Recent Results from KATRIN

Diana Parno, Carnegie Mellon University

NuPhys / London / 17 December 2019
The Unbearable Lightness of Neutrinos

Why are neutrinos so light compared to all other fundamental particles?

What is the absolute neutrino mass scale?

Plot from Luke Kippenbrock

Image from Symmetry Magazine
The Plan

- Neutrino mass
- How the KATRIN experiment works
- Modeling the KATRIN spectrum
- Closing in on the neutrino mass

Tomorrow: Joe Formaggio on Project 8
Neutrino Mass Scale

- Oscillation experiments give splittings between mass states
- What can we say about the offset of the lightest mass from zero?


Neutrino mass ordering?

CP violation?

Baryon asymmetry of the Universe?

Neutrinoless double beta decay?

Beyond the 3 flavor framework? (Sterile neutrinos?)

Are neutrinos Majorana particles?

Absolute neutrino mass?

http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

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Neutrino mass $m_i$ (eV)

Lightest neutrino mass $m_1$ (eV)

Pre-2019 limit: $m_\nu < 2$ eV (Mainz and Troitsk experiments)
Direct Mass Probe Through T Decay

- Super-allowed decay
  - $Q = 18.6$ keV
  - $T_{1/2} = 12.3$ yr
- Extract effective neutrino mass from spectral shape near endpoint

\[ m_{\nu,\text{eff}}^2 = \sum_{i} |U_{ei}|^2 m_i^2 \]

\[ \approx m_{\nu}^2 \text{ (quasi-degenerate regime)} \]
The Challenge

- Start with a huge number of decays
- Precisely measure energy, rate near endpoint
- Somehow ignore all the low-energy decays with no useful information

$\nu_m = 1 \text{ eV}$

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

$\sim 10^{-13}$ of decays

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The MAC-E Filter

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

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

\[ \text{T}_2 \text{ source} \]

\[ \text{Analyzing plane} \]

\[ qE \]

\[ \text{Electrodes} \]

\[ \text{Detector} \]

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

\[ \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \]

Detailed application to KATRIN: Kleesiek et al., EPJC 79 204 (2019)
A Quick Tour of the Beamline

Diana Parno

Recent Results from KATRIN

NuPhys 2019

Gaseous $^3$H$^3$He source

$10^{11}$ e/sec

Electron transport + tritium retention

Calibration

$10^3$ e/sec

Detect $\beta$s

Analyze $\beta$ energy

$1$ e/sec
KATRIN by the Numbers

- Expected $m_\nu$ sensitivity in 5 calendar years: **0.2 eV** at 90% confidence

- Magnetic field range 3 G – 60,000 G
- Source activity: $10^{11}$ decays every second
- 95% tritium purity
- Main spectrometer volume: 1240 m$^3$
1240 m³ in Real Life

Leopoldshafen, Germany
November 2006
Photo: KIT
The Plan

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Molecular Final-State Distribution

- Electronic excitations in T atoms
- Additional excitations in T₂ gas
  - Electronic: 20 eV
  - Vibrational: ~0.1 eV
  - Rotational: ~0.01 eV
- Beta spectrum depends on excitation energies \( V_k \) and on probabilities \( P_k \)

\[
\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2 \theta_C}{2\pi^3 \hbar^7} |M_{\text{nuc}}|^2 F(Z, E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\text{max}} - E_e - V_k) \\
\times \sqrt{(E_{\text{max}} - E_e - V_k)^2 - m_{\nu i}^2} \times \Theta(E_{\text{max}} - E_e - V_k - m_{\nu i})
\]
How often does $^3\text{HeT}^+$ stay bound after beta decay?

$$P_{\text{bound}} = \frac{N(\ ^3\text{HeT}^+)}{N(\ ^3\text{He}^+ + \text{T}) + N(\ ^3\text{He}^+\text{T}^+) + N(\ ^3\text{He}^+)}$$

<table>
<thead>
<tr>
<th>Theory</th>
<th>Snell Experiment*</th>
<th>Wexler Experiment*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT</td>
<td>$0.55 - 0.57$</td>
<td>$0.932 \pm 0.019$</td>
</tr>
<tr>
<td>$T_2$</td>
<td>$0.39 - 0.57$</td>
<td></td>
</tr>
</tbody>
</table>

Jonsell, Saenz, Froelich, PRC 60, 034601 (1999)  

* = Not really comparable ...
TRIMS (at University of Washington) aims to resolve the issue with a modern time-of-flight mass spectrometer.

