The Windowless Gaseous Tritium Source of KATRIN

W. Käfer, for the KATRIN Collaboration
Karlsruhe Institute of Technology

International School for Nuclear Physics:
Neutrinos in Astro- Particle- and Nuclear Physics
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Outline

- Why is the WGTS important?
- What processes do we have to understand?
- How do experimental conditions and theoretical calculations affect the KATRIN spectrum?
KATRIN Overview

Karlsruhe Tritium Neutrino experiment

Transport sections
DPS, CPS

Rear section

Tritium source
WGTS

(Windowless Gaseous Tritium Source)

Pre and main spectrometer
(both are MAC-E filters)

Electron detector

Differential $\beta$–Spectrum

Integrated $\beta$ Spectrum

Rate/bin [Hz]

$U$ [V]

$E_{[eV]}$

$dn/dE$
Functional description of the WGTS

**Purpose:** Delivery of $10^{11}$ $\beta$ decay electrons per second

### Beamtube
- **Length:** 10 m
- **Diameter:** 90 mm
- **Temperature:** 30 K

### Tritium injection
- **Flow rate:** 0.208 mbar·l·s$^{-1}$
- **Pressure:** $3.35 \times 10^{-3}$ mbar

### Requirements
- **Stability of $T_2$ density profile of** $10^{-3}$
  - $\mathcal{T}$(injection rate, purity, beamtube temperature, pump rate)
- **For inner 9.5 m of beamtube**
  - **Temperature homogeneity:** ±30 mK
  - **Temperature stability:** ±30 mK·h$^{-1}$
systematic errors (Katrin design report)

<table>
<thead>
<tr>
<th>Source of systematic shift</th>
<th>Systematic shift $\sigma_{\text{syst}}(m_\nu^2)[10^{-3}\text{ eV}^2]$</th>
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</thead>
<tbody>
<tr>
<td>Final State Distributions</td>
<td>&lt;6</td>
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<td>Unfolding energy loss function/determination of $f_{\text{res}}$</td>
<td>&lt; 2</td>
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<td>$\rho d$ monitoring</td>
<td>$&lt; \sqrt{5} \cdot 0.65$</td>
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<td>HV variations</td>
<td>&lt;5</td>
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<td>Magnetic field variations in WGTS</td>
<td>&lt;2</td>
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</tbody>
</table>

Understanding the WGTS is crucial!!!
**WGTS Model**

**Experimental Input**
- Temperature Readings
- Pressure Readings
- $T_2$ Purity (Laser Raman)
- Hall Probes
  ...

**Theoretical Input**
- Scattering cross sections
- Final States
- Radiative corrections
- Synchrotron radiation
  ...

**Auxiliary Models**
- e.g. gas dynamics

**Intermediate results**
- Density distribution
- Scattering probabilities
- Velocity distribution
- Magnetic field

**β - Spectrum, taking into account experimental conditions and theoretical modifications**

**TODAY**

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**WGTS Model**

$\beta$ - Spectrum, taking into account experimental conditions and theoretical modifications

(simple) spectrometer model
WGTS gas dynamics

- **Input:**
  - Temperature-Profile
  - Inlet/Outlet Pressure

- **Output:** density + velocity profile

- Different flow regimes
  - solve Boltzmann equation

- **Numerical code**
  - F. Sharipov et al.
  - (Univ. Parana)
First Look at Radial dependency
Velocity profile $\rightarrow$ Doppler Effect

- Maxwell Boltzmann distribution + bulk velocity $U_z$

\[ f(\vec{r}, \vec{v}) \approx \frac{n(z)}{(\sqrt{\pi}v_u)^3} \exp \left[ -\frac{v_r^2 + v_\phi^2 + (v_z - U_z)^2}{v_0^2} \right] \]

