Electron Capture in $^{163}$Ho experiment – ECHo and discussion of recent results

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Outline

- Introduction
- Electron capture in $^{163}$Ho and neutrino mass
- Requirements to achieve sub-eV sensitivity on the electron neutrino mass
- $^{163}$Ho-based experiments
- Conclusions and outlook
Massive Neutrinos
Knowing neutrino mass scale....

**Particle Physics**
- Neutrino mass generation

**Astrophysics**
- Supernova neutrinos

**Cosmology**
- Matter distribution in the Universe

\[ m_\nu = 0 \quad \text{or} \quad m_\nu > 0 \]
Neutrino mass determination

Cosmology

\[ M_\nu = \sum m_i \]

- Model dependent
- Need of satellites
- Present limit 0.12 – 1 eV
- Next future 15-50 meV
Neutrino mass determination

Cosmology

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Neutrinoless Double beta decay

\[ m_{\beta\beta} = \left| \sum U_{ei}^2 m_i \right| \]

• Model dependent
• Laboratory experiments
• Present limit 0.1 – 0.4 eV
• Next future 15-50 meV
Neutrino mass determination

**Cosmology**

\[ M_\nu = \sum m_i \]

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- Need of satellites
- Present limit 0.12 – 1 eV
- Next future 15-50 meV

**Neutrinoless Double beta decay**

\[ m_{\beta\beta} = \left| \sum U_{ei}^2 m_i \right| \]

- Model dependent
- Laboratory experiments
- Present limit 0.1 – 0.4 eV
- Next future 15-50 meV

**Kinematics of β-decay and electron capture**

\[ m^2(\nu_e) = \sum |U_{ei}|^2 m^2_i \]

- Model independent
- Laboratory experiments
- Present limit 2 eV
- Next future 200 meV
Direct neutrino mass determination

Kinematics of beta decay

\[ m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2 \]

- Model independent
- Laboratory experiments

\[ m(\bar{\nu}_e) < 2 \text{ eV} \] \(^{3}\text{H}\) \(1\)

Current Limits

Beta decay mass (eV)

Lightest neutrino mass (eV)

Direct neutrino mass determination

Kinematics of beta decay

\[ m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2 \]

- Model independent
- Laboratory experiments

\[ m(\overline{\nu}_e) < 2 \text{ eV} \] \( ^3\text{H} \) (1)

\[ m(\nu_e) < 225 \text{ eV} \] \( ^{163}\text{Ho} \) (2)

---

Current Limits

Direct neutrino mass determination

Kinematics of beta decay

\[ m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2 \]

- Model independent
- Laboratory experiments

\[ m(\bar{\nu}_e) < 2 \text{ eV} \quad ^3\text{H} \quad (1) \]

\[ m(\nu_e) < 225 \text{ eV} \quad ^{163}\text{Ho} \quad (2) \]

- Next future 200 meV


Beta decay and electron capture

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

\[ ^{163}_{67}\text{Ho} \rightarrow ^{163}_{66}\text{Dy}^* + \nu_e \]

\[ ^{163}_{66}\text{Dy}^* \rightarrow ^{163}_{66}\text{Dy} + E_C \]

- \( \tau_{1/2} \approx 12.3 \text{ years} \quad (4 \times 10^8 \text{ atoms for 1 Bq}) \)

- \( Q_\beta = 18\ 592.01(7) \text{ eV} \)

- \( \tau_{1/2} \approx 4570 \text{ years} \quad (2 \times 10^{11} \text{ atoms for 1 Bq}) \)

- \( Q_{EC} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}}) \text{ keV} \)
Beta decay and electron capture

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\[ \frac{dW}{dE} \propto (Q - E)^2 \sqrt{1 - \frac{m_\nu^2}{(Q - E)^2}} \]

- \( \tau_{1/2} \approx 12.3 \text{ years} \) \( (4 \times 10^8 \text{ atoms for 1 Bq}) \)
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Beta decay of $^3$H

