A model for Rydberg-atom induced backgrounds resulting from deposition of Rn-progeny in the KATRIN Main Spectrometer

Fabian Harms for the KATRIN Collaboration, LRT Conference, Seoul 2017
Outline

- Background characteristics at KATRIN
- The Rydberg-atom based background model
- Radon progeny in the Main Spectrometer
- Conclusion & Outlook
Background characteristics at KATRIN

Overview

- Count rate of ~10 mcps close to tritium endpoint → Design background level in same order of magnitude.
- Main Spectrometer (1240 m³) represents main source of background.
- Current background level is ~200 - 600 mcps depending on electromagnetic field setting.
Background characteristics at KATRIN

Expected background sources

- Two main sources expected from earlier experiments with MAC-E filter spectrometers:
  
  **Stored-particle related**
  
  **Secondary-electron emission related**

\[ \Delta \mu / \gamma \]

\[ \Delta \mu / \gamma \]

Vessel surface
Background characteristics at KATRIN

Expected background sources

- Two main sources expected from earlier experiments with MAC-E filter spectrometers:

  Stored-particle related

  Secondary-electron emission related

See talk by J. Wolf
Background characteristics at KATRIN
Magnetic-field dependence

Background turns out to be independent of magnetic field strength

→ Purely volume dependent
Impact of electrostatic shielding on radial background distribution

- Shielding impacts background radial independently
- Contradicts model of secondary-electron emission induced background
Background characteristics at KATRIN

Spectrometer bakeout

- Impact of spectrometer surface conditions on radial background profile

- Shielding impacts background radial independently

- Contradicts model of secondary-electron emission induced background
The Rydberg-atom based background model
Characteristics

How to combine volume dependent background with surface conditions and $\Delta U$-dependence?
The Rydberg-atom based background model
Characteristics

How to combine volume dependent background with surface conditions and $\Delta U$-dependence?

→ Neutral messenger particles (Hydrogen Rydberg atoms)

→ Explains volume dependence.

→ Explains impact of electric shielding

→ Explains impact of bake-out.
The Rydberg-atom based background model
Characteristics

How to combine volume dependent background with surface conditions and $\Delta U$-dependence?

→ Neutral messenger particles (Hydrogen Rydberg atoms)

→ Explains volume dependence.

→ Explains impact of electric shielding

→ Explains impact of bake-out.

→ Explains low-energy background electrons.

→ Generation mechanism?
Radon progeny in the Main Spectrometer
Observation of $^{210}\text{Pb}$ signature

- Found small traces of $^{210}\text{Pb}$ contamination in the Main Spectrometer ($\approx 1\text{Bq} / \text{m}^2$).

- $^{210}\text{Pb}$ must have been deposited in spectrometer over the course of inner electrode assembly and commissioning.
Radon progeny in the Main Spectrometer

Deposition mechanism

- Spectrometer was vented to ambient air for years during installation of inner electrode system.
Radon progeny in the Main Spectrometer
Deposition mechanism

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- Rn-progeny is plated-out on spectrometer surfaces by various transport mechanisms.
Radon progeny in the Main Spectrometer

Deposition mechanism

- Spectrometer was vented to ambient air for years during installation of inner electrode system.

- Rn-progeny is plated-out on spectrometer surfaces by various transport mechanisms.

- Implantation of $^{210}\text{Pb}$ into sub-surface layers due to recoil of $^{214}\text{Po}$.

- No direct background contribution by $^{210}\text{Pb}$ in KATRIN standard operation.
Radon progeny in the Main Spectrometer

Consequences

- Recoil of $^{210}$Po α-decay causes sputtering on the inner surfaces of the Main Spectrometer.

- Short bursts of secondary electron emission on ms-timescale.
Radon progeny in the Main Spectrometer

Consequences

- Recoil of $^{210}\text{Po}$ $\alpha$-decay causes sputtering on the inner surfaces of the Main Spectrometer.
- Short bursts of secondary electron emission on ms-timescale.
- Idea: Rydberg atoms are generated in sputtering process.
Radon progeny in the Main Spectrometer

Experimental test

- Idea: Use short-lived alternative for $^{210}\text{Pb} \rightarrow ^{212}\text{Pb}$.

