Limitations of next generation $0
\nu\beta\beta$
germanium experiments:
The Good, the Bad and the Ugly

The good:

The bad:

And the ugly:

Metallization

$^{210}\text{Pb}$ on surfaces,

$^{68}\text{Ge}$

Béla Majorovits
Max-Planck-Institut für Physik, München, Germany
Ton Scale Required Background:

- $10^{-3}$ counts/kg/keV/yr
- $10^{-4}$ counts/kg/keV/yr
- $10^{-5}$ counts/kg/keV/yr

Ton scale experiment requires background of $10^{-5}$ cts/(kg keV y)

Aluminum as background

Aluminum: used for many useful things
Aluminum as background

Used to metallize HPGe detectors.

Example case:

Full metallization of HPGe type detector with 75 mm diameter and 70 mm height

\[
2 \cdot \pi \cdot 3.75\text{cm} \cdot 300\text{nm} \cdot 7\text{cm} \cdot 2.7\text{g/cm}^3 = 13.4\text{mg}
\]

of aluminum on the outer surface

→ Primordials: \(^{238}\text{U} - ^{232}\text{Th}\)
→ Cosmogenics: \(^{26}\text{Al}, ^{22}\text{Na}\)
Aluminum as background

$^{26}\text{Al}$: β+ decay,
Q-value: 4 MeV,
T$_{1/2}$ = 7.4 $\cdot$ 10$^5$ years
Can not be removed easily from bulk aluminium
Can not wait for decay

$^{22}\text{Na}$: Q-value: 2.84 MeV,
T$_{1/2}$ = 2.6 years
Easily produced if at sea level
Can wait for decay
Aluminum as background

Aluminum is refined from Bauxite.

Bauxite mines:
mainly open pits
Top soil overburden: < 1m
Layer thickness: 2m – 4m

Deposits formed by weathering
Rested on surface since its formation

⇒ Assume full exposure to cosmic rays since millions of years

Weipa mine NE Australia
Aluminum as background

Secondary neutron flux

Secondary proton flux

at sea level, New York, averaged over 2m bauxite layer and averaged in a 2m bauxite layer under 1m soil:
Aluminum as background

Excitation functions for $^{26}$Al and $^{22}$Na
Aluminum as background
Expectations from naive calculations

<table>
<thead>
<tr>
<th></th>
<th>$^{26}$Al [(g y)$^{-1}$]</th>
<th>$^{26}$Al [mBq/kg]</th>
<th>$^{22}$Na [(g y)$^{-1}$]</th>
<th>$^{22}$Na [mBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>n [surface Ziegler]</td>
<td>142</td>
<td>4.5</td>
<td>56</td>
<td>1.8</td>
</tr>
<tr>
<td>n [surface Gordon]</td>
<td>80</td>
<td>2.5</td>
<td>43</td>
<td>1.3</td>
</tr>
<tr>
<td>n[2m self absorption]</td>
<td>21</td>
<td>0.67</td>
<td>11</td>
<td>0.4</td>
</tr>
<tr>
<td>n[1m soil 2m self abs.]</td>
<td>1.4</td>
<td>0.04</td>
<td>1.0</td>
<td>0.03</td>
</tr>
<tr>
<td>p [surface]</td>
<td>17</td>
<td>0.54</td>
<td>8.7</td>
<td>0.1</td>
</tr>
<tr>
<td>n + p in 2m bauxite</td>
<td>23</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea level, half equilibrium</td>
<td></td>
<td></td>
<td>32</td>
<td>1.0</td>
</tr>
</tbody>
</table>

![Graph 1](image1.png)

![Graph 2](image2.png)
Aluminum as background

MC of $^{26}$Al and $^{22}$Na (1.0 mBq/kg)

$\rightarrow$ Relevant background contribution for ton scale experiment even for activity ten times less than naïve expectation!

