Commissioning of the KATRIN spectrometer and detector section

Nancy Wandkowsky for the KATRIN collaboration

561. WEH-Seminar „Massive Neutrinos“, Bad Honnef

- The KATRIN experiment
- Hardware commissioning
- SDS measurements
  - Transmission measurements
  - Background measurements
The KATRIN experiment

Direct determination of \( m(\overline{\nu}_e) \)

- \( \beta \)-decay: \( (A,Z) \rightarrow (A,Z+1) + e^- + \overline{\nu}_e \)
- Electron energy spectrum:

Expected count rate: \( 10^{-2} \) cps
The KATRIN experiment

KArlsruhe TRItium Neutrino experiment (KATRIN)

- sensitivity:
  - upper limit: 200 meV (90% CL)
  - discovery: 350 meV (5σ)
- predecessor experiments (Mainz, Troitsk): $m(\bar{\nu}_e) < 2.1$ eV
The KATRIN experiment

KArlsruhe TRItium Neutrino experiment (KATRIN)

Key requirements:
- low endpoint $\beta$ source
- high count rate
- high energy resolution
- low background ($<10^{-2} \text{ cps}$)

source  transport  spectrometer  detector

70 m
The KATRIN experiment

KArlsruhe TRItium Neutrino experiment (KATRIN)

source transport spectrometer detector

70 m

key requirements:
- low endpoint $\beta$ source
- high count rate
- high energy resolution
- low background (<10^{-2} cps)

$E_0 = 18.6$ keV

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The KATRIN experiment

KArlsruhe TRItium Neutrino experiment (KATRIN)

source
transport
spectrometer
detector

70 m

key requirements:
- low endpoint $\beta$ source
- high count rate
- high energy resolution
- low background ($<10^{-2}$ cps)
The KATRIN experiment

Magnetic adiabatic collimation & electrostatic filter

orb. magn. moment $\mu = \frac{E_{\perp}}{B} = \text{const.}$

$\mathbf{p}$

MAC

$\mathbf{E}$ filter

$B_{\text{min}}$ $B_{\text{max}}$

1:20000

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The KATRIN experiment

Magnetic adiabatic collimation & electrostatic filter

High acceptance angle

Energy resolution:

$$\Delta E = E_0 \frac{B_{\text{min}}}{B_{\text{max}}} = 1\ eV$$
The KATRIN experiment

KArlsruhe TRItium Neutrino experiment (KATRIN)

key requirements:
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source  transport  spectrometer  detector
The KATRIN experiment

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Hardware commissioning
Hardware commissioning

SDS Commissioning in 2013
SDS = spectrometer and detector section

- inner electrode system
- electron-gun
- Air coil system
- NEG pumps and baffle system

SDS = spectrometer and detector section

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Hardware Commissioning

Air coil system

- without any air coil system (solenoids only)
- distorted flux tube due to earth magnetic field
- central field too weak

Flux tube transporting signal electrons

\[ B = 1 \times 10^{-4} \, \text{T} \]

\[ B = 6 \, \text{T} \]
Hardware Commissioning

Air coil system

- with earth magnetic field compensation system (EMCS)
- flux tube symmetric around spectrometer axis
- central field too weak (desired value: $3 \cdot 10^{-4}$ T)

$B = 6$ T

EMCS

$B = 1 \cdot 10^{-4}$ T
Hardware Commissioning

Air coil system

- with EMCS and low field correction system (LFCS)
- central field at desired value: $3 \cdot 10^{-4}$ T
- full transmission

B = $3 \cdot 10^{-4}$ T  B = 6 T
Hardware Commissioning

**Air coil system**

- with EMCS and low field correction system (LFCS)
- central field at desired value: $3 \cdot 10^{-4}$ T
- full transmission & background suppression (factor $10^5$)
LFCS

large Helmholtz coil system

main spectrometer vessel

EMCS

$\varnothing = 12.6 \text{ m}$
Hardware commissioning

Inner electrode & high voltage system

- Smooth electric potential
- Maximal potential in center (-18.6 kV)
- Single layer: factor ~10
- Double layer: factor 100
Inner Electrode System

Jan. 31, 2012
Hardware commissioning

NEG pump & baffle system

- 6 turbo-molecular pumps: $10^4 \, \text{l/s (H}_2\text{)}$
- 3 NEG-pumps (3000 m strips): $\sim 10^6 \, \text{l/s (H}_2\text{)}$
- 3 LN$_2$-cooled baffles: $\sim 170 \, 000 \, \text{l/s (Rn)}$

J. Wolf – Poster 23
Hardware commissioning

Closing the vessel after completion of installations within vessel

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Hardware commissioning

Ultra-high vacuum (UHV)

- goal: $10^{-11}$ mbar in volume of 1240 m$^3$
- spectrometer bake-out:
  - water removal from surface
  - activation of chemical getter pump
- achieved: $10^{-10}$ mbar
Hardware commissioning

Spectrometer bake-out: vessel expansion

J. Wolf

insulator

fix point

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Hardware commissioning

Electron gun

- Quasi-monoenergetic
- Angular selective

M. Zacher – Poster 24
Hardware commissioning

Electron gun

- Quasi-monoenergetic
- Angular selective

- Diagnostic tool
- Study of signal electron transport
Hardware commissioning

Integration of detector and spectrometer

- May 16, 2013: SDS connection established
- May 28, 2013: opening gate valve

148 pixel Si-PIN diode
Detector performance

Peaks are measurement artefact.

