$^{222}$Rn daughters in liquid nitrogen

Krzysztof Pelczar
M. Smoluchowski Institute of Physics
Jagiellonian University, Cracow
Outline

• Motivation – search for neutrinoless double beta decay
• $^{222}$Rn induced background in cryoliquids
• The ionic model
• The experimental setup
• Results of $\alpha$-activity measurements
• Summary
Double beta decay – The GERDA Experiment

\[ \text{2νββ} \]

\[ (Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e \]

Allowed in SM and observed for several isotopes with forbidden single beta decay. Conserves lepton number. Long half-lifetimes \((10^{19} \div 10^{21} \text{y})\).

\[ \text{0νββ} \]

\[ (Z, A) \rightarrow (Z+2, A) + 2e^- \]

Does not conserve lepton number \((\Delta L=2)\). Possible if neutrinos are Majorana particles. Expected lifetimes \(> 10^{24} \text{y}\).
2\(\beta\)\(0\nu\) limits on \(T_{1/2}^{0\nu}\) if no events observed

Without background

\[
T_{1/2}^{0\nu} > A\varepsilon \ln(2) T \frac{m}{m_{\text{mol}}} N_A
\]

In the presence of background \(B_E\)

\[
T_{1/2}^{0\nu} > A\varepsilon \frac{\ln(2)}{m_{\text{mol}}} \sqrt{\frac{m T}{B_E \delta_E}} N_A
\]

<table>
<thead>
<tr>
<th>A</th>
<th>isotope abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varepsilon)</td>
<td>registration efficiency</td>
</tr>
<tr>
<td>(T)</td>
<td>time of measurement [y]</td>
</tr>
<tr>
<td>(N_A)</td>
<td>Avogadro constant</td>
</tr>
<tr>
<td>(m)</td>
<td>detector mass [kg]</td>
</tr>
<tr>
<td>(m_{\text{mol}})</td>
<td>molar mass of Ge [kg/mol]</td>
</tr>
<tr>
<td>(B_E)</td>
<td>background in (Q_{\text{ee}}) region [y(^{-1})keV(^{-1})kg(^{-1})]</td>
</tr>
<tr>
<td>(\delta_E)</td>
<td>energy resolution [keV]</td>
</tr>
</tbody>
</table>
$^{222}$Rn induced background in cryoliquids

- $^{226}$Ra present in most of the construction materials;
- Gaseous $^{222}$Rn emanation dissolves into the cryoliquids;
- Ionized decay products are subject to electric field, induced in the cryoliquid (e.g. drift chambers);
- Energy released in alpha, beta and gamma decays in $^{226}$Ra decay chain are above e.g. $Q_{\beta\beta}$ (neutrinoless double beta decay);
- Natural intrinsic source of background in majority of the low background experiments.
The model highlights

• Box model of germinate neutralization
  – Probability $\varepsilon_C$ of the initial $C_0$ charge survival is a function of external electric field strength $E$ and type of ionizing decay
  – $N_i$ is the number of electron-cation pairs produced within a box of dimensions $a$, $\alpha$ is the recombination coefficient, $\mu_-$ is the electron mobility
    • $\xi_\beta E = 840$ V/cm for 364 keV electrons
    • $\xi_\alpha E = 470$ kV/cm (5.64 MeV alpha-decays)

• Bulk recombination on electronegative impurities;

• Changes of impurity concentration in time (in a long timescale) due to diffusion and adsorption.

$$\varepsilon_C = \frac{C}{C_0} = \frac{\ln(1 + \xi)}{\xi}$$

$$\xi = \frac{N_i \alpha}{4a^2 \mu_- E}$$
The model – selected scenarios

**α decay**

- Drifting in E-field

**β decay**

- Germinate recombination
- Recombination on electronegative impurities
- Diffusion of impurities

\[ T_{1/2} = 164 \mu s \]
The experimental setup

Charge preamplifier and MCA

Diode bias voltage supply

Dewar bias voltage supply +/− HV

Electrically isolated dewar

Bare Si PIN diode (housing grounded)

Radon doped liquid nitrogen

Balance recording weight loss
Results of $\alpha$-activity measurements (selection)

2 $^{214}$Po signal (15 min bins)

0 V 2 kV

2 $^{214}$Po signal (15 min bins)

2 kV -2 kV

Time since HV switch (days)
Experimental results

- The ion lifetime parameters ($T_{\text{max}}$ for negative ions fixed to $^{214}\text{Bi}$ lifetime – fit results were always divergent);
- Systematical errors originate from the $^{222}\text{Rn}$ doping uncertainties. They are not discussed.
- Abundances [a.u.] of $^{222}\text{Rn}$ daughters on the surface of the Si-PIN detector;
- Amount of $^{218}\text{Po}$ is consistent with 0.

<table>
<thead>
<tr>
<th>Bias</th>
<th>0→2 kV</th>
<th>2→-2 kV</th>
<th>-2→2 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_C$ (%)</td>
<td>47.1 ± 0.5</td>
<td>0.65 ± 0.02</td>
<td>55.6 ± 0.3</td>
</tr>
<tr>
<td>$T_0$ (s)</td>
<td>5.9 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.098 ± 0.008</td>
</tr>
<tr>
<td>$T_{\text{max}}$ (s)</td>
<td>21.6 ± 0.3</td>
<td>1188</td>
<td>9.56 ± 0.06</td>
</tr>
<tr>
<td>$r$ (d$^{-1}$)</td>
<td>4.4 ± 0.2</td>
<td>11.8 ± 1.0</td>
<td>10.4 ± 0.2</td>
</tr>
</tbody>
</table>

| Ions             | positive | neg.-like | positive |

<table>
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<tr>
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<th>2→-2 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{218}\text{Po}$</td>
<td>0 ± 4</td>
<td>0 ± 0.7</td>
<td>0 ± 0.6</td>
</tr>
<tr>
<td>$^{214}\text{Pb}$</td>
<td>3 ± 5</td>
<td>0.1 ± 0.7</td>
<td>0.5 ± 0.7</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>9.4 ± 0.2</td>
<td>0.21 ± 0.05</td>
<td>2.00 ± 0.05</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.11 ± 0.02</td>
<td>0 ± 0.009</td>
<td>0 ± 0.005</td>
</tr>
</tbody>
</table>
Summary

