Status of the KATRIN Experiment and commissioning of the spectrometer and detector section

Thomas Thümler for the KATRIN collaboration
DESY-Physikseminar, June 2013, Hamburg & Zeuthen
Goal of KATRIN

- model-independent neutrino mass determination
- precise spectroscopy of Tritium $\beta$-decay
- unprecedented sensitivity of $200 \text{ meV/c}^2$ (90% C.L.)

Introduction and KATRIN setup
Spectrometer-, Detector-Section
Status and Commissioning runs
Summary and Outlook
Motivation: Neutrinos in Astroparticle Physics

**cosmology**: role of ν’s as hot (warm?) dark matter?

**particle physics**: origin and hierarchy of the ν-mass?

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### Millennium Simulation

336 ν / cm³

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### Neutrinos

- Mass [GeV]
- Fermions
- Bosons
- Massless Bosons

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### Diagram

- ν₁
- ν₂
- ν₃
- Offset?
- Δm²_{12}
- Δm²_{23}
- m=0

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### Motivations:

- Neutrinos in Astroparticle Physics
Clear evidence for neutrino flavour oscillations:

- Atmospheric neutrinos: \((\Delta m_{32})^2 \approx 2.4 \times 10^{-3} \text{ eV}^2/c^4\)
- Solar neutrinos: \((\Delta m_{21})^2 \approx 7.6 \times 10^{-5} \text{ eV}^2/c^4\)

→ Well established fact: \(m_\nu \neq 0\)

Input from Cosmology:

- Measures \(\Sigma m_i\) and HDM \(\Omega_\nu\)
- Very sensitive, but model dependent!
- Planck: \(\Sigma m_i < 0.98\) eV
  (Planck 2013 results. XVI. Cosm. param.)
- Potential: \(\Sigma m_i = 20-50\) meV
  (Planck, LSST, weak lensing)
Neutrino Mass: Status and Perspectives

neutrino masses
in lab. experiments
Neutrino Mass: Status and Perspectives

neutrino masses in lab. experiments

search for $0\nu\beta\beta$

effective Majorana mass $m_{\beta\beta}$

model-dependent (CP-phases)

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$

- probe $\nu$ as Majorana particle: $\nu = \bar{\nu}$?
- status: $m_{\beta\beta} < 0.35$ eV, evidence?
- potential: $m_{\beta\beta} = 20-50$ meV
- GERDA, EXO, SNO+, MAJORANA, Cuore, KamLAND-Zen, ...

T. Thümmler - Status and commissioning of KATRIN
Neutrino Mass: Status and Perspectives

neutrino masses in lab. experiments

search for 0νββ

model-dependent (CP-phases)
effective Majorana mass \( m_{\beta\beta} \)

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kinematics of \( \beta \)-decay

absolute \( \nu_e \)-mass: \( m_\nu \)

model-independent

squared neutrino mass:

\[
m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2
\]

- direct, from kinematics
- status: \( m_\nu < 2.3 \) eV
- potential: \( m_\nu = 200 \) meV
- KATRIN, MARE, Project 8, ECHO
$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$

observable $m^2(\nu_e)$: effective electron-$\nu$-mass

$\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2$

$\nu$-mass
\[ \frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i) \]

observable \( m^2(\nu_e)\): effective electron-\( \nu \)-mass

\[ m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2} \]

- small modifications by final states, radiative & recoil corrections
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**Observable \( m^2(\nu_e) \): effective electron-\( \nu \)-mass**

\[ m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2} \]

**Key requirements:**
- Low endpoint \( \beta \) source
- High count rate
- High energy resolution
- Extremely low background

**Small modifications by final states, radiative & recoil corrections**

**Region close to \( \beta \) end point**

\[ \frac{\Delta E}{E_0}^3 \leq 2 \times 10^{-13} \text{ of all decays in last } 1 \text{ eV} \]
The MAC-E filter

**Magnetic Adiabatic Collimation with Electrostatic Filter**

Design Facts:

- \( B_{\text{max}} = 6 \, \text{T} \)
- \( B_{\text{min}} = 0.3 \, \text{mT} \)
- \( B_{\text{min}} / B_{\text{max}} = 5 \times 10^{-5} \)
- \( \mu = E_\perp / B = \text{const.} \)
- \( U_0 = 18.6 \, \text{kV} \)
- \( E = 18.6 \, \text{keV} \)
- \( E = E_\perp + E_\parallel \)

