First results from the KATRIN experiment

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Neutrino mass

Upper bound from laboratory measurements

Lower bound from oscillation experiments
Neutrino mass

Cosmology

*model-dependent*

potential: $m_\nu = 15$-50 meV
e.g. Planck

$$m_{\text{cosmo}} = \sum_i m_i$$

Search for $0\nu\beta\beta$

*Laboratory-based*

potential: $m_{\beta\beta} = 15$-50 meV
e.g. LEGEND

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

Kinematics of $\beta$-decay

*Laboratory-based*

potential: $m_\beta = 50$ - 200 meV
e.g. KATRIN

$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$
General idea

• Kinematic determination of the neutrino mass
• Non-zero neutrino mass distorts the spectrum close to the endpoint
General idea

- Kinematic determination of the neutrino mass
- Non-zero neutrino mass distorts the spectrum close to the endpoint

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

Key requirements:

• Ultra-strong $\beta$-source ($10^{11}$ cps)
• Excellent energy resolution ($\sim 1$ eV)
• Low background level ($\sim 10$ mcps)
• Precise understanding of spectrum

Only $10^{-13}$ of all decays in last 1 eV
Where do we stand?

• Limit before KATRIN 1st Results: Mainz and Troitsk Experiment
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• Ongoing experiments:
  Distinguish between degenerate and hierarchical scenario
Where do we stand?

- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment

- Ongoing experiments:
  Distinguish between degenerate and hierarchical scenario

- New ideas:
  Resolve normal vs inverted neutrino mass hierarchy
Karlsruhe
Tritium
Neutrino
Experiment
• Experimental site: Karlsruhe Institute of Technology (KIT)
• International Collaboration (150 members)
• Sensitivity $m_\nu = 0.2 \text{ eV (90\% CL)}$ after 3 net-years
KATRIN Working Principle

<table>
<thead>
<tr>
<th>3H</th>
<th>super-allowed β-decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{1/2}$</td>
<td>12.3 years</td>
</tr>
<tr>
<td>$E_0$</td>
<td>18.6 keV</td>
</tr>
</tbody>
</table>

High intensity tritium source ($10^{11}$/s)

70-m long

High resolution spectrometer (~1eV)
KATRIN Working Principle

- High stability and luminosity
  \(10^{11}\) decays/sec

- \(\beta\)-decay

- Windowless Gaseous Molecular Tritium Source
KATRIN Working Principle

- Tritium flow reduction by 14 orders of magnitude
- β-decay
- Differential pumping = active pumping by TMPs
- Cryogenic pumping = cryosorption on Ar-frost
KATRIN Working Principle

Electrostatic filter selects high energy electrons

β-decay

Spectrometer Section
KATRIN Working Principle

Integral measurement down to 40 eV below the endpoint

148-pixel Si focal plane detector

β-decay

Model
Measurement
KATRIN Working Principle

excellent energy resolution: \(\sim 1\ \text{eV}\)

large angle acceptance: \(\sim 50^\circ\)

\(\beta\)-decay

Magnetic adiabatic collimation + electrostatic filter (MAC-E)
KATRIN (in real)

Windowless gaseous tritium source

Differential pumping section

Large Air Coil System

Detector system

Cryogenic pumping section

Inner electrode system
18-years of KATRIN history

Letter of Intent | Main spectrometer | Krypton calibration | First neutrino mass
---|---|---|---
Design Report | First light | First tritium

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18-years of KATRIN history

Letter of Intent 2001
Main spectrometer 2004
Krypton calibration 2006
First neutrino mass 2016
Design Report 2016
First light 2017
First tritium 2018

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KATRIN neutrino mass campaign #1 (KNM-1)

• First ever high-activity tritium operation of KATRIN
• April 10 – May 13 2019: 780 h (~4 weeks)
• high-quality data collected 2 million electrons

☑ First neutrino mass result 😊

arXiv:1909.06048
Tritium source operation

- tritium gas density: 22% of nominal (burn-in period)
- high isotopic tritium purity: 97.5%
- high source activity: $2.45 \cdot 10^{10}$ Bq (24.5 GBq), throughput: 4.9 g/day
Tritium source operation

- Electron gun
- Laser Raman Cell
- Forward beam monitor
- Krypton sources
Spectrometer operation

