERDA published Phase I results (21.6 kg yr and 0.01 cts/(keV kg yr))
  - GERDA Phase I: $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr at 90% C.L.
  - $^{76}\text{Ge} (+\text{IGEX+HdM})$: $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr
  - $|m_{\text{ee}}| < 0.2 - 0.4$ eV (depending on matrix element)
  - Previous $0\nu\beta\beta$ claim only explained with 1% probability by GERDA in a model independent way

- Phase II transition ongoing. Main improvements:
  - Additional 20 kg BEGe detectors
  - Liquid argon scintillation veto
BACKUP
Light Majorana Neutrinos

**Effective neutrino mass:**
(only for dominant light Majorana neutrino exchange)

\[
\left(T_{1/2}^{0\nu}\right)^{-1} = F^{0\nu} \cdot |M^{0\nu}|^2 \cdot |m_{ee}|^2
\]

\[m_{ee} = \left| \sum_i m_i U_{ei}^2 \right|\]
\[|m_{ee}| = |m_1 |U_{e1}^2| + m_2 |U_{e2}^2| \cdot e^{i(\alpha_2 - \alpha_1)} + m_3 |U_{e3}^2| \cdot e^{-i(\alpha_1 + 2\delta)}|\]

\[F^{0\nu} : \text{phase space factor} \]
\[M^{0\nu} : \text{nuclear matrix element} \]
\[m_{ee} : \text{effective neutrino mass} \]

**Disfavored by 0νββ**

\[\Delta m_{31}^2 < 0 \]
\[\Delta m_{32}^2 > 0 \]

**Normal hierarchy**

**Inverted hierarchy**

GERDA: Search for 0νββ
Other $0\nu\beta\beta$ Mechanisms

- **Standard process**: Light Majorana neutrino exchange
- There are also other lepton number violating processes that can trigger $0\nu\beta\beta$
- **Schechter-Valle theorem**: 
  If $0\nu\beta\beta$ exists, it can always be interpreted as a neutrino Majorana mass term

\[
\mathcal{L} = m_D \bar{\nu}_R \nu_L + m_M \bar{\nu}_L \nu_L^c
\]

Possible processes (not exhaustive)

- light Majorana
- Higgs triplet
- SUSY particle
- right handed currents
Double Beta Decay Isotopes

**Effective neutrino mass:**

(only for dominant light Majorana neutrino exchange)

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = F^{0\nu} \cdot |M^{0\nu}|^2 \cdot |m_{ee}|^2
\]

- **Phase space factor** (atomic physics)
- **Matrix element** (nuclear physics)
- **Beyond SM process** (particle physics)

\( F^{0\nu} \) : phase space factor  
\( M^{0\nu} \) : nuclear matrix element  
\( m_{ee} \) : effective neutrino mass

\( 0\nu\beta\beta \) half-life (\( m_{ee} = 1 \text{eV} \))
Double Beta Decay Experiments

**Sensitivity:** (for Gaussian background)

\[ T_{1/2}^{\text{limit}} \propto \alpha \cdot \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}} \]

- \(\alpha\): isotopic abundance
- \(\eta\): active volume fraction
- \(\epsilon\): detection efficiency
- \(M \cdot T\): exposure
- \(B\): background index
- \(\Delta E\): energy resolution

**Advantage \(^{76}\text{Ge}:**

- Excellent energy resolution \(\mathcal{O}(0.1\%)\)
- Good detection efficiency \(\mathcal{O}(80\%)\)
- Intrinsic low background (Semiconductor)

**Disadvantages \(^{76}\text{Ge}:**

- Expensive enrichment
- \(Q\)-value \(< 2614\) keV
### DBD Isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$Q$ (MeV)</th>
<th>Percent natural abund.</th>
<th>Element cost [$/kg]</th>
<th>$G^{0\nu}$ $(10^{-14}/\text{yr})$</th>
<th>$M^{0\nu}$ (avg)</th>
<th>Annual world production [tons]</th>
<th>$0\nu/2\nu$ rate $(10^{-8})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4.27</td>
<td>0.19</td>
<td>0.16</td>
<td>6.06</td>
<td>1.6</td>
<td>$2.4 \times 10^8$</td>
<td>0.016</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2.04</td>
<td>7.8</td>
<td>1650</td>
<td>0.57</td>
<td>4.8</td>
<td>118</td>
<td>0.55</td>
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<tr>
<td>$^{82}$Se</td>
<td>3.00</td>
<td>9.2</td>
<td>174</td>
<td>2.48</td>
<td>4.0</td>
<td>2000</td>
<td>0.092</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>3.35</td>
<td>2.8</td>
<td>36</td>
<td>5.02</td>
<td>3.0</td>
<td>$1.4 \times 10^6$</td>
<td>0.025</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.04</td>
<td>9.6</td>
<td>35</td>
<td>3.89</td>
<td>4.6</td>
<td>$2.5 \times 10^5$</td>
<td>0.014</td>
</tr>
<tr>
<td>$^{110}$Pd</td>
<td>2.00</td>
<td>11.8</td>
<td>23000</td>
<td>1.18</td>
<td>6.0</td>
<td>207</td>
<td>0.16</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.81</td>
<td>7.6</td>
<td>2.8</td>
<td>4.08</td>
<td>3.6</td>
<td>$2.2 \times 10^4$</td>
<td>0.035</td>
</tr>
<tr>
<td>$^{124}$Sn</td>
<td>2.29</td>
<td>5.6</td>
<td>30</td>
<td>2.21</td>
<td>3.7</td>
<td>$2.5 \times 10^5$</td>
<td>0.072</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2.53</td>
<td>34.5</td>
<td>360</td>
<td>3.47</td>
<td>4.0</td>
<td>$\sim 150$</td>
<td>0.92</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>2.46</td>
<td>8.9</td>
<td>1000</td>
<td>3.56</td>
<td>2.9</td>
<td>50</td>
<td>1.51</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>3.37</td>
<td>5.6</td>
<td>42</td>
<td>15.4</td>
<td>2.7</td>
<td>$\sim 10^4$</td>
<td>0.024</td>
</tr>
</tbody>
</table>
@ LNGS, L’Aquila, Italy
Laboratori Nazionali del Gran Sasso

