Low-background techniques in direct dark matter searches

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Outline

• Introduction
• Low Radioactivity Assay Techniques
• Selected results
• Summary
Introduction

• Detectors devoted to direct dark matter searches require ultra-low (zero) background
• Background sources: producing events, which can mimic the signal (e.g. radioactive decays, n, muons, detector-specific sources)
• Background reduction techniques:
  ✓ Graded shielding: traveling inward to the center, each component is more radio-pure and it is protected from external radiation by the preceding one
  ✓ Active (definition of FV, Čerenkov veto) and passive (buffer volume) suppression of external radiation
  ✓ Careful selection of construction materials and detector components with respect to content of radioactive isotopes, $^{222}$Rn emanation and permeability
  ✓ Preventing surface contamination
  ✓ Application of appropriate purification (liquids, gases) and cleaning techniques
238U decay chain

\[ \begin{array}{c}
230\text{Th} \\
\alpha \quad T_{1/2} = 7.5 \cdot 10^4 \text{ y} \\
E = 4.7 \text{ MeV} \\
P = 73 \%
\end{array} \]

\[ \begin{array}{c}
234\text{U} \\
\beta \quad T_{1/2} = 1.17 \text{ min} \\
E_m = 2.3 \text{ MeV} \\
P = 94 \%
\end{array} \]

\[ \begin{array}{c}
234\text{mPa} \\
\beta \quad T_{1/2} = 24.1 \text{ d} \\
E_m = 0.198 \text{ MeV} \\
P = 69 \%
\end{array} \]

\[ \begin{array}{c}
234\text{Th} \\
\alpha \quad T_{1/2} = 4.5 \cdot 10^9 \text{ y} \\
E = 4.2 \text{ MeV} \\
P = 75 \%
\end{array} \]

\[ \begin{array}{c}
226\text{Ra} \\
\alpha \quad T_{1/2} = 1622 \text{ y} \\
E = 4.8 \text{ MeV} \\
P = 94 \%
\end{array} \]

\[ \begin{array}{c}
222\text{Rn} \\
\alpha \quad T_{1/2} = 3.8 \text{ d} \\
E = 5.5 \text{ MeV} \\
P = 99.9 \%
\end{array} \]

\[ \begin{array}{c}
222\text{Ra} \\
\alpha \quad T_{1/2} = 3.1 \text{ m} \\
E = 6.0 \text{ MeV} \\
P \sim 100 \%
\end{array} \]

\[ \begin{array}{c}
214\text{Po} \\
\alpha \quad T_{1/2} = 164 \mu\text{s} \\
E = 7.7 \text{ MeV} \\
P \sim 100 \%
\end{array} \]

\[ \begin{array}{c}
206\text{Pb} \\
\beta \quad T_{1/2} = 138.4 \text{ d} \\
E = 5.3 \text{ MeV} \\
P \sim 100 \%
\end{array} \]

\[ \begin{array}{c}
210\text{Pb} \\
\beta \quad T_{1/2} = 22.3 \text{ y} \\
E_m = 0.06 \text{ MeV} \\
P = 81 \%
\end{array} \]

\[ \begin{array}{c}
210\text{Bi} \\
\beta \quad T_{1/2} = 5.0 \text{ d} \\
E_m = 1.2 \text{ MeV} \\
P = 100 \%
\end{array} \]

\[ \begin{array}{c}
210\text{Bi} \\
\beta \quad T_{1/2} = 1.17 \text{ min} \\
E_m = 0.198 \text{ MeV} \\
P = 69 \%
\end{array} \]

\[ \begin{array}{c}
214\text{Po} \\
\beta \quad T_{1/2} = 19.8 \text{ m} \\
E_m = 1.5 \text{ MeV} \\
P = 40 \%
\end{array} \]

\[ \begin{array}{c}
214\text{Bi} \\
\beta \quad T_{1/2} = 26.8 \text{ m} \\
E_m = 0.7 \text{ MeV} \\
P = 48 \%
\end{array} \]

\[ \begin{array}{c}
214\text{Pb} \\
\beta \quad T_{1/2} = 1.17 \text{ min} \\
E_m = 2.3 \text{ MeV} \\
P = 94 \%
\end{array} \]

\[ \begin{array}{c}
230\text{Th} \\
\alpha \quad T_{1/2} = 2.5 \cdot 10^5 \text{ y} \\
E = 4.8 \text{ MeV} \\
P \sim 69 \%
\end{array} \]
**238U decay chain**

