The KATRIN Neutrino Mass Experiment

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on behalf of the KATRIN Collaboration
The KATRIN Collaboration

- Carnegie Mellon University
- Case Western Reserve University
- CEA/Saclay
- Complutense University of Madrid
- Institute for Nuclear Research, Troitsk
- Karlsruhe Institute for Technology
- Lawrence Berkeley National Lab
- Max Planck Institut für Kernphysik, Heidelberg
- Nuclear Physics Institute of the ASCR
- Massachusetts Institute of Technology
- Max Planck Institute for Physics, Munich
- Technical University of Munich
- University of Applied Science, Fulda
- University of Bonn
- University of Mainz
- University of Münster
- University of North Carolina
- University of Washington
- University of Wuppertal

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The Neutrino Mass Scale

- Lower bound on $m_2, m_3$ from oscillation

![Graph showing normal hierarchy of neutrino masses](image-url)
The Neutrino Mass Scale

- Lower bound on $m_2, m_3$ from oscillation
- Upper bound from $\beta$ decay

$$m_{\nu\beta} = \sqrt{\sum_{i}^{3} |U_{ei}|^2 m_i^2}$$

Normal hierarchy

<table>
<thead>
<tr>
<th>Neutrino mass $m_i$ (eV/c$^2$)</th>
<th>Lightest $\nu$ mass $m_1$ (eV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>$10^{-4}$</td>
</tr>
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The Neutrino Mass Scale

- Lower bound on $m_2, m_3$ from oscillation
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$$m_{\nu\beta} = \sqrt{\sum_{i}^{3} |U_{ei}|^2 m_i^2}$$

$$\approx m_\nu \quad \text{(quasidegenerate regime)}$$

$$\leq 2 \text{ eV} \quad \text{(Mainz, Troitsk)}$$
The Neutrino Mass Scale

- Lower bound on $m_2, m_3$ from oscillation
- Upper bound from $\beta$ decay

![Graph showing Neutrino mass vs. Lightest $\nu$ mass](normal_hierarchy.png)

$$m_{\nu\beta} = \sqrt{\sum_{i}^{3} |U_{ei}|^2 m_i^2}$$

$\approx m_\nu$ (quasidegenerate regime)

$\leq 2\ eV$ (Mainz, Troitsk)
From $T_2$ to $m_{\nu\beta}$

- Extract $m_{\nu\beta}^2$ from fit to spectral shape near endpoint
- Almost model-independent

$$m_{\nu\beta} = 0 \text{ eV}$$

$$m_{\nu\beta} = 1 \text{ eV}$$

$2 \times 10^{-13}$ decays in last eV

$Q = 18.6$ keV
• Intense $T_2$ source ($10^{11}$ decays/second)
• Spectrum analysis with electromagnetic filter
• Design resolution 0.93 eV
• Design $m_{\nu\beta}$ sensitivity: 0.2 eV/c$^2$ at 90% confidence level
KATRIN - Overview
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Gaseous $^3\text{H}$ $^3\text{He}$ source

$10^{11}$ $\text{e}^-/\text{sec}$

Gaseous $T_2$ source
KATRIN - Overview

$^{3}\text{H}$ $^{3}\text{He}$ $\nu_{e}$

$10^{11}$ $e^{-}$/sec

Gaseous $T_{2}$ source

Electron transport
KATRIN - Overview

Analyze $\beta$ energy

$^3\text{H} \rightarrow ^3\text{He} + \nu_e$

10^{11} e$^-$/sec

Gaseous $T_2$ source

10^3 e$^-$/sec

Electron transport

Analyse $\beta$ energy
KATRIN - Overview

Gaseous $^3$He source

$10^{11}$ e$^-$/sec

$10^3$ e$^-$/sec

Electron transport

Analyze $\beta$ energy

$^3$H $^3$He $^3$He $\nu_e$ $e^-$ $e^-$

$^3$H $^3$He $\nu_e$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$
KATRIN - Overview

Electron transport

Detect $\beta$s

Analyze $\beta$ energy

$10^{11}$ $e^{-}$/sec

$10^3$ $e^{-}$/sec

$1$ $e^{-}$/sec

Gaseous $T_2$ source

$^3$H $^3$He $v_e$ $e^-$

$^3$H $^3$He $v_e$ $e^-$

$^3$H $^3$He $v_e$ $e^-$

KATRIN Experiment

XVII Int. Workshop on Neutrino Telescopes
March 15, 2017
KATRIN - Overview

- **Gaseous \( T_2 \) source**
  - \( ^3\text{H} \rightarrow \text{He}^+ + e^- \), \( 10^{11} \text{ e}^-/\text{sec} \)

