A background veto system for GERDA based on scintillation of liquid argon

Nuno Barros for the GERDA collaboration
Institut für Kern- und Teilchenphysik
Technische Universität Dresden

DPG Frühjahrstagung, March 4, 2013
\( \beta\beta \) decay

- \( 2\nu\beta\beta: (A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\nu_e \)
  - Predicted by the SM
  - Observed in more than 10 isotopes
- \( 0\nu\beta\beta: (A, Z) \rightarrow (A, Z + 2) + 2e^- + 0\nu_e \)
  - \( \Delta L = 2 \)
  - One claim and many limits...
  - \( \left[ T^{0\nu}_{1/2} \right]^{-1} = F^{0\nu} \cdot |M^{0\nu}|^2 \cdot m_{\beta\beta}^2 \)

\[ T^{0\nu}_{1/2} \approx \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \]

Ways to improve sensitivity

- More mass
- Better energy resolution
- Longer measurement
- Lower background
Germanium Detector Array

\[ T^{0\nu}_{1/2} \approx \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \]

Phase I

- Check existing claim with HPGe
  - Exposure: ~20 kg yr
  - \( B_1 : 2.43 \times 10^{-2} \text{ cts/(keV kg yr)} \)

Phase II

- Expand sensitivity with enriched BEGe (+20 kg)
  - Exposure: ~100 kg yr
  - \( B_1: \leq 1.0 \times 10^{-3} \text{ cts/(keV kg yr)} \)

Background reduction in the ROI around \( Q_{\beta\beta} \) crucial for GERDA objectives

Double beta decay in Ge:

\[ 2\nu\beta\beta : ^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- + 2\nu \]

\[ 0\nu\beta\beta : ^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- \]

Reducing the background in GERDA

- **Background index (BI)**
  - present (Phase I): \(2.43 \times 10^{-2}\) cts/(keV kg yr)
  - aspired (Phase II): \(\leq 1.0 \times 10^{-3}\) cts/(keV kg yr)

- Employed background suppression techniques:
  - Water Cherenkov veto (muons)
  - Detector anti-coincidence
  - Pulse shape discrimination (PSD)

**LAr scintillation veto**

- Tag background events by detecting light from scintillation of argon
Background suppression in GERDA

- **ββ-event**
  - Single site event (energy deposited in a single crystal)
  - **Not vetoed**

Events in ROI around 2039 keV
Background suppression in GERDA

- **ββ-event**
  - Single site event (energy deposited in a single point)
  - **Not vetoed**

- **Surface event ($^{214}$Bi, $^{42}$K)**
  - Often not vetoed by LAr instrumentation
    - **High veto efficiency from PSD**

Events in ROI around 2039 keV
Background suppression in GERDA

- **ββ-event**
  - Not vetoed

- **Surface event (^{214}Bi, ^{42}K)**
  - Often not vetoed by LAr instrumentation

- **External event (^{208}Tl, ^{214}Bi)**
  - Energy deposited in multiple crystals
    - **Detector anti-coincidence veto**
Background suppression in GERDA

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  - Not vetoed

- **Surface event ({}^{214}\text{Bi}, {}^{42}\text{K})**
  - Often not vetoed by LAr instrumentation

- **External event ({}^{208}\text{TI}, {}^{214}\text{Bi})**
  - Energy deposited in multiple crystals
    - Detector anti-coincidence veto
  - Multi site events
    - PSD veto
Background suppression in GERDA

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  - Not vetoed

- **Surface event (\(^{214}\text{Bi}, \, ^{42}\text{K})**
  - Often not vetoed by LAr instrumentation

- **External event (\(^{208}\text{TI}, \, ^{214}\text{Bi})**
  - Energy deposited in multiple crystals
    - Detector anti-coincidence veto
  - Multi site events
    - PSD veto
  - Energy deposited both in the detector and in the surrounding LAr
    - **Often vetoed by LAr instrumentation**
LAr scintillation for background suppression

• Advantages:
  • Very high light yield: \( \sim 4 \times 10^4 \) \( \gamma \)/MeV
  • Single re-emission peak: \( \lambda = 128 \) nm (XUV)
  • Very distinctive short and long decay times
    - \( T_s \sim 6 \) ns
    - \( T_l \sim 1200 – 1500 \) ns

• Challenges:
  • Hard to measure optical properties
    - Very dependent on impurities
  • Light cannot be detected directly (XUV)
    - Need to use WLS
LArGe test facility

- lock system
- 9x 8” PMTs
- reflector foil & wavelength shifter
- bare Ge-detector
- cryostat with LAr
  - volume 1000 l
- Shield (unfinished)
  - Cu 15 cm,
  - Pb 10 cm,
  - Steel 23 cm,
  - PE 20 cm

Location: Germanium detector lab
LNGS @ 3800 m w.e.