$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$
The KATRIN experiment

- **Main ideas:**
  - high activity source $10^{11}$ e$^-$/s
  - high resolution MAC-E* filter to select electrons close to the end point
  - count electrons as function of retarding potential
    $\Rightarrow$ integral spectrum

*MAC-E: Magnetic Adiabatic Collimation with Electrostatic Filter*
The KATRIN experiment: present status

Photo K. Valerius

Large Helmholtz coil system
The KATRIN experiment: present status

First light 14th October 2016
3H based experiments

**KATRIN - Karlsruhe Tritium Neutrino Experiment**

Main ideas:
- **high activity source**: $10^{11}$ e$^-$/s
- high resolution MAC-E filter to **select electrons close to the end point**
- count electrons as function of retarding potential
  → **integral spectrum**

**Project8**

Main ideas:
- **Source = detector**: $10^{11} - 10^{13}$ $^3$H$_2$ molecules /cm$^3$
- Use **cyclotron frequency** to extract electron energy
- **Differential spectrum**

**PTOLEMY - Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield**

Main ideas:
- large area tritium source: **100 g atomic $^3$H**
- MAC-E filter to **select electrons close to the end point**
- RF tracking and **time-of-flight systems**
- cryogenic calorimetry → **differential spectrum**
Beta decay and electron capture

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

\[ ^{163}_{67}\text{Ho} \rightarrow ^{163}_{66}\text{Dy}^* + \nu_e \]

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Electron capture in $^{163}$Ho: $Q_{EC}$ determination

- $Q_{EC} = m(^{163}$Ho$) - m(^{163}$Dy$)$
- $^{163}$Ho$ \rightarrow ^{163}$Dy$^* + \nu_e$
- $^{163}$Dy$^* \rightarrow ^{163}$Dy + $E_C$

- $\tau_{1/2} \approx 4570$ years (2*10$^{11}$ atoms for 1 Bq)
- $Q_{EC} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}})$ keV

Electron capture in $^{163}\text{Ho}$: $Q_{\text{EC}}$ determination

- Calorimetric measurements
- Measurements of x-rays
- Penning Trap Mass Spectroscopy
  @TRIGA TRAP (Uni-Mainz) (*)
  @SHIPTRAP (GSI – Darmstadt) (**)  

$$Q_{\text{EC}} = m(163\text{Ho}) - m(163\text{Dy})$$

$Q_{\text{EC}}$ determination
- $\tau_{1/2} \approx 4570$ years \((2*10^{11} \text{ atoms for 1 Bq})\)
- $Q_{\text{EC}} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}}) \text{ keV}$

Electron capture in $^{163}\text{Ho}$: spectrum

Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions

$^{163}\text{Ho} \rightarrow^{163}\text{Dy}^* + \nu_e$

$^{163}\text{Dy}^* \rightarrow^{163}\text{Dy} + E_C$

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Electron capture in $^{163}\text{Ho}$: spectrum

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- X-ray emission
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Source  $\nu_e$  Detector

$^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e$

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Electron capture in $^{163}\text{Ho}$: spectrum

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Calorimetric measurement

Source = Detector

$^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e$

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$^{163}$Ho$\rightarrow^{163}$Dy$^* + \nu_e$

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CALORIMETRIC MEASUREMENTS OF $^{163}$HOLMIUM DECAY AS TOOLS TO DETERMINE THE ELECTRON NEUTRINO MASS

A. DE RÚJULA and M. LUSIGNOLI

CERN, Geneva, Switzerland
Electron capture in $^{163}\text{Ho}$: spectrum

Atomic de-excitation:
- X-ray emission
- Auger electrons
- Coster-Kronig transitions

Calorimetric measurement

$$dW = A(Q \text{EC} - E_C)^2 \sqrt{1 - \frac{m_e^2}{(Q \text{EC} - E_C)^2}} \sum B_H \phi_H^2(0) \frac{\Gamma_H}{2\pi} \frac{\Gamma_H^2}{4 (E_C - E_H)^2}$$

