Status of the KArlsruhe TRItium Neutrino Experiment

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for the KATRIN collaboration

PPC 2015, Deadwood, South Dakota

- Overview: neutrino masses & direct probes
- KATRIN: measurement principle and set-up
- Commissioning measurements & outlook
Neutrino masses: overview

Wealth of \( \nu \) oscillation data:

- Neutrino mixing & \( m(\nu_i) \neq 0 \) established
- Oscillation experiments: tiny mass splittings
  \[ \Delta m_{\text{atm}}^2 = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2 \]
  \[ \Delta m_{\text{sol}}^2 = (7.5 \pm 0.2) \times 10^{-5} \text{ eV}^2 \]
- Which mass ordering (normal, inverted)?
- What is the absolute \( \nu \) mass scale?

So far: only **upper** (< 2 eV) and **lower bounds** (>0.01 resp. >0.05 eV)
Complementary paths towards the $\nu$ mass scale

<table>
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<tr>
<th>Tool</th>
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<th>Neutrinoless double $\beta$-decay</th>
<th>$\beta$-decay endpoint and EC</th>
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$\rightarrow$ J. Hamann, IX

$\rightarrow$ M. Lindner, VI

$\rightarrow$ MAJORANA Dem., GERDA, EXO-200/nEXO, SNO+, KamLAND-Zen
## Complementary paths towards the ν mass scale

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→ J. Hamann, IX  
→ M. Lindner, VI  
→ this talk  

→ MAJORANA Dem., GERDA, EXO-200/nEXO, SNO+, KamLAND-Zen
Direct neutrino mass measurements

Imprint of $m_\nu$ on **endpoint region** of $\beta$ spectrum (similar for EC):

$$\frac{d\Gamma}{dE} = C \cdot F(Z, E) \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m^2(\nu_e)}$$

$$m^2(\nu_e) = \sum |U_{ei}|^2 m_i^2$$

**Key requirements**

- Source isotope:
  - Large decay rate (short $T_{1/2}$)
  - Low spectral endpoint $Q$
- Instrument:
  - Excellent energy resolution
  - Very low background

-measured quantity:
  - effective mass square

-Imprint of $m_\nu$ on **endpoint region** of $\beta$ spectrum (similar for EC):

-Region close to $\beta$ end point

-Only $2 \times 10^{-13}$ of all decays in last 1 eV

-$m(\nu_e) = 0 \text{ eV}$

-$m(\nu_e) = 1 \text{ eV}$
Direct neutrino mass measurements

Imprint of $m_\nu$ on endpoint region of $\beta$ spectrum (similar for EC):

$$\frac{d\Gamma}{dE} = C \cdot F(Z, E) \cdot \rho \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m^2(\nu_e)}$$

$$m^2(\nu_e) = \sum |U_{ei}|^2 m_i^2$$

Key requirements

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Experimental options

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<tr>
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<th>$^3$H ($\beta$)</th>
<th>$^{187}$Re ($\beta$)</th>
<th>$^{163}$Ho (EC)</th>
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<tr>
<td>Q value</td>
<td>18.6 keV</td>
<td>2.5 keV</td>
<td>$\sim$2.5 keV</td>
</tr>
<tr>
<td>$T_{1/2}$</td>
<td>12.3 yr</td>
<td>41 Gyr</td>
<td>4.5 kyr</td>
</tr>
<tr>
<td>technique</td>
<td>spectrometer</td>
<td>cryogenic micro-calorimeter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>source $\neq$ det.</td>
<td>source within detector</td>
<td></td>
</tr>
<tr>
<td>present m($\nu$) sens.</td>
<td>$&lt; 2$ eV Mainz, Troitsk $\sim$2004</td>
<td>$&lt; 15$-30 eV Milan, Genoa $\sim$2004</td>
<td>$&lt; 225$ eV Livermore 1987</td>
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ν-mass measurement in tritium β-decay

### 3H β-decay

- Short $T_{1/2}$ of 12.3 y → high-intensity source
- Low endpoint of 18.6 keV → good rel. signal strength
- Gas, closed loop → high isotopic purity
- Computation of final states, radiative & recoil corrections

### MAC-E filter technique

**Magnetic Adiabatic Collimation with Electrostatic filter**

Picard et al., NIM B63 (1992) 345

- Isotropic emission, strong $B_s$
- Energy filtering, weak $B_{min}$
- Energy resolution:
  \[
  \frac{\Delta E}{E} = \frac{B_{min}}{B_{max}} = \frac{1}{20000} \quad \text{(at KATRIN)}
  \]