- Mass-3 dissociated ions are faster than mass-6 bound ions.

Plot from Ying-Ting Lin

**Tritium Recoil-Ion Mass Spectrometer**

HT – T₂ gas mix

Preliminary

Ion Timing – Beta Timing (ns)

Ion Energy (keV)

H⁺, ³He⁺, T⁺, ³HeH⁺, ³HeT⁺

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KATRIN’s Response Function

- Electrons lose energy via scattering in the gas
- Test model with electron gun at upstream end of beamline
- Fold into experimental response
A Rube Goldberg Background

Rube Goldberg, Collier’s Magazine, 1931
A Rube Goldberg Rydberg Background

1) Ambient air

\[ ^{222}\text{Rn} \rightarrow ^{214}\text{Po} \]

- Dominant background
- Tested with \(^{220}\text{Rn}\) source
  - All daughters are short-lived

Slide credit: Luke Kippenbrock
Rydberg Backgrounds II: I Want to Believe

- Blackbody radiation really can ionize these atoms

- Simulations reproduce measured rate, dependences

**Graph:**

- Hydrogen binding energies, $8 \leq n \leq 40$
- BBR spectrum, 293 K

**Table:**

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Intensity (arb. u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>12</td>
</tr>
<tr>
<td>0.05</td>
<td>10</td>
</tr>
<tr>
<td>0.10</td>
<td>8</td>
</tr>
<tr>
<td>0.15</td>
<td>6</td>
</tr>
<tr>
<td>0.20</td>
<td>4</td>
</tr>
<tr>
<td>0.25</td>
<td>2</td>
</tr>
<tr>
<td>0.30</td>
<td>0</td>
</tr>
<tr>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>0.40</td>
<td>0</td>
</tr>
</tbody>
</table>

**Graph:**

- Inner electrode offset potential (V)
- Relative background reduction

**PhD thesis, Nikolaus Trost (KIT)**
The Plan

- Neutrino mass
- How the KATRIN experiment works
- Modeling the KATRIN spectrum
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Spring 2019: KATRIN Takes Off

Segmented KATRIN detector
Rate goes up as voltage drops

◆ A few glitches remained

KATRIN, PRL 123 (2019) 221802
Glitch I: Column Density

- Tritium-decay $\beta$ energy means radiochemistry
- Tritiated methane forms in source and freezes in capillary
- Ran at 20% nominal column density to control blockage
- Now solved via purging and thermal cycling
Glitch 2: Backgrounds

- Backgrounds 30x higher than design goal!
- Two weird sources: Rydberg atoms and Rn decay
- But, rates were stable and we have some countermeasures

![Graph showing rate (cps) over time with standard deviation]
A KATRIN spectral fit ideally has four parameters:

- Amplitude / intensity
- Background rate
- Endpoint energy
- $m_{\nu}^2$

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**PhD thesis, Marco Kleesiek (KIT), 2014**
Fitting the Data (in Practice)

- Fit of modeled to measured spectrum over all data
  - Treat detector as one uniform pixel
  - “Stack” similar high-voltage settings
  - 4 fit parameters: intensity, background, endpoint, neutrino mass

KATRIN, PRL 123 (2019) 221802
Systematics

<table>
<thead>
<tr>
<th>Effect</th>
<th>relative uncertainty</th>
<th>$\sigma(m^2_{\nu})$ in eV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho d \cdot \sigma$</td>
<td>0.85%</td>
<td>0.05</td>
</tr>
<tr>
<td>energy loss $\varepsilon(\delta E)$</td>
<td>$O(1%)$</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Beamline</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_{WGTS}$</td>
<td>2.5 %</td>
<td>0.05</td>
</tr>
<tr>
<td>$B_{\text{min}}$</td>
<td>1 %</td>
<td></td>
</tr>
<tr>
<td>$B_{\text{max}}$</td>
<td>0.2 %</td>
<td></td>
</tr>
<tr>
<td><strong>Molecular physics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final state distribution</td>
<td>$O(1%)$</td>
<td>0.02</td>
</tr>
<tr>
<td>Fluctuations in scan $k$</td>
<td></td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Drifts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV stacking</td>
<td>2 ppm</td>
<td></td>
</tr>
<tr>
<td>$\rho d$ variation</td>
<td>0.8%</td>
<td></td>
</tr>
<tr>
<td>isotopologue fractions</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>background slope</td>
<td>1.7%/keV</td>
<td>0.07</td>
</tr>
<tr>
<td>non-Poisson background</td>
<td>6.4%</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Total syst. uncertainty</strong></td>
<td></td>
<td>0.32</td>
</tr>
<tr>
<td><strong>Statistical</strong></td>
<td></td>
<td>0.97</td>
</tr>
</tbody>
</table>
The Results

