Cosmogenic background for the GERDA experiment

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Cosmogenic Activity and Background Workshop, Berkeley – April 15th, 2011
GERDA experiment at LNGS

The GERmanium Detector Array experiment will look for $0\nu2\beta$ decay in $^{76}\text{Ge}$ using HP-Ge detectors enriched in $^{76}\text{Ge}$

Hosted in the Hall A of the Gran Sasso Laboratory (INFN), in central Italy

Suppression of $\mu$-flux $> 10^6$
$0
\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

Neutrinoless $2\beta$-decay violates the lepton number conservation: $\Delta L = 2$

Explore the Dirac/Majorana nature of neutrino and the absolute mass scale

Very rare process: $T_{1/2} > 10^{25}$ y

New generation experiments require unprecedented low-background conditions!

Claim from Klapdor-Kleingrothaus et al., NIM A 522 (2004) 371
GERDA concept

- Background reduction strategy:
  - Deep underground site for suppression of cosmic ray muons
  - Graded shielding against ambient radiation (Water, LAr)
  - Rigorous material selection for radiopurity
  - Signal analysis
- Phase I: 15 kg of $^{enr}\text{Ge}$ (existing at LNGS). Goal: $10^{-2}$ counts/(keV kg y). Verify KK claim
- Phase II: add 20 kg of more $^{enr}\text{Ge}$ detectors. Goal: $10^{-3}$ counts/(keV kg y)
Unloading of vacuum cryostat
(6 March 08)
Produced from selected low-background austenitic steel
Construction of water tank

\[ \varnothing \, 10 \text{ m} \]
\[ H = 9.5 \text{ m} \]
\[ V = 650 \text{ m}^3 \]

\[ \text{Designed for external } \gamma, n, \mu \text{ background } \sim 10^{-4} \text{ cts/(keV kg y)} \]
Nov/Dec.’09: Liquid argon fillinf

Jan ’10: Commissioning of cryogenic system

Apr/May ’10: emergency drainage tests of water tank

Apr/May ’10: Installation c-lock

May ’10: 1st deployment of FE&detector mock-up (27 pF) - pulser resolution 1.4 keV (FWHM); first deployment of non-enriched detector

June ‘10: Start of commissioning run with natGe detector string

Next: start of Phase I physics data taking
The detector string

- Three low-background \( \text{nat}^\text{Ge} \) detectors deployed in the commissioning string
- They belong to the former Genius Test Facility at LNGS (GTF) and are underground since several years
- Naked detectors, total Ge mass about 7.5 kg
- Dedicated MC simulation performed with the MaGe framework
- Help with the background analysis and interpretation
Cosmogenic background in GERDA

1. prompt $\mu$-induced interactions underground
   - Cherenkov veto very effective

2. short-lived (but $T_{1/2} > 100 \text{ ms}$) isotopes produced by muon showers underground in detectors and other materials
   - $^{77}\text{Ge}$, $^{77m}\text{Ge}$, $^{40}\text{Cl}$, $^{38}\text{Cl}$, etc.
   - not always possible to use delayed coincidence with the $\mu$ veto signal

3. long-lived isotopes produced by cosmogenic activation above ground in detectors ($^{60}\text{Co}$, $^{68}\text{Ge}$) or other materials ($^{39}\text{Ar}$, $^{60}\text{Co}$, ...)
   - waiting is not an option: $T_{1/2}$ years or centuries
Monte Carlo simulations

- Run **MC campaign** in 2006-2007 using the **reference GERDA design** at that time
  - Cu cryostat
  - paper published on NIM A
- Re-run later on with the **new design**
  - Stainless steel cryostat with Cu internal lining
  - Unpublished → I cannot sell it as a “prediction”
- Used **MaGe/Geant4** in both cases, primary spectrum from MUSUN
What did we expect? (1)

Energy spectrum in the detectors

Notice: simulation run for reference Phase-I array, not for commissioning string. For this plot, used the old version of GERDA geometry (Cu cryostat)

For reference Phase I, without anti-coincidence, expected 1.9⋅10^{-2} counts/(keV·kg·y)