[arXiv: 0701001, TAUP 2011 proc.]
LArGe test facility
LArGe: suppression of internal $^{228}$Th

- Suppression factor at $Q_{\beta\beta} \pm 35$keV
- LAr veto: ~1200
LArGe: suppression of internal $^{228}$Th

- Suppression factor at $Q_{\beta\beta} \pm 35$ keV
  - LAr veto: $\sim 1200$
  - PSD: $\sim 2.4$
  - LAr + PSD: $\sim 5200$
LArGe : suppression of internal $^{226}$Ra

- Suppression factor at $Q_{\beta\beta} \pm 35$ keV
  - LAr veto : $\sim 4.6$
  - PSD : $\sim 4.1$
  - LAr + PSD: $\sim 45$

Demonstrated by LArGe:
- Concept works
- Complementarity with PSD
- Efficient background suppression for select backgrounds
• **LArGe results used to validate MC model**
  • Simpler geometry
  • Measurements available

**Tuning of optical properties:**
• Material reflectivities
  • Cu, Ge, teflon,…
• LAr properties:
  • Attenuation length, light yield, triplet lifetime
• WLS properties
  • Absorption and re-emission spectra

Unknown accurate source geometry affects fraction of escaped betas.
LAr instrumentation in GERDA

- Combination of technologies for maximized veto efficiency.
  - PMTs (as verified in LArGe)
  - Scintillation fibers [T 109.2].

Requirements

- Large instrumented volume
- Low background contribution
  - After self-veto
- Low mass
  - Instrumentation deployed with Ge crystals
The hybrid design

- **top PMTs**
  - (9 x 3” Hamamatsu R11065-10/-20)

- **600 x 490 mm**
  - Cu coated with Tetratex + TPB [HK 46.8]

- **Scintillating fibers + WLS (1000 x 490 mm)**
  - BCF-91A fibers coated with TPB
  - Light readout by SiPMs at upper end

- **bottom PMTs**
  - (7 x 3” Hamamatsu R11065-10/-20)
Breakdown of the designs

**PMTs**
- Proven technology (LArGe)
- Low background contribution
  - Clean PMTs
  - Distance from the crystals

**Scintillating fibers**
- Sensitive LAr volume not confined
- High solid angle coverage
- Low background contribution
  - Can afford to place fibers closer to detectors

Photomultiplier - Hardware
- 18 low bg PMTs available
  - 9 x R11065-10
  - 9 x R11065-20

Screening results
- Th228: 1.94 mBq/PMT
- Ra226: 1.7 mBq/PMT

R11065-20 has higher QE than R11065-10

Anne Wegmann (MPIK)
LAr veto for GERDA
DPG, 04.03.2013 14 / 17
Hardware: PMTs [T 109.1]

- 18 low background PMTs
  - 9 x R11065-10
  - 9 x R11065-20

- Custom made voltage dividers
  - Encapsulation to prevent discharges/flashing

- Tight control on weight of setup
  - Share same cable chain as detectors

**Screening results**

- $^{228}\text{Th} : \leq 1.94 \text{ mBq/PMT}$
- $^{226}\text{Ra} : \leq 1.7 \text{ mBq/PMT}$
Hardware : PMTs [T 109.1]

- Intensive tests of all parts
  - Tight control of background

- Run in test stand with in MPIK
  - 4 PMTs with negative voltage dividers
  - So far no flashing occurred

PMT support successfully tested
Hardware: Fibers [T 109.2]

- Coupling 9 fibres per SiPM
  - Readout on one end
  - Reflective surface on other end