- Extract best-fit value and construct Lokhov-Tkachov* confidence belt

\[ m_\nu^2 = (-1.0^{+0.9}_{-1.1}) \text{ eV}^2 \]
\[ m_\nu < 1.1 \text{ eV (90\% C.L.)} \]

*S. Lokhov and O. Tkachov, Phys. Part. Nucl. 46 347 (2015)
Funding and support from: **Helmholtz Association (HGF)**, **Ministry for Education and Research BMBF** (05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), **Helmholtz Alliance for Astroparticle Physics (HAP)**, and **Helmholtz Young Investigator Group (VH-NG-1055)** in Germany; **Ministry of Education, Youth and Sport** (CANAM-LM2011019), cooperation with the **JINR Dubna** (3+3 grants) 2017–2019 in the Czech Republic; and the **Department of Energy** through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, DE-SC0011091, and **DE-SC0019304** in the United States.
Conclusion

- We’ve learned a lot about neutrino mass in the last 8 months
  - Factor of 2 improvement on direct neutrino-mass limit
- The KATRIN experiment is up and running in Germany.
  - Better systematics
  - More statistics
  - End goal: 0.2 eV sensitivity at 90% confidence
- Stay tuned!

Thank you!
Backup
Different Neutrino Mass Probes

<table>
<thead>
<tr>
<th>Observable</th>
<th>$\Delta m^2_{ij} = m_i^2 - m_j^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present knowledge</td>
<td>$\Delta m^2_{21} = 7.53(18) \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td></td>
<td>$\Delta m^2_{32} = 2.44(6) \times 10^{-3} \text{eV}^2$</td>
</tr>
<tr>
<td>Next generation</td>
<td></td>
</tr>
<tr>
<td>Model dependence of mass extraction</td>
<td>No mass-scale information</td>
</tr>
</tbody>
</table>
LANL, LLNL and the FSD

- Any mistake in the FSD variance will shift the mass observable:

\[ \Delta m^2_{\nu\beta} \approx -2\Delta \sigma^2_{FSD} \]


Older calc. (Fackler et al. 1985)
Modern calc. (Saenz et al. 2000)

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TABLE IX. Atomic mass difference and neutrino mass squared extracted from two experiments, in one case with the original 1985 theoretical calculations of the FSD and in the second case with a more modern calculation.

<table>
<thead>
<tr>
<th></th>
<th>LANL [15]</th>
<th>LLNL [16]</th>
</tr>
</thead>
<tbody>
<tr>
<td>As published.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m^2_{\nu} ) (eV^2)</td>
<td>-147(79)</td>
<td>-130(25)</td>
</tr>
<tr>
<td>Re – evaluated.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m^2_{\nu} ) (eV^2)</td>
<td>20(79)</td>
<td>37(25)</td>
</tr>
</tbody>
</table>

Rydberg: Does This *Really* Make Sense?

- Dominant background is homogeneously distributed in the volume
- Background electrons are created with very low energy (< 1 eV)
- Rate dependence on temperature, inner-electrode offset, bakeout

**Graph:**
- Shows the total rate in mcps as a function of electric field (V/cm).
- Data points and lines indicate before and after baking.
- Parameters:
  - Unbaked: $A = 774 \pm 5$ x $= -0.0967 \pm 0.0044$
  - Baked: $A = 547 \pm 7$ x $= -0.1118 \pm 0.0066$

**Legend:**
- Unbaked and baked acquisitions.

**Note:**
- Diana Parino -- Recent Results from KATRIN -- NuPhys 2019
Radon-Induced Backgrounds

- $^{219}$Rn emanates from NEG pumps
- Shakeoff electrons are magnetically trapped and ionize residual gas molecules
- Detected electrons show motion pattern of progenitors

Slide credit: Florian Fränkle, KIT
Suppression: Radon-Induced Background

- LN-cooled baffle at each pump port
- ~97% suppression with all three baffles cold
- Testing optimal regeneration strategy

**PhD thesis, Fabian Harms (KIT)**