For the real GERDA geometry (stainless steel cryostat) and the Phase I reference array expected 0.9⋅10^{-2} counts/(keV·kg·y)
What did we expect? (2)

- Considered isotopes having $Q$-value $> Q_{\beta\beta}$ and 100 ms $< T_{1/2} <$ days
  - In crystals: $^{74}\text{Ga}$, $^{75}\text{Ga}$, $^{76}\text{Ga}$, $^{68}\text{Ge}$, $^{69}\text{Ge}$, $^{77}\text{Ge}$, $^{71}\text{Zn}$
  - In cryoliquid: $^{13}\text{N}$, $^{11}\text{C}$, $^{12}\text{B}$, $^{38}\text{Cl}$, $^{39}\text{Cl}$, $^{40}\text{Cl}$
  - In water: $^{16}\text{N}$, $^{14}\text{O}$, $^{12}\text{B}$, $^{6}\text{He}$, $^{13}\text{B}$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Liquid Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nucl/(kg·y)</td>
</tr>
<tr>
<td>$^{74}\text{Ga}/^{75}\text{Ga}/^{76}\text{Ga}$</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$^{68}\text{Ge}$</td>
<td>0.08</td>
</tr>
<tr>
<td>$^{69}\text{Ge}$</td>
<td>1.8</td>
</tr>
<tr>
<td>$^{77}\text{Ge}/^{77m}\text{Ge}$</td>
<td>0.51</td>
</tr>
<tr>
<td>$^{38}\text{Cl}$</td>
<td>46 day$^{-1}$</td>
</tr>
<tr>
<td>$^{40}\text{Cl}$</td>
<td>2.7 day$^{-1}$</td>
</tr>
</tbody>
</table>

Results for the old GERDA geometry, but new ones are similar as order of magnitude. Notice: considered $^{enr}\text{Ge}$

LP et al. NIM A 570 (2007) 149
Now have a look at the data!

- Have a **look at the data** and verify the MC predictions!
- Check how many events observed in GERDA with the *muon veto* flag on (and correct for inefficiency)
  - to compare to *simulation*, do not apply anti-coincidence cut (different array, so different suppression efficiency)

### Counts/(keV·kg·y)

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Goal</th>
</tr>
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<tbody>
<tr>
<td>Q_{bb} no cut</td>
<td></td>
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### Results

- $R_{\text{exp}} = (0.7 \pm 0.3) \cdot 10^{-2}$
- $R_{\text{MC (old)}} = (1.90 \pm 0.04) \cdot 10^{-2}$
- $R_{\text{MC (new)}} = (0.88 \pm 0.02) \cdot 10^{-2}$

Counts/(keV·kg·y) Not too bad!
Now have a look at the data!

- Agreement for prompt $\mu$-induced background does not imply agreement also for isotope production underground!
- **Look** for lines in the experimental spectrum corresponding to $^{41}\text{Ar}$ (1293.6 keV), $^{38}\text{Cl}$ (2167 keV), $^{40}\text{Cl}$ (2839 keV)
  - most intense expected from the MC
  - still, no chance to see them with the GERDA exposure
Look for other cosmogenics

- Look for **cosmogenic isotopes** produced during the detector live **above ground** ($^{60}\text{Co}$, $^{68}\text{Ge}$)
- GTF detectors are stored **underground since years**
- **No indication** of $^{60}\text{Co}$ and $^{68}\text{Ge}$/68Ga characteristic $\gamma$ lines (1173 keV, 1332 keV, 1077 keV)
  - can **place a limit** on their activity in the detectors
  - need a **Monte Carlo** simulation
  - presently **in progress**
- Clearly seen $^{58}\text{Co}$ (811 keV line, $T_{1/2} = 70$ day) coming from a Cu encapsulation (used only in one GERDA run) which was **flown** to LNGS
Cosmogenic contaminants of Ar (1)

- $^{39}\text{Ar}$ (1.01 Bq/kg, $T_{1/2} = 269$ y)
  - pure beta emitter with low Q-value (565 keV)
    - not an issue for GERDA, much below the region of interest
  - dominates the low-energy counting rate
  - cosmogenic production in atmosphere via (n,2n)