$10^{-6}$ cts/(kg y keV) $\rightarrow$ Have to limit $^{26}$Al activity to 0.6 mBq/kg $^{22}$Na activity to 2mBq/kg
Aluminum as background

MC of $^{226}$Ra and $^{228}$Th (1.0 mBq/kg)

$\rightarrow$ Relevant background contribution for ton scale experiment even for activity ten times less than naïve expectation!

$10^{-6}$ cts/(kg y keV) $\rightarrow$ Have to limit $^{226}$ Ra activity to 0.4 mBq/kg $^{228}$Th activity to 0.2 mBq/kg
# Aluminum as background

**Measurements of ULB Aluminium:**

**Activities in mBq/kg**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{26}\text{Al}$</th>
<th>$^{22}\text{Na}$</th>
<th>$^{226}\text{Ra}$</th>
<th>$^{228}\text{Th}$</th>
<th>$^{40}\text{K}$</th>
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<tbody>
<tr>
<td>Kryal, Hydro Aluminium, UTH 1</td>
<td>0.6±0.3</td>
<td>0.7±0.3</td>
<td>&lt; 0.38</td>
<td>&lt;1.9</td>
<td>&lt;21</td>
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<td>Kryal, VAW, UTH 0.25</td>
<td>&lt; 0.15</td>
<td>&lt; 0.26</td>
<td>&lt;0.28</td>
<td>&lt;0.58</td>
<td>&lt;22</td>
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<tr>
<td>Highpural, VAW</td>
<td>&lt; 0.45</td>
<td>&lt; 0.37</td>
<td>&lt;3.7</td>
<td>47±5</td>
<td>&lt;5.5</td>
</tr>
<tr>
<td>ULB I [6]</td>
<td>0.2±0.1</td>
<td>&lt; 0.32</td>
<td>&lt;0.7</td>
<td>3.8±0.7</td>
<td>4.9 ±1.8</td>
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<tr>
<td>ULB II [5]</td>
<td>0.38±0.19</td>
<td>&lt; 0.18</td>
<td>0.27±0.19</td>
<td>1.4±0.2</td>
<td>1.1 ±0.2</td>
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$^{26}\text{Al}$ and $^{22}\text{Na}$ found in ULB aluminum!

Clean Aluminum does exist!

→ HPGe measurements sensitive enough to select $^{26}\text{Al}$ and $^{22}\text{Na}$ and $^{232}\text{Th}$ “free” Aluminum
Aluminum as background

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Contaminations on HPGe surfaces

$^{210}$Pb lead on surfaces with dead layer $<$20μm thickness

$\alpha$ contaminations ($^{210}$Pb, $^{210}$Bi) seen in Heidelberg, Moscow, Edelweiss, CDMS, GERDA experiments.

→ Investigation of surface treatment!
Contaminations on HPGe surfaces

Effect of etching: Removal and deposition efficiencies of $^{210}$Pb and its daughters during etching of germanium

(in collaboration with G. Zuzel, MPI-K, M. Wojcik, Jagellonian Univ., Cracow and Canberra France, Lingolsheim, France):

NPGe / HPGe discs and DI water exposed to $^{222}$Rn source for 7 months at MPI-K in Heidelberg

1.4 MBq Rn
($^{226}$Ra) source

10 l gas volume in two excsicatrors
Contaminations on HPGe surfaces

Clean HPGe disc etched in contaminated etching solution

Contaminated disc etched in clean etching solution

Samples were etched by Canberra France-Lingolsheim according to procedure of HPGe detector etching
Contaminations on HPGe surfaces

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Initial count rate [cpm]</th>
<th>Count rate after cleaning [cpm]</th>
<th>Reduction factor R</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>2.09 ± 0.12</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>2.12 ± 0.21</td>
<td>&lt; 0.02</td>
<td>&gt; 106</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>40.7 ± 1.3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>46.1 ± 1.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>50.0 ± 1.5</td>
<td>0.06 ± 0.02</td>
<td>833 ± 279</td>
</tr>
<tr>
<td></td>
<td>47.0 ± 1.4</td>
<td>0.05 ± 0.02</td>
<td>940 ± 377</td>
</tr>
</tbody>
</table>