- Thermal velocity $\sim 288$ m/s
- Bulk velocity $\sim 10$-40 m/s

**Example:**
- Electron energy: 18575 eV (endpoint)
- $T_2$ velocity: 288 m/s
- Energy shift for parallel emission:
  \[ \Delta E = 129 \text{ meV} \]
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**WGTS Model**

- (simple) spectrometer model

**$\beta$ - Spectrum**, taking into account experimental conditions and theoretical modifications
WGTS model: Principle

\[ N(qU, E_0, m_\nu^2) = \int R(E, qU) \frac{dN}{dE}(E, E_0, m_\nu^2) \, dE \]
3D WGTS model

- First WGTS model: *only integrated properties considered*
- Refined WGTS model (3-dimensional) to include inhomogeneities
- With detailed distributions: Create “voxelized” $\beta$ spectra
Calculation of the $\beta$ Spectrum

Response functions for 10 bins

- Transmission probability
- bin at front end
- bin at rear end

$E$ [eV]
Rate/bin [Hz]
$U$ [V]

Differential $\beta$ Spectrum

integrated $\beta$ Spectrum (Endpoint)
Experimental Input
• Temperature Readings
• Pressure Readings
• T₂ Purity (Laser Raman)
• Hall Probes
...

Theoretical Input
• Scattering cross sections
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e.g. gas dynamics

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WGTS Model
beta - Spectrum, taking into account experimental conditions and theoretical modifications

(simple) spectrometer model

WGTS Model

Wolfgang Kaefer
Erice 2009
Final State Distribution

Daughter molecule ($^3\text{HeT} / ^3\text{HeD}$) has rotational/vibrational/electronic excitations

- additional energy loss
- modified $\beta$ Spectrum

$$\frac{dN}{dE} \propto \sum_f P_f \left( E_0 - E_f - E \right) \sqrt{(E_0 - E_f - E)^2 - m_v^2} \Theta \left( E_0 - E_f - E - m_v \right)$$

Effect of $m_\nu$

Doss/Tennyson

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Effect of $m_\nu$

Doss/Tennyson
Summary & Outlook

- Understanding the WGTS is important for KATRIN systematics
- Broad range of physics
- 3D WGTS model:
  - Calculation of $\beta$ – Spectrum for segments of the WGTS
- Validation with test experiments and monitoring
  - Next: “Demonstrator” measurements end of this year
Backup
Source and transport section (tritium system)

T = 77 K  T = 27 K

DPS2-R  DPS1-R  WGTS  DPS1-F  DPS2-F  CPS

5%  95%  inner loop  95%  5%

R = 10^7  T = 77 K

cryo-pump (CPS)

diff. pumping system (DPS)

diff. pumping system (WGTS)

diff. pumping system

cryopump

tritium source

T = 27 K

R = 10^7

T = 77 K

T = 3 K

1%

longitudinal density profile

T = 3 K

R = 10^7

diffusion pumping systems

cryopumps

tritium sources

R = 10^7

T = 27 K

T = 77 K

T = 3 K

every 60 days (<1 Ci)

T_2 retention

controlled T_2 injection

T_2 processing isotope separation

existing TLK infrastructure

Source and transport section (tritium system)
Energy loss of electrons in Tritium

For 1 (a) or 2 interactions (b)

BT cooling – Ne/Ar thermosiphon

- Ne/Ar condenser
- Ne/Ar return line
- He supply
- He return
- Magnet vessel bore
- Inner shield
- Tritium supply
- Krypton supply
- 90 mm beamtube
- Sensor holder
- 16 mm Ne/Ar evaporator tubes
Neutrino mass and $\beta$-decay

kinetic measurement of the neutrino mass

\[
\frac{d\Gamma}{dE} = C p (E + m_e) (E_0 - E) \sqrt{(E_0 - E)^2 - m_{\nu_e}^2} F(E) \theta(E_0 - E - m_{\nu_e})
\]

experimentally observable

- $T_2$: half-life 12.3 a
- $E_0$: 18574 eV