Neutrino Background

- Most abundant particle
- Lightest subatomic particle to have mass (very small though)
- Fundamental particle
- 3 flavors: Tau neutrinos, electron neutrinos and mu neutrinos
What is KATRIN?

- Karlsruhe Tritium Neutrino experiment
- Designed to directly measure effective $m_{\bar{\nu}_e}$
- Uses kinematics of Beta-decay to measure $m_{\bar{\nu}_e}$
Tritium Beta-Decay Formula

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

- Why Tritium?
- Relatively short half-life of 12.3 years
- Well-known theoretical representation
- Low endpoint of 18.6 keV
First Tritium Campaign

- To control rate of source stability, these parameters were closely monitored:
  1. Beam tube temperature
  2. Buffer vessel pressure
  3. Isotopic purity
Spectral Measurement

- Obtained by applying different retarding energies to spectrometer
- Then counting the number of transmitted Beta-electrons with focal plane detector
- Applied in an increasing, decreasing, and random voltages
- Scans last from 1-3 hours
- Total of 122 scans and 168 hours, resulting in about 0.6 million electrons

\[ t_{scan} = \sum t(qU_i) \]
Spectral Measurement (continued)
Beta-Decay Tritium Spectrum

\[ R_{\text{calc}}(qU_i) = A_s N_T \int_{qU_i}^{E_0} R_\beta(E) f_{\text{calc}}(E, qU_i) \, dE + R_{\text{bg}} \]

- Derived in “Analysis of KATRIN Neutrino Experiment”
Differential Beta-Electron Spectrum and Experimental Response Function

\[ R_\beta(E) = C \cdot F(E, Z') \cdot p \cdot (E + m_e) \cdot (E_0 - E) \sqrt{(E_0 - E)^2 - m_v^2} \]

Where \[ C = \frac{g^2}{2\pi^3} \cos^2 \Theta C |M_{nucl}|^2 \] and \[ m_v^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \]

\[ f_{calc}(E, qU_i) = \int_0^E T(E - \varepsilon, qU_i) (P_0 \delta(\varepsilon) + P_1 f(\varepsilon) + P_2 (f \otimes f)(\varepsilon) + ...) \, d\varepsilon \]
Observed Endpoint

- Setting the beginning of the spectra at 0, we need to find the cut-off energy of our fit:

\[ E_0^{\text{fit}} = E_0 + \Phi_{\text{WGTS}} - \Phi_{\text{MS}} \]
Data Selection

- Scan Selection: 40 scans were excluded due to parameter testing, 82 usable
- Pixel Selection: Some pixels were excluded (past detector range)
- Fit Range Selection: Data past $qU^\text{min} = E_0 - 100\text{eV}$ were irrelevant
Fitting Procedure

- Single-scan fit: to observe time-dependence of fit parameters
- Stacking: counts in sub-scans added to construct high statistics single spectrum but relies on high reproducibility of individual electron retarding energy settings
- Appending: eliminates the need for high reproducibility of individual electron retarding energy settings
- Single-pixel fit: to observe spatial dependence of fit parameters
- Uniform fit: detector pixels can be averaged because of transmission function to make calculations easier (but worsens energy resolution)
- Multi-pixel fit: all pixel dependent spectra are fitted simultaneously
Treatment of Systematics

- Nuisance Parameters: can treat uncertainties as systematic parameters
- Covariance Matrix: spectrum prediction is run thousands of times while changing system parameters each time to extract variances
- Monte Carlo Propagation: fit is varied instead to extract variances
- Maximum Error Estimation: shift method
Systematic Uncertainties

- Systematic Budget
- Column Density
- Tritium Concentration
- Energy-loss Function
- Magnetic Fields
- Electric Potentials
- Final-State Distributions
- Detector Efficiency
- Background
## Systematic Uncertainties (continued)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Description</th>
<th>1 σ uncertainty</th>
<th>1 σ uncertainty of fitted endpoint (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source scattering</td>
<td>Column density</td>
<td>3 %</td>
<td>0.13</td>
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<tr>
<td></td>
<td>Incl. scat. cross-section</td>
<td>2 %</td>
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<tr>
<td>DT concentration fluctuation</td>
<td>For single sub-scan (60 s)</td>
<td>1.5 %</td>
<td>0.03</td>
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<tr>
<td></td>
<td>For all scans combined (40000 s)</td>
<td>0.08 %</td>
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<tr>
<td>Energy-loss function</td>
<td>Excitation peak position $P_1$</td>
<td>0.017 eV</td>
<td>0.11</td>
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<td></td>
<td>Ionization peak position $P_2$</td>
<td>0.18 eV</td>
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<td>Excitation peak width $W_1$</td>
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<td>Ionization peak width $W_2$</td>
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<tr>
<td></td>
<td>Normalization</td>
<td>0.15 eV$^{-1}$</td>
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<tr>
<td>Final-state distribution</td>
<td>Normalization</td>
<td>1 %</td>
<td>0.08</td>
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<tr>
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<td>Ground-state variance</td>
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<tr>
<td></td>
<td>Excited-states variance</td>
<td>3 %</td>
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<tr>
<td>Magnetic fields</td>
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<tr>
<td></td>
<td>Analyzing plane</td>
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<td></td>
<td>Maximum field at pinch</td>
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<tr>
<td>Detector efficiency</td>
<td>Retarding potential dependence</td>
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<tr>
<td>Background</td>
<td>slope</td>
<td>5 mcps/keV</td>
<td>0.02</td>
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<tr>
<td>Gas density profile</td>
<td>on/off</td>
<td>&lt; 0.01</td>
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<tr>
<td>Theoretical correction</td>
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<td>Stacking</td>
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<tr>
<td>Total systematic uncertainty</td>
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<tr>
<td>Statistical uncertainty</td>
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<tr>
<td>Total uncertainty (stat. and syst.)</td>
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<td>0.25</td>
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</table>
Results

- Combining all data of golden scans, treating golden pixels as single effective pixel, and performing a fit at $qU_{\text{min}} = E_0 - 100 \text{eV}$ we get

\[
E_0^{\text{fit}}(\text{DT}) = 18574.39 \pm 0.17(\text{stat}) \pm 0.19(\text{sys}) \text{ eV} \\
= 18574.39 \pm 0.25(\text{tot}) \text{ eV},
\]
Now that the ends of our spectra have been measured our best fit value is

\[ m^2_{\nu} = (-1.0 \pm 0.9) \text{ eV}^2 \]

\[ \sigma_{\text{stat}} = 0.97 \text{ eV}^2 \]

\[ \sigma_{\text{sys}} = 0.32 \text{ eV}^2 \]
Works Cited

