Introduction
The Karlsruhe Tritium Neutrino experiment KATRIN
Outlook on possible improvements & sterile neutrinos
Summary
Direct determination of $m(\nu_e)$ from $\beta$ decay (similarly EC)

$\beta$ decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

$\beta$: $dN/dE = K \cdot F(E,Z) \cdot p \cdot E_{tot} \cdot (E_0-E_e) \cdot \sqrt{(E_0-E_e)^2 - "m(\nu_e)"^2}$

phase space: $p_e \cdot E_e \cdot E_v \cdot p_v$

(modified by electronic final states, recoil corrections, radiative corrections)

Need: low endpoint energy
very high energy resolution & very high luminosity & very low background

$\Rightarrow$ Tritium $^3H$, ($^{187}Re$, $^{163}Ho$)

$\Rightarrow$ MAC-E-Filter
(or bolometer for $^{187}Re$, $^{163}Ho$)

Complementary to $0\nu\beta\beta$ and cosmology

E.W. Otten & C. Weinheimer

G. Drexlin, V. Hannen, S. Mertens,
The classical way: Tritium $\beta$-spectroscopy with a MAC-E-Filter

- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation: $\mu = E_\perp / B = \text{const.}$ ⇒ parallel $e^-$ beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{\text{min}} / B_{\text{max}} = 0.93 \text{ eV (KATRIN)}$

$\Rightarrow$ sharp integrating transmission function without tails →

Magnetic Adiabatic Collimation + Electrostatic Filter
The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview

Sensitivity on $m(\nu_e)$:
$2 \text{ eV/c}^2 \rightarrow 200 \text{ meV/c}^2$
Molecular Windowless Gaseous Tritium Source WGTS

WGTS: tub in long superconducting solenoids
- Ø 9cm, length: 10m, T = 30 K

Tritium recirculation (and purification)
- $p_{\text{inj}} = 0.003$ mbar, $q_{\text{inj}} = 4.7$Ci/s

allows to measure with near to maximum count rate using
- $\rho_d = 5 \cdot 10^{17}$/cm$^2$

with small systematics

check column density by e-gun, $T_2$ purity by laser Raman

per mill stability source strength request:
- $\frac{dN}{dt} \sim f_T \cdot N / \tau \sim n = f_T \cdot p \cdot V / R \cdot T$

tritium fraction $f_T$ & ideal gas law
Status of Windowless Gaseous molecular Tritium Source WGTS

Assembly of beam tube, magnets and cryostat:

- Temperature stability tests of „demonstrator“ very successful
- Management now in the hand of KIT
- Progress according schedule
- Arrival at KIT in 2015

Complete WGTS
Transport and differential & cryo pumping sections

• old cryostate safety system failed → had to build new differential pumping section
• based on simple warm beam-tube and pump port design surrounded by superconducting warm-bore magnets
• S. Lukic et al., Vacuum 86 (2012) 1126

• active pumping: 4 TMPs
• Tritium retention: $10^5$
• magnetic field: 5.6 T
• under construction, full delivery mid 2014
Transport and differential & cryo pumping sections

- based on by cryo-sorption
- Tritium retention: $>10^7$
- magnetic field: 5.6 T
- delivery end of 2014

O. Kazachenko et al., NIM A 587 (2008) 136
F. Eichelhardt et al, Fusion Science and Technology 54 (2008) 615
Tritium source systematics

Sensors & calibration:
Tritium activity: x-ray detector
Tritium purity: Laser Raman spectroscopy LARA
WGTS stabilization: temperature & pressure stab.
Potential stabilization: rear wall with well-defined work fcn
Column density: energy loss measurement with e-gun
Beam intensity: forward beam monitor
Energy loss and response function: e-gun, $^{83m}$Kr source

Simulations:
Gas dynamics
Beta spectrum
ray-tracing of betas with KASSEIPEIA

M. Babutzka et al., NJP 14 (2012) 103046
S. Grohmann et al., Cryogenics 55 (2013) 5

more details on the posters:
Kassiopeia (D. Furse)
WGTS (L. Kuckert)
Calibration & Monitoring System (F. Heizmann et al.)
KATRIN spectrometers