- “Dirtiest” parts far from detectors

- Fibers coated with TPB
  - Fibers themselves are WLS

- Large solid angle coverage maximizes detection efficiency
  - Does not penalize PMTs
- **SiPMs**
  - Work at LN temperature
  - Good QE, negligible Dark Rate
  - Candidates: Hamamatsu and Ketek SiPMs

- **TPB coated WLS fiber concept already demonstrated**

**Screening results**

- $^{228}$Th: 0.058 mBq/kg
- $^{226}$Ra: 0.042 mBq/kg
- $^{40}$K: 0.46 mBq/kg

**Concept tested in small scale (< 20 l)**
**Extensive MC simulation campaign of designs:**
- Implemented in MaGe
  - GERDA simulation software based on Geant4
- Tuned with LArGe data

**Two-fold objective:**
- Initial comparison of technologies
- Optimization of geometries (detectors and instrumentation)

**Simulation details:**
- Simulation of known nuclear decays in detector parts
  - LAr, detector holders, LAr instrumentation, Ge crystals
  - Most relevant simulated decays: $^{214}$Bi, $^{208}$Tl
- Photon tracking only if event deposits energy in Ge inside the ROI
  - Performance optimization
MC simulations

$2^{14}\text{Bi in detector holders}$

$2^{08}\text{Ti in detector holders}$

$$SF = \frac{\text{total events in ROI}}{\text{unvetoeed events in ROI}}$$

- ROI: $Q_{\beta\beta} \pm 100$ keV
- Same window used to determine the BI.
MC simulations: results

Simulation campaign was iterative process
- Designs evolved/improved with results from simulations

<table>
<thead>
<tr>
<th>Location</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}\text{Tl}$ holders</td>
<td>320 ± 34</td>
</tr>
<tr>
<td>external</td>
<td>112 ± 39</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$ surface</td>
<td>3.5 ± 0.1</td>
</tr>
<tr>
<td>holders</td>
<td>10.3 ± 0.3</td>
</tr>
<tr>
<td>homogeneous in LAr</td>
<td>54.8 ± 7.9</td>
</tr>
</tbody>
</table>

Sources simulated in earlier designs (approximate values)

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}\text{Co}$</td>
<td>detectors</td>
<td>10</td>
</tr>
<tr>
<td>$^{42}\text{K}$</td>
<td>homogeneous in LAr</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>crystal surface</td>
<td>1</td>
</tr>
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</table>
Some parameters hard to measure
- Literature values used
- Systematic studies of their effect performed

**Attenuation of XUV light**
- Absorption highly dependent on purity of LAr
- Literature value: 60 cm [NIM A 384 (1997)]
- **Major systematic uncertainty**

**Reflectivity of materials**
- Measurements in visible range performed at MPIK
- Literature values used for XUV range

<table>
<thead>
<tr>
<th>Systematic</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>10.3 ± 0.3</td>
</tr>
<tr>
<td>0.2 * Attenuation</td>
<td>8.9 ± 0.3</td>
</tr>
<tr>
<td>0.1 * Reflectivity</td>
<td>9.4 ± 0.3</td>
</tr>
</tbody>
</table>
MC simulations : systematics studies (II)

- **Effect in p.e. yield more clear**
  - **Attenuation**: Reduction of p.e. yield of factor $\sim 2$
  - **Reflectivity**: Elimination of high p.e. tails.
    - Reflectivity has small effect in the simulations.

![Graph showing effects of different parameters on p.e. yield](image)
MC simulations: systematics studies

- Effect of increased attenuation highly dependent on p.e. threshold
  - Other systematics not so critical
- Purity of argon and threshold of instrumentation critical for its efficiency
A LAr scintillation veto is planned for phase II of GERDA
  • Principle demonstrated in LArGe
  • Favored design of combination of PMTs and scintillating fibers
    • Hardware tests ongoing
    • Both technologies demonstrated on smaller scale
    • Construction has started
  • Extensive MC simulation campaign performed
    • Used LArGe results for validation and tuning
    • Provided optimizations to the hardware designs.
  • LAr veto suppression factors look promising:
    • > 10^2 for ^{228}\text{Th} (~300 close by, ~100 far from detectors)
    • ~ 10 for nearby ^{226}\text{Rn} backgrounds
  • Instrumentation induced BI within allowed budget
    • Counting self-veto