Status of the KATRIN Experiment

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Neutrino mass: laboratory experiments

**search for 0νββ decay**

- model-dependent (CP-phases)
  - effective Majorana mass:
    \[ m_{ee} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right| \]
  - probes Majorana nature of ν
  - status: \( m_{ββ} < 0.2 - 0.4 \text{ eV} \)
  - potential: \( m_{ββ} = 20 - 50 \text{ meV} \)

GERDA, EXO/nEXO, SNO+, MAJORANA, CUORE, CANDLES, KamLAND-Zen, NEXT ...

**kinematics of β-decay or EC**

- model-independent
  - squared neutrino mass:
    \[ m^2(ν_e) = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \]
  - **direct**, from kinematics
  - status: \( m_ν < 2.3 \text{ eV} \)
  - potential: \( m_ν = 200 \text{ meV} \)

KATRIN, MARE, Project 8, ECHO

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This session II.1 & II.2 Poster 167

Track 3 Session I + II.5
Direct neutrino mass measurements

Imprint of $m_\nu$ on endpoint region of $\beta$ spectrum (similar for EC):

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

observable: effective mass square

$$m^2(\nu_e) = \sum |U_{ei}|^2 m_i^2$$

key requirements

- low-endpoint $\beta$ source
- high count rate
- very good energy resolution
- very low background

$\beta$-decay: $^3\text{H} (^{187}\text{Re})$
EC: $^{163}\text{Ho}$
ν-mass measurement in tritium β-decay

**3H β-decay**
- Short $T_{1/2}$ of 12.3 y → high-intensity source
- Low endpoint of 18.6 keV → good rel. signal strength
- Gas, closed loop → high isotopic purity
- Computation of final states, radiative & recoil corrections

**MAC-E filter technique**
Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345

- Isotropic emission, strong $B_s$
- Energy filtering, weak $B_{\text{min}}$
- Resolution:

\[
\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} = \frac{1}{20000} \quad \text{(at KATRIN)}
\]

\[
\mu = \frac{E_{\perp}}{B} = \text{const.}
\]
KATRIN: overview

sensitivity on $m(\nu_e)$:
2 eV/c$^2 \rightarrow 200$ meV/c$^2$

~ 70 m
KATRIN: main components

Source & transport section
- Windowless gaseous tritium source
- Intensity \(10^{11} \text{ s}^{-1}\)
- Stability \(10^{-3} \text{ h}^{-1}\)
- Isotopic purity (> 95%)
- Tritium retention factor (> \(10^{14}\))
- Adiabatic transport of electrons

Spectrometer & detector section
- Spectrometer UHV \((p < 10^{-11} \text{ mbar})\)
- Energy resolution (<1 eV at 18.6 keV)
- High voltage stability (ppm/month)
- Low background rate \((10^{-2} \text{ cps})\)
- High detection efficiency (mHz to kHz)
Windowless gaseous tritium source

Pressure-stabilized tritium injection
Circulation & purification (throughput 20 g/day)
10 m beam tube

Novel 2-phase neon cooling:
T = (30 ± 0.03) K  (1 h stability requirement)

demonstrator experiment: successful cold-test on site (2010-12)
Transport and pumping sections

Differential pumping section (DPS)
- 4 turbo-molecular pumps
- Tritium retention $\sim10^5$
- Magnetic guiding of $\beta$'s (5.6 T)

Cryogenic pumping section (CPS)
- Cryo-sorption on 3-4 K argon frost
- Tritium retention $>10^7$
- Magnetic guiding of $\beta$'s (5.6 T)

DPS being installed right now

CPS under construction, delivery end of 2014
### Spectrometer and detector section

#### Installation of wire electrodes (~2007-2012)

- 240 modules
- 23000 wires
- 2 layers
- UHV compatible

#### Detector tests (until spring 2013)

- 148 pixel Si-PIN diode
- FWHM < 1.5 keV at 18.6 keV
- Post-acceleration up to 10 kV

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#### Bake-out at 300°C (Jan 2013)

\[ p = 4 \times 10^{-11} \text{ mbar} \]

#### Commissioning of main spec. & detector: mid-2013 (phase I)
KATRIN: commissioning measurements

Set-up for spectrometer & detector commissioning, phase I (summer 2013)