- **Electron transport**
  - \( 10^3 \text{ e}^-/\text{sec} \)

- **Monitor energy threshold**
  - \( 1 \text{ e}^-/\text{sec} \)

- **Analyze \( \beta \) energy**
  - \( \nu_e \)

- **Detect \( \beta \)s**
  - \( 10^3 \text{ e}^-/\text{sec} \)
T₂ Spectroscopy: MAC-E Filter

- Measure integral spectrum with moving threshold
- **Magnetic Adiabatic Collimation + Electrostatic filter**

\[ \Delta \Omega = 2\pi \]

- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation: \( \mu = \frac{E}{B} = \text{const.} \)
  \( \Rightarrow \) parallel e⁻ beam
- Energy analysis by electrostat. retarding field
  \( \Delta E = E \cdot \frac{B_{\text{min}}}{B_{\text{max}}} = 0.93 \text{ eV (KATRIN)} \)

\( \hat{p}_e \) (without E field)
Source, Transport & Pumping

Monitoring & calibration system

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping with Argon snow at LHe temperatures

T₂-injection 1.8 mbar l/s (STP) = 1.7*10¹¹ Bq/s = 40 g/d

4 10⁻⁷ mbar l/s

< 2.5 10⁻¹⁴ mbar l/s

8 adiabatic electron guiding & T₂ reduction factor of ~10¹⁴
Rear section - Calibration & Monitoring

Essential for diagnostics of tritium source & spectrometer transmission
- photoelectron gun: spectrometer transmission & energy losses in source
- rear wall: definition of source potential, neutralization of tritium plasma
- X-ray detectors: online monitoring of tritium $\beta$-decay activity via X-rays (BIXS)
Windowless Gaseous molecular Tritium Source WGTS

tube in long superconducting solenoids
5 9cm, length: 10m, T = 30 K
WGTS: Temperature stability and density
Differential and Cryo Pumping

- based on cryo-sorption at Ar snow at 3-4 K
- Tritium retention: $>10^7$
- magnetic field: 5.6 T
- active pumping: 4 TMPs
- Tritium retention: $10^5$
- magnetic field: 5.6 T
- Ion monitoring by FTICR and ion manipulation by dipole and monopole electrodes inside
Detector

Requirements
- detection of $\beta$-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
- (passive and active shielding)
- good energy resolution (< 1 keV)

Properties
- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- segmented wafer (148 pixels)
  - record azimuthal and radial profile of the flux tube
  - investigate systematic effects
  - compensate field inhomogeneities
- detector magnet 3 - 6 T
- post acceleration (30kV)
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Main spectrometer and detector commissioning objectives

Primary objectives:

- test of hardware, software and slow control components
- provide ultra high vacuum conditions at the $p \leq 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter ($E = 18.6$ keV with $\Delta E = 0.93$ eV resolution) compared to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes
Main spectrometer and detector commissioning results

\[ \sigma_E = 50 \text{ meV} \] (single angular emittance)

TF with UV LED
First Light

14 October 2016

Major Milestone: Photo electrons transported over full 70m apparatus.

- Illuminate rear wall
- Magnetically guide photoelectrons along beamline
- First all-KATRIN commissioning
First Light

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- Magnetically guide photoelectrons along beamline
- First all-KATRIN commissioning

Last beamline valve opens
Various processes can contribute to the spectrometer background.

Spectrometer backgrounds were investigated in detail during two measurement phases (SDS1 & SDS2).
All previously known background processes are efficiently suppressed.

