Motivation of $m_\nu$ measurement

KATRIN experiment
  - Measurement principle
  - Status

KATRIN, an experiment for determination of the $\nu$-mass: status and outlook

DSU2012
Impact of the neutrino mass on cosmology

Simulation of evolution of universe
→ Massive neutrinos smear out large scale structure

Even tiny neutrino mass has impact on energy content of the universe

Neutrino mass is an important input parameter for cosmology

$m_\nu < 2 \text{ eV/c}^2$ (PDG10)

$1 \text{ eV/c}^2 \cong 1.8 \cdot 10^{-36} \text{ kg}$
Tritium beta decay

\[ E_0 = 18.6 \text{ keV} \]
\[ T_{1/2} = 12.3 \text{ y} \]

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

Requirements:

- High tritium activity
  \( \rightarrow \) Strong source (> 1 GBq)
- High energy resolution (< 1 eV@18.6 keV)
- Low background + small systematic uncertainties

KATRIN experiment:
200 meV sensitivity (90 % C.L)

After 3 years data (5y real time)
The KATRIN experiment

Adiabatic guiding of electrons on meV level

Strong gaseous tritium source > 1 GBq

Electron transport and tritium retention

Energy analysis + detection

Tritium flow rate reduction by 14 orders of magnitude

$T_2$ gas flow: 1.8 mbar $\ell$/s

Required: small systematic uncertainties

→ stability of source profile better 0.1%

Energy resolution $\Delta E/E = 0.92$ eV

Required: Low background rate < 10 mHz

→ avoid trapped particles

→ UHV better $10^{-11}$ mbar

→ $T_2$ pressure < $10^{-20}$ mbar
STS = Source & Transport System

CMS

WGTS

DPS2-F

CPS

Tritium flow rate reduction by 14 orders of magnitude & electron transportation

- stability of pressure profile on 0.1% level
- temperature stability on 0.1% level @ 30 K

→ Processing system “tritium loops”
Requirements to tritium source and loops

- column density: \(5 \times 10^{17}\) molecules/cm\(^2\)
- activity: \(1.1 \times 10^{11}\) Bq
- injection: \(5 \times 10^{19}\) molecules/s \(\approx 40\) g Tritium / day!
- content: ultrapure molecular tritium (> 95%)
- stability: 0.1% (injection, purity, temperature, \(\Delta P_{\text{in}}/P_{\text{in}}\))

= limit of what technically can be done!
KATRIN location

Germany

Tritium Laboratory Karlsruhe (TLK)

- Commissioned with tritium 1994
- License to handle 40 g tritium
- Scientific Mission:
  - Tritium fuel cycle of fusion reactors
  - KATRIN experiment

Karlsruhe Institute of Technology
Campus North (Research Center Karlsruhe)
Key data of TLK

- **Unique**, semi-technical facility

- **Long experience in tritium handling**
  at technical scale and in a closed loop
  - License: 40 g tritium
  - Commissioning (tritium): 1994
  - About 20 g tritium on site
  - 13 glove box systems
    (total volume of about 125 m³)
    on an area of about 1450 m²
  - **Currently 57 people “on board”**
The Tritium Source
Windowless gaseous tritium source (WGTS) for KATRIN

- Closed tritium loop
  40g tritium / day = $1.5 \cdot 10^{16}$ Bq /day
  tritium purity $\varepsilon_T > 95$
  Pressure stabilization $\Delta p/p < 0.1$

Laser Raman spectroscopy with 0.1% (1σ) precision

- WGTS cryostat
  Superconducting solenoids (3.6T)
  10 m long beam tube @ 30 K with $\Delta T < 30$ mK
  2 phase Ne cooling circuit

$\rightarrow$ Experimental test necessary “Demonstrator”
Status of the WGTS

Inner Loop system

Pressure fluctuations < 0.02% → 5 times better than specified

Laser Raman system (LARA)

Study of systematic effects

Nonstop test of LARA > 21 days

0.1% precision (1σ) reached → KATRIN requirements fulfilled
WGTS demonstrator at KIT
WGTS demonstrator at KIT

Demonstrator on site
Test measurements nearly finished

Temperature stability in mK range
→ Improvement by 10 – 20 w.r.t. specification
Transport Section
Adiabatic guidance of electrons to spectrometers
Reduction of tritium flow rate by $>10^{14}$

**Transport section**

- **Differential pumping section**
  - $B_{\text{max}} = 5.6\ \text{T}$
- **Cryogenic pumping section**
  - $T = 3 - 4.5\ \text{K}$

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<thead>
<tr>
<th>Tritium flow reduction</th>
<th>DPS</th>
<th>CPS</th>
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<tr>
<td>$10^5$</td>
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<td>$&gt;10^7$</td>
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Status of DPS2-F:

- Gas-flow reduction measurement (without dipoles & FT-ICR) in agreement with simulation

- Instrumentation for ion detection and elimination

- FT-ICR Trap (in collaboration with MPIK-Heidelberg)

