Absolute neutrino mass scale and the KATRIN experiment

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Colloquium -Towards CP Violation in Neutrino Physics
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1. Applied methods of $m_\nu$ measurements and current results

2. Educational role of previous $\beta$-decay experiments

3. Principle and technique of the KATRIN experiment

4. Expected results of KATRIN

A nuclear spectroscopist note on neutrino sources:

Each of you emits about 4000 neutrinos per second into $4\pi$ due to $\beta$-decay of $^{40}\text{K}$ in your body

140 g of potassium, 0.01 % abundance of $^{40}\text{K}$, $T_{1/2} = 1.2 \cdot 10^9$ y
1. Applied methods of $m_\nu$ measurements and current results

**Model independent methods**

- $E^2 = p^2 c^2 + m^2 c^4$
- laws of energy and momentum conservation
- $F = -e \left[ E + (v \times H) \right]$

**Examples**

- **two body decay of $\pi^+$ at rest:** $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  
  $\sigma_{rel} = 3 \cdot 10^{-6}$ for $m_\pi$, $4 \cdot 10^{-8}$ for $m_\mu$, $4 \cdot 10^{-6}$ for $p_\mu$
  
  $m(\nu_\mu) \leq 190$ keV at 90% C.L.

Ernst Otten: “A relativistic particle hides away its rest mass!”
• **Time-of-flight method** \[ \Delta t_\nu = t_c - t \]

assuming \( m_\nu = 2 \text{ eV} \)

\( \Delta t_\nu \) is too small for terrestrial experiments
  e.g. in the OPERA experiment:
  \[ <E_\nu> = 17 \text{ GeV}, \; d = 730 \text{ km}, \; t_c = 2.4 \text{ ms} \]
  \( \Rightarrow \) expected time delay \( \Delta t_\nu = 2 \cdot 10^{-23} \text{ s} \)

Extraterrestrial experiments:
  e.g. for 10 MeV neutrinos from SN1987a
  \( \Rightarrow \) expected time delay \( \Delta t_\nu = 0.1 \text{ s} \)

**BUT** assumptions about the supernova explosion are needed
• **β-spectrum shape in the endpoint region**
  where (according to Fermi theory, 1934)

\[
dN/dE \sim (E_0 - E)^2 \cdot \left[ 1 - m^2_v/(E_0 - E)^2 \right]^{1/2}
\]

\(E_0\) is the endpoint for \(m_v = 0\)

Since neutrinos oscillate \(|\nu_\alpha> = \Sigma U_{\alpha i} \cdot |\nu_i>\)
and \(|m_i - m_k| \ll \Delta E_{\text{instr}}\)

β-spectrum analysis yields the effective mass

\[m^2(\nu_e) = m^2_\beta = \Sigma |U_{ei}|^2 \cdot m^2_i\]

*this is a weighted average, no phases
thus no possible cancellations*
More sensitive but model dependent methods

• search for $0\nu\beta\beta$ - nuclear matrix elements, alternative modes of decay

• supernova explosion - time distribution of emitted neutrinos

• cosmology
  - mainly from cosmic microwave background and large scale structures of galaxies
  - up to 10 fitted parameters
  - dark matter and dark energy (95% of the total) are not yet explained
Current results

*Particle Data Group*
Effective $\nu$ mass from kinematic experiments:

\[
\begin{align*}
&m(\nu_e) < 2 \text{ eV} \\
&m(\nu_\mu) < 0.19 \text{ MeV} \\
&m(\nu_\tau) < 18.2 \text{ MeV}
\end{align*}
\]

- $\beta$-decay
- $\pi^+$ decay
- $\tau^-$ decay

*Other methods:*

- $T_{1/2} (0\nu\beta\beta)$: $\langle m_\nu \rangle_{\beta\beta} < 0.1 - 0.9 \text{ eV}$, one claim for 0.4 eV
- TOF (SN1987a): $m(\nu_e) < 5.7 \text{ eV}$
- Cosmology: $\Sigma m_i < 0.6 - 1.7 \text{ eV}$
- $\nu$ oscillations: $m_i \geq 0.05 \text{ eV}$ at least for the heaviest mass state
2. Educational role of previous $\beta$-decay experiments