- **Collimation:** adiabatic transport: \( E_\perp \rightarrow E_\parallel \) due to \( \mu = \text{const.} \)
- **Energy Analysis:** only electrons with \( E_\parallel > eU_0 \) (retarding potential) can pass analysing plane → **high-pass filter** with a sharp transmission function, no tails!
- **Energy Resolution:** \( \Delta E = E \cdot B_{\text{min}} / B_{\text{max}} = 0.93 \, \text{eV} \)
The KATRIN Setup - Overview

**Tritium source**
- $^3\text{H}$ decay
- $\beta$ decay
- $10^{11}$ $e^-$ /s
- $E = 18600$ eV

**Transport section**
- $^3\text{He}$
- $\bar{\nu}_e$
- $e^-$

**Pre spectrometer**
- $10^{11}$ $e^-$ /s
- $E > 18.3$ keV

**Spectrometer**
- $10^3$ $e^-$ /s
- $\Delta E = 0.93$ eV

**Detector**
- $1$ $e^-$ /s
- $\approx 70$ m

E = 0.93 eV
E > 18.3 keV

T. Thümmler - Status and commissioning of KATRIN
magnetic field & electrostatic potential

T. Thümmler - Status and commissioning of KATRIN
10^{-3} stability of tritium source column density $\rho_d$
retention factor for molecular tritium $R = 10^{14}$
effective removal of ions
fully adiabatic (meV scale) transport of electrons over > 50 m
avoid particle storage in Penning-like traps
avoid contermination by Rn in the volume
Windowless Gaseous Tritium Source WGTS

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>$1.7 \times 10^{11}$ Bq</td>
</tr>
<tr>
<td>injection rate</td>
<td>$5 \times 10^{19} \text{ T}_2/\text{s} \approx 40 \text{ g/day} \approx 10 \text{ kg/y}$</td>
</tr>
<tr>
<td>Tritium purity</td>
<td>$&gt;95% \pm 0.1%$</td>
</tr>
<tr>
<td>temperature</td>
<td>$T = 27 \text{ K} \pm 30 \text{ mK}$</td>
</tr>
<tr>
<td>pressure</td>
<td>$p_{\text{inj}} \approx 10^{-3} \text{ mbar}$</td>
</tr>
<tr>
<td>magnetic guiding</td>
<td>$B = 3.6 \text{ T}$</td>
</tr>
</tbody>
</table>

Tritium Laboratory Karlsruhe - a unique research facility in Europe

CAPER facility
Windowless Gaseous Tritium Source WGTS

Up and running extremely stable!
- designed for a stability at $10^{-3}$ level
- achieved: $2 \times 10^{-4}$ over 4 months
Windowless Gaseous Tritium Source WGTS

KATRIN requirement:
T = 27 K with ΔT < 30 mK

WGTS Demonstrator:
- on-site and cold tested in 2010
- ΔT_max = ± 3 mK

S. Grohmann et al., Cryogenics, Volume 51, Issue 8, August 2011

2-phase Neon
s.c. heater
Helium vessel

β-decay
ν_e
e^-

Average temperature T_m = 30.243 K
Maximum peak-to-peak variation ΔT_max = ±0.003 K
Standard deviation σ_T = ±0.0014 K
- active pumping, 4 TMPs
- Tritium retention $10^5$
- magnetic field: 5.6 T
- under construction, to be installed 2014

- pumping by cryo-sorption
- Tritium retention $>10^7$
- magnetic field: 5.6 T
- delivery Spring 2014
Electrostatic Spectrometers

**pre-filter option**
- 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

**precision filter - scanning**
- variable retarding potential
- \( U_0 = \) -18.4 ... -18.6 kV
- \( \Delta E \sim 0.93 \text{ eV} \) (100% transmission)

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

\[ 10^{11} \text{ electrons/s} \Rightarrow 10^{-2} \text{ electrons/s} \]
KATRIN Main Detector

- Si-PIN diode
- detection of transmitted β’s (mHz to kHz)
- low background for T₂ endpoint investigation
- high energy resolution:
  \[ \Delta E = 1.48(1) \text{ keV (FWHM)} \text{ at } 18.6 \text{ keV} \]
- 12 rings with 30° segmentation + 4-fold center = 148 pixels
  - minimize bg, investigate systematic effects
  - compensate field inhomogeneities of spectrometer’s analyzing plane.

\[ E = 1.48(1) \text{ keV (FWHM)} \text{ at } 18.6 \text{ keV} \]
KATRIN Main Detector

- detector commissioning completed
- first light from spectrometer – May 2013
Air Coil System