• We have observed positive and negative-like ions.
• Negative-like ions are probably formed as bigger compounds
  – Long ionic lifetime in technical grade cryoliquids.
• Positive ions exhibit long ionic lifetime – possible source of background.
• Proposed semi-empirical model well describes results
  – Mobility of the ions not known precisely (assumed);
  – Germinate neutralization depends on the type of decay and external electric field strength.
• Further improvements
  – Direct measurements of $^{218}$Po;
  – Electric field modeling;
  – Measurements in different cryoliquids (liquid argon, xenon);
  – Controlled purity;
  – Dedicated measurements of ion mobilities.
Backup slides – Neutrinoless double beta decay

Energetically forbidden $\beta$ decay

Allowed double $\beta$ decay
Backup slides – Energy spectrum of double beta decays

\[ \frac{dN}{d(E/Q_{ee})} \text{ [a.u.]} \]

- \(2\beta^{2\nu}\)
- \(2\beta^{0\nu}\)
Backup slides – Neutrinoless double beta decay

In theory:

\[ \frac{1}{T_{1/2}^{0\nu}} = G(Q)|M|^2 \langle m_{ee} \rangle^2 \]

\[ \langle m_{ee} \rangle = \sum_i U_{ei}^2 m_i \]

- $G(Q)$ – Kinematic coefficient
- $|M|^2$ – Nuclear matrix element
- $\langle m_{ee} \rangle$ – effective Majorana neutrino mass

$T_{1/2}^{0\nu}$ will be determined experimentally
Backup slides – $^{222}$Rn doping procedure

Rn source

Cold trap -65°C to -70°C

Gaseous nitrogen

Gas flow

Dewar with cryoliquid

ZnS(Ag) scintillation chamber and PMT
Backup slides

- The positive high voltage bias repels positive ions towards the Si-PIN detector, close to the ground potential
- The negative bias repels negative-like ions towards the detector
Backup slides – persistence of ions in cryoliquids

- In dense environments (liquefied gases used in low background experiments) the differences in energies required to free a bound electron ensures persistence of the ions.

- High purity of the liquids enhances the ionic lifetime and probably reduces chances to form negative-like compounds.

<table>
<thead>
<tr>
<th>Atom</th>
<th>1st IP [eV]</th>
<th>2nd IP [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rn</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>Po</td>
<td>8.4</td>
<td>-</td>
</tr>
<tr>
<td>Pb</td>
<td>7.4</td>
<td>15</td>
</tr>
<tr>
<td>Bi</td>
<td>7.3</td>
<td>17</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Gap energy [eV]</th>
</tr>
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<tbody>
<tr>
<td>Ar 16</td>
</tr>
<tr>
<td>N₂ 15</td>
</tr>
<tr>
<td>Kr 14</td>
</tr>
<tr>
<td>Xe 12</td>
</tr>
</tbody>
</table>

- IP – ionization potential
Backup slides – mobilities of ions in cryoliquids

- Mobilities of $^{222}$Rn daughters not known
  - A typical value of $^{226}$Th mobility in liquid argon (NBP) is $2.4 \cdot 10^{-2} \text{mm}^2\text{V}^{-1}\text{s}^{-1}$
    [K. Wamba et. al., NIMA, 555 (2005), 205-210]
- Mobilities of impurities well known
  - Oxygen ions in liquid argon (NBP) – $2.5 \cdot 10^{-1} \text{mm}^2\text{V}^{-1}\text{s}^{-1}$
    [B. Henson, Phys. Rev., 135, 4A (1964), 1002-1008]
Backup slides – impurities concentration

- Bulk recombination on electronegative impurities
  - \([Y^+]\) is the time dependant concentration of the ions.

- Concentration of impurities changes in time. Concentration \([Z]\) is related to the ionic half-lifetime \(T\) via attachment rate \(k_Z\): \(T(t) = \ln 2 \times k_Z [Z](t)\);

- Changes of impurity concentration \([Z]\) in time (in a long timescale) as a limited growth function
  - Solution to a differential equation, where \(x(t) \equiv T(t)/T_{\max}\);

- The maximum concentration is limited by the total amount of ions dissolved in the liquid volume – minimum ionic lifetime \(T_0\);

- The minimum concentration is limited by the diffusion and convection flows (mixing) – maximum ionic lifetime \(T_{\max}\);

- Change rate \(r\) is related to the diffusion of the impurities – timescale order of hours;

\[
[Y^+](t) = [Y^+]_0 e^{-k_Z [Z](t) t}
\]

\[
\frac{dx}{dt} = rx(1 - x)
\]

\[
T(t) = \frac{T_0 T_{\max} e^{rt}}{T_{\max} + T_0 \left(e^{rt} - 1\right)}
\]
The GERDA Experiment @ LNGS

LNGS Assergi

1400 m ~ 3.500 m.w.e. shielding against muons
Backup slides – GERDA

Steel cryostat with internal Cu shield

Clean room Lock system

Array of bare Ge-diodes

Water: $\gamma, n$ shield Cherenkov medium for $\mu$ veto

High-purity liquid argon (LAr) shield & coolant
Optional: active veto