- Artificially contaminate Main Spectrometer surfaces.

$^{210}\text{Pb}$ contamination in Main Spectrometer is root cause of elevated background rate at KATRIN!
Radon progeny in the Main Spectrometer
Countermeasures against Rydberg background

- Cleaning inner surfaces to get rid of radon progeny.
  - Well established techniques from other experiments (Borexino, Gerda, etc.)
  - Difficult to carry out in case of KATRIN (vessel size, electrode system, etc.)

- Using strong UV light source (LightHammer) to reduce hydrogen reservoir on the inner spectrometer surface.

→ Tests are currently ongoing.
Radon progeny in the Main Spectrometer
Consequences of Rydberg background for KATRIN

- Measured background level is 56x higher than design level. Without any optimizations this worsens the KATRIN sensitivity to ~350 meV.

- Optimizations:
  → Scanning strategy
  → Analysis interval
  → Reduce volume with drawback of worse energy resolution

- KATRIN still reaches a sensitivity of 240 meV (90% C.L.)
Conclusion & Outlook

- Current background level at KATRIN significantly higher than design.

- Background not related to background sources observed in predecessor experiments.

- Background characteristics indicate neutral messenger particles from spectrometer walls that are being ionized in the volume → Model of Rydberg atom induced background.

- Recent measurement results prove direct link between deposition of Rn-progeny on inner spectrometer surfaces and background level.

- Tests of intense UV light source as potential countermeasure are ongoing.

- Even with elevated background level, KATRIN can reach sensitivity of 240 meV / c² (90% C.L.).
The KATRIN Collaboration
Backup Slides
The KATRIN experiment
Single beta decay

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \]

\[ t_{1/2} = 12.3 \text{ a} \]

\[ E_0 = 18.6 \text{ keV} \]

\[
\frac{d\Gamma}{dE} = C \rho (E + m_e) (E_0 - E) \sqrt{(E_0 - E)^2 - m_{\nu_e}^2} F(E) \theta(E_0 - E - m_{\nu_e})
\]

\[ m_\nu < 0.2 \text{ eV (90 \% C.L.)} \]

\[ m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \]
The KATRIN experiment
Measurement principle

Integrated $T_2 \beta$ spectrum close to kinematic endpoint at $E_0 = 18.6$ keV

Impact of nonzero $m_\nu$ on spectral shape is most pronounced a few eV below $E_0$

Optimized measurement time distribution to increase sensitivity
The KATRIN experiment
MAC-E filter

\[ \mu = \frac{E_\perp}{B} = \text{const.} \]

\[ E_{\text{kin}} = E_{\parallel} + E_\perp \]

\[ \Delta E = 0.93 \text{ eV} \]
The KATRIN experiment
Experimental beamline

- Calibration & monitoring
- Artificial electron source

- Windowless gaseous tritium source
- Tritium β-decay rate of $10^{11}$ 1/s
- Operating parameters (T, p, etc.) stabilized at $10^{-3}$ level

- Transport Section
- Adiabatic $e^-$ transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$

- Pre-spectrometer
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Operated at UHV conditions ($<10^{-10}$ mbar)

- Main Spectrometer
- Detector
- Si-PIN diode array
- Highly efficient $e^-$ counting

~70 m

- Closed beamline at 23rd September 2016
- First Light event on 14th October 2016
Background characteristics at KATRIN

Expected background sources

- Investigated muon vs. secondary electron correlation.
- Small fraction of secondary electron rate is found to be muon induced.

For symmetric case no correlation was found!

\[ a = 13.6 \pm 0.8 \% \]
Background characteristics at KATRIN

Effect of electric dipole

- Electric dipole to drift-out stored particles of energies $E > 1$ eV.

$\Rightarrow$ No significant impact of electric dipole on background level observed.

$\Rightarrow$ Background electrons must be low-energetic ($E < 1$ eV).