- Assay methods: ICP-MS / AMS / GDMS
- Inductively Coupled Plasma Mass Spectrometry supported by a proper sample preparation methodology allows for the analysis of various materials and specialty components important in ultralow background physics experiments
- Assay of materials, which can be put into liquid form (polymers, electronic components, wires/cables, metals, etc.)
- Extremely sensitive, fast (couple of days for a measurement), requires small amounts of sample (< 1 g)
- Commercially available instruments can reach < 0.01 ppt sensitivity for U/Th (< 0.1 µBq/kg)

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230Th → 234U → 234mPa → 234Th → 238U

- $T_{1/2}^{230\text{Th}} = 7.5 \times 10^4$ y, $E = 4.7$ MeV, $P \approx 73\%$
- $T_{1/2}^{234\text{U}} = 1.17$ min, $E_m = 2.3$ MeV, $P = 94\%$
- $T_{1/2}^{234\text{mPa}} = 24.1$ d, $E_m = 0.198$ MeV, $P = 69\%$
- $T_{1/2}^{234\text{Th}} = 2.5 \times 10^5$ y, $E = 4.8$ MeV, $P \approx 69\%$
238U decay chain

Gamma-ray spectroscopy: GeMPIs (MPIK-HD)
- Sensitivity: ~10 µBq/kg (~1 ppt U equiv.)

High sensitivity Rn emanation
- Chambers coupled to the cryogenic Rn detector
- Integrated automatic pumping system
- Integrated automatic heating system (emanation tests up to 150 ºC possible)
- Simultaneous real-time detection of emanated 220Rn and 222Rn
- Detection limit of ~10 µBq

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Radio-chemical method
- Dissolution of a sample in acid
- Deposition of $^{210}\text{Po}$ on a (silver) disc
- Counting with an ultra-low background alpha spectrometer
- Sensitivity: $\sim 1 \text{ mBq/kg (bulk + surface)}$

Direct counting of $^{210}\text{Po}$
- Large surface low background alpha spectrometer
- Assay of bulk and surface contamination
- Sensitivity: $\sim 50 \text{ mBq/kg (bulk)}$
  $\sim 1 \text{ mBq/m}^2 \text{ (surface)}$

A series of measurements of $^{210}\text{Po}$ in time for the same sample provides information about $^{210}\text{Pb}$

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\( ^{232}\text{Th} \) decay chain

\[ ^{228}\text{Th} \rightarrow ^{228}\text{Ac} \rightarrow ^{228}\text{Ra} \rightarrow ^{232}\text{Th} \]

- \( ^{228}\text{Th} \):
  - \( T_{1/2} = 1.91 \text{ y} \)
  - \( E = 5.423 \text{ MeV} \)
  - \( P = 71\% \)

- \( ^{228}\text{Ac} \):
  - \( T_{1/2} = 6.15 \text{ h} \)
  - \( E_m = 1.173 \text{ MeV} \)
  - \( P = 31\% \)

- \( ^{228}\text{Ra} \):
  - \( T_{1/2} = 5.75 \text{ y} \)
  - \( E_m = 0.039 \text{ MeV} \)
  - \( P = 60\% \)

- \( ^{232}\text{Th} \):
  - \( T_{1/2} = 14.05 \times 10^9 \text{ y} \)
  - \( E = 4.0 \text{ MeV} \)
  - \( P = 77\% \)

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\( ^{224}\text{Ra} \)

- \( T_{1/2} = 3.66 \text{ d} \)
- \( E = 5.7 \text{ MeV} \)
- \( P = 95\% \)

\( ^{220}\text{Rn} \)

- \( T_{1/2} = 55.6 \text{ s} \)
- \( E = 6.3 \text{ MeV} \)
- \( P = 99.9\% \)

\( ^{216}\text{Po} \)

- \( T_{1/2} = 0.145 \text{ s} \)
- \( E = 6.8 \text{ MeV} \)
- \( P \approx 100\% \)

\( ^{212}\text{Po} \)

- \( E_m = 2.25 \text{ MeV} \)
- \( E = 6.05 \text{ MeV} \)

\( ^{208}\text{Tl} \)

- \( E_m = 1.8 \text{ MeV} \)
- \( E = 8.8 \text{ MeV} \)

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\( ^{212}\text{Bi} \)

- \( T_{1/2} = 60.6 \text{ m} \)

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\( ^{212}\text{Pb} \)

- \( E_m = 0.33 \text{ MeV} \)
- \( E = 6.05 \text{ MeV} \)
- \( P = 82.5\% \)

