The GeMSE Low-Background Facility for Meteorite and Material Screening

Diego Ramírez García
Albert-Ludwigs-Universität Freiburg

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Motivation

- Material screening
  - Rare event searches (e.g., Dark Matter, 0νββ) require low-background detector components
  - Selection of suitable materials for the construction of XENONnT and DARWIN projects

- Meteorite research
  - Identification of cosmogenic activated isotopes (e.g., $^{22}\text{Na}$, $^{27}\text{Al}$, $^{44}\text{Ti}$) in meteorites allows for terrestrial age determination
  - Pairing of samples
  - Need for a non-destructive analysis of chemical composition
  - User-friendly remote control and analysis/simulations framework
GeMSE Location

- Vue des Alpes underground laboratory (Switzerland)
  - 620 m.w.e. rock overburden
  → 2000x reduction of cosmic muons

- Location in a car tunnel provides very easy access
- One-hour drive from Bern
→ Short-lived isotopes from meteorites can be measured
GeMSE Design

- 24 x 24 x 35 cm³ sample cavity
- HPGe read-out by 14-bit digital MCA (CAEN DT5781A)
  - 10 ns resolution
  - Saves pulse height and time stamp for each event
- Scintillator panels as muon veto
  - Discard HPGe signals 10 μs after veto trigger → ~ 0.5 % dead time introduced
- Multi-layer passive shielding
  - 8 cm of Cu-OFE (> 99.99 % purity)
  - 5 cm low activity Pb (7 Bq/kg $^{210}$Pb)
  - 15 cm normal Pb (91 Bq/kg $^{210}$Pb)
- N₂ purged glovebox
  - Remove $^{222}$Rn and protection against dust
GeMSE Design

Canberra ultra-low background HPGe

- 2.2 kg Ge crystal
- Standard coaxial, $p$ type
- U-style cryostat
- Low-background Cu housing
GeMSE Design
GeMSE Background

- Initial background goal of 250 counts/day (100-2700 keV)
- Location and shielding design optimized via GEANT4 simulations

\begin{center}
\end{center}
GeMSE Background

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- Total reduction by a factor of $\sim 10^5$ with respect to above-ground levels

**BACKGROUND MC-DATA MATCHING**

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Chain/Isotope</th>
<th>GeMSE Count Rate (day$^{-1}$)</th>
<th>Gator Count Rate (day$^{-1}$)</th>
<th>GeMPI Count Rate (day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>122</td>
<td>$^{57}$Co (ext.)</td>
<td>1.6 ± 0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>144</td>
<td>$^{57}$Co (int.)</td>
<td>1.1 ± 0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1125</td>
<td>$^{65}$Zn</td>
<td>1.2 ± 0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1173</td>
<td>$^{60}$Co</td>
<td>0.84 ± 0.15</td>
<td>0.5 ± 0.1</td>
<td>0.26 ± 0.06</td>
</tr>
<tr>
<td>1333</td>
<td>$^{60}$Co</td>
<td>0.84 ± 0.15</td>
<td>0.5 ± 0.1</td>
<td>0.21 ± 0.05</td>
</tr>
<tr>
<td>662</td>
<td>$^{137}$Cs</td>
<td>&lt; 0.03</td>
<td>0.3 ± 0.1</td>
<td>0.34 ± 0.16</td>
</tr>
<tr>
<td>1461</td>
<td>$^{40}$K</td>
<td>0.23 ± 0.10</td>
<td>0.5 ± 0.1</td>
<td>0.52 ± 0.07</td>
</tr>
<tr>
<td>239</td>
<td>$^{232}$Th$^{212}$Pb</td>
<td>0.34 ± 0.17</td>
<td>&lt; 0.5</td>
<td>-</td>
</tr>
<tr>
<td>583</td>
<td>$^{232}$Th$^{208}$Tl</td>
<td>0.17 ± 0.10</td>
<td>-</td>
<td>≤ 0.13</td>
</tr>
<tr>
<td>911</td>
<td>$^{234}$Th$^{228}$Ac</td>
<td>&lt; 0.14</td>
<td>&lt; 0.5</td>
<td>-</td>
</tr>
<tr>
<td>2615</td>
<td>$^{232}$Th$^{208}$Tl</td>
<td>0.27 ± 0.08</td>
<td>0.2 ± 0.1</td>
<td>0.11 ± 0.03</td>
</tr>
<tr>
<td>352</td>
<td>$^{238}$U$^{214}$Pb</td>
<td>0.67 ± 0.17</td>
<td>0.7 ± 0.3</td>
<td>≤ 0.14</td>
</tr>
<tr>
<td>609</td>
<td>$^{238}$U$^{214}$Bi</td>
<td>0.51 ± 0.14</td>
<td>0.6 ± 0.2</td>
<td>≤ 0.15</td>
</tr>
<tr>
<td>1120</td>
<td>$^{238}$U$^{214}$Bi</td>
<td>&lt; 0.02</td>
<td>0.3 ± 0.1</td>
<td>-</td>
</tr>
<tr>
<td>1765</td>
<td>$^{238}$U$^{214}$Bi</td>
<td>0.14 ± 0.08</td>
<td>0.08 ± 0.06</td>
<td>-</td>
</tr>
<tr>
<td>100-2700</td>
<td>integral</td>
<td>246 ± 2</td>
<td>226 ± 1</td>
<td>41 ± 1</td>
</tr>
</tbody>
</table>

GeMSE Background

- Initial background goal of 250 counts/day (100-2700 keV)
- Location and shielding design optimized via GEANT4 simulations
- Total reduction by a factor of $\sim 10^5$ with respect to above-ground levels
- Expected decrease of cosmogenic lines
GeMSE Background

- Initial background goal of 250 counts/day (100-2700 keV)
- Location and shielding design optimized via GEANT4 simulations
- Total reduction by a factor of \(~ 10^5\) with respect to above-ground levels
- Expected decrease of cosmogenic lines → In agreement with measurement after 2.5 years!