$Q_{\text{EC}} = 2.833$ keV
Electron capture in $^{163}\text{Ho}$: spectrum

Atomic de-excitation:
- X-ray emission
- Auger electrons
- Coster-Kronig transitions

Calorimetric measurement

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\[
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\]
Electron capture in $^{163}$Ho: history

(a) F. Gatti et al., Physics Letters B 398 (1997) 415-419
(b) E. Laesgaard et al., Proceeding of 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), (1984).
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Electron capture in $^{163}$Ho: present

- Calorimetric measurement of the $^{163}$Ho spectrum
- Three international collaborations

**ECHo** (1)

**HOLMES** (2)

**NuMECS** (3)

Common challenges to reach sub eV sensitivity:
- Detector performance
- High purity $^{163}$Ho source
- Background reduction
- Description of the $^{163}$Ho EC spectrum

(1) The ECHo Collaboration EPJ-ST 226 8 (2017) 1623
(3) M. Croce et al., arXiv:1510.03874
Requirements for sub-eV sensitivity in ECHO
Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{\text{ev}} > 10^{14} \rightarrow A \approx 1 \text{ MBq}$

Fraction of events at endpoint regions

- In the interval 2.832 - 2.833 keV
  - only $6 \times 10^{-13}$
Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region
• $N_{ev} > 10^{14} \rightarrow A \approx 1$ MBq

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)
• $f_{pu} < 10^{-5}$
• $\tau_r < 1$ µs $\rightarrow a \sim 10$ Bq
• $10^5$ pixels
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Precision characterization of the endpoint region
• \(\Delta E_{FWHM} < 3\) eV
Requirements for sub-eV sensitivity in ECHO

Statistics in the end point region
• $N_{ev} > 10^{14} \rightarrow A \approx 1 \text{ MBq}$

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• $10^5$ pixels

Precision characterization of the endpoint region
• $\Delta E_{FWHM} < 3 \text{ eV}$

Background level
• $< 10^{-6}$ events/eV/det/day
Low temperature detectors for direct determination of the electron neutrino mass
Low temperature micro-calorimeters

\[ \Delta T \cong \frac{E}{C_{\text{tot}}} \]

- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
- Very sensitive temperature sensor

\[ E = 10 \text{ keV} \]
\[ C_{\text{tot}} = 1 \text{ pJ/K} \]
\[ \sim 1 \text{ mK} \]
Temperature sensors

Resistance of highly doped semiconductors

Resistance at superconducting transition, TES

Magnetization of paramagnetic material, MMC
Temperature sensors

Resistance of highly doped semiconductors

Resistance at superconducting transition, TES

Magnetization of paramagnetic material, MMC
Metallic magnetic calorimeters (MMCs)

- Paramagnetic Au:Er sensor
  Ag:Er

\[
\Delta \Phi_s \propto \frac{\partial M}{\partial T} \Delta T \quad \rightarrow \quad \Delta \Phi_s \propto \frac{\partial M}{\partial T} \frac{E}{C_{sens} + C_{abs}}
\]
Metallic magnetic calorimeters (MMCs)

- Fast risetime
- \( \rightarrow \) Reduction un-resolved pile-up
Metallic magnetic calorimeters (MMCs)

- Fast risetime
  - Reduction un-resolved pile-up
- Extremely good energy resolution
  - Reduced smearing in the end point region
Metallic magnetic calorimeters (MMCs)

- **Fast risetime**
  - → Reduction un-resolved pile-up

- **Extremely good energy resolution**
  - → Reduced smearing in the end point region

- **Excellent linearity**
  - → Precise definition of the energy scale

**Graphs:***

- **55Mn, $K_\alpha$**
  - $\Delta E_{FWHM} = 1.58$ eV

- **Escape lines**

- **Energy scale definition**
  - $E_m - E_p$ vs. $E_p$
MMC geometry and read-out

- Planar temperature sensor
- B-field generated by persistent current
MMC geometry and read-out