**Reference BG:** 531 +/- 9 mcps

**Dipole active:**
542 +/- 10 mcps

**Dipole inactive:**
497 +/- 6 mcps
The Rydberg-atom based background model

Characteristics

How to combine volume dependent background with surface conditions and $\Delta U$-dependence?

→ Neutral messenger particles
   (Hydrogen Rydberg atoms)

![Graph showing radial distribution of background]

<table>
<thead>
<tr>
<th>Radii on the detector wafer m</th>
<th>Volume normalized background rate, etc. units</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.8</td>
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<tr>
<td>0.005</td>
<td>1.0</td>
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<tr>
<td>0.010</td>
<td>1.2</td>
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<td>0.015</td>
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<td>0.020</td>
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<td>1.8</td>
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<tr>
<td>0.030</td>
<td>2.0</td>
</tr>
<tr>
<td>0.035</td>
<td>2.2</td>
</tr>
</tbody>
</table>

![Diagram illustrating BBR and SFI]
Rydberg model – temperature dependence

- Spectrometer temperature was increased from 19°C to 43°C
- Linear increase expected for large $n$
- Most of background could be due to Rydberg atoms

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**Normalized slope (average):** $0.79 \pm 0.12$

**Correlation factor:** 0.6
Spectrometer baking improved background, but same behavior after baking

Rydberg atoms are ionized by the electric field between vessel and electrodes and hence can not reach the inner spectrometer volume
Rydberg model test

- attach $^{228}$Th source to main spectrometer
- “contaminate” inner surface with $^{212}$Pb
- close valve to $^{228}$Th source and check for exponentially decaying background rate
- alternative proposal: use short lived implanted radium source ($^{223}$Ra, $^{224}$Ra)

$^{228}$Th $T_{1/2} = 1.9$ yr
$\alpha$, 5.5 MeV

$^{220}$Rn $T_{1/2} = 56$ s
$\alpha$, 6.4 MeV

$^{212}$Pb $T_{1/2} = 10.6$ h
$\beta^-$, 331 keV

$^{212}$Bi $T_{1/2} = 1$ h
$\alpha$, 6.2 MeV (36%)

$^{212}$Po $T_{1/2} = 0.3$ µs
$\beta^-$, 2.3 MeV (64%)

$^{208}$Tl $T_{1/2} = 183$ s
$\beta$, 5.0 MeV

$^{208}$Pb stable
**228Th source – contamination phase**

- Source courtesy of XENON collaboration (Thanks to V. Hannen / C. Weinheimer)
- Exposure started on Dec 1st, 2016
- Exposure time 20h 6min (about 2×T_{1/2}, 73%)

rate after opening valve to source (warm baffles): 78 ± 0.8 cps

rate before closing valve to source (cold baffles): 28 ± 0.5 cps
Observed half-life matches $^{212}$Pb literature value of $10.64 \pm 0.01$ very well

Assuming similar processes, $^{210}$Pb contamination < 5.1 kBq
\[^{212}\text{Pb} \text{ contamination – decay phase}\]

- Rate from vessel wall shows the same exponential decay \((T_{1/2} = 10.9 \, \text{h})\)
- There is a very strong correlation between electrons from the vessel wall and electrons from the spectrometer volume
Background signature

- induced background has the same behavior as existing background

→ main spectrometer $^{210}$Pb contamination is root cause of background
The experimental beamline
Overview

Windowless gaseous tritium source

- Tritium β-decay rate of $10^{11}$ 1/s
- Operating parameters (T, p, etc.) stabilized at $10^{-3}$ level

Specified Stability: ±30 mK/h
Measured Stability: ±10.1 mK/48 h

Timespan 12 Nov 2016 - 13 Nov 2016
The experimental beamline
Overview

- Calibration & monitoring
- Artificial electron source

Windowless gaseous tritium source

- Tritium β-decay rate of $10^{11}$ 1/s
- Operating parameters (T, p, etc.) stabilized at $10^{-3}$ level

