The upgraded low-background germanium counting facility Gator for high-sensitivity $\gamma$-ray spectrometry

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Alexander Bismark

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alexander.bismark@physik.uzh.ch
Motivation

- Required low backgrounds in rare event searches (e.g. DM, $0\nu\beta\beta$)
- Germanium spectroscopy: non-destructive and high resolution screening method for material radioassay
- Selection of radiopure detector materials and precise background simulations
- Gator facility used for...
  - XENON100, XENON1T and XENONnT, GERDA and LEGEND-200
  - Future: LEGEND-1000 and DARWIN

Nuclear recoil backgrounds in XENON1T from materials (red), predicted from screening measurements, and external sources (blue)\footnote{\cite{1}}

\footnote{1} Eur. Phys. J. C77 (2017) 890
The Gator Facility

- Low-background germanium counting facility for high-sensitivity γ-ray spectrometry [2]
- Located at the Gran Sasso underground laboratory in Italy (LNGS) at a depth of 3600 m water equivalent
- Core: p-type coaxial high-purity germanium (HPGe) detector with 2.2 kg sensitive mass and a relative efficiency of 100.5%
- Sample chamber volume: 25×25×33 cm³
- Recent upgrades to decrease background level, noise contribution in low-energy region, facilitate sample handling process

The Upgraded Gator Detector

(a) HPGe detector inside Cu-OFE cryostat (cooled with LN₂ via copper coldfinger), (b) OFHC Cu cavity, (c) lead shield, polyethylene sheet, (d) airtight stainless steel enclosure (purged with GN₂), (e) glove ports, (f) sample load lock
Detector Operation and Performance

- Stable operation for over 10 years
- Remote monitoring (incl. alarms) of operations parameters to ensure detector stability and data quality
- Regular calibrations of the detector with radioactive sources (e.g. $^{228}\text{Th}$, $^{137}\text{Cs}$, or $^{60}\text{Co}$) or high-activity samples
  - FWHM at 1332 keV: $(1.98 \pm 0.07)$ keV (Maeve: 3.19 keV\textsuperscript{[3]}, GeOroel: 1.85 keV\textsuperscript{[4]})
  - Verification of simulated efficiencies and consistent activities related lines

\textsuperscript{[3]} Eur. Phys. J. C80 (2020) 1044
\textsuperscript{[4]} Bandac, "Ultra-Low Background Services in the LSC", DS-Mat Meeting, GSSI, 2019
Background Contributions

- Integrated background rate in the energy region 100-2700 keV:
  \((86.2\pm0.7)\) d\(^{-1}\)kg\(^{-1}\);
as compared to value from 2010\(^{[2]}\):
  \((102.8\pm0.7)\) d\(^{-1}\)kg\(^{-1}\);
stable within runs (\(\chi^2/\text{ndf} < 2\))

- Low energies (\(\leq 35\) keV):
  - electronic noise

- Higher energies:
  - detector & shielding materials
  - environmental radon

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>Isotope</th>
<th>Rate '21 [d(^{-1})]</th>
<th>Rate '10 [d(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>351.932</td>
<td>Pb-214</td>
<td>&lt; 0.7</td>
<td>0.7 ± 0.3</td>
</tr>
<tr>
<td>609.312</td>
<td>Bi-214</td>
<td>0.53 ± 0.11</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>1120.29</td>
<td>Bi-214</td>
<td>0.15 ± 0.06</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>1764.49</td>
<td>Bi-214</td>
<td>0.10 ± 0.03</td>
<td>0.08 ± 0.06</td>
</tr>
<tr>
<td>661.657</td>
<td>Cs-137</td>
<td>0.17 ± 0.08</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>1173.24</td>
<td>Co-60</td>
<td>&lt; 0.3</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>1332.51</td>
<td>Co-60</td>
<td>0.11 ± 0.05</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>1460.88</td>
<td>K-40</td>
<td>0.46 ± 0.08</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>2614.51</td>
<td>Tl-208</td>
<td>0.14 ± 0.05</td>
<td>0.2 ± 0.1</td>
</tr>
</tbody>
</table>