- Planar temperature sensor
- B-field generated by persistent current
- Transformer coupled to SQUID

- Two-stage SQUID read-out
Multiplexing readout

**Microwave SQUID multiplexing**
Single HEMT amplifier and 2 coaxes to read out **100 - 1000** detectors

- Reliable fabrication of 64-pixel array
- Successful characterization of first prototypes → optimization of design parameters

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Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
First detector prototype for $^{163}$Ho – ECHo-0

- Absorber for calorimetric measurement
  - ion implantation @ ISOLDE-CERN in 2009 on-line process

- About 0.01 Bq per pixel

- Operated over more than 4 years

Calorimetric spectrum

- Rise Time ~ 130 ns
- $\Delta E_{\text{FWHM}} = 7.6 \text{ eV} \ @ \ 6 \text{ keV} \ (2013)$
- Non-Linearity < 1% @ 6keV

<table>
<thead>
<tr>
<th></th>
<th>$E_h\ \text{bind.}$</th>
<th>$E_h\ \text{exp.}$</th>
<th>$\Gamma_h\ \text{lit.}$</th>
<th>$\Gamma_h\ \text{exp}$</th>
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<tbody>
<tr>
<td>MI</td>
<td>2.047</td>
<td>2.040</td>
<td>13.2</td>
<td>13.7</td>
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<tr>
<td>MII</td>
<td>1.845</td>
<td>1.836</td>
<td>6.0</td>
<td>7.2</td>
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<td>NI</td>
<td>0.420</td>
<td>0.411</td>
<td>5.4</td>
<td>5.3</td>
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<tr>
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<td>0.333</td>
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<td>OI</td>
<td>0.050</td>
<td>0.048</td>
<td>5.0</td>
<td>4.3</td>
</tr>
</tbody>
</table>

First calorimetric measurement of the OI-line

P. C.-O. Ranitzsch et al., accepted for publication in PRL (2017)
$Q_{EC}$ determination

\[
\Phi_H(E) = \sqrt{\frac{n_H}{\varphi_H^2(0)B_H}} \propto \sqrt{C(Q_{EC} - E_H)}
\]

Line amplitudes are affected by the phase space factor
$Q_{EC}$ determination

$\Phi_H(E) = \sqrt{\frac{n_H}{\varphi_H^2(0) B_H}} \propto \sqrt{C (Q_{EC} - E_H)}$

$Q_{EC} = (2.858 \pm 0.010_{stat} \pm 0.05_{syst})$ keV

Our result:

Penning Trap Mass Spectrometry result:

$Q_{EC} = (2.833 \pm 0.030_{stat} \pm 0.015_{syst})$ keV

Gatti et al., 1997
ECHO, 2012

$\Phi(E) = m_o \cdot E + n_0$
$m_o = -0.308 \pm 0.002$ keV$^{-1}$
$n_0 = 0.879 \pm 0.004$

$Q_{EC} = 2.858 \pm 0.010$ keV
\( Q_{EC} \) determination

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Penning Trap Mass Spectrometry result:
\( Q_{EC} = (2.833 \pm 0.030_{\text{stat}} \pm 0.015_{\text{syst}}) \text{ keV} \)

Good agreement between the two measurements

Gatti et al., 1997

ECHo, 2012

P. C.-O. Ranitzsch et al., accepted for publication in PRL (2017)
Scaling up
ECHO-1k (2015 - 2018)

$^{163}$Ho activity: $A_t = 1$ kBq

Detectors: Metallic Magnetic Calorimeters

- Energy resolution $\Delta E_{\text{FWHM}} \leq 5$ eV
- Time resolution $\tau \leq 1$ $\mu$s

Unresolved pile-up fraction $f_{\text{pu}} \leq 10^{-5}$

- Activity per pixel: $A = 10$ Bq
- Number of detectors $N = 100$

Read-out: Parallel read-out: 1 array ~50 single pixels

- Demonstrate Microwave SQUID Multiplexing

Background $b < 10^{-5}$/eV/det/day

Measuring time $t = 1$ year

$m(\nu_e) < 10$ eV 90% C.L.