Pre spectrometer:
- successful tests & developments of new concepts

Main spectrometer:
- huge size: 10m diameter, 24m length
  1240 m$^3$ volume, 690 m$^2$ inner surface
- ultra-high vacuum: $p = O(10^{-11}$ mbar)
- ultra-high energy resolution: $\Delta E = 0.93$ eV
- vacuum vessel on precise high voltage (ppm precision)

$\Rightarrow \Delta E = E \cdot \frac{B_{\text{min}}}{B_{\text{max}}} = E \cdot \frac{1}{20000} = 0.93$ eV
The detector

Requirements
• detection of $\beta$-electrons (mHz to kHz)
• high efficiency (> 90%)
• low background (< 1 mHz) (passive and active shielding)
• good energy resolution (< 1 keV)

Properties
• 90 mm Ø Si PIN diode
• thin entry window (50nm)
• detector magnet 3 - 6 T
• post acceleration (30kV) (to lower background in signal region)
• segmented wafer (148 pixels)
→ record azimuthal and radial profile of the flux tube
→ investigate systematic effects
→ compensate field inhomogeneities
Main spectrometer and detector commissioning – objectives

Primary objectives:
- test of individual hardware, software and slow control components
- provide ultra high vacuum conditions at the $p \approx 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter ($E = 18.6$ keV with $\Delta E = 0.93$ eV resolution) and compare to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes
First switch on with full high voltage on August 13/14, 2013

Could switch on main spectrometer without large background rate
all other MAC-E-Filters (Troitsk, Mainz, KATRIN pre spectrometer)
exhibited rates > $10^5$ cps when switched on for the first time
→ No large Penning traps (advanced KATRIN design works)

This first measurement without wire electrode on screening potential,
LN$_2$ baffles cold and active counter measures against stored electrons

But still KATRIN requires a background rate of $10^{-2}$ cps
Commissioning of main spectrometer and detector

\[ \sigma_E = 50 \text{ meV} \]
(single angular emittance)

\[ \chi^2 / \text{n df} = 382.9 / 20 \]
\[ \mu = -1.651 \pm 0.0003893 \]
\[ \sigma = 0.04922 \pm 0.0004421 \]
\[ \text{amp} = 575.9 \pm 1.314 \]
\[ \text{bkg} = 6.79 \pm 0.2158 \]

time-of-flight, see also N. Steinbrink et al., NJP 15 (2013) 113020
Suppress secondary electron background from walls on high potential

Secondary electrons from wall/electrode by cosmic rays, environmental radioactivity, ...

Excellent magnetic shielding by nearly perfect axial sym.

Additionally double layer wire electrode on slightly more negative potential

(ca. 23,000 wires, 200 μm precision, UHV compatible)
6 electric shorts between layer 1 and layer 2 of electrode system due to out-baking

→ test wire electrode shielding by applying asymmetric B-fields switching off magnetic shielding

Secondary electrons from wall
- a lot, but screened by wire electrode
- dual wire electrode system is order of magnitude more efficient

April 2014: electric shorts in central cylindrical part of wire electrode removed!
Secondary electron background from radon decays in the volume

- $^{219,220}$Rn emanation mainly from SAES getter pumps (zirconium vanadium iron alloy) conversion, Auger, shake-off electrons can get stored by my magnetic mirror effect

- **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

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

F. Fränkle et al., APP 35 (2011) 128
S. Mertens et al., APP 41 (2012) 52
N. Wandkowsky et al., NJP 15 (2013) 8
Radon elimination by LN$_2$-cooled baffles in the pre & main spectrometer

**Pre spectrometer baffle prototype with NEC pump**

**Warm baffle:**
30 min intervals with 250 mHz – 300 mHz

**LN$_2$ cold baffle:**
background is always < 50 mHz

Successful application at pre spectrometer
Understanding the background: Radon and other background sources

Measurements at elevated pressure to shorten time difference between ionisation processes.