NPGe disc:

46.5 keV gamma with HPGe det: 1% est. efficiency

β - particles with Si det: 10% est. efficiency

α – particle with 4π Si det. system: 15% estimated efficiency

Measurements performed at Jagellonian University Cracow by M. Wojcik

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<tr>
<td>$^{210}\text{Pb}$</td>
<td>0.717 ± 0.011</td>
<td>&lt; 0.001</td>
<td>&gt; 717</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>14.70 ± 0.12</td>
<td>&lt; 0.017</td>
<td>&gt; 865</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>11.88 ± 0.19</td>
<td>0.102 ± 0.006</td>
<td>117 ± 7</td>
</tr>
</tbody>
</table>
### Contaminations on HPGe surfaces

#### Deposition efficiencies on HPGe disc:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Initial count rate [cpm]</th>
<th>Count rate after cleaning [cpm]</th>
<th>Count rate increase [cpm]</th>
<th>Number of nuclei on disc</th>
<th>Increase factor $B_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>$0.0163 \pm 0.0009$</td>
<td>$0.023 \pm 0.001$</td>
<td>$0.0066 \pm 0.0013$</td>
<td>$1.1 \cdot 10^7$</td>
<td>$1.4$</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>$0.111 \pm 0.006$</td>
<td>$0.217 \pm 0.007$</td>
<td>$0.106 \pm 0.009$</td>
<td>$7500$</td>
<td>$1.9$</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$0.064 \pm 0.005$</td>
<td>$0.087 \pm 0.006$</td>
<td>$0.023 \pm 0.007$</td>
<td>$1.7 \cdot 10^4$</td>
<td>$1.4$</td>
</tr>
</tbody>
</table>

**Significant amount of $^{210}\text{Pb}$, $^{210}\text{Bi}$ and $^{210}\text{Po}$ deposited on HPGe disc**

**HPGe measurement of $^{210}\text{Pb}$ concentration of DI water (upper limit):** $A < 20$ Bq

**Probability of plating onto HPGe from 100ml DI water:**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>$&gt; 1.2%$</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>$&gt; 1.2%$</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>$&gt; 0.16%$</td>
</tr>
</tbody>
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Accepted for publication in NIM A

Béla Majorovits 18
Contaminations on HPGe surfaces

MC simulation: one $^{210}$Pb nucleus on detector surface:

$\sim 10^{-7}$ cts/(kg y keV)

Allowed number of nuclei on active surface:
max. $10 \rightarrow 0.01$ nuclei per cm$^2$

in etchant (1.2% deposition eff.): $\sim 850$ $^{210}$Pb nuclei $\sim 10 \mu$Bq/l!

$\rightarrow$ $^{210}$Pb Screening methods & Clean etchants needed
Contaminations on HPGe surfaces

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Intrinsic HPGe contamination

Expected count rate due to $^{68}\text{Ge}$ in HPGe:
One $^{68}\text{Ge}$ nucleus per kg: $1.8 \cdot 10^{-5}$ cts/(kg y keV) [K. Kröninger, PhD]

$\Rightarrow$ To keep the level below $10^{-6}$ cts/(kg y keV):
Roughly 55 $^{68}\text{Ge}$ nuclei per tonne allowed (0.055 per kg).

Production rates:

$^{\text{nat}}\text{Ge}$: 50 $^{68}\text{Ge}$ nuclei (kg day)$^{-1}$
$^{\text{enr}}\text{Ge}$: 7 $^{68}\text{Ge}$ nuclei (kg day)$^{-1}$

$\Rightarrow$ Max. 11 minutes above ground!

Cosmogenic production of $^{60}\text{Co}$ and $^{68}\text{Ge}$ in germanium can be avoided by storage underground.

$\Rightarrow$ Enrichment underground!
Intrinsic HPGe contamination

In equilibrium in $^\text{nat}\text{Ge}$: $2 \cdot 10^4$ $^{68}\text{Ge}$ nuclei/kg

Enrichment of germanium does deplete $^{68}\text{Ge}$ content.