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\( ^{208}\text{Pb} \)

- \( E = 6.8 \text{ MeV} \)
- \( P = 100\% \)

Stable
# Examples of dis-equilibrium

## $^{238}$U chain: BX nylon / steel for the GD cryostat

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{226}$Ra / $^{238}$U equiv.</th>
<th>$^{238}$U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capron B73ZP foil</td>
<td>220 µBq/kg / 18 ppt</td>
<td>~1 ppt</td>
</tr>
<tr>
<td>Sniamid foil</td>
<td>16 µBq/kg / 1.3 ppt</td>
<td>~10 ppt</td>
</tr>
<tr>
<td>Acroni/Slovenia, G5</td>
<td>$(1.0 \pm 0.6)$ mBq/kg</td>
<td>(54 ± 16) mBq/kg</td>
</tr>
</tbody>
</table>

References:
- NIM A 498 (2003) 240
- NIM A 593 (2008) 448

## $^{232}$Th chain: steel for the GD cryostat

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{228}$Ra [mBq/kg]</th>
<th>$^{228}$Th [mBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acroni/Slovenia, G4</td>
<td>&lt; 3</td>
<td>5.1 ± 0.5</td>
</tr>
<tr>
<td>Acroni/Slovenia, G7</td>
<td>1.9 ± 1.0</td>
<td>5.2 ± 0.5</td>
</tr>
</tbody>
</table>

Gamma-ray spectroscopy

References:
- NIM A 593 (2008) 448
# Rn emanation studies

<table>
<thead>
<tr>
<th>Sample</th>
<th>(^{222}\text{Rn})</th>
<th>(^{220}\text{Rn})</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT Cu window</td>
<td>&lt; 90 (\mu\text{Bq/piece})</td>
<td>&lt; 80 (\mu\text{Bq/piece})</td>
</tr>
<tr>
<td>TPB coated PMT Cu window</td>
<td>((140 \pm 70) \mu\text{Bq/piece})</td>
<td>&lt; 80 (\mu\text{Bq/piece})</td>
</tr>
<tr>
<td>PMT R11410_10</td>
<td>&lt; 80 (\mu\text{Bq/piece})</td>
<td>((330 \pm 140) \mu\text{Bq/piece})</td>
</tr>
<tr>
<td>Kapton-Cu cable</td>
<td>((37 \pm 13) \mu\text{Bq/m})</td>
<td>((38 \pm 16) \mu\text{Bq/m})</td>
</tr>
<tr>
<td>Feedthroughs</td>
<td>&lt; 30 (\mu\text{Bq/piece})</td>
<td>&lt; 40 (\mu\text{Bq/piece})</td>
</tr>
<tr>
<td>DS-50 cryostat</td>
<td>((140 \pm 40) \mu\text{Bq})</td>
<td>--</td>
</tr>
<tr>
<td>DS-50 TPC</td>
<td>((1350 \pm 400) \mu\text{Bq})</td>
<td>--</td>
</tr>
<tr>
<td>HP Ti sponge</td>
<td>&lt; 0.15 (\text{mBq/kg})</td>
<td>&lt; 0.10 (\text{mBq/kg})</td>
</tr>
<tr>
<td>SAES Getter pellets</td>
<td>((2.7 \pm 0.7) \text{mBq/kg})</td>
<td>((3.2 \pm 0.8) \text{mBq/kg})</td>
</tr>
</tbody>
</table>

All measurements performed at room temperature
• Only $^{210}$Po studied
• Low background, large surface alpha spectrometer
• Sample size: $43 \times 43$ cm
• Possibility to determine bulk and surface contamination
Assay of $^{210}\text{Pb}$-$^{210}\text{Po}$ sub-chain

ROI: (1 – 6) MeV

- Commercially pure Ti, Gr2
- 304 Stainless Steel
- ETP Cu, z4 (half-hard)

$R_{\text{Ti}} = 2700 \text{ cts/(d} \times \text{m}^2\text{)}$

$R_{\text{SS}} = 700 \text{ cts/(d} \times \text{m}^2\text{)}$

$R_{\text{Cu}} = 460 \text{ cts/(d} \times \text{m}^2\text{)}$
Assay of commercial Ti

Spectrum of commercial high purity Ti (Gr2) sample
### $^{210}$Po in various samples