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

Sensitivity on $m(v_e)$: 2 eV $\rightarrow$ 200 meV

Predecessors:
Mainz/Troitsk experiments $\rightarrow$ KATRIN

- Statistics (source luminosity) $\times 100$
- Systematics $\div 100$
- Scaled up linear dimensions (at roughly same background level)

$\sim 70$ m

K. Valerius | Status of the KATRIN Experiment | PPC 2015
KATRIN: main components

Source & transport section
- Windowless gaseous tritium source
  - Intensity ($10^{11}$ s$^{-1}$)
  - Stability ($10^{-3}$ h$^{-1}$)
  - Isotopic purity (> 95%)
- Tritium retention factor (> $10^{14}$)
- Adiabatic transport of electrons

Spectrometer & detector section
- Spectrometer UHV ($p < 10^{-11}$ mbar)
- Energy resolution (<1 eV at 18.6 keV)
- High voltage stability (few ppm/month)
- Low background rate (10 mcps)
- High detection efficiency (mcps to kcps)
**KATRIN: main components**

**WGTS demonstrator:** $\Delta T/T \sim 10^{-4}$

**SDS2:** HV post-regulation: $\Delta U/U \sim 1$ ppm

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**Graph:**
- **Y-axis:** temperature $T_{\text{eff}}$ [K]
- **X-axis:** time [s]
- **Legend:**
  - Voltage
  - 1-sigma
  - 1 ppm

**Graph Details:**
- $\sigma = 16$ mV
- S. Grohmann et al., Cryogenics 55–56 (2013) 5
- M. Erhardt et al. (in prep.)

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**K. Valerius | Status of the KATRIN Experiment | PPC 2015**
Windowless gaseous tritium source

- Closed-loop processing of $10^{16}$ Bq/day
- $10^{-3}$ relative stability of $T_2$ column density:
  → injection & pumping rate, isotopic purity, temperature stability & homogeneity

S. Grohmann et al., Cryogenics 55–56 (2013) 5

WGTS assembly, delivery to KIT 08/2015

August 2014
Transport and pumping sections

Differential pumping section (DPS)
- Turbomolecular pumps
- Tritium retention $\sim 10^5$
- Magnetic guiding of electrons

Cryogenic pumping section (CPS)
- Cryo-sorption on 3-4 K argon frost
- Tritium retention $> 10^7$
- Magnetic guiding of electrons

DPS site acceptance tests at KIT almost completed

CPS being prepared for transport to KIT
Spectrometer and detector section

**Installation of wire electrodes (2007-2012)**

**Large Helmholtz coil system (2011)**

**Detector tests (until spring 2013)**

- 148 pix. Si-PIN diode

Since mid-2013: commissioning of main spectrometer & detector
Commissioning measurements

Set-up for spectrometer & detector commissioning

- Magnetic fields
  - s.c. magnets
  - Field-shaping air coil systems

- Precision high voltage vessel + wire electrode at separate HV

- Electron gun
  - Well-defined, sharp energy and angle

- Vacuum system
  - TMPs
  - 3 x 1 km NEG strips, $10^6 \ell/s$ (+ LN$_2$-cooled baffles)

- 148-pix detector
  - Spatial & timing info
Commissioning measurements

Characterisation of spectrometer transmission using precision electron source: mono-energetic, point-like, angular selective

Transmission characteristics of main spec. as expected (limited by e-gun systematics ...)

Radial dependence of retardation potential as expected (precision mapping by e-gun)

Energy spread $\sigma \sim 200$ meV at 18.6 keV
Commissioning measurements

Characterisation of backgrounds

- Very efficient magnetic & electrostatic shielding, but only for charged particles (e\textsuperscript{-} and H\textsuperscript{+})
- Neutral, unstable atoms (\textsuperscript{219, 220}Rn, H*) can penetrate into inner flux tube
  → further measures required, e.g. passive shielding against Rn-induced secondaries

\[
477 \pm 3 \text{ mcps background level achieved}
\]
KATRIN: $\nu$-mass sensitivity

Shape analysis of $\beta$ spectrum (no external endpoint information)

4-parameter fit:

- $m^2_\nu$  
  eff. neutrino mass square
- $E_0$  
  spectral endpoint
- $A_{\text{sig}}$  
  signal rate
- $R_{\text{Bg}}$  
  background rate

$\sigma_{\text{stat}}(m^2_\nu) \leq 0.018 \text{ eV}^2$

$\sigma_{\text{syst}}(m^2_\nu) \leq 0.017 \text{ eV}^2$ – total systematic uncertainty budget

- Source-related (final states, energy loss, column density, plasma potential, ...)
- Other (HV fluctuations, transmission function, non-Poissonian backgrounds, ...)