\(^{[2]}\) JINST 6 (2011) P08010
Sample Simulation and Analysis

- Determination of the material-, geometry-, and energy-dependent detection efficiency $\varepsilon$ of the respective $\gamma$-lines through GEANT4 Monte Carlo simulations for each sample
Sample Simulation and Analysis

- Calculation of the specific activities $A$ from the background- and Compton-subtracted counts $S_{\text{net}}$ at the location (±3σ) of the most prominent lines as
  \[ A = \frac{S_{\text{net}}}{r \cdot \epsilon \cdot m \cdot t} \]
  (branching ratio $r$, sample mass $m$, measuring time $t$)

- Combination to activities of isotopes / subchains ($L_d @ \sim 95\% \, \text{C.L.}$)

\[ S_{\text{net}} = S - B \cdot \frac{t_S}{t_B} - B_C \]
\[ L_d = k^2 + 2 \cdot L_c \]
\[ L_c = k \cdot \sigma_{\text{net}} \]

Sample Simulation and Analysis

- Isotopes / chains of interest:
  - primordial: $^{238}$U, $^{232}$Th, $^{40}$K
  - cosmogenic: $^{54}$Mn, $^{46}$Sc, $^{60}$Co,…
  - anthropogenic: $^{137}$Cs, $^{110m}$Ag,…

  \[ \text{decay products may mimic signals (e.g. NRs of neutrons from } (\alpha, n) \text{ reactions in XENON) or leak into the signal region} \]

- Typical sensitivities: < a few mBq/kg for exposures of 1-3 weeks and several kg sample mass (a few \( \mu \text{Bq/kg} \) for radio-pure samples, longer exposure & higher mass)

71.7 kg OFHC copper sample
Summary and Outlook

- Upgraded low-background germanium counting facility Gator for high-sensitivity gamma-ray spectrometry
- Integrated background rate (100-2700 keV) of \((86.2 \pm 0.7) \text{ d}^{-1}\text{kg}^{-1}\) comparable to world's most sensitive HPGe detectors
- Prospective material screenings for LEGEND-1000, DARWIN,...

Thank you for your attention.
Appendix
Th-228 Calibrations

\[ \text{Fit: } \frac{c}{E} = \sqrt{\frac{a}{E}} + \frac{b}{E} + c \]
- \( a = 1.89 \times 10^{-3} \text{ keV}^2 \)
- \( b = 4.06 \times 10^{-6} \text{ keV} \)
- \( c = 1.5 \times 10^{-4} \)
- \( \chi^2/\text{d.o.f.} = 13.7 / 8 \)
- Peak Width \( \sigma \)

\[ \text{Linear Fit: } y = ax + b \]
- \( a = 0.164668, \ b = 0.593 \)
- \( \chi^2/\text{d.o.f.} = 18.4 / 8 \)
- Peaks \(^{139}\)Th Calibration

\[ \text{Detection Efficiency } \varepsilon \]
- Simulation
- Measurement

\[ \text{Mean: } 0.94 \pm 0.01(\text{stat.}) \pm 0.04(\text{syst.}) \]
Reproducible Low-Energetic Noise

- Observed low-energetic electronic noise, temporally correlated with LN$_2$ dewar refills, that might leak into the ROI (going up to energies of up to ~ 150 keV)
- Unbiased removal of data based on derivative of LN$_2$ level reading
Example: Hamamatsu PMT R12699-406-M4

For isotopes where detection limit is exceeded, current (not yet optimized) prototype model has, per active photocathode area*,

- equal – threefold activities w.r.t. developed R11410 units [1]
- lower activity compared to the R8520 PMTs [5]