But how efficiently?

![Graph showing enrichment coefficient vs. mass number]

- Looks like plateau for lower mass numbers!
- Measurements for $^{70}\text{Ge}$ inconsistent!
Intrinsic HPGe contamination

Ratios of abundances natural to enriched materials:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>$10.9 \pm 0.1$</td>
<td>$11.0 \pm 0.4$</td>
<td>$11.2 \pm 0.1$</td>
<td>$11.2 \pm 0.1$</td>
<td>$11.4 \pm 0.1$</td>
<td>$11.1 \pm 0.1$</td>
</tr>
<tr>
<td>$^{74}$Ge</td>
<td>$0.362 \pm 0.001$</td>
<td>$0.356 \pm 0.006$</td>
<td>$0.334 \pm 0.002$</td>
<td>$0.336 \pm 0.008$</td>
<td>$0.290 \pm 0.001$</td>
<td>$0.358 \pm 0.002$</td>
</tr>
<tr>
<td>$^{73}$Ge</td>
<td>$(2.1 \pm 0.1) \times 10^{-2}$</td>
<td>$(3.2 \pm 1.0) \times 10^{-2}$</td>
<td>$(9.0 \pm 0.1) \times 10^{-3}$</td>
<td>$(2.0 \pm 0.1) \times 10^{-2}$</td>
<td>$(1.64 \pm 0.03) \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>$^{72}$Ge</td>
<td>$(2.20 \pm 0.04) \times 10^{-2}$</td>
<td>$(1.7 \pm 0.7) \times 10^{-2}$</td>
<td>$(2.93 \pm 0.03) \times 10^{-3}$</td>
<td>$(2.6 \pm 0.8) \times 10^{-3}$</td>
<td>$(1.02 \pm 0.04) \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>$^{70}$Ge</td>
<td>$(2.16 \pm 0.05) \times 10^{-2}$</td>
<td>$(1.5 \pm 1.0) \times 10^{-2}$</td>
<td>$(2.45 \pm 0.02) \times 10^{-3}$</td>
<td>$(8.8 \pm 3.7) \times 10^{-4}$</td>
<td>$(6.9 \pm 0.5) \times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

Assume (!) deenrichment of $^{68}$Ge of $10^{-4}$ (optimistic (?) for existing technology

→ Expect two nuclei per kg enriched material

→ Need to wait 5.18 half lives (3.84 years) to reach 0.055 nuclei/kg limit

→ Need R&D on deenrichment of $^{68}$Ge

The Ugly
Conclusions:

<table>
<thead>
<tr>
<th>The Good</th>
<th>Metallization:</th>
<th>Significant background if not taken care of. Can be controlled via HPGe screening of aluminum.</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Bad</td>
<td>Surfaces:</td>
<td>Need clean etchant. R&amp;D for etchant screening!</td>
</tr>
<tr>
<td>The Ugly</td>
<td>$^{68}$Ge:</td>
<td>Depletion efficiencies have to be studied and improved!</td>
</tr>
</tbody>
</table>

It’s a long way to the ton scale HP$^{enr}$Ge experiment
Donald Rumsfeld knew it all:
[Press Conference at NATO Headquarters, Brussels, Belgium, June 6, 2002]

“there are no "knowns." There are things we know that we know. There are known unknowns. That is to say there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know. “

\[
\begin{array}{c}
\text{know} \\
\text{don’t know}
\end{array}
\begin{array}{c}
\text{know} \\
\text{don’t know}
\end{array}
\]

\[
\left(\begin{array}{c}
2^{6}\text{Al}, 2\nu\beta\beta, \ldots \\
?\ldots? \\
\text{Surface } \alpha\text{-s, } \ldots \\
\text{Ton scale}
\end{array}\right)
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\[
\begin{align*}
\text{know} & : & \text{don’t know} \\
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\text{know} & : & \{\nu\beta\beta\} \\
\text{don’t know} & : & \{\text{Ton scale}\} \\
\end{align*}
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