KATRIN: An experiment to determine the neutrino mass

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**Motivation from cosmology**

Upper limit on neutrino mass: $m_\nu < 2.3 \text{eV (}\beta\text{-decay)}$

- determine absolute neutrino mass scale
- probe cosmological relevant region
- help to understand neutrino mass generation mechanism

**KATRIN**: only model independent determination of “electron anti-neutrino mass”, sensitivity: 0.2 eV
Tritium $\beta$-decay

Fermi theory of $\beta$-decay:

$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p(E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

observable:

$$m_{\nu e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

tritium as $\beta$ emitter:

- high specific activity (half-life: 12.3 years)
- low endpoint energy $E_0$ (18.57 keV)
- super-allowed

$$3H \rightarrow 3He + e^- + \bar{\nu}_e$$
The KATRIN experiment (KArlsruhe TRItium Neutrino experiment, location: Forschungszentrum Karlsruhe) involves the following processes:

- Tritium decay
- Electron transport
- Tritium retention
- Energy analysis

The experimental setup is 70 m long. Key parameters include:

- **β-decay rate:** $10^{11}$ Hz
- **T$_{2}$ pressure:** $10^{-6}$ mbar

The background rate is significantly lower:

- **Background rate:** $10^{-2}$ Hz
- **T$_{2}$ pressure:** $10^{-20}$ mbar

Approximately 14 orders of magnitude separate the decay rate from the background rate.
**WGTS**

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

**requirements**:
- Stability of $T_2$ density profile of $10^{-3}$ (function of: injection rate, purity, beamtube temperature $T_B$, pump rate)
- $T_B$ homogeneity $\pm 30$ mK
- $T_B$ stability $\pm 30$ mK $\cdot$ h$^{-1}$

**properties**:
- Beam tube: 10m length, 90mm diameter, absolute temperature 30K
- Tritium loop: 40g $T_2$ / day

**status**:
- Demonstrator to test new cooling concept 2009
- Construction 2010/11
- Commissioning 2012

TLK provides complex infrastructure to handle tritium
Tritium retention

**Differential Pumping Section:**

**Purpose:** reduce $T_2$ flux by $10^5$

- differential pumping of $T_2$ (TMPs)
- magnetic guiding of electrons (5.6T)
- removal of positive ions (dipole)

**Status:**
- Delivered to FZK 2 days ago!
- Acceptance tests
- Test program 2010

**Cryogenic Pumping Section:**

**Purpose:** reduce $T_2$ flux by $10^7$

- Cryosorption of $T_2$ on Argon frost
- Concept successfully tested (TRAP)

**Status:**
- Technical design report is ready
- Presently being manufactured at ASG
- Delivery to FZK on 10.2010
- Commissioning 2011
 Arrival of DPS
**Tritium Retention**

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**Differential Pumping Section Diagram:**
- Stainless steel
- Cryogenic Pumping Section Diagram:
**main spectrometer**

**purpose:** energy analysis

**requirements:**
- energy resolution 0.93eV @ 18.6keV
- pressure < 10^{-11}mbar
- background event rate < 10mHz
- stable HV system (1ppm @ -18.6kV)

**properties:**
- MAC-E filter (integrating high pass filter)
- volume: 1240m³, surface: 689,6m²
- inner electrode system
- variable voltage to scan $E_0$ region

**status:**
- First vacuum test without getter pump successful (10^{-10}mbar)!
- Mounting of inner electrode system
- Electro-magnetic test measurements 2010

**background rejection:**
- $U_0=-18.4kV$
- $U_0-100V$
- $U_0-200V$
main spectrometer
detector system

**purpose:** counting transmitted $\beta$-decay electrons

**requirements:**
- intrinsic background rate < 1mHz in RoI
- electron energy range 5 to 100keV
- energy resolution < 1keV

**properties:**
- segmented monolithic Silicon PIN Diode
- 148 pixels, area ~ 50mm$^2$ each
- post acceleration (up to 30kV)

**status:**
- Assembly and initial commissioning until 02/2010
- Delivery to FZK 03/2010
**pre-spectrometer**

**purpose:** reduce $\beta$-decay electron flux by $10^6$

- MAC-E filter
- energy resolution 70eV @ -18.4keV
- pressure $10^{-11}$mbar

**prototype for main spectrometer:**
- vacuum concept successfully tested ($p = 10^{-11}$mbar, routinely)
- active HV stabilization tested
- test of new electromagnetic design
- background suppression
- optimization of electrode system

**status:**
- end of test measurements 12/2009
- relocation of pre-spectrometer to main spectrometer hall 2010
Penning trap

Combination of electric and magnetic fields can create Penning traps

- Detailed investigations of Penning traps
- Check of parameter space: pressure, potential, magnetic field

→ Penning discharge can be major background source!
new electrodes

- new electrodes to remove Penning trap
- design also applied to main spectrometer

Anti Penning electrode

Ground electrode

G 0kV
A -18kV
B -18kV
new electrodes

- new electrodes to remove Penning trap
- design also applied to main spectrometer
Penning discharge

- a 180V deep penning trap ignites after some minutes.
- ignition stops if $B < A$ (as expected from calculation)

→ Penning discharge is under control!
summary & outlook

- KATRIN will measure electron anti-neutrino mass with a sensitivity of 0.2 eV
- Tritium source: construction 2011/12
- Tritium retention:
  - DPS: arrived 2 days ago, acceptance tests & test program
  - CPS: TDR ready, presently being manufactured, delivery to FZK 10/2010
- Pre-spectrometer: test setup important for main spectrometer design
- Main Spectrometer: electrode installation & start of EM test program 2010
- Detector: assembly & initial commissioning, delivery to FZK 03/2010
- Assembly of components & system integration 2011/12
- Start of $T_2$ measurements: summer 2012
discovery potential

\begin{align*}
\text{discovery potential} \ [\sigma] \quad m_\nu &= 0.4 \text{eV} \\
\text{discovery potential} \ [\sigma] \quad m_\nu &= 0.3 \text{eV} \\
\text{discovery potential} \ [\sigma] \quad m_\nu &= 0.2 \text{eV}
\end{align*}

full beam time \ [y]

90\% up. lim. on \ m_\nu \ [\text{eV}]

full beam time \ [\text{months}]

\begin{align*}
90\% \text{ up. lim. on } m_\nu \ [\text{eV}] \\
0 &\quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12
\end{align*}
energy spectra

counts per HV bin

residuals

$\text{m(\nu)} = 0 \text{eV}$

$\text{m(\nu)} = 0.5 \text{eV}$

10 MHz bgd

endpoint energy

$<\text{res}> = +1.5$

$<\text{res}> = -0.05$
MAC-E filter

Magnetic Adiabatic Collimation combined with an Electrostatic Filter

Magnetic moment:

\[ \mu = \frac{E_t}{B} = \text{const} \]

Energy resolution:

\[ \Delta E = \frac{B A}{B_{\text{max}}} E_t \]

transmission if \( E > E_0 + E_t \frac{B_A}{B_{\text{max}}} \sin^2(\alpha) \)