The KATRIN neutrino mass experiment - status update and first tritium measurements

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Neutrino mass in particle physics

- Nature of the neutrino: Majorana or Dirac particle, i.e. is the neutrino its own anti-particle?

- How to explain the many orders of magnitude difference between neutrino mass limits and masses of the charged fermions of the standard model → sea-saw type I and type II mechanisms

- Possible connection to the generation of the observed matter - antimatter asymmetry in the universe → leptogenesis
Neutrino mass in cosmology

- Neutrinos are (after γ's) the second most abundant particle species in the universe.
- As part of the hot dark matter, neutrinos have a significant influence on structure formation.

\[ \Sigma m_\nu = 0 \text{ eV} \]
\[ \Sigma m_\nu = 1 \text{ eV} \]
\[ \Sigma m_\nu = 7 \text{ eV} \]
\[ \Sigma m_\nu = 4 \text{ eV} \]

- For large \( \Sigma m_\nu \) values fine grained structures are washed out by the free streaming neutrinos.

Chung-Pei Ma 1996
Search for neutrino mass

**β-decay: absolute ν-mass**
model independent, kinematics
status: $m_\nu < 2.3$ eV
potential: $m_\nu \approx 0.2$ eV
e.g.: KATRIN, Project-8, ECHO HOLMES, NuMECS

**0νββ-decay: eff. Majorana mass**
model-dependent (CP-phases)
status: $m_{\beta\beta} < 0.31$ eV
potential: $m_{\beta\beta} \approx 20$-50 meV
e.g.: GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA, KamLAND-Zen

**cosmology: ν hot dark matter $\Omega_\nu$**
model dependent, analysis of CMB and structure formation data
status: $\Sigma m_\nu < 0.23$ eV
possible signal: $\Sigma m_\nu = 0.11 \pm 0.03$eV
(Emami et al., arXiv:1711.05210)
Kinematic determination of $m(\nu_e)$

$$\frac{d\Gamma}{dE} = C \, p(E + m_e)(E_0 - E)\sqrt{(E_0 - E)^2 - m_{\nu_e}^2} \, F(Z + 1, E) \Theta(E_0 - E - m_{\nu_e}) S(E)$$

$$C = \frac{G_F^2}{2\pi^3} \cos^2 \theta_C |M|^2$$

(modified by final state distribution, recoil corrections, radiative corrections, ...)

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

Tritium

- $E_0 = 18.6$ keV, $T_{1/2} = 12.3$ a
- $S(E) = 1$ (super-allowed)

Detector requirements:

- large solid angle or source=detector approach
- high energy resolution
- low background
- low dead time / no pile up
Signature of sterile neutrinos

Shape modification below $E_0$ by active ($m_a^2$) and sterile ($m_s^2$) neutrinos:

$$\frac{d \Gamma}{dE} = \cos^2(\theta_s) \frac{d \Gamma}{dE}(m_a^2) + \sin^2(\theta_s) \frac{d \Gamma}{dE}(m_s^2)$$

additional kink in $\beta$-spectrum at $E = E_0 - m_s$

light sterile $\nu$, $m_s = 3$ eV

keV sterile $\nu$, $m_s = 7$ keV
- adiabatic transport $\rightarrow \mu = \frac{E_{\perp}}{B} = \text{const.}$
- $B$ drops by $2 \cdot 10^4$ from solenoid to analyzing plane $\rightarrow E_{\perp} \rightarrow E_{\parallel}$
- only electrons with $E_{\parallel} > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\perp,\text{max, start}} \cdot \frac{B_{\text{min}}}{B_{\text{max}}} < 1$ eV
KATRIN experiment at KIT

Gaseous $^3$H source

- $^3$H
- $^3$He
- $^3$H decay
- $e^-$
- $10^{10} e^-/s$

Transport section

- $e^-$
- $10^{10} e^-/s$

Pre-Spectrometer

- $E > 18.3$ keV
- $10^3 e^-/s$
- $\Delta E = 0.92$ eV

Spectrometer

- $e^-$
- $1 e^-/s$

Detector

Diagnostics

$E = 18600$ eV

70 m
Statistical uncertainty:

\[ \sigma_{\text{stat}} \approx 0.018 \text{ eV}^2 \]

Systematic uncertainty:

\[ \sigma_{\text{sys,tot}} \approx 0.017 \text{ eV}^2 \]

Sensitivity for upper limit:

\[ 0.2 \text{ eV/c}^2 \text{ (90\% C.L.)} \]

\[ m(\nu_e) = 0.35 \text{ eV observable with 5}\sigma \]
Windowless Gaseous Tritium Source