Very good background understanding: spike pulses can also be removed by LN2 baffle → indeed stored electrons by radon decays.
Active stored particle removal by electric dipole and magnetic zeroing

more details on the posters:
- Monitoring of the KATRIN HV (M. Slezak, M. Erhard)
- Active background reduction (D. Hilk, J. Behrens)
- Main spectrometer commissioning (M. Kraus, T. Thümmler)
- First spectrometer & detector measurements (S. Groh, N. Wandkowsky)

\[ \mathbf{v}_D = \mathbf{E} \times \mathbf{B} / B^2 \]

\(^{83}\text{m}\text{Kr} \) injected to enhance no of stored particles

loss of magnetic guidance
As smaller $m(\nu)$ as smaller the region of interest below endpoint $E_0$ → quantum mechanical thresholds help a lot!

**A few contributions with $\Delta m_{\nu}^2 \leq 0.007 \text{ eV}^2$ each:**

1. Inelastic scatterings of $\beta$’s inside WGTS
   - dedicated e-gun measurements, unfolding of response fct.

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

3. WGTS charging due to remaining ions (MC: $\varphi < 20\text{mV}$)
   - monocrystaline rear plate short-cuts potential differences

4. Final state distribution
   - reliable quantum chem. calculations

5. Transmission function
   - detailed simulations, angular-selective e-gun measurements

6. HV stability of retarding potential on ~3ppm level required
   - precision HV divider (with PTB), monitor spectrometer beamline
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Systematic uncertainties

- inelastic scatterings of \( \beta \)'s inside WGTS
- dedicated e-gun measurements, unfolding
- fluctuations of WGTS column density (required < 0.1%)
- rear detector, Laser-Raman spectroscopy, \( T=30\text{K} \) stabilisation, e-gun measurements
- monocrystalline rear plate short-cuts potential differences
- reliable quantum chem. calculations
- detailed simulations, angular-selective e-gun measurements
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Measuring the last 25 or 30 eV only KATRIN becomes nearly a "single final state" experiment as cryo-bolometers

\[
\begin{align*}
\text{sensitivity:} & \quad m_{\nu} < 0.2\text{eV (90\%CL)} \\
\text{discovery potential:} & \quad m_{\nu} = 0.3\text{eV (3\sigma)} \\
& \quad m_{\nu} = 0.35\text{eV (5\sigma)}
\end{align*}
\]
- Commissioning spectrometer & detector phase 2 Q3+4/2014
  * dual layer wire electrode (in central part at least)
  * better egun
  * better alignment
  * better high voltage settings
  * full magnetic zeroing
  * full operational LN$_2$ baffles
  * electrical heated NEG pumps

- Tritium retention units DPS and CPS functional Q2/2015
- Tritium source WGTS final mounting completed mid-2015
- Spectrometer upgrade completed Q3/2015
- All source elements & tritium loops integrated Q4/2015
- First tritium in source, ramp up to nominal $\rho$ Q1-Q2/2016
- First tritium data with entire beam line mid-2016
Upgraded Troitsk nu mass setup and sterile neutrinos search

Sterile neutrino search up to $m(\nu_4) = 5$ keV
with 1% of original source strength of $10^{17}\text{cm}^{-2}$
Troitsk sensitivity

For KATRIN:
energy loss measurements
space charge experiment
E-gun

more details on the poster by V. Pantuev

more details on the poster by S. Mertens

J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP 02 (2011) 011

Spectrometer inner/outer diameter 2.20/2.75 m, length 8.10 m.
Resolution 1.8 eV (@18 keV)
Can KATRIN be largely improved? Problems to be solved

1) The source is already opaque
   → need to increase size transversally
   magnetic flux tube conservation
   requests larger spectrometer too
   but a Ø100m spectrometer is not feasible

Three possible ways out:

a) source inside detector
   using cryogenic bolometers (ECHo, HOLMES)
   (see talk by L. Gastaldo)

b) hand-over energy information of $\beta$ electron
   to other particle (radio photon),
   which can escape tritium source (Project 8)

c) make better use of the electrons
   → time-of-flight spectroscopy

2) Resolution is limited to $\sigma = 0.34$ eV
   when using molecular tritium by the
   excitation of ro-vibrational states in the final state
General idea:

- Source = KATRIN tritium source technology:
  uniform B field + low pressure T$_2$ gas

- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and
  carries the information of the $\beta$-electron energy

$\beta$ electron radiates coherent cyclotron radiation

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$
## Project 8's phase 1 goal:
Detect single electrons from $^{83m}$Kr