Background rate about 50 times larger than design value (10 mcps), presumably due to ionization of Rydberg atoms by black body radiation.
Decays of neutral particles

$^{219}\text{Rn}$ from getter (and artificial $^{220}\text{Rn}$ source)

$^{219}\text{Rn}$ atoms:
- $^{219}\text{Rn}$ emanates from NEG
- stored electrons eV...keV
- bg-rate: $\sim$500 mcps

Countermeasure (passive):
- cryotrap in front of NEG
- 3 LN$_2$-cooled Cu-baffles eliminate $\sim$97% of emanated $^{219}\text{Rn}$ atoms
Rydberg model:

- Remaining spectrometer background independent of magnetic field
- Approximately constant “background density” -> volume effect
- No cluster events at elevated pressure -> background not due to radioactive decays in spectrometer volume
- No effect of active methods -> no trapped particles

Rydberg model:

- Rydberg atoms created in the decay of $^{210}$Pb and accompanying processes, enter the spectrometer volume where they are ionized by thermal radiation, thus creating low-energy electrons
Rydberg model $^{228}$Th 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

$^{228}$Th $\alpha$, 5.5 MeV $T_{1/2} = 1.9$ yr
$^{220}$Rn $\alpha$, 6.4 MeV $T_{1/2} = 56$ s
$^{212}$Pb $\beta^-$, 331 keV $T_{1/2} = 10.6$ h
$^{212}$Bi $\alpha$, 6.2 MeV (36%) $T_{1/2} = 1$ h
$^{212}$Po $\alpha$, 9.0 MeV $T_{1/2} = 0.3$ µs
$^{216}$Po $\beta^-$, 2.3 MeV (64%) $T_{1/2} = 183$ s
$^{208}$Tl $\beta$, 5.0 MeV $T_{1/2} = 10.6$ h
$^{208}$Pb stable
induced background has the same behavior as existing background

→ main spectrometer $^{210}\text{Pb}$ contamination is root cause of background
Spectrometer Background

- 2015 commissioning revealed high backgrounds
  - ~50x higher than design value (10 mcps)
- Primary mechanism: $^{210}\text{Po}$ decay in/on wall
  - Secondary particles via sputtering
  - Rydberg atoms ($\text{H}^*$) enter flux tube
  - $\text{H}^*$ ionized via blackbody radiation
  - Low-energy $e^-$ created in flux tube!
- Countermeasures
  - reduce H-atom surface coverage:
    - extended bake-out phase
    - strong UV source illumination
  - revise data taking strategy
Mitigating High Backgrounds

Ideas and early plan

- Optimize scanning
- Enlarge analysis window
- Increase $B_{\text{min}}$

![Graph showing sensitivity on $m_\nu$ in meV (90% C.L.) vs. background rate in mcps for different $E_0$ values: $E_0 = 30$ eV, $E_0 = 45$ eV, $E_0 = 60$ eV. The graph indicates a preliminary sensitivity of $\sim 240$ meV with $\Delta E \sim 2.5$ eV at 558 mcps and optimized scanning.]}
Right now:
- Analysis of commissioning data (up to late 2016)
- Final work on tritium related hardware loops
- Continued work on monitoring systems
- Maintenance, upgrades, software work preparing for:

Summer/Fall 2017: System commissioning with $^{83m}$Kr, H$_2$, and D$_2$

Early 2018: First tritium data

And beyond:
- Early mass results (final sensitivity: 3 beam yrs)
- Sterile neutrino searches
- Searches for physics beyond the Standard Model
Backup slides
Molecular Final-State Distribution

- Electronic excitations in T atoms
- Excitations in T$_2$ gas
  - Electronic: 20 eV
  - Vibrational: ~0.1 eV
  - Rotational: ~0.01 eV
- Beta spectrum depends on excitation energies $V_k$ and probabilities $P_k$

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2 \theta_C}{2\pi^3 \hbar^7} |M_{\text{nuc}}|^2 F(Z, E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\text{max}} - E_e - V_k)$$

$$\times \sqrt{(E_{\text{max}} - E_e - V_k)^2 - m_{\nu_i}^2} \times \Theta(E_{\text{max}} - E_e - V_k - m_{\nu_i})$$
Describing $T_2$ Final States

- Precise ab initio calculations
- Uncertainty hard to estimate
- Enters directly into analysis

<table>
<thead>
<tr>
<th>Calculation</th>
<th>LANL $m_\nu^2$</th>
<th>LLNL $m_\nu^2$</th>
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<tbody>
<tr>
<td>1985</td>
<td>-147(79) eV$^2$</td>
<td>-130(25) eV$^2$</td>
</tr>
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</table>

Bodine, DSP, Robertson, PRC 91, 035505 (2015)

- KATRIN needs $\sigma_{FSD}$ to 1%
  - New calculations
  - Initial-state source characterization

- TRIMS experiment to resolve historical discrepancy

Saenz et al., PRL 84 (2000) 242
Fackler et al., PRL 55 (1985) 1388