- beam tube \( \varnothing = 9 \text{ cm}, L = 10 \text{ m} \)
- guiding field \( 3.6 \text{ T} \)
- temperature \( T = 30 \text{ K} \pm 30 \text{ mK} \)
- \( T_2 \) flow rate \( 5 \cdot 10^{19} \text{ molecules/s} \) (40 g of \( T_2 \)/day)
- \( T_2 \) purity \( 95\% \pm 0.1 \% \)
- \( T_2 \) inlet pressure \( 10^{-3} \text{ mbar} \pm 0.1 \% \)

- column density \( 5 \cdot 10^{17} \text{ } T_2/\text{cm}^2 \)
- luminosity \( 1.7 \cdot 10^{11} \text{ Bq} \)

WGTS at Tritium Laboratory Karlsruhe
Main-Spectrometer

- 18.6 kV retardation voltage, $\sigma < 60$ meV
- 0.93 eV resolution
- pressure $< 10^{-11}$ mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping

$\sigma_E = 50$ meV (single angular emittance)

TF with UV LED
Focal Plane Detector

Focal plane detection system

- segmented Si PIN diode: 90 mm Ø, 148 pixels, 50 nm dead layer
- energy resolution ≈ 1 keV
- pinch and detector magnets up to 6 T
- post acceleration (10kV)
- active veto shield

segmented Si-PIN wafer

pre-amplifier wheel

detector magnets at KIT
Project milestones: first light 2016

Technical inauguration of KATRIN, October 2016

Testing complete 70m long beamline
with electrons:
- alignment
- magn. steering of pencil beam
and with ions:
- ion removal

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Photoelectrons with E ~ 100 eV
2017: scientific campaign with $^{83m}\text{Kr}$

Use of monoenergetic conversion electrons from $^{83m}\text{Kr}$ sources to investigate stability and MAC-E filter spectroscopic properties

- **gaseous Kr**: > 10 m long, full flux tube
- **condensed Kr**: sub-monolayer, spot-like

$^{83m}\text{Kr}$ from 1GBq $^{83}\text{Rb}$ source

repeated scans of L3-32 line over a week:
- required ± 60 meV
- GKrS measured
  → excellent long term stability

CKrS line stability with pre-plating
- ≈ 1meV/h
**Official KATRIN inauguration: first tritium campaign (engineering run)**

**Motivation:**
- method: inject known gas mix from prepared cylinders (80% of nominal $\rho_d$, ~1% DT and ~99% D2 corresponds to <1% of nominal activity \(\approx 500 \text{ Mbq}\))
- verify functionality of all system components and demonstrate 0.1% global stability
- study beta spectrum for systematic effects and test analysis strategies
Stability of experimental parameters

Source stability over 12h period

Blue arrow: systematic uncertainty
Red dashed line: ± 0.1% stability required for neutrino mass taking

Source parameters are stable and within the specifications

DT concentration measured by laser Raman spectroscopy

Schlösser et al., J. Mol. Spect. 1044 61 (2013)
First tritium: model fits

Analysis of first tritium scan (200 eV):
- model gives very good understanding of both rate and shape (even up to 2 keV!!)
- fit ($E_0$, bckg., Amp.) results agree with expectations

![Graph showing model (no fit) and measurement](Image)

Endpoint stability

![Graph showing $E_0 - \langle E_0 \rangle$ vs. Retarding energy](Image)

72 runs = 5.3 days
KATRIN physics programme

KATRIN physics channels:
- model-independent electron (anti-)neutrino mass: $m(\nu_e)$, sensitivity 0.2 eV @ 90% CL
- search for sterile neutrinos in the eV to keV range
- constrain local relic-ν density, search for Lorentz violations, exotic currents, BSM physics ...

KATRIN $m(\nu_e)$ sensitivity

observed increased spectrometer background can largely be mitigated by optimized measurement procedure → 0.24 eV sensitivity not the final word ...


projected sensitivity to keV scale neutrinos

A. Boyarsky et al., arXiv:1807.07938

sensitivity to eV scale neutrinos

Formaggio & Barrett, PL B706 (2011) 68

Riis & Hannestad, JCAP 02 (2011) 011

TRISTAN prototype
Summary

- Studies of β-decay kinematics offer a model-independent way to determine the neutrino mass, complementary to cosmology and 0νββ searches

- KATRIN will probe the neutrino mass range down to 0.2 eV

- By default, KATRIN is also sensitive to eV scale sterile neutrinos and, with a future detector upgrade, able to probe for keV sterile neutrinos

- First tritium measurements with reduced activity in June 2018

- Tritium data taking with full source strength beginning 2019
Thank you for your attention!