Magnetic fields
- s.c. magnets
- field-shaping air coil systems

Precision high voltage vessel + wire electrode at separate HV

Electron gun
well-defined, sharp energy and angle

Vacuum system
- TMPs
- 3 x 1 km NEG strips, $10^6 \ell$/s (+ LN-cooled baffles)

148-pix detector spatial & timing info
KATRIN: commissioning measurements

**Characterisation of transmission**

Quasi-monoenergetic, angular selective electron source

- At 18.6 kV, width < 100 meV
- Sharpest transmission function of a MAC-E filter

... will be improved during 2014 commissioning runs

**Extensive background studies**

Radial dependence; various E, B, residual gas pressure settings

- Discriminate cosmic- and Rn-induced BG
- Need to cut down total rate to \( \sim 0.01 \text{ cps} \)

mean total rate: 0.78 \(\pm\) 0.20 cps

mean total rate: 0.47 \(\pm\) 0.09 cps

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Next steps for KATRIN

Spectrometer & detector commissioning:
**phase II** starting 09/2014

- improved background suppression
  - double-layer wire electrode
  - continuous operation of cold baffles

- upgrade of electron gun
  - improved angular selectivity and energy res.

- upgrade of vacuum system
  - electrical heating of NEG pumps

- refined system alignment
  - imaging of flux tube onto detector
KATRIN: $\nu$-mass sensitivity

Reference neutrino mass sensitivity
- Observable: $m^2(\nu_e)$
- After 3 yrs of data (5 calendar yrs): balance of statistics and systematics

$\sigma_{\text{stat}}(m^2_{\nu}) \leq 0.018 \text{ eV}^2$ (even $0.016 \text{ eV}^2$ with optimized measuring time distribution)

$\sigma_{\text{syst}}(m^2_{\nu}) \leq 0.017 \text{ eV}^2$ – total systematic uncertainty budget
- Source-related (final states, energy loss, column density, plasma potential, ...)
- Other (HV fluctuations, transmission function, non-Poissonian backgrounds, ...)
KATRIN: $\nu$-mass sensitivity … and more:

Explore physics potential

- close to the spectral endpoint $E_0$:
  - RH currents
    Bonn et al. (2011)
  - Violation of Lorentz symmetry
    Diaz, Kostelecky & Lehnert (2013)

Constraining local CvB overdensities
e.g. Kaboth & Formaggio (2010)

- and further away from $E_0$:
  - search for keV-mass scale sterile $\nu$ as WDM candidates
    N. Steinbrink et al. (2013), S. Mertens et al. (in prep.)

Capture of relic $\nu$ on $\beta$-instable nuclei

Search for eV-scale sterile $\nu$

$\sim 1$ eV$^2$

Non-standard operation, requires novel concepts
Search for eV-scale sterile neutrinos

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

\[
\frac{d\dot{N}}{dE} = \cos^2 \theta_s \frac{d\dot{N}}{dE} (m_a^2) + \sin^2 \theta_s \frac{d\dot{N}}{dE} (m_s^2)
\]

additional kink in \( \beta \) spectrum at \( E = E_0 - m_s \)
Search for eV-scale sterile neutrinos

- “Reactor antineutrino anomaly”: $\Delta m^2_s \sim 1$ eV$^2$, $\sin^2(2\theta_s) \sim 0.1$
- Favoured parameter space can be probed by KATRIN:

See also
Formaggio & Barrett, PLB 706 (2011) 68;
Sejersen Riis & Hannestad, JCAP02 (2011) 011;
esmaili & Peres, arXiv:1203.2632
Status & outlook

- $\beta$ decay offers model-independent, direct access to neutrino mass scale
- KATRIN sensitivity on $m(\nu_e)$: $200\text{ meV/c}^2$ (90% CL, 3y)
  → ultimate MAC-E type experiment using molecular tritium

“Cyclotron spectroscopy”: exciting exploratory work with Project 8
(→ talk M. Fertl)

Status of KATRIN hardware & system integration

Tritium-bearing components currently under construction; delivery & system integration in 2014 and 2015

Spectrometer & detector section successfully completed commissioning phase I just now entering phase II

First runs with entire KATRIN beam line in 2016