<table>
<thead>
<tr>
<th>Phase</th>
<th>Timeline</th>
<th>Scientific Goal</th>
<th>Source</th>
<th>R&amp;D Milestone</th>
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<tbody>
<tr>
<td>Phase I</td>
<td>2010-2014</td>
<td>Proof of principle; Kr spectrum</td>
<td>$^{83m}$Kr</td>
<td>Single electron detection</td>
</tr>
<tr>
<td>Phase II</td>
<td>2014-2016</td>
<td>T-He mass difference</td>
<td>$^3$He</td>
<td>Tritium spectrum; calibration and error studies</td>
</tr>
<tr>
<td>Phase III</td>
<td>2016-2018</td>
<td>0.2 eV scale</td>
<td>$^3$He</td>
<td></td>
</tr>
<tr>
<td>Phase IV</td>
<td>2018+</td>
<td>0.05 eV scale</td>
<td>$^3$He</td>
<td>High rate sensitivity</td>
</tr>
</tbody>
</table>

**A lot of R&D necessary**
- Is it really possible?
- What are the systematic uncertainties & other limitations?

more details on the poster 134 by N. Oblath
Alternative spectroscopy: measure time-of-flight through KATRIN spectrometer

N. Steinbrink et al., NJP 15 (2013) 113020

Advantage: measure full $\beta$-spectrum by time-of-flight at one (a few) retarding potential

Stop: Can measure time-of-arrival with KATRIN detector with $\Delta t = 50$ ns $\rightarrow$ ok

Start: $e^-$-tagger: Need to determine time-of-passing-by of $e^-$ before main spectrometer without disturbing energy and momentum by more than 10 meV:
  $\rightarrow$ Need „detector“ with 10 meV threshold seems not to be forbidden but unrealistic for the near future!
Added value: significant background reduction by coincidence!

$\rightarrow$ factor 5 in $\Delta m(\nu)^2_{\text{stat}}$ under ideal cond.

or: Use pre spectrometer as a „gated-filter“
  by switching fast the retarding voltage
  $\rightarrow$ As sensitive on the neutrino mass as standard KATRIN!

or: Reduce pre spectrometer to a minimal small one,
  add a Project 8-type tagger within a long solenoid

RF tagger
Summary

KATRIN is the next generation direct neutrino mass experiment
with a neutrino mass sensitivity of 200 meV
it looks also to sterile eV neutrinos (and maybe to keV neutrinos)

Main spectrometer & detector successfully commissioned (phase 1)
Tritium source and electron transport/tritium retention system on a good way
Start regular data taking in 2016!

Troitsk nu mass setup upgraded:
- helps KATRIN, own keV \( \nu \) program

Outlook to further improvements:
- Project 8: does it work?
- Time-of-flight: how to realize e\(^-\) tagging?

THANK YOU FOR YOUR ATTENTION!

Many thanks to those who provided me information:
G. Drexlin, J. Formaggio, N. Oblath,
T. Thümmler, V. Pantuev, N. Titov
Enlarging the strength of the KATRIN tritium source?

→ max. count rate near $E_0$ is limited:

$S \propto A_A \Delta E / \sigma_{\text{inelastic}}$

cannot make source thickness larger

source area transversally limited by $A_A \cdot \Delta E$
Summary: $\beta$-spectrum incl. electronic final states + $\nu$ mixing

Including electronic excited final states of excitation energy $V_j$ with probability $W_j$

$$W_j = |\langle \Psi_0 | \Psi_{f,j} \rangle |^2$$

Using $\varepsilon_j = E_0 - V_j - E$

$$\frac{d^2 N}{dt \, dE} = A \cdot F(E, Z + 1) \cdot p \cdot (E + m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j^2 - m^2(\nu_c)} \cdot \Theta(\varepsilon_j - m(\nu_c))$$

Final states of $\beta$-decay:

The electron spectrum coming out of a $\beta$-source is even more complicated due to inelastic scattering, backscattering. ...