LN2 baffle installed in main spectrometer pump port.
Systematic effects and error budget

1. Inelastic scattering of $\beta$'s in the source (WGTS)
   - calibration measurements with e-gun necessary
   - deconvolution of electron energy loss function

2. Fluctuations of WGTS column density (required $< 0.1\%$)
   - rear wall detector, Laser - Raman spectroscopy,
     T=30K stabilization, e-gun measurements

3. Transmission function
   - spatially resolved e-gun measurements

4. WGTS charging due to decay ions (MC: $\phi < 20mV$)
   - Injection of low energy (meV) electrons from the
     rear end, diagnostic tools available

5. Final state distribution
   - reliable quantum chem. calculations

6. HV stability of retarding potential on 3ppm level required
   - precise HV-Divider (PTB), monitor spectrometer,
     calibration sources

fluctuations $\sigma^2$ lead to a downward shift in $m_\nu^2$

$$\Delta m_\nu^2 = -2 \sigma^2$$

allow only few contributions with $\Delta m_\nu^2 \leq 0.007 \text{ eV}^2$

$$\Leftrightarrow \sigma < 60 \text{ meV}$$

$$\Delta U = \frac{0.06}{18575} \approx 3 \cdot 10^{-6}$$

$$\Rightarrow 3 \text{ ppm long term stability}$$
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**KATRIN sensitivity:**

5 year measurement
\( \text{(eff. 3 y of data)} \)

- statistical uncertainty
  \( \sigma_{\text{stat}} \approx 0.018 \text{ eV}^2 \)
- systematic uncertainty
  \( \sigma_{\text{sys,tot}} \approx 0.017 \text{ eV}^2 \)

\( \rightarrow \) sensitivity for upper limit: \( 0.2 \text{ eV/c}^2 \) (90% C.L.)
\( m(\nu_e) = 0.35 \text{ eV} \) observable with 5σ

\( \Delta \frac{U}{U} = \frac{0.06}{18575} \approx 3 \cdot 10^{-6} \)
\( \Rightarrow 3 \text{ ppm long term stability} \)
KATRIN background studies

- 8 sources of background investigated and understood
- 7 out of 8 avoided or actively eliminated by
  - fine-shaping of special electrodes
  - symmetric magnetic fields
  - LN$_2$-cooled baffles (cold traps)
  - wire electrode grids

- 1 out of 8 remaining:
  caused by $^{210}$Pb on spectrometer walls (neutral H* atoms ionised by black-body radiation in spectrometer)
Background from Rydberg atoms

H* Rydberg atoms:
- desorbed from walls due to $^{206}$Pb recoil ions from $^{210}$Po decays
- non-trapped electrons on meV-scale
- bg-rate: $\sim 0.5$ cps

Testing this hypothesis:
artificially contaminating the spectrometer with implanted short-living daughters of $^{220}$Rn

counter measures:
- reduce H-atom surface coverage:
  a) extended bake-out phase: done
  b) strong UV illumination source

Mitigation strategies for higher (Rydberg) background rate:
use larger data range ($E_0 - 60$ eV), an optimized magnetic field setting (lower energy resolution, but smaller flux-tube volume) and a different measurement time distribution
\[ \tau = \tau_{^{212}\text{Pb}} \]
→ 240 meV (without further background reduction)
**KATRIN background & sensitivity**

**Problem:** current background level much higher than design value

**Mitigation strategy:**

- optimized measurement time distribution
- enlarged energy range of spectral analysis
- flux tube compression by increasing $B_{\text{min}}$

![Graph showing the sensitivity on m_e in meV (90% C.L.) for different energy levels and B-fields.]

- $E_0 = 30 \text{ eV}$
- $E_0 = 45 \text{ eV}$
- $E_0 = 60 \text{ eV}$

558 mcps non-optimized

- $\Delta E \approx 240 \text{ meV}$
- TDR 2004 optimized for 10 mcps
- $\Delta E \approx 2.5 \text{ eV}$

![Diagram illustrating the optimized measurement with B-fields of 0.38 mT, 0.50 mT, and 0.80 mT.]