- Can use GERDA low-energy data to cross-check the $^{39}$Ar specific activity
- need a Monte Carlo to predict the $^{39}$Ar contribution in the detector array (bremsstrahlung and direct $\beta$-rays)
- preliminary work done (simplified Monte Carlo) → fair agreement between GERDA signal and expectations for 1.01 Bq/kg rate
Cosmogenic contaminants of Ar (2)

- $^{42}\text{Ar} (<42 \mu\text{Bq/kg}, T_{1/2} = 32.9 \text{ y})$
  - cosmogenic via ($\alpha, 2p$), nuclear explosions/reactors via ($n, \gamma$)($n, \gamma$)
  - $^{42}\text{Ar}$ itself not a concern, but its progeny $^{42}\text{K}$ is a background source for GERDA ($Q_\beta = 3520 \text{ keV}, T_{1/2} = 12 \text{ h}$)

- Signature of $^{42}\text{K}$: $\gamma$ ray at 1524.7 keV (18%)

- Literature limit(*) corresponds to about 0.1 counts/(kg·d) at 1525 keV for the GERDA 3-detector array
  - contribution at $Q_{\beta\beta}$ (MC) of a few $10^{-3}$, counts/(keV kg y) dominated by $\beta$ rays penetrating through the dead layer

- Only upper limits, no positive measurement

(*) Ashitkov at al., arXiv: nucl-ex/0309001
First GERDA Run: surprise!

- Observed 1525 keV line at ca. 2 cts/(kg·d) \(\rightarrow\) \(x20\) literature limit! How possible?
- But: we have electric fields dispersed in LAr...
- not the case in standard cryostats
- outer detector surface biased at 3 kV
- \(^{42}\text{K}\) may be charged
- are we concentrating \(^{42}\text{K}\) closer to the detectors?
Play with the electric fields (1)

- Add a mini-shroud (MS) (thin Cu foil) to block drift and close electric field lines

shroud (already installed to prevent $^{222}$Rn concentration by drift/convection)

before MS

after MS

suppression factor: $\sim4.5$
Play with the electric fields (2)

- In the **same setup**, one can also **change the relative** $V$ **between shroud and mini-shroud**
- Check if you can **attract** $^{42}\text{K}$ ions!

$^{42}\text{K}$ signal **sensitive** to electric fields!

\[
V_{S-MS} = +700 \text{ V} \\
\text{increase by a factor of 4}
\]

\[
V_{S-MS} = -400 \text{ V}
\]
42Ar/42K signal & GERDA

- Confirmed independently in the LArGe R&D setup underground at LNGS
- Positive measurement of 42Ar contamination in Ar (for the first time!) $\rightarrow$ need field-free configuration to avoid bias
  - Anyway larger than the existing upper limit (43 $\mu$Bq/kg)
- 42K signal can be reduced/suppressed by electric field. Tried a few different configurations of electric fields
  - no major changes at $Q_{\beta\beta}$ $\rightarrow$ GERDA background not dominated by 42K
- Anyway, danger at $Q_{\beta\beta}$ only if $\beta$-rays penetrate directly in the detector (only a rare high-energy $\gamma$)
  - expected $7 \cdot 10^{-3}$ counts/(keV kg y) for uniform distribution, OK for Phase I
  - many handles to further reduce: additional passivation, encapsulation, repel 42K ions by electric fields, etc.
Conclusions

- GERDA experiment will look for $0\nu2\beta$ decay in $^{76}\text{Ge}$ at LNGS using naked HPGe detectors operated in LAr
- Construction completed, commissioning presently in progress: 3 $^{nat}\text{Ge}$ detectors operated
- Estimates/MC simulations for cosmogenic backgrounds: direct (prompt) $\mu$-events, activation under ground and activation above ground $\rightarrow$ now can check with data
- Muon-induced background (prompt & delayed) consistent with expectations
- Surprise: relevant $^{42}\text{Ar}/^{42}\text{K}$ signal. First positive measurement
  - sensitive to electric fields
  - not an issue: several handles to reduce the background at $Q_{\beta\beta}$
  - run a field-free set-up to quantify the $^{42}\text{Ar}$ specific activity in LAr
    - but surely larger than upper limit from the literature