Including neutrino mixing

$$\frac{d^2 N}{dt \, dE} = A \cdot F(E, Z + 1) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \left( \sum_i |U_{ci}|^2 \cdot \sqrt{\varepsilon_j^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

$\Rightarrow$ “Electron neutrino mass”

$$m^2(\nu_c) := \sum_i |U_{ci}|^2 \cdot m^2(\nu_i)$$
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer

Time-of-flight spectrum is sensitive to the neutrino mass. To determine the neutrino mass, one retardation potential is required, and the measurement is done differentially rather than integrally.
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer

Comparison of TOF spectra for different neutrino masses $\nu_e$

Electric potential on main spectrometer $z$ axis

- Sensitivity on spectral shape originates from strongly retarding the electrons by retarding potential
Sensitivity improvement on $m^2(\nu_e)$ by ideal TOF determination

Measure at 2 (instead of $\approx 30$) different retarding potentials since TOF spectra contain all the information

Coincidence request between start and stop signal $\rightarrow$ nice background suppression

$\rightarrow$ Factor 5 improvement in $m^2_{\nu}$ w.r.t. standard KATRIN, but ideal case!

$N. \text{ Steinbrink et al.}\n\text{NJP 15 (2013) 113020}$
Very successful cool-down and stability tests of the WGTS demonstrator

Very successful cool-down and stability tests of the WGTS demonstrator

arrival of WGTS demonstrator at KIT: April 2010

Beam tube Ø=90mm

cooling concept of WGTS: pressurized 2-phase Ne

S. Grohmann et al., Cryogenics, Cryogenics 55 (2013) 5

Currently: constructing of WGTS out of demonstrator

per mill stability source strength request:
\[
dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \cdot V / R \cdot T
\]

tritium fraction \( f_T \) & ideal gas law

\[\Delta T/T = 5 \times 10^{-5} \text{ h}^{-1}\]

Average temperature \( T_{av} = 30.243 \text{ K} \)
Maximum peak-to-peak variation \( \Delta T_{max} = 43.005 \text{ K} \)
Standard deviation \( \sigma_{T} = 15.0014 \text{ K} \)
Measurement of tritium concentration by laser Raman spectroscopy

M. Sturm et al., Las. Phys. 20 (2010) 493

H₂ / HD / T₂ / DT / HT
= 0.820 / 0.083 / 0.003 / 0.005 / 0.005

LARA-Cell
Spectrometer
Photo-diode
Filter
CCD
Fibre
Laser 5W 532 nm

Spectrograph
1:1 lens
Fibre bundle
45° mirror
Faraday isolator
vertical polarisation
1-5 W
"Spec-10" detector
"HTS" CDO
1:1 lens
Raman cell
Beam dump
"VA-DPSL" Laser

Simulation spectrum (SpecGen)
Vibrational-Rotational
Q_p-branch
Δν = 0
ΔJ = +2
Q_s-branch
Δν = 1
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Tritium loops at Tritium Laboratory Karlsruhe

tritium source: loop system

- $10^{-4}$ stability of loop system achieved for $p_{in}$ in test set-up
Stability of retarding potential /
energy calibration: ppm at 18.6 kV

- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined electron line with monitor spectrometer

\[ T_{1/2} = 86.2 \text{ d} \]

\[ \Delta E = 5 \text{ eV} \rightarrow 1 \text{ eV} \]

Electron sources:
- condensed \(^{83}\text{Kr}\): Münster/Mainz
- \(^{83}\text{Rb}/^{83}\text{Kr}\): Rez/Mainz/Münster/Karlsruhe
- \(^{83}\text{Rb}\) production: Bonn, Rez

D. Venos, arXiv 0902.0291
A new pulsed angular-defined UV LED photoelectron source

Idea:
fast non-adiabatic acceleration
with adjustable non-parallel E and B fields

Angle at
electron source: 0°
pinch magnet: 0°

K. Valerius et al., NJP 11 (2009) 063018
K. Valerius et al., JINST 6 (2011) P01002
K. Hugenberg,
Prog. Part. Nucl. Phys. 64 (2010) 288

Preliminary

resolution 5 eV
angle 12 deg

normalized intensity

U (V)

0 0.2 0.4 0.6 0.8 1 1.2
60 61 62 63 64 65 66

E

B

UV LED

fibre

e−

U = 1.75 kV
U = 2.00 kV
U = 3.00 kV
U = 3.50 kV
UV LED photoelectron source for the main spectrometer