- 3800 m.w.e. overburden
- Muon suppressed by $10^6$
History

LOW-RADIOACTIVITY
BACKGROUND TECHNIQUES

G. Heusser
Max-Planck-Institut für Kernphysik, P.O. Box 103 980, D-69029 Heidelberg, Germany

the idea ‘95

Hall A before construction

Water tank construction

Hall A today

The cryostat

The muon veto

Official inauguration

Moriond, 17/03/14 Bjoern Lehnert GERDA: Search for 0νββ
Run Calibration and Stability

Detector calibration with
- 3 $^{228}$Th sources 1h per week
- 0.05 Hz pulser

- Energy shift usually <1 keV between calibrations
- Energy resolution stable

FWHM @ $Q_{bb}$ (2039 keV):
- Coaxial: $4.8\pm0.2$ keV (0.23 %)
- BEGe: $3.2\pm0.2$ keV (0.16 %)

Shifts are small compared to FWHM at $Q_{bb}$
Pulse-shapes more complex in coaxial detectors. Three approaches:

1. **Artificial Neural Network** (baseline method)
2. Likelihood analysis
3. Pulse asymmetry
• Alpha decays close to thin p+ dead layer
• Low energy tail contributes to background in $Q_{\beta\beta}$
• Rate decays in agreement with $^{210}\text{Po}$ $T_{1/2}$ (138.4 d)

Best fit: $130.4 \pm 22.4$ d
very early GERDA spectrum

- Larger $^{42}\text{Ar}$ contribution than expected
- 1.5 years of commissioning to understand and mitigate $^{42}\text{K}$ background

Conclusion:
- $^{42}\text{K}$ is charged and attracted by HV
- Installation of mini-shroud in Phase I
2νββ Measurement


- Binned ML fit with 32 parameters (Bayesian analysis)
- 5.04 kg yr exposure: 7030 2νββ events
- Larger than previous S/B ratio: 4:1

GERDA Result

\[ T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08} \text{ fit} +0.11_{-0.06} \text{ syst}) \cdot 10^{21} \text{ yr} \]
Phase I: $0\nu\beta\beta$ Blind Analysis

1. Data after Jan 2012 was blinded in $\pm 20$ keV around $Q_{\beta\beta}$
   - Avoid tuning the analysis towards signal or no-signal outcome

2. All data processing, quality cuts and statistical analysis methods were fixed
   - Paper with background model, pulse shape methods (including all analysis parameters) fixed prior to final unblinding

3. Final unblinding at GERDA Collaboration meeting June 2013 in Dubna

Cutout because of background line

$\pm 100$ keV  $\pm 20$ keV

Blinded Window

$E$ (keV)

$\Delta E$
Why not compare to Klapdor 2006 Claim?

a) 2004 publications: NIM A522 371 & PL B586 198

\[ Q_{\beta\beta} = 71.7 \text{ kg} \cdot \text{yr} \]

entire data set: \( 71.7 \text{ kg} \cdot \text{yr} \) (active mass)

\[ T_{1/2}^{0\nu} = \left( 1.19^{+0.37}_{-0.23} \right) \cdot 10^{25} \text{ yr} \]

data for PSD analysis: \( 51.4 \text{ kg} \cdot \text{yr} \)

\[ 19.58 \pm 5.41 \text{ signal events} \]

\[ T_{1/2}^{0\nu} = \left( 1.25^{+0.49}_{-0.27} \right) \cdot 10^{25} \text{ yr} \]

with PSD applied:

\[ 12.36 \pm 3.72 \text{ events} \]

DEP survival fraction \( \sim 62\% \)

\[ \rightarrow T_{1/2}^{0\nu} = 1.23 \cdot 10^{25} \text{ yr} \]