M. Kleesiek
What about sterile neutrinos?

- **Reactor anomaly**: ca. 6% deficit in observed neutrino flux measured close to nearly 20 nuclear power stations (*Mention et al., Phys.Rev.D83:073006, 2011*)

  → could be a hint to the existence of so-called **sterile** neutrinos

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e \text{ sterile}} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu \text{ sterile}} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau \text{ sterile}}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_{\text{sterile}}
\end{pmatrix}
\]

- Sterile neutrinos: only interact gravitationally, produced by mixing with standard (active) neutrino species

- 3+1 scenario: consider only one large mass splitting between lower (L) and upper (U) mass regime: \(\Delta m^2_S \approx \bar{m}_U^2 - \bar{m}_L^2\)

  → best fit from combined data of reactor flux measurements, GALLEX and SAGE calibration data and MiniBooNE:

\[
|\Delta m^2_S| > 1.5 \text{ eV}^2, \quad \sin^2(2\theta_S) = 0.14 \pm 0.08
\]
Sterile neutrinos as warm dark matter

- $\Lambda$CDM (Cold Dark Matter with cosmological constant) models predict too much structure at galactic scales (too many satellite galaxies)

  - CDM (100 GeV)
  - non-thermal WDM (1keV)
  - thermal WDM (1keV)

(e.g. A. Kamada at Meudon Workshop 2011)

  → Warm Dark Matter (e.g. keV sterile neutrinos) could resolve this problem

- In KATRIN: look for a kink a few keV below the endpoint of the $\beta$ - spectrum

- **But:** Systematic uncertainties due to
  - Electronic excitation of daughter molecules
  - Inelastic scattering of decay electrons in the source

  → careful investigation required to see if we have a chance for detection
Monte Carlo framework KASSIOPEIA

- KATRIN requires precise numerical simulations of all experiment components to minimize systematic uncertainties

- many software packages have been written for the individual subsystems
  → need a coherent framework to unify these efforts
  → development of a global simulation package: KASSIOPEIA

- tailored to the special needs of the KATRIN experiment:
  - ultra high precision
  - calculation of electromagnetic fields
  - particle generation / tracking / scattering
  - inclusion of a realistic geometrical model of the experiment
  - compatibility with KATRIN database and DAQ
Spectrometer calibration and monitoring

- T₂ β-decay electrons
- Electron gun
- ⁸³Kr conv. electrons
- Monitor spectrometer

HV-supplies
- up to 35 kV
- 5 ppm/8h

D. Venos, arXiv 0902.0291;
M. Rasulbaev et al.,

⁸³Kr conversion electrons
natural standard via 17.8 keV
conversion electrons from ⁸³Kr

T. Thümmler et al.,
New Jour. Phys. 11, 103007 (2009)

Precision HV dividers (with PTB)
error budget: \( \Delta m^2_u < 0.0075 \text{ eV}^2/c^4 \rightarrow \sigma_u < 60 \text{ mV} \) @ 18.6 kV
Pumping sections

**Differential Pumping Section (DPS2-F)**
- magnetic guiding field $B = 5.6$ T
- differential pumping using 2000 l/s TMPs
  $\rightarrow$ tritium reduction factor: $1 \cdot 10^5$
- ion monitoring by FTICR
- ion manipulation by electrodes

**Cryogenic Pumping Section (CPS)**
- magnetic guiding field $B = 5.6$ T
- cryosorption of $T_2$ on Ar frost at $\approx 3$ K
  $\rightarrow$ tritium reduction factor $1 \cdot 10^7$
- within 60 days: accumulation of 1 Ci
Pre-Spectrometer

Testing ground for many systematical effects and background sources, e.g.:

- **Removal of Penning traps** (special electrode shapes)
- **Compensation of high frequency HV noise** (triode shunt circuit)
- **Removal of trapped particles** (dipole mode, HF excitation)
- **Removal of Radon induced background** (LN2 baffle)
- **Remaining background** $\approx 20 \text{ mHz}$

- Pre-filter with a fixed potential: $E = 18.3 \text{ keV}$
- Transmission of high energy electrons only
  \[ \text{\rightarrow reduction from } 10^{10} \text{ to } 10^3 \text{ e}^-/s \]
  \[ \text{\rightarrow reduction of background due to scattering in the main spectrometer} \]
Current knowledge and open questions

**What we know (from ν oscillations):**

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm² values known (with varying accuracies)

**What we don't know:**

- Normal or inverted hierarchy?
- Dirac or Majorana particle?
- CP violating phases in mixing matrix?
- No information about absolute mass scale! (only upper limits)
- Existence of sterile neutrinos?