- Earth magnetic field compensation & low field correction

- Earth magnetic/environmental fields distort magn. flux tube in low field region (0.3 mT)
- Needs to be compensated!
- Low field correction:
  - Optimize flux tube
  - Fine tune transmission and resolution.
Air Coil System

- Earth magnetic field compensation & low field correction

- Earth magnetic/environmental fields distort magn. flux tube in low field region (0.3 mT)
- Needs to be compensated!
- Low field correction:
  - Optimize flux tube
  - Fine tune transmission and resolution.
Main Spectrometer:
- MAC-E Filter principle → precise energy analysis
- Vacuum vessel on retarding potential
- High resolution: $\Delta E = 0.93 \text{ eV}$

$$\frac{\Delta E}{E_0} = \frac{B_{\text{min}}}{B_{\text{max}}} = 1/20000$$

- $\varnothing$ 10 m, length 23 m
  - Volume: 1240 m$^3$
  - Inner surface: 690 m$^2$

- Reduce background rate:
  - Ultra high vacuum (UHV): $p < 10^{-11}$ mbar
  - Induced by cosmic ray muons:
    → background increase
    → Counter measure: wire electrode

Precision Energy Filter:
- Variable retardation
- $U_0 = -18.4 \ldots -18.6 \text{ kV}$
- $\Delta E \sim 0.93 \text{ eV}$

![Graph showing region close to $\beta$ end point](image)
Spectrometer itself is a source of background

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

K. Valerius et al., Particle and Nuclear Physics, Volume 64, Issue 2, April 2010
Wire Electrode Installation - completed

- Wire installation until Jan. 2012 (7 Years)
- Entry electrodes mid 2012
- Baffle and getter pump and complete vacuum system until Nov. 2012
- Next: baking / vacuum conditioning
Radon as Background Source

- $^{219}\text{Rn}$ emanation from St707 NEG getter strips (3 $\cdot$ 1 km) in pump ports
Radon as Background Source

$^{219}$Rn emanation from St707 NEG getter strips (3 $\cdot$ 1 km) in pump ports
Radon as Background Source

- $^{219}$Rn emanation from St707 NEG getter strips (3 · 1 km) in pump ports

F.M. Fränkle et al.,
Astropart. Phys. 35 (2011) 128

S. Mertens et al.,
Astropart. Phys. 41 (2013) 52
Radon as Background Source

- passive background reduction: **LN2-cooled baffles** to cryocondense $^{219}\text{Rn}$
Background Reduction

- $^{219,220}$Rn emanation from bulk material of vessel
- need active background suppression

- stored multi-keV electrons:
  - rapid cyclotron motion
  - intermediate axial oscillation
  - slow magnetron drift

- Background process continues:
  - ionization of residual gas $\rightarrow$ secondary electrons
  - primary electron energies: $100 \text{ eV} < E < 500 \text{ keV}$
  - up to 5000 secondary electrons per stored primary
  - significant background increase for hours
1 kV between dipole halves, vessel Ø 10m → E=100 V/m

ExB drifts: electrons hit wall  
(works for E < 2 keV)
Background Reduction Methods

- **Electric Dipole**
  - 1 kV between dipole halves, vessel Ø 10m → E=100 V/m
  - ExB drifts: electrons hit wall (works for E < 2 keV)

- **Magnetic Pulse**
  - Maxwell law of induction:
    \[ \text{rot} \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \vec{E} = -\frac{r}{2} \frac{\partial \vec{B}}{\partial t} \]
  - Reduction of field strength → increased cyclotron radius → electrons hits the wall (works for all energies, but reversible)

- **Energy [eV]**

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Background Reduction Methods

**electric dipole**
- 1 kV between dipole halves, vessel Ø 10m → E=100 V/m
- ExB drifts: electrons hit wall (works for E < 2 keV)

**magnetic pulse**
- Maxwell law of induction:
  \[
  \text{rot} \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \vec{E} = -\frac{r}{2} \frac{\partial \vec{B}}{\partial t}
  \]
- Reduction of field strength → increased cyclotron radius → electrons hits the wall (works for all energies, but reversible)

**electron cyclotron resonance**
- Stochastic heating: RF pulsed matched to cycl. freq.
  \[
  \omega_{\text{RF}} = \omega_{\text{cycl}}, \quad \omega = \frac{eB}{m\gamma}
  \]
  → inc. cyclotron radius → electron hits the wall (works for all energies)
Vacuum conditioning for the commissioning measurements

- **aim:** UHV in huge spectrometer: $p \approx 10^{-11}$ mbar
- **to do:** spectrometer bake-out at $T = 300$ °C
- **achieved in January 2013** ✔
Spectrometer bake-out: procedure