Without efficiency correction:

\[ T_{1/2}^{0\nu} = 1.98 \cdot 10^{25} \text{ yr} \]

No efficiency correction is applied in any publication!
Why not compare to Klapdor 2006 Claim?

b) 2006 publication: Mod Phys Lett A21  p. 1547-1566

PSD based on 3 previous methods (2 neural networks + pulse boardness) & library of SSE pulses:
Event accepted IF pulse in library OR found by neural network of Ref. 16 but not by the other two neural networks

NO event overlap between the 2 sets!?

statement of publication:
- “multi site events are suppressed by 100%”,
- $0\nu\beta\beta$ efficiency = 1 used for $T_{1/2}^{0\nu}$

fit gives 11.32±1.75 signal events

$T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr

error on signal count not correct since smaller than Poisson error

efficiency factor not considered
→ calculation of $T_{1/2}^{0\nu}$ not correct
→ GERDA does not use this result
Phase II: BEGe Detectors

- Whole production chain from $^{enr}$GeO$_2$ to BEGe diode organized by GERDA and tested with $^{dep}$Ge (JINST 8 P04018 2013)
- Total gain 30 BEGe detectors with 20.5 kg (58 % yield)
- Detector characterization in HADES underground facility, Belgium
- Exposure to cosmic rays reduced as much as possible:
  - Transport in shielded container
  - Storage and testing underground
Phase II: BEGe Detector Transport

- Minimization of cosmic ray exposure
- Transport in 26t container shielded with steel and water
- Storage and testing underground
Phase II: LAr Scintillation Veto

- Experimental proof of principle in R&D facility LArGe (LNGS)
- Investigation of different design principles for GERDA with tuned MC simulations:
  - **PMT arrays** on top and bottom
  - **Fiber shroud** with SiPM readout
  - **SiPMs** inside mini shroud (if deployed)
- Combination of designs is favored

![Graph showing Th228 suppression in LArGe](image)
Mini shroud advantages:

- Metal: Electric field
- Transparent: Improved LAr veto
- Hermetic: Limits $^{42}$K convection

Suppression factors from MC for nylon MS:

- $>100$ ($^{208}$Th Holders)
- $\approx 30$ ($^{241}$Bi LAr), $\approx 10$ ($^{241}$Bi Holders)
- $\approx 10$ ($^{42}$K LAr), $\approx 1$ ($^{42}$K Surface)

Investigated options

- Mesh MS
- Copper MS with SiPMs inside
- Nylon MS
- PE MS
- Mesh MS with readout
Outlook

Background expectations for Phase II

<table>
<thead>
<tr>
<th>Background</th>
<th>without cuts ((10^{-3} \text{ cts/(keV\cdot kg\cdot yr)}))</th>
<th>after PSD + Veto ((10^{-3} \text{ cts/(keV\cdot kg\cdot yr)}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{228}\text{Th}) (near)</td>
<td>(\leq 5)</td>
<td>(\leq 0.01)</td>
</tr>
<tr>
<td>(^{228}\text{Th}) (1m away)</td>
<td>(\leq 3)</td>
<td>(\leq 0.01)</td>
</tr>
<tr>
<td>(^{228}\text{Th}) (distant)</td>
<td>(\leq 3)</td>
<td>(\leq 0.1)</td>
</tr>
<tr>
<td>(^{214}\text{Bi}) (holder/MS)</td>
<td>(\leq 5)</td>
<td>(\leq 0.13)</td>
</tr>
<tr>
<td>(^{214}\text{Bi}) (near (p^+))</td>
<td>(\leq 6)</td>
<td>(\leq 0.03)</td>
</tr>
<tr>
<td>(^{214}\text{Bi}) ((n^+))</td>
<td>(\leq 7)</td>
<td>(\leq 0.15)</td>
</tr>
<tr>
<td>(^{214}\text{Bi}) (1m away)</td>
<td>(\leq 3)</td>
<td>(\leq 0.08)</td>
</tr>
<tr>
<td>(^{60}\text{Co}) (near)</td>
<td>1</td>
<td>0.001</td>
</tr>
<tr>
<td>(^{60}\text{Co}) (in Ge)</td>
<td>(\leq 0.3)</td>
<td>(\leq 0.0004)</td>
</tr>
<tr>
<td>(^{68}\text{Ga}) (in Ge)</td>
<td>(\leq 2.3)</td>
<td>(\leq 0.04)</td>
</tr>
<tr>
<td>(^{226}\text{Ra}) ((\alpha) near (p^+))</td>
<td>1.5</td>
<td>(\leq 0.03)</td>
</tr>
<tr>
<td>(^{42}\text{K}) ((\beta) on (n^+))</td>
<td>(\sim 20)</td>
<td>(\leq 0.86)</td>
</tr>
<tr>
<td>unknown ((n^?))</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

- PSD in BEGe + LAr instrumentation
- Background estimation from Phase I
- PSD suppression can be optimized with 0\(\nu\)\(\beta\)\(\beta\) efficiency

Sensitivity

Phase I

Phase II