Supported by DFG through Research Unit FOR 2202/1
${}^{163}\text{Ho}$ activity: \( A_t = 1 \text{ MBq} \)

**Detectors:** Metallic Magnetic Calorimeters
- Energy resolution: \( \Delta E_{\text{FWHM}} \leq 3 \text{ eV} \)
- Time resolution: \( \tau \leq 0.1 \mu\text{s} \)

Unresolved pile-up fraction: \( f_{\text{pu}} \leq 10^{-6} \)
- Activity per pixel: \( A = 10 \text{ Bq} \)
- Number of detectors: \( N = 10^5 \)

**Read-out:** Microwave SQUID Multiplexing
- 100 arrays with ~1000 single pixels

**Background** \( b < 10^{-6} \text{/eV/det/day} \)

**Measuring time** \( t = 1 - 3 \text{ year} \)

\[ m(\nu_e) < 1 \text{ eV} \text{ 90\% C.L.} \]
**$^{163}$Ho high purity source**

Required activity in the detectors: Final experiment $\rightarrow >10^6 \text{Bq} \rightarrow >10^{17} \text{atoms}$

- Neutron irradiation
  
  \((n,\gamma)\)-reaction on $^{162}$Er

  High cross-section

Radioactive contaminants

---

Required activity in the detectors: Final experiment $\rightarrow >10^6$ Bq $\rightarrow >10^{17}$ atoms

- Neutron irradiation
  \((n,\gamma)\)-reaction on \(^{162}\text{Er}\)

High cross-section

Radioactive contaminants $\rightarrow$ Excellent chemical separation

\(^{163}\text{Ho high purity source}\)

Mass separation and $^{163}$Ho ion-implantation

- Resonant laser ion source efficiency 41%
- Suppression of neighboring masses $> 700$
  $\Rightarrow ^{166m}$Ho/$^{163}$Ho $< 10^{-8}$
- Optimization of beam focalization

Chemically purified $^{163}$Ho sample

F. Schneider et al., *NIM B* 376 (2016) 388
Mass separation and $^{163}$Ho ion-implantation

Chemically purified $^{163}$Ho sample

Backscattering and sputtering of absorber atoms affect implantation process: Implantation activity $\neq$ beam current $\times$ irradiation time

Solution: in situ deposition of gold

F. Schneider et al., *NIM B* **376** (2016) 388
Enclosing $^{163}$Ho in MMC absorbers

ECHo-0 detector showed asymmetric detector response

- Loss of high energy phonons to the substrate
- Full contact between sensor and absorber

![Graph showing counts vs. energy for $^{163}$Ho without stems]

Counts / 2 eV

$E / \text{keV}$

Low energy tails
Enclosing $^{163}$Ho in MMC absorbers

ECHo-0 detector showed asymmetric detector response
- Loss of high energy phonons to the substrate
- Full contact between sensor and absorber

→ New detector fabrication process
  reduced contact area between absorber and sensor

Definition of the implantation area by microstructuring a photoresist layer on overhanging absorbers
Enclosing $^{163}\text{Ho}$ in MMC absorbers

ECHo-0 detector showed asymmetric detector response:
- Loss of high energy phonons to the substrate
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Counts / 2 eV

$163\text{Ho}$

$E / \text{keV}$

Low energy tails

Substrate

Sensor

Sputtered Au

$180 \, \mu\text{m}$
Enclosing $^{163}$Ho in MMC absorbers

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![Graph showing ECHO-0 detector response with low energy tails and E / keV on the x-axis and Counts / 2 eV on the y-axis.](image)
Enclosing $^{163}$Ho in MMC absorbers

Definition of the implantation area by microstructuring a photoresist layer on overhanging absorbers.