- Slow heating: expansion of vessel and electrode by 10 cm
- Temperature breakpoints:
  - 200°C – water vapor removal
  - 300°C – activation of getter material

Baking cycle (4. - 30.1.2013)

Graph showing temperature and pressure over time in hours:
- Temperature range: 0°C to 350°C
- Pressure range: 10^-11 mbar to 10^-05 mbar

Leak developed at 10^-11 mbar level
Pressure back at standard activation conditions
Spectrometer Commissioning Status

Spectrometer bake-out: procedure

- slow heating: expansion of vessel and electrode by 10 cm

at 20 °C

Remember what’s inside!

at 300 °C
Spectrometer Commissioning Status

Spectrometer bake-out: procedure

° slow heating: expansion of vessel and electrode by 10 cm

10 cm left

at 20 °C

10 cm right

at 300 °C

Remember what’s inside!
Spectrometer – Detector Integration

- Detector integration requires valve inside magnet bore: *beam-line valve*
- Deformation of O-Ring during baking disabled the valve’s basic function
- Challenge to attach detector without venting / getter contamination

Visual and X-ray images showing the detector integration process.
Spectrometer – Detector Integration

- Replacing the O-Ring requires work under Ar gas atmosphere
- NEG pump requires Ar of quality N9.0 to prevent contamination

- O-Ring exchanged under Ar over pressure
- Beal-line valve leak tight
- Detector section attached

144 bottles of Argon gas N6.0

XENON 1t gas purification technology
SDS Commissioning

Commissioning of the Spectrometer and Detector Sections
(= all non Tritium parts of KATRIN)

- Main Spectrometer
- Main Detector
- Monitor Spectrometer
- E-Gun

developed at Uni Münster
Present Status:

- pressure $p = 7 \times 10^{-11}$ mbar
- identical to situation before venting
- all subsystems operational:
  - Vacuum and High Voltage
  - S.C. Magnets, Air Coils
  - Detector and DAQ
  - Monitoring and Database
  - Online-Analysis
- first light seen on May 31, 2013
SDS Commissioning & First Light

- asym. magn. field
- map electrode structure onto detector
SDS Commissioning & First Light

- asym. magn. field
- map electrode structure onto detector
- rate related to electrode potential

Event Rate

Rate [cps]

preliminary

T. Thümmler - Status and commissioning of KATRIN
SDS Commissioning & First Light

- asym. magn. field
- map electrode structure onto detector
- rate related to electrode potential
- rings identified

Preliminary
sym. magn. field
MAC-E filter conditions
rate dropped to 1.6 cps at retarding pot. $U = -600$ V
preliminary and to be improved!
Setup, DAQ, Database and Analysis working fine
- there is room for improvements

Background rate is low, but not low enough for KATRIN
- 1.6 cps at 146 pixels makes $10^{-2}$ cps per pixel
- Tritium runs requires $10^{-2}$ cps for all pixels
- no evidence for Penning-like traps found

Angular selective electron gun to be commissioned next
- check transmission properties of MAC-E filter

Commission high-voltage operation up to 35 kV
- check background and transmission under KATRIN conditions

Commission LN2 baffle system
- investigate Rn-related background
- investigate background reduction methods

Qualify main spectrometer for Tritium operation in 2015
KATRIN Sensitivity

- **reference ν-mass sensitivity** for 3 `full beam´ years (5y cal. time):
  - statistical & systematic errors contribute equally:
    - statistics $\sigma_{\text{stat}} = 0.018 \text{ eV}^2$
    - systematics $\sigma_{\text{syst}} < 0.017 \text{ eV}^2$

  **sensitivity** $m(\nu) = 200 \text{ meV (90% CL)}$

  350 meV (5σ)

- **plans for a later KATRIN phase II:**
  - differential β-energy spectrum:
    - cryo-bolometer array with $\Delta E \sim 1\text{eV}$?
    - synchrotron emission (GHz-range)?
  - precision external value end point $E_0$
  - atomic tritium source?
Summary & Outlook

- motivation for neutrino mass meas. from particle and astroparticle physics
- $\beta$ decay offers a model-independent method to determine $m_\nu$
- KATRIN is designed to reach a sensitivity of 200 meV on $m_\nu$

- KATRIN continuing construction and started commissioning:
- Source under construction, to be delivered in early 2015
- Transport sections under construction, to be delivered Spring 2014
- Main Spectrometer and Detector commissioning just started
  - First Light on May 31\textsuperscript{st}
  - Continuing with HV and Baffle operation until September.
- Upgrade program in Fall 2013