→ Good potential for future improvements through material selection

* R12699 ~ 23.5 cm², R11410 ~ 32.2 cm², R8520 ~ 4.2 cm²

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Hamamatsu R12699-406-M4</th>
<th>Hamamatsu R11410-21</th>
<th>Ratio R12699/R11410</th>
<th>Hamamatsu R8520-06</th>
<th>Ratio R12699/R8520-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>238U</td>
<td>&lt; 8.02 (8 ± 2)</td>
<td>–</td>
<td>–</td>
<td>&lt; 15</td>
<td>–</td>
</tr>
<tr>
<td>226Ra</td>
<td>(0.75 ± 0.19) (0.6 ± 0.1)</td>
<td>(1.3 ± 0.4)</td>
<td>–</td>
<td>&lt; 0.28</td>
<td>–</td>
</tr>
<tr>
<td>228Ra</td>
<td>&lt; 1.23 (0.7 ± 0.2)</td>
<td>–</td>
<td>–</td>
<td>&lt; 0.59</td>
<td>–</td>
</tr>
<tr>
<td>228Th</td>
<td>(0.54 ± 0.17) (0.6 ± 0.1)</td>
<td>(0.9 ± 0.3)</td>
<td>(0.3 ± 0.1)</td>
<td>(1.8 ± 0.7)</td>
<td>–</td>
</tr>
<tr>
<td>235U</td>
<td>&lt; 0.37 (0.37 ± 0.09)</td>
<td>–</td>
<td>–</td>
<td>&lt; 0.67</td>
<td>–</td>
</tr>
<tr>
<td>60Co</td>
<td>(2.03 ± 0.19) (0.84 ± 0.09)</td>
<td>(2.4 ± 0.3)</td>
<td>(0.60 ± 0.04)</td>
<td>(3.4 ± 0.4)</td>
<td>–</td>
</tr>
<tr>
<td>40K</td>
<td>(26.2 ± 3.2) (12 ± 2)</td>
<td>(2.2 ± 0.5)</td>
<td>(12.0 ± 0.8)</td>
<td>(2.2 ± 0.3)</td>
<td>–</td>
</tr>
<tr>
<td>137Cs</td>
<td>(0.16 ± 0.05)</td>
<td>–</td>
<td>–</td>
<td>&lt; 0.1</td>
<td>–</td>
</tr>
<tr>
<td>54Mn</td>
<td>&lt; 0.229</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>54Mn</td>
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<tr>
<th>Detector</th>
<th>Location (Depth)</th>
<th>Mass</th>
<th>Efficiency</th>
<th>FWHM</th>
<th>Rate (60-2700 keV)</th>
<th>[cts/(kg.day)]</th>
</tr>
</thead>
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<tr>
<td><strong>Gator</strong></td>
<td>LNGS (3600 m.w.e)</td>
<td>2.2 kg</td>
<td>100.5 %</td>
<td>1.98 keV</td>
<td>93.2</td>
<td></td>
</tr>
<tr>
<td><strong>Maeve</strong></td>
<td>SURF (4300 m.w.e)</td>
<td>2.0 kg</td>
<td>85 %</td>
<td>3.19 keV</td>
<td>956.1</td>
<td></td>
</tr>
<tr>
<td><strong>GeMPI</strong></td>
<td>LNGS (3600 m.w.e)</td>
<td>2.2 kg</td>
<td>102 %</td>
<td>- keV</td>
<td>18.7 [*]</td>
<td></td>
</tr>
<tr>
<td><strong>Belmont</strong></td>
<td>Boulby (2805 m.w.e.)</td>
<td>3.2 kg</td>
<td>160 %</td>
<td>1.92 keV</td>
<td>135.0</td>
<td></td>
</tr>
<tr>
<td><strong>GeOroel</strong></td>
<td>LSC (2450 m.w.e.)</td>
<td>2.3 kg</td>
<td>109 %</td>
<td>1.85 keV</td>
<td>165.3</td>
<td></td>
</tr>
<tr>
<td><strong>GeMSE</strong></td>
<td>VdA (620 m.w.e)</td>
<td>2.0 kg</td>
<td>107.7 %</td>
<td>1.96 keV</td>
<td>123.0 [*]</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Location, mass, efficiency, energy resolution and background rate (integrated from 60 to 2700 keV) of the the Gator detector in comparison to other gamma-screening HPGe detectors. All of these detectors are located underground, in the respective laboratories (in order of depth): the Sanford Underground Research Facility (SURF), the LNGS, the Boulby Underground Laboratory (Boulby), the Laboratorio Subterráneo Canfranc (LSC), and in the La Vue-des-Alpes laboratory (VdA). [*] The background rates of the GeMPI and GeMSE detectors were integrated from 100-2730 keV, and from 100-2700 keV, respectively.
References


[4] Bandac, “Ultra-Low Background Services in the LSC.” Talk at the DS-Mat Parallel meeting at GSSI, 2019