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk $^{210}$Po [mBq/kg]</th>
<th>Surface $^{210}$Po [mBq/kg]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>OF Copper</td>
<td>54</td>
<td>$\leq$ 3</td>
<td>z4 (half hard)</td>
</tr>
<tr>
<td>ETP Copper</td>
<td>75</td>
<td>$\leq$ 3</td>
<td>z4 (half hard)</td>
</tr>
<tr>
<td>„Old” ETP Copper</td>
<td>280</td>
<td>170</td>
<td>z4 (half hard)</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>80</td>
<td>$\leq$ 3</td>
<td>Type 304</td>
</tr>
<tr>
<td>Titanium</td>
<td>1500</td>
<td>68</td>
<td>GR2</td>
</tr>
<tr>
<td>Teflon</td>
<td>$\leq$ 46</td>
<td>–</td>
<td>High purity, ATP</td>
</tr>
</tbody>
</table>

Introduction

Selected results

Assay methods

Summary

Submitted by: [Authors]

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Polishing mixture: 95% H$_3$PO$_4$ + 1% 1-butanol
Polishing conditions: 2.5 A/dm$^2$, 3 V, 20 min, distance between plates: 2 cm, room temperature

R$_{ROI}$ = (6583 ± 90) cts/d/m$^2$
R$_{ROI}$ = (284 ± 25) cts/d/m$^2$
R$_f$ = (23 ± 3)
Electro-polishing of stainless steel

SS 1.4301 (304): sheet No. 2, 43 cm x 43 cm x 0.1 cm,

- Polishing mixture: 1:1 of 95% H$_2$SO$_4$ and 85% H$_3$PO$_4$
- Washing: 5 min in 15% HNO$_3$ and later in HP water
- Polishing conditions: 2.5 A/dm$^2$, 2 V, 25 min, distance between plates: 2 cm, T ~ 50 °C

$^{210}$Po

$R_{ROI} = (2716 \pm 62)$ cts/d/m$^2$

$R_{ROI} = (116 \pm 8)$ cts/d/m$^2$

$R_f = (23.5 \pm 0.1)$
Etching of copper

“Dynamic” etching, 3 single runs

<table>
<thead>
<tr>
<th>Substance</th>
<th>ROI Count Rate (cts/d/m²)</th>
<th>f Count Rate (cts/d/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>210Po</td>
<td>(10466 ± 120)</td>
<td>(458 ± 20)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(22.9 ± 1.2)</td>
</tr>
</tbody>
</table>

- Etching procedure: 3 x 1 min wash with a mixture of 1% H₂SO₄ + 3% H₂O₂
- Passivation with 1% citric acid at the end
- Washing in high-purity deionized water (18 MΩ×cm)
Etching of copper

Multiple etching

![Graph showing Po-210 reduction factor vs. number of etching steps.](image)
DARKSIDE $^{222}$Rn-free clean rooms

Avoiding deposition of long-lived $^{222}$Rn daughters

- Class 10 - 100
- Radon daughters plating out on surfaces of the detector may cause dangerous alpha-induced nuclear recoils
- Dedicated scrubbing system reducing $^{222}$Rn concentration in the air down to $\sim 1$ mBq/m$^3$ has been implemented
- DARKSIDE clean rooms are supplied with the $^{222}$Rn-free air
- $^{222}$Rn content in the clean rooms is monitored online by a dedicated detector

Typical radon in hall C air $\sim 50$ Bq/m$^3$
Cleanroom radon levels 5 – 50 mBq/m$^3$
**DARKSIDE $^{222}$Rn-free clean rooms**

**Introduction**

**Selected results**

**Assay methods**

**Summary**

![Graph showing $^{222}$Rn specific activity over time](image)

**Person entering CRH**

**Date**

**222 Rn specific activity [mBq/m$^3$]**

Summary

- Ultra-low (ultimately zero) background is required in direct dark matter searches
- Proper estimation of background from various sources (e.g. n from $\alpha$-n reactions) requires assay of all U/Th sub-chains
- MS techniques for the assay of the long-lived U/Th isotopes sensitive down to 0.01 ppt (0.1 $\mu$Bq/kg)
- $\gamma$-ray spectrometers for determination of Ra isotopes sensitive down to 10 $\mu$Bq/kg (10 ppt equiv.). Better sensitivity may be achieved in some cases by performing Rn emanation studies
- Presently, the bottom part of the $^{238}$U chain is accessible only at some tens of mBq/kg (~1 ppb equiv.)
- Determination of Ra and $^{210}$Pb at lower specific activities needed (e.g. $^{210}$Pb in PTFE down to at least 1 mBq/kg) → new developments