- interval: \( E_0 - 40 \text{ eV} , E_0 + 50 \text{ eV} \)
- \# HV set points: 27
- scanning time: 2 hours
- Number of scans: 274
- Sequence of scans: alternating up/down
- HV stability: 20 mV (ppm-level)

➢ One β-decay spectrum for each scan
Stable operation

- Scan-wise analysis
- Neutrino mass fixed to zero
- Effective endpoint stable over time
Tritium spectrum calculation

- Molecular final states
- Theoretical corrections
- Doppler broadening
- ...

\[ I(qU) = \int_{qU}^{E_0} D(E)R(E, qU)dE \]

- Spectrometer resolution
- Scattering in the source
- Synchrotron radiation
- ...

Differential spectrum

Integral spectrum

Experimental response
3-fold bias free analysis

Freeze analysis on fake data
- Generate MC-copy of each scan

Blinded model
- Modified molecular final state dist.

Two independent analysis strategies
- Covariance matrix
- Monte Carlo propagation
Two independent analysis approaches

Covariance matrix
- Systematic: **Spectrum** computed $10^5$ times
- $\chi^2 = (\vec{m} - \vec{d})^T V_{\text{tot}}^{-1} (\vec{m} - \vec{d})$

MC propagation
- Systematics: **Fit** performed $10^5$ times
- $-2 \log L = 2 \sum_i [m_i - d_i + d_i \log(d_i/m_i)]$
Systematic uncertainties

- Column density x cross section
- Magnetic fields
- Energy loss
- Final state dist.
- Background-slope
- Non-Poisson background
- Stacking of scans
Budget of uncertainties

we are largely statistics dominated !!!
What do we expect to measure?

- If the neutrino mass was zero...
- ... and we would repeat KATRIN 1,000,000 times...
- 68% probability: $m^2_\nu$ in $[-1; +1]$eV$^2$
- 95% probability: $m^2_\nu$ in $[-2; +2]$eV$^2$
Final fit result

- 2 million events
- 4 free parameters: background, signal normalization, $E_0, m^2$
- Excellent goodness-of-fit:
  p-value = 0.56
- Blind-analysis,
  2 independent analysis methods
- Neutrino mass best fit:
  $m^2 = (-1.0^{+0.9}_{-1.1}) \text{eV}^2$
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- Neutrino mass best fit: $m_{\nu}^2 = (-1.0^{+0.9}_{-1.1}) \text{eV}^2$
- Improved upper limit: $m_{\nu} < 1.1 \text{ eV @ 90\% CL}$
Final fit result

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u$
- excellent goodness-of-fit: p-value = 0.56
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u = (-1.0^{+0.9}_{-1.1}) \text{eV}^2$
- Improved upper limit: $m_
u < 1.1 \text{ eV} @ 90\% \text{ CL}$
Historical context
Improvements in statistics

Squared neutrino mass Uncertainties obtained from tritium $\beta$-decay in the period 1990-2019

- Multi-year measurements
  - sub-eV frontier
  - 1st KATRIN Science Run
  - 5 days@100 GBq
  - KATRIN 3y@100 GBq
Improvements in systematics

Squared neutrino mass Uncertainties obtained from tritium $\beta$-decay in the period 1990-2019

- **sub-eV frontier**
- improvement x 6
- improvement x 10

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KATRIN backgrounds

Large surface
Large volume
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KATRIN backgrounds

Radon decays in the volume

Getter pump

Black Body Radiation

Rydberg atom

$^{210}$Pb
KATRIN backgrounds

- Effective reduction of radon-induced background via nitrogen-cooled baffle system
  
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004

- Effective mitigation of Rydberg background by shifting analyzing plane
  
  not yet applied, under investigation at the moment

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KATRIN backgrounds

1. Effective reduction of radon-induced background via nitrogen-cooled baffle system
2. Effective mitigation of Rydberg background by shifting analyzing plane

✓ Successful test measurements show feasibility of the technique
Conclusion

- New World Best Direct Neutrino Mass Measurement: $m_\nu < 1.1$ eV (90% C.L.)
  - 2nd measurement campaign completed
    - Calibration runs ongoing
  - Final sensitivity of 0.2 eV reached after 5-years
Thank you for your attention

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