Requirements for a $\beta$-ray spectrometer:

**Simultaneously:**
- high energy resolution $\Delta E_{\text{instr}}$
- large solid angle $\Omega_{\text{input}}$
- low background
Neutrino mass from the $\beta$-spectrum shape

$m_\nu < 5$ keV  
- $\beta$-spectrum of $^{35}$S ($E_0=167$ keV)  
- magnetic spectrometer  

$m_\nu < 1$ keV  
- $\beta$-spectrum of gaseous tritium ($E_0=18.6$ keV)  
- proportional counter  

$m_\nu < 60$ eV  
- $\beta$-spectrum of implanted tritium  
- magnetic spectrometer with $100 \times$ increased source area  
- part of $Q_\beta$ goes into excited states of daughter $^3$He$^+$ ion  
  ⇒ measured spectrum is a sum of partial $\beta$-spectra with various $E_{0,i}$
\( m_\nu \approx 30 \text{ eV} \)  
8 eV relic neutrinos would create all dark matter 
- excellent toroidal magnetic spectrometer 
- but tritium in complicated organic compound 
- underestimated energy losses of \( \beta \)-particles 
- wrong fitted \( E_0 \) supported by wrong \( Q_\beta \) from mass spectrometry

\( m^2_\nu < 0 \)  
- 7 laboratories, 3 types of magnetic spectrometers 
- various solid and gaseous tritium sources 
- none of them \( m^2_\nu \) positive, two of them 6\( \sigma \) negative 
- wrong theoretical spectrum of final states? NO 
  but mostly underestimated energy losses of \( \beta \)-particles

\( m_\nu \approx 0 + \text{ up to } 3\% \text{ of } m_\nu = 17 \text{ keV} \)  
- from \( \beta \)-spectra of several radionuclides 
- observed only with semiconductor detectors 
  not found by magnetic spectrometers 
- caused by electron scattering in radioactive sources 
  and on spectrometer slits
$m_\nu < 2.3 \text{ eV}$ Mainz neutrino mass experiment 2005

- electrostatic retardation spectrometer with adiabatic magnetic collimation
- condensed tritium source
- detailed analysis of systematic errors
- $m^2_\nu = (-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}}) \text{ eV}^2$

Similar results reported the Troitsk neutrino mass experiment in 2003
- spectrometer of the same type
- gaseous tritium source
- $m^2_\nu = (-2.3 \pm 2.5_{\text{stat}} \pm 2.0_{\text{syst}}) \text{ eV}^2$
  but only after artificial correction of $\beta$-spectrum with two additional fitting parameters

**Final Troitsk result in 2011**
- enlarged data set
- removed runs with unstable tritium density
- $m^2_\nu = (-0.67 \pm 1.89_{\text{stat}} \pm 1.68_{\text{syst}}) \text{ eV}^2$
  without any artificial correction
During 63 years, β-ray spectroscopists improved the model independent limit of experimentally observable $m^2_\nu$ by 6 orders of magnitude.

weighted average of Mainz (2005) and Troitsk (2011)

$m^2_\nu = -0.6 \pm 1.9 \text{ eV}^2$

$\Rightarrow m_\nu < 2.0 \text{ eV at 95\% C.L. using the conservative approach}$

Next improvement by 2 orders of magnitude is expected from KATRIN
Electrostatic retardation spectrometer with adiabatic magnetic collimation of electrons (MAC-E-filter)

Advantages:
- Large $\Omega_{\text{input}}$ and narrow line width $\Delta E_{\text{instr}}$ simultaneously
- No scattering on slits defining electron beam
- No high energy tail of the response function

Disadvantage:
- Danger of magnetic traps for charged particles

Developed independently at Mainz and Troitsk

$(\Delta E / E)_{\text{instr}} = B_{\text{min}} / B_{\text{max}}$

$\sin \theta_{\text{max}} = (B_s / B_{\text{max}})^{1/2}$

$\Omega_{\text{input}}$ up to 50% of $4\pi$

Advantages:
- Large $\Omega_{\text{input}}$ and narrow line width $\Delta E_{\text{instr}}$ simultaneously
- No scattering on slits defining electron beam
- No high energy tail of the response function