Integral rate 100-2700 keV:
- Oct 2016: 246 ± 2 counts/day
- Mar 2019: 167 ± 2 counts/day
GeMSE Efficiency

- Dead layer from Li-diffused n+ contact
- Determined by MC matching
  - 81 keV / 356 keV peak ratio of $^{133}$Ba → 0.67 ± 0.01 mm
  - CBSS2 source with certified activity → 0.65 ± 0.05 mm
- Active volume implemented in GeMSE GEANT4 framework for efficiency calculation

GeMSE Remote Operation

DOBERMAN Slow Control (v4):

- Monitoring:
  - HV of HPGe detector
  - Leakage current of HPGe detector
  - Muon veto rate
  - Automatic LN$_2$ refill
  - N$_2$ flow inside glovebox
  - Temperature inside glovebox
  - ...
- 100% uptime
- Configurable without restarting
- Remotely accessible

In addition, remote switch for:

- HPGe DAQ
- LN$_2$ refill

$\Rightarrow$ Three to four weeks of autonomy $\Leftarrow$

Analyzing a Sample with GeMSE

(Analysis environment set up for non-physics users)

i. Measure your sample and background
ii. Get rid of Rn contamination in your data
iii. Derive energy calibration and resolution
iv. Perform efficiency simulations for your sample
v. Fit gamma peaks of interest

XENONnT PMTs (Hamamatsu R11410)

PTFE holders (background)
10-PMTs batch + PTFE holders
Analyzing a Sample with GeMSE

i. Measure your sample and background

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v. Fit gamma peaks of interest

Using the timestamps of the hits:
Analyzing a Sample with GeMSE

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ii. Get rid of Rn contamination in your data
iii. Derive energy calibration and resolution
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v. Fit gamma peaks of interest
Analyzing a Sample with GeMSE

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iii. Derive energy calibration and resolution

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• GEANT4 branching ratio validation

Gammas to be simulated separately
Analyzing a Sample with GeMSE

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- GEANT4 branching ratio validation
- Sample implementation
Analyzing a Sample with GeMSE

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- GEANT4 branching ratio validation
- Sample implementation
- Complex 3D geometries can also be imported
  - Relevant to determine self-absorption of meteorites
Analyzing a Sample with GeMSE

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SIMULATED DETECTOR EFFICIENCY

![Graph showing energy vs. efficiency]
Analyzing a Sample with GeMSE


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- Analysis based on the *Bayesian Analysis Toolkit*
- Uncertainty on detection efficiency as Gaussian prior
- *Background-only* and *signal+background* fit in 5σ region

Calculate Bayes Factor

\[ BF = \frac{P(B \mid data)}{P(S \mid data)} \]

- BF < 0.33: Calculate activity
- BF > 0.33: Calculate upper limit
Analyzing a Sample with GeMSE

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- Perform efficiency simulations for your sample
- Fit gamma peaks of interest

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Batch 1 [mBq/PMT]</th>
<th>Batch 2 [mBq/PMT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>&lt; 5.0</td>
<td>&lt; 6.3</td>
</tr>
<tr>
<td>$^{228}\text{Th}$</td>
<td>&lt; 1.6 \cdot 10^{-1}</td>
<td>(1.1 \pm 0.4) \cdot 10^{-1}</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$</td>
<td>(4.1 \pm 0.9) \cdot 10^{-1}</td>
<td>(2.4 \pm 0.9) \cdot 10^{-1}</td>
</tr>
<tr>
<td>$^{228}\text{Ra}$</td>
<td>(2.5 \pm 1.4) \cdot 10^{-1}</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>(3.8 \pm 0.8) \cdot 10^{-1}</td>
<td>(5.3 \pm 0.8) \cdot 10^{-1}</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>&lt; 6.0 \cdot 10^{-2}</td>
<td>&lt; 5.0 \cdot 10^{-2}</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>5.5 \pm 1.2</td>
<td>6.1 \pm 1.7</td>
</tr>
</tbody>
</table>

Results fit expectations from bulk materials’ contamination

Summary

- GeMSE operates under very stable conditions since November 2015
- Slow control allows for three to four weeks of autonomous activity
  - Foreseen improvements in LN₂ refill system and remote control
- Reached background design goal in 2016
  - Current rate of 167 ± 2 counts/day (100-2700 keV), from the decrease on the cosmogenic-activated component
  - Comparable to most sensitive screening facilities in the world
- Flexible and user-friendly sample analysis chain
- Precise efficiency simulations framework based on the GEANT4 toolkit
  - Able to process complex-shaped volumes
- Participating in the XENONnT screening campaign
- Essential role in the (non-invasive) verification and classification of claimed meteorite falls from various point in the planet