![Graph showing integrated rate vs. retarding potential with labels](image)
KATRIN: $\nu$-mass sensitivity

![Plot showing sensitivity to neutrino mass as a function of full beam time.](image)

**Reference neutrino mass sensitivity**
- Measured quantity: $m^2(\nu_e)$
- After 3 yrs of data (5 calendar yrs): balance of *statistics* and *systematics*

**$\sigma_{\text{stat}}(m^2_\nu) \leq 0.018 \text{ eV}^2$**

**$\sigma_{\text{syst}}(m^2_\nu) \leq 0.017 \text{ eV}^2$ – total systematic uncertainty budget**
- Source-related (final states, energy loss, column density, plasma potential, ...)
- Other (HV fluctuations, transmission function, non-Poissonian backgrounds, ...)

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200 meV: 90% CL
350 meV: 5\(\sigma\)
KATRIN: $\nu$-mass sensitivity ... and more:

Explore physics potential

- **close to the spectral endpoint $E_0$:**
  - RH currents
    - Bonn et al. (2011)
  - Violation of Lorentz symmetry
    - e.g. Diaz, Kostelecky & Lehnert (2013)

Constraining local CvB overdensities
- e.g. Kaboth & Formaggio (2010), Fässler et al. (2013)

- **and further away from $E_0$:**
  - search for keV-scale sterile $\nu$ as WDM candidates
  - S. Mertens et al. (2015)

Capture of relic $\nu$ on $\beta$-instable nuclei

Search for eV-scale sterile $\nu$
- $\sim 1 \text{ eV}^2$
- Non-standard operation, requires novel concepts

Standard operation mode for KATRIN
Search for eV-scale sterile neutrinos

Shape modification below $E_0$ by active $(m_a)^2$ and sterile $(m_s)^2$ neutrinos:

$$\frac{d\Gamma}{dE} = \cos^2\theta_s \frac{d\Gamma}{dE} (m_a^2) + \sin^2\theta_s \frac{d\Gamma}{dE} (m_s^2)$$

$\rightarrow$ additional kink in $\beta$ spectrum at $E = E_0 - m_s$

$\sim 1 \text{ eV}^2$

$\rightarrow$ P. Machado, Sterile neutrinos
Search for eV-scale sterile neutrinos: Mainz data

68%, 90%, 95% C.L. Mainz exclusion region

EXO-200 data

solar + KamLAND osc. analysis

95% and 90% C.L. favoured regions, reactor ν anomaly


Search for eV-scale sterile neutrinos: KATRIN

- “Reactor antineutrino anomaly”: \(|\Delta m^2_s| > 1.5 \text{ eV}^2\), \(\sin^2(2\theta_s) = 0.14 \pm 0.08\) (95% CL)
- Favoured parameter space can be probed by KATRIN:

See also
Formaggio & Barrett, PLB 706 (2011) 68;
Sejersen Riis & Hannestad, JCAP 02 (2011) 011;
Esmaili & Peres, arXiv:1203.2632

Reactor anomaly (90% CL)
G. Mention et al., PRD 83 (2011) 073006

KATRIN exclusion
(3 net years, 90% CL)
M. Kleesiek, PhD thesis, 2014

See also
Formaggio & Barrett, PLB 706 (2011) 68;
Sejersen Riis & Hannestad, JCAP 02 (2011) 011;
Esmaili & Peres, arXiv:1203.2632
Status & Outlook

- $\beta$ decay offers model-independent, **direct** access to neutrino mass scale
- KATRIN sensitivity on $m(\nu_e)$: **200 meV** (90% CL, 5 cal. yrs)
  → ultimate MAC-E type experiment using molecular tritium
  → will exhaust degenerate neutrino mass regime

**Status of KATRIN hardware & system integration**

- Tritium-bearing components currently under construction; delivery & system integration in 2015
- Spectrometer & detector section successfully completed commissioning phases I and II
- First runs with entire KATRIN beam line in 2016