Disadvantage:
- Danger of magnetic traps for charged particles

Radioactive sources for $\beta$-spectroscopy

$\lambda_{\text{inel}} (\text{Al}) = 30 \text{ nm for } E_e = 20 \text{ keV}$

$\Rightarrow$ large source area $S$

large luminosity $L = S \cdot \Omega_{\text{input}}$

large spectrometer dimensions
3. Principle and technique of the KATRIN experiment

*at the Karlsruhe Institute of Technology (KIT = FZK + Tech. Uni.)*

The next generation tritium β-decay experiment measuring $m_\nu$ in sub-eV region in a model independent way

Founded in 2001 by physicists from Germany, Russia, USA and Czech Republic

*Our NPI ASCR has a long tradition in nuclear electron spectroscopy*

*the best resolution in the field (at expense of a low transmission)*
Tritium Laboratory Karlsruhe
KATRIN main components

source and transport section | spectrometer section

- source parameter
- stable tritium column density
- electron transport tritium retention
- reflection of low energy electrons
- high precision energy analysis of electrons
- position sensitive electron counter

source (WGTS) | diff. pumping | pre-spectrometer | main spectrometer | detector

- $\beta$-decay: $e^-$
- $3 \times 10^{-3}$ mbar ±1 kV
- $10^{10}$ e$^-$/s
- $10^{10}$ e$^-$/s
- $10^3$ e$^-$/s
- $10^{-11}$ mbar -18,4 kV
- $10^{-11}$ mbar -18,574 kV
- 1 e$^-$/s

~70 m
Technical challenges of KATRIN

• Long term recirculation and purification of tritium on the kCi scale isotopic composition (95% of $T_2, TH, TD$) checked by Raman laser spectroscopy

• $\pm 30$ mK temperature stability of tritium in gaseous source at 27 K achieved by liquid/gaseous phase transition on Ne

• vacuum $< 10^{-11}$ mbar in volume of 1400 m$^3$
  TMP and non-evaporable getters, but cold traps to avoid spots of Rn

• background of the position sensitive electron detector $< 0.01$/s
  contribution from tritium in the main spectrometer $< 0.001$/s
  no walls in the electron beam line: strong differential pumping + cryosorption

• $\pm 60$ mV long-term stability of high voltage at 18.6 kV
  unrecognized shift by 50 mV $\Rightarrow 0.04$ eV error in fitted $m_\nu$
Windowless Gaseous Tritium Source

WGTS tube: stainless steel, 10 m length, 90 mm diameter

**Magnetic field:**
3.6 Tesla (± 2%)

**Source tube temperature:**
27 K (± 0.1% stable)

**T₂ injection rate:**
1.8 cm³/s (± 0.1%)

at pressure of 3.4 · 10⁻³ mbar

**Isotopic purity:**
>95%

**Total pumping speed:**
12000 l/s

*Probably the most complex cryostat ever built*
**Aim:** only the uppermost part of $\beta$-spectrum into the main spectrometer

$10^{10} \ \beta/s \rightarrow 10^3 \ \beta/s$

- **Vacuum chamber:**
  - 1.7 m in diameter,
  - 3.4 m in length

- **Superconducting magnets**

- **Turbomolecular pumps + getter strips (Zr+V+Fe alloy)**

$10^{-11}$ mbar achieved
Vacuum chamber of the main spectrometer

- Diameter: 10 m
- Length: 23 m
- Weight: 200 t

9000 km on sea around Europe

The last 7 km to the KIT
Wire electrodes of the main KATRIN spectrometer

- **Reduce background** due to secondary electrons from the wall
- **Secure precise form** of the retarding electrostatic field
  - *no magnetic traps for e⁻ and ions*

240 modules
23 000 wires

Mounting wire electrodes into a clean spectrometer interior
Two ways of monitoring the KATRIN energy scale stability

The NPI tasks for KATRIN: radioactive sources of monoenergetic electrons for long-term monitoring and calibration