Symmetric detector response

C. Hassel et al., *JLTP* 184 (2016) 910
64 pixels which can be loaded with $^{163}\text{Ho}$ + 4 detectors for diagnostics

Design performance:

$\Delta E_{\text{FWHM}} \sim 5 \text{ eV}$

$\tau_r \sim 90 \text{ ns (single channel readout)}$

$\tau_r \sim 300 \text{ ns (multiplexed read-out)}$
100% of the chips selected at RT have good performance at low temperature
ECHO-1k array

- High geometrical efficiency for $^{163}$Ho implantation
- Presence of non-implanted chips for in-situ background determination
Background in ECHo

**Background sources:**

- Radioactivity in the detector
- Environmental radioactivity
- Cosmic rays
  
**Induced secondary radiation**

Study of background sources through:

- Monte Carlo simulations
- Dedicated experiments

**Screening facilities**

- Uni-Tübingen
- Felsenkeller

Material screening
Underground labs
\(\mu\)-Veto
Background in ECHo

Background sources:

- Radioactivity in the detector presence of $^{166m}$Ho in Ho samples for implantation

RISIKO @ Physics Institute, Mainz University

$^{166m}$Ho/$^{163}$Ho < $10^{-8}$
Background in ECHO

Background sources:

- **Radioactivity in the detector**
  presence of $^{166\text{m}}$Ho in Ho samples for implantation

RISIKO @ Physics Institute, Mainz University

$^{166\text{m}}$Ho/$^{163}$Ho < $10^{-8}$
Background in ECHo

Background sources:

- **Radioactivity in the detector**
  presence of $^{166m}$Ho in Ho samples for implantation

RISIKO @ Physics Institute, Mainz University

$\Rightarrow$ $^{166m}$Ho/$^{163}$Ho $<$ $10^{-8}$

Accelerator Mass Spectrometry (AMS) is a very powerful technique for measuring the corresponding very low isotopic ratio
Background in ECHo

Background sources:

- **Radioactivity in the detector**
  presence of $^{166m}$Ho in Ho samples for implantation

RISIKO @ Physics Institute, Mainz University

$^{166m}$Ho/$^{163}$Ho < $10^{-8}$

Accelerator Mass Spectrometry (AMS) is a very powerful technique for measuring the corresponding very low isotopic ratio.

First tests at the DREsden AMS facility (DREAMS) at Helmholtz-Zentrum Dresden-Rossendorf for experimental determination of the ratio $^{163}$Ho/$^{166m}$Ho in ECHo samples.
Background in ECHo

Background sources:

- Radioactivity in the detector
- **Environmental radioactivity**
- Cosmic rays
  Induced secondary radiation

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{40}$K [mBq/kg]</th>
<th>$^{208}$Tl [mBq/kg]</th>
<th>$^{212}$Pb [mBq/kg]</th>
<th>$^{214}$Bi [mBq/kg]</th>
<th>$^{214}$Pb [mBq/kg]</th>
<th>$^{226}$Ra [mBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat copper</td>
<td>&lt;480</td>
<td>&lt;80</td>
<td>&lt;190</td>
<td>&lt;96</td>
<td>&lt;600</td>
<td></td>
</tr>
<tr>
<td>Cryoperm [mBq/kg]</td>
<td>&lt;335</td>
<td>&lt;25</td>
<td>&lt;45</td>
<td>&lt;170</td>
<td>&lt;40</td>
<td>&lt;200</td>
</tr>
<tr>
<td>Connectors [mBq/kg]</td>
<td>5600</td>
<td>1600</td>
<td>10800</td>
<td>10800</td>
<td>10800</td>
<td>8000</td>
</tr>
<tr>
<td>Connectors [mBq] p.p.</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Circuit board [mBq/kg]</td>
<td>625</td>
<td>4800</td>
<td>16300</td>
<td>8700</td>
<td>8000</td>
<td>5300</td>
</tr>
<tr>
<td>Circuit board [mBq/cm$^2$]</td>
<td>0.45</td>
<td>1.39</td>
<td>4.75</td>
<td>2.53</td>
<td>2.33</td>
<td>1.54</td>
</tr>
<tr>
<td>Cables [mBq/cm$^2$]</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Background in ECHo