Angular-selective electron gun

UV illumination

High-energy electrons

Low-energy electrons
The experimental beamline
Overview

Rear Section
- Calibration & monitoring
- Artificial electron source

Windowless gaseous tritium source
- Tritium β-decay rate of $10^{11} \text{1/s}$
- Operating parameters (T, p, etc.) stabilized at $10^{-3}$ level

Transport Section
- Adiabatic e⁻ transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$
The experimental beamline

Overview

Rear Section
- Calibration & monitoring
- Artificial electron source

Windowless gaseous tritium source
- Tritium β-decay rate of $10^{11}$ 1/s
- Operating parameters (T, p, etc.) stabilized at $10^{-3}$ level

Transport Section
- Adiabatic $\text{e}^-$ transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$

Condensed $^{83m}\text{Kr}$ source

Cryogenic Pumping section

Forward beam monitor

Institute for Nuclear Physics (IKP), KIT
The experimental beamline
Overview

- Calibration & monitoring
- Artificial electron source
- Tritium β-decay rate of $10^{11}$ 1/s
- Operating parameters (T, p, etc.) stabilized at $10^{-3}$ level
- Adiabatic e⁻ transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Operated at UHV conditions ($<10^{-10}$ mbar)

Rear Section
Windowless gaseous tritium source
Transport Section

Main Spectrometer
Pre-spectrometer
The experimental beamline

Overview

- Calibration & monitoring
- Artificial electron source
- Tritium β-decay rate of $10^{11}$ 1/s
- Operating parameters (T, p, etc.) stabilized at $10^{-3}$ level
- Adiabatic e⁻ transport
- Cryogenic & differential pumps
- Tritium retention factor of $>10^{12}$
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Operated at UHV conditions ($<10^{-10}$ mbar)

Detector

- Si-PIN diode array
- Highly efficient e⁻ counting

The detector wafer
Magnetic guidance of electrons over 70 m
First Light Measurements

Ion investigations

Beamline alignment
Neutrino-mass measurement with KATRIN
Measurement principle – The MAC-E filter

\[ E_{\text{kin}} = E_{\parallel} + E_{\perp} \]
\[ \mu = \frac{E_{\perp}}{B} = \text{const.} \]
\[ \Delta E = \frac{B_{\text{min}}}{B_{\text{max}}} \cdot 18.6 \text{ keV} = 0.93 \text{ eV} \]
$B_{\text{min}} = 0.3 \text{ mT}$

$B_e = 4.5 \text{ T}$

$B_{\text{max}} = 6 \text{ T}$
Monoenergetic, angular ($\theta$) and radial ($r$) selective electron source.Used in SDS commissioning to characterize MAC-E filter.

M. Erhard, Phd thesis in prep.
Normalized electron rate (a.u.)

Surplus energy (eV)

Transmission edge

Preliminary (M. Erhard, Phd thesis in prep.)
Backup

Preliminary (M. Erhard, Phd thesis in prep.)
Storage of keV-electrons emitted in radioactive decays
• Artificially elevate pressure in the spectrometer to reduce cool-down times.
• Identify single radon decays as spike in the background rate.
• Determine efficiency of LN$_2$-baffle system as Rn countermeasure.

Counts / 5 s

Time (s)

Rn-decay

$P \approx 10^{-8}$ mbar
$P \approx 10^{-10}$ mbar

Baffle status:

- all warm
- one cold
- two cold
- three cold

95.1 ± 0.3 %
Backup

- 75 000 muons / second
- Use muon veto to correlate flux to electron rate
Institute for Nuclear Physics (IKP), KIT

\[ R_e(t) = \alpha \cdot R_\mu(t) + C \]

\[ \frac{R_e(t)}{R_e} = \frac{\overline{R_\mu}}{R_e} \cdot \frac{R_\mu(t)}{R_\mu} + \frac{C}{R_e} \]

\[ a = 13.6 \pm 0.8 \% \]

→ Only small fraction of secondary electrons are caused by muons!
Backup

≈500 Bq/kg

55 - 70 Bq/kg

Rate (cps)
Measurements with water shielding showed no significant background reduction.

Characteristic clustering of secondary emission observed

→ Use artificial γ-source to check for clustering of events.
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