\(^{83}\text{mRb}/^{83}\text{mKr}\) source of 17.8 keV electrons

- implanted \(^{83}\text{mRb}\) sources
  - 90% retention of \(^{83}\text{mKr}\)
  - electron energy drift \(<\ 3 \text{ ppm/month}\)

- 1 GBq \(^{83}\text{mKr}\) source for testing the whole KATRIN setup with monoenergetic electrons
  - \(^{83}\text{Rb}\) production at the NPI cyclotron
  - deposition in zeolite: no escape of \(^{83}\text{Rb} (T_{1/2}=86\text{d})\)
  - high release of \(^{83}\text{mKr} (T_{1/2}=1.8\text{h})\)

High-voltage divider metrology precision
Analysis of measured $\beta$–spectrum: final $(THe)^+$ states

d$N$/d$E = K \times F(E,Z) \times p \times E_{tot} \times \sum P_i (E_0 - V_i - E_e) \times \left[ (E_0 - V_i - E_e)^2 - m_v^2 \right]^{1/2}$

- Rotational-vibrational excitations of electronic ground state
- Electronic excited states

$(THe)^+, (HHe)^+$ from gaseous $T_2, HT$

(Saenz et al., PRL 2000)
4. Expected results of KATRIN

1) **The effective neutrino mass**

*If no neutrino mass is observed:*

- $m_\nu < 1$ eV soon after the start of KATRIN (2013/14)
- $m_\nu < 0.2$ eV at 90% C.L. after 1000 days of measurement (in 5 years)

*Discovery potential* $m_\nu = 0.35$ eV (5σ effect)

In a model independent way

Regardless neutrino type (Dirac or Majorana)

Possible unaccounted **right-handed couplings**
will change the fitted $m_\nu$ by less than 10%
2) **Distinguishing between the two neutrino mass scenarios**

- e.g. $m_1 \approx 0.30$ eV, $m_2 \approx 0.31$ eV, $m_3 \approx 0.35$ eV

- e.g. $m_1 \approx 0$, $m_2 \approx 0.01$ eV, $m_3 \approx 0.05$ eV

Both in accord with oscillation experiments

KATRIN:
- will explore the whole quasi-degenerate region
- the hierarchical region is below its sensitivity
3) **Contribution of relic neutrinos to the hot dark matter**

\[ 0.001 < \Omega_\nu < 0.15 \]

- From neutrino oscillation experiments assuming hierarchical neutrino masses with only one mass eigenstate contributing to \( \Omega_\nu \).
- From current tritium \( \beta \)-decay experiments assuming quasi-degenerate neutrino masses.

**KATRIN**

- Will be **sensitive to** \( \Omega_\nu = 0.01 \).
- It will either significantly constrain or fix the role of neutrino hot dark matter.
4) **Sterile neutrinos with masses in the eV range**
A possibility indicated by cosmology and several reactor and accelerator oscillation experiments

Riis & Hannestad
arXiv:1008.1495v2

**KATRIN would see sterile neutrinos**
with
\[ \Delta m^2_{s1} = 6.49 \text{ eV}^2 \]
\[ |U_{e4}|^2 = 0.12 \]
\[ \Delta m^2_{s2} = 0.89 \text{ eV}^2 \]
\[ |U_{e5}|^2 = 0.11 \]
and similar cases.

Well separated from signal of all three light active neutrinos

from Giunti and Kim:
Fundamentals of neutrino physics and astrophysics (2011)
5) *Local density of relic neutrinos*

KATRIN tritium gaseous source as a target for \( \nu_e + T \rightarrow ^3\text{He}^+ + e^- \) with relic neutrinos

KATRIN sensitivity \( \rho(\nu_e)_{\text{local}} / \rho(\nu_e)_{\text{average}} \geq 2 \cdot 10^9 \)

Non observation will rule out certain hypotheses about local neutrino gravitation clustering.

\[ E_\nu = 2 \cdot 10^{-4} \text{eV}, \quad \rho(\nu_e)_{\text{average}} = 56 \text{ cm}^{-3}, \quad \sigma = 8 \cdot 10^{-45} \text{ cm}^2 \]

5.3 \cdot 10^{19} \text{ tritium atoms, mass of 0.26 g, monoenergetic}
KATRIN Collaboration will do its best to fulfill these tasks