Background sources:

- Radioactivity in the detector
- **Environmental radioactivity**
- Cosmic rays

Induced secondary radiation

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{40}$K</th>
<th>$^{208}$Tl</th>
<th>$^{212}$Pb</th>
<th>$^{214}$Bi</th>
<th>$^{214}$Pb</th>
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Circuit board [mBq/kg]  

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Circuit board [mBq/cm²]  

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<th>1.54</th>
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</table>

Cables [mBq/cm²]  

| Cables [mBq/cm²] | 0.49 |

After comparison with MC simulations none of these item would lead to background above the unresolved pile up limit
Background in ECHO

**Background sources:**

- Radioactivity in the detector
- Environmental radioactivity
- Cosmic rays
  Induced secondary radiation

On-going
ECHo cryogenic platform

- Large space at MXC enough for several ECHo phases
- Cooling power: $15\mu W @ 20\, mK$
- Possibility to load 200kg for passive shielding

50cm x 50cm
ECHo cryogenic platform

- Large space at MXC enough for several ECHo phases
- Cooling power: $15\mu W \ @ \ 20 \ mK$
- Possibility to load 200kg for passive shielding
- Presently equipped with:
  
  2 RF lines for microwave multiplexing readour of 2 MMC arrays

  12 ribbons each with 30 Cu98Ni2 0.2 mm, 1.56 Ohm/m, cables from RT to mK
  \[ \rightarrow \text{allows for parallel readout of} \]
  
  36 two-stage SQUID set-up
ECHo-1k set-up

- ECHo-1k chip implanted at RISIKO Uni-Mainz
  \[ {^{163}\text{Ho}} \text{ activity } A = 2 \text{ Bq} \]
- 4 Front-end chips each with 8 dc-SQUIDs
ECHo-1k set-up

- Circuit board designed for the ECHo-1k experiment
  → Parallel read-out of 64 pixels

ECHo-1k chip and 4 dc-SQUID chips

Connector for field and heat currents

Connectors for connection to the amplifier SQUIDs
ECHo-1k set-up

Aluminum superconducting shield
ECHo-1k set-up
ECHo-1k set-up

Towards high statistics
$^{163}$Ho spectrum
$^{163}$Ho spectral shape

No good agreement between experimental spectrum and theory

- A. Faessler and F. Simkovic
- A. De Rujula and M. Lusignoli
  JHEP 05 (2016) 015, arXiv:1601.04990v1
- A. Faessler et al.
- R. G. H. Robertson
- A. Faessler et al.
- A. Faessler et al.
New approach

*Ab inito* calculation of the $^{163}$Ho electron capture spectrum

Brass et al., https://arxiv.org/abs/1711.10309

Restricted to **bound-states only**, i.e. the spectrum is given by a finite number of resonances

→ Include decay to the continuum states
→ Study the effect of metallic host
Sterile neutrinos search in ECHO

L. Gastaldo, C. Giunti, E. Zavanin.,

A White Paper on keV Sterile Neutrino Dark Matter, JCAP01(2017)025
Conclusions and outlook

The ECHo collaboration aims to reach sub-eV sensitivity on the electron neutrino mass analysing high statistics and high resolution $^{163}$Ho spectra

- **Independent** $^{163}$Ho $Q_{\text{EC}}$ measurement
  
  $Q_{\text{EC}} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}}) \text{ keV}$

  $Q_{\text{EC}} = (2.858 \pm 0.010^{\text{stat}} \pm 0.05^{\text{syst}}) \text{ keV}$

- **High purity** $^{163}$Ho sources have been produced

- $^{163}$Ho ions can be successfully enclosed in microcalorimeter absorbers

- **Large arrays** have been tested and **microwave SQUID multiplexing** has been successfully proved

- **A new limit on the electron neutrino mass is approaching**

Thank you!