- New protection diode layout based on design for WGTS and CPS
CPS: Status of assembly

status:
- presently being manufactured at ASG
- delivery to KIT in 2014
Energy analysis
Electrostatic Spectrometers:

**pre-filter**
- fixed retarding potential
  - \( U_0 = -18.3 \text{ kV} \)
  - \( \Delta E \sim 100 \text{ eV} \)
- filter out all \( \beta \)-decay electrons without \( m(\nu) \)-info
- reduce background from ionising collisions

**tandem design:** pre-filter & energy analysis

**precision filter - scanning**
- variable retarding potential
  - \( U_0 = -18.4 \ldots -18.6 \text{ kV} \)
  - \( \Delta E \sim 0.93 \text{ eV (100\% transmission)} \)
the final 7km: passing Leopoldshafen

November 25, 2006: after an 8800 km sea-going voyage the main Spectrometer vessel was manoeuvred on road over 7 km to the final destination at the KATRIN experimental halls… (30.000 visitors)

arrival at Leimersheim ferry & reloading onto SPMT with heavy-duty crane
Status of the main spectrometer

Wire defined electrostatic filter:
- 248 modules, 23000 wires
- precision requirement 0.2 mm
- compatible to UHV

Wire modules installed
First test measurements in 2012

$U_0 = -18.4 \text{kV}$
$U_0 - 100 \text{V}$
$U_0 - 200 \text{V}$

spectrometer wall
wire frame module
KATRIN – Impressions (Main Spectrometer)

Length: 24 m
Diameter: 10 m
Volume: 1240 m³
Surface: 690 m²
Weight: 200 t
Pressure: 10⁻¹¹ mbar
Outgassing: 10⁻¹² mbar l/s @ 20°C

Heating/cooling: from -20...+350°C
3 pump ports: 1700 mm diameter
10⁴ l/s with 6 TMPs MAG W 2800 for H₂
4.5 * 10⁵ l/s with 3000 m of NEG (with baffle) for H₂
The detector system

- Segmented Si-PIN diode
- Detection of transmitted beta decay electrons (Hz to kHz)
- Low intrinsic background (< 1 mHz)
- Commissioning ongoing

Detector system at University of Washington before shipping

Delivery to KIT, July 2011
Summary

- Measurement of $m_\nu$ with 200 meV/c$^2$ design sensitivity (90 % C.L.)
- Commissioning of components ongoing
- Many central parameters better than specified
- Many systematic effects understood
- Start of tritium measurements 1 year after delivery of WGTS

http://www.katrin.kit.edu
Thank you for your attention
Motivation for neutrino mass measurement

**Cosmology**

0νββ decay

\[ \left\langle m_{\beta\beta} \right\rangle = \left| \sum_{i=1}^{3} U_{e,i} \right|^2 m_i \cdot e^{i\alpha_i} \leq 0.35 \text{ eV} \]

(Heidelberg-Moscow, IGEX)

\[ \sum m_\nu < (0.6 - 2) \text{ eV/c}^2 \]

(95 % C.L.) (Hannestad)

**Direct beta decay measurements (Mainz, Troitsk):**

\[ m_\nu < 2 \text{ eV/c}^2 \] (95 % C.L.) (PDG08)

**Improved direct measurement necessary**

**Mass hierarchy**

**Neutrino oscillations:**

Atmospheric neutrinos:

\[ (\Delta m_{32}^2)^2 \approx 2.4 \times 10^{-3} \text{ eV}^2/\text{c}^4 \]

Solar neutrinos:

\[ (\Delta m_{21}^2)^2 \approx 7.6 \times 10^{-5} \text{ eV}^2/\text{c}^4 \]

\[ \Rightarrow m_\nu \neq 0 \] (PDG08)
After 3 years data (5y real time):

- **discovery potential**: $m(\nu) = 0.35 \text{ eV/c}^2$ (5$\sigma$)
- **sensitivity (90% CL)**: $m(\nu) < 0.2 \text{ eV/c}^2$

\[ \sigma_{\text{tot}}^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{systot}}^2 \approx 0.025 \text{ eV}^2/\text{c}^4 \]
\[ \sigma_{\text{stat}} = \sigma_{\text{systot}} \leq 0.017 \text{ eV}^2/\text{c}^4 \]

\[ \Delta m_{\text{stat}}^2 = 0.018 \text{ eV}^2/\text{c}^4 \]
\[ \Delta m_{\text{sys,tot}}^2 \leq 0.017 \text{ eV}^2/\text{c}^4 \]
The MAC-E spectrometers

Pre spectrometer | Spectrometer | Detector

ΔE = E·B_{min} / B_{max} = 0.93 eV (E_0 = 18.6 keV)

B_{min} = 2·10^{-4} B_{max}

Magnetic moment \( \mu = E_t / B = \text{const.} \)

Magnetic adiabatic collimation \( \rightarrow \) Large solid angle (2\pi)


\[ \Delta E = 0.93 \text{ eV} \]