→ Total background in ROI: $<4.6 \pm 0.2$ mcps (goal: 1 mcps)
Hardware commissioning

- 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**

**X-rays**
Hardware commissioning

- replacing the O-ring requires work under inert gas atmosphere (Ar)
- NEG pump requires Ar of quality N9.0 to prevent contamination

☑ O-ring exchanged in Ar atmosphere
☑ beam-line valve now leak tight
☑ detector section attached

144 bottles Argon N6.0

XENON 1t gas purification system (SAES)
SDS measurements
Spectrometer-Detector-Section commissioning

Main goals:
- Test of Hardware and Slow Control components
- Understanding of transmission properties
- Measurement and Understanding of background
- Verification of simulations software and models
First „light“

Asymmetric magnetic field

- May 31, 2013
- map field emission from electrode onto detector
- misalignment: tilted detector chamber
- confirmed by simulations
First „light“

Asymmetric magnetic field

- May 31, 2013
- map field emission from electrode onto detector
- misalignment: tilted detector chamber
- confirmed by simulations
- shadow: flapper valve

![Diagram showing asymmetric magnetic field with data and simulation results.](image-url)
SDS measurements

- Transmission of β-electrons: magnetic guiding & electrostatic retardation

- Background: spectrometer acts as a magnetic bottle, long storage (h)
Transmission measurements

Study of signal electron transport

Transmission probability

e-gun energy distribution
(schematically)

\[ |U_2| < |U_1| \]

starting energy

\[ E_{\text{start}} - q \times U_{\text{AP}} \]
Transmission measurements

Study of signal electron transport

![Graph showing transmission probability vs. energy difference](image-url)

- Measurement
- Monte Carlo

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Transmission measurements

Study of signal electron transport

- Transmission functions measured at various retarding potentials [0, -18.6 kV]
- … and radial positions (e-gun manipulator used to pinpoint individual pixels)
- width of transmission function dominated by systematic effects of the electron gun (energy spread and angular spread) → spectrometer works as expected
Background measurements

First look at background @ full high voltage setup

- initial background already below 1 cps!  (previous spectrometers: $10^5$ cps)
- goal: $10^{-2}$ cps = 10 mcps

781.9 ± 2.7 mcps
Background measurements

Background sources: muons and radon

How large are the individual background contributions?
Background measurements

Muon-induced background: theory

- total muon-flux onto spectrometer: 75 kµ/s
- a small fraction produces single hit events at the detector
Background measurements

Muon-induced background: countermeasure

- Background suppression by inner electrode
- Single layer: factor 10 suppression
- Prospect for double layer: > factor 100

![Graph showing electron rate vs. wire module potential difference](image)

- Both wire layers at vessel potential
- Both wire layers at same potential
- 100 V potential difference between wire layers

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Background measurements

Radon-induced background
Background measurements

Radon-induced background

- nuclear decays inside spectrometer volume
- magnetic bottle effect: stored electrons
- ionization of residual gas → many secondary electrons on detector
- UHV (10^{-11} mbar) → storage time up to several hours
Background measurements

Disentanglement of background sources

- Measurement at increased pressure: \(10^{-11} \text{ mbar} \rightarrow 10^{-8} \text{ mbar}\) (Ar injection)
- Individual radon events as spikes in count rate
- Background contribution: radon : muon \(\approx 40 : 60\)

![Graph showing disentanglement of background sources](image)
Background measurements

Passive background reduction: principle

LN$_2$ cooled baffle

spectrometer vessel

NEG-Pump

$^{219}$Rn
Background measurements

Passive background reduction: measurement

- Background reduction by ~40% → muon-dominated
- high pressure measurements confirm very high baffle efficiency
- minimal bg: ~0.6 cps (scaled to full detector) → 300 meV m(ν) sensitivity

![Graph](image)

- electron rate vs. wire module potential difference
- both wire layers at vessel potential
- both wire layers at same potential
- 100 V potential difference between wire layers

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Background measurements

Active background reduction

- idea: influence electron flight path by modification of electromagnetic fields

J. Behrens – Poster 1
D. Hilk – Poster 7
Background measurements

**Active background reduction**

- test with Kr source (artificial bg increase)
- factor 10 reduction of stored particle bg achievable
- requires UHV $p \leq 10^{-11}$ mbar
Summary & Outlook

- KATRIN: determine $m_\nu$ with 200 meV sensitivity (90% CL)
- Successful commissioning of spectrometer and detector section (non-tritium part of beam line)
  - Electron transmission: spectrometer works as MAC-E filter
  - Background: cosmic muon, radon induced, passive & active background reduction methods
  - Minimal achieved bg rate: $\sim$600 mcps (goal: 10 mcps)
- Prepare 2\textsuperscript{nd} commissioning phase (summer/autumn 2014)
  - Improve spectrometer-detector alignment
  - Inner electrode & NEG pump modifications
  - Bake-out in July
- Start of tritium operation: 2016
Thanks for your attention!