Experiment KATRIN limited the neutrino mass to less than 1 eV

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International experiment:
• 150 researchers
• 20 institutes from 6 countries: D, USA, RU, Czech Rep, ESP, FR

Research institutes at Řež

Karlsruhe Institute of Technology (KIT)

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1. Mysterious shape of β-ray spectra

2. Neutrinos – the most abundant massive particles

3. The KATRIN experiment

4. The first scientific run of KATRIN

5. KATRIN perspectives
1. Mysterious shape of $\beta$-ray spectra

The laws of energy and momentum conservation:

Decay in two parts $\rightarrow$ discrete energy spectra

$^{226}\text{Ra} \rightarrow ^{222}\text{Rn} + \alpha$ (4.777 MeV)

$^{99m}\text{Tc} \rightarrow ^{99}\text{Tc} + \gamma$ (140 keV)

James Chadwick
1914:

- Electron spectrum of RaB+C ($^{214}\text{Pb}+^{214}\text{Bi}$)
  $E_\beta$ up to 3.3 MeV
- Magnetic spectrometer
- Two different detectors

$\beta$-spectrum is continuous! WHY?

Wolfgang Pauli and Niels Bohr
The neutrino hypothesis

Wolfgang Pauli

(then 30 years old theoretical physicist and future Nobel prize winner)

Proposed on 4th December 1930:

a new particle
a NEUTRINO is also emitted in the β-decay:

\[ {^{35}\text{S}} \rightarrow {^{35}\text{Cl}} + e^- + \bar{\nu}_e \quad {^{3}\text{H}} \rightarrow {^{3}\text{He}} + e^- + \bar{\nu}_e \]

Decay in three parts → continuous energy spectra

Assumed neutrino properties: light, neutral, penetrating

Only protons and electrons were known at that time
Enrico Fermi  
(33 years old experimental and theoretical physicist, also future Nobel prize winner)

Developed the β-decay theory incorporating the Pauli’s neutrino already in 1934:

\[ ^{35}\text{S} \rightarrow ^{35}\text{Cl} + e^- + \bar{\nu}_e \quad ^{3}\text{H} \rightarrow ^{3}\text{He} + e^- + \bar{\nu}_e \]

Calculated β-spectrum shape agreed with the experiment:

"the neutrino mass is smaller than the electron mass, most probably zero"
β-decay of $^6$He $\rightarrow$ $^6$Li + e$^-$ + $\bar{\nu}_e$ in Wilson cloud chamber

- β-decay energy = 3.5 MeV
- Maximum energy of recoiled atom = 1.4 keV
- $T_{1/2}$ = 0.8 s

Csikai and Szalay, 1957

It cannot be: $^6$He $\rightarrow$ $^6$Li + e$^-$
This is not a two-particle decay

Electron trajectory in magnetic field
2. Neutrinos – the most abundant massive articles

- relic $\nu$ from Big Bang: $\sim 300 \, \text{cm}^{-3}$ of the Universe
- $\nu$ flux from the Sun: $6 \times 10^{10} \, \text{cm}^{-2} \, \text{s}^{-1}$ on the Earth surface
- supernova explosion: $10^{58}$ neutrinos in a few seconds
- atmospheric $\nu$ created by cosmic rays
- nuclear reactors ($1000 \, \text{MW}_{\text{el}} \sim 5 \times 10^{20} \, \overline{\nu}_e \, \text{s}^{-1}$) and accelerators
- terrestrial $\nu$ from natural radioactivity
- each of you: $4000 \, \text{s}^{-1}$ into $4\pi$ due to $^{40}\text{K}$ decay in your body
  (140 g of K, 0.01 % of $^{40}\text{K}$, $T_{1/2} = 1.2 \times 10^9 \, \text{y}$)
Three kinds of neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$

Neutrinos are electrically neutral particles

Penetrability ($\sigma_v \approx 10^{-20} \sigma_{\text{nucl. phys.}}$)

Neutrino kinetic energy: $10^{-4} - 10^{20}$ eV

Neutrinos are not dangerous to a man
But the neutrino mass is still unknown!

- **Standard model of particle physics** assumed $m_\nu = 0$

- **Neutrino oscillation experiments** proved $m_\nu \neq 0$

\[ |m_{\nu\alpha} > = \Sigma U_{\alpha i} \cdot |m_i > \]

\( \alpha = e, \mu, \tau \) weak interaction eigenstates

\( i = 1, 2, 3 \) mass eigenstates

\[ |m_i > \]

\[ \Sigma \]

\[ U_{\alpha i} \]

\[ \alpha = e, \mu, \tau \]

\[ i = 1, 2, 3 \]

At least one $m_i > 0.05$ eV, at least two $m_i > 0.01$ eV

- All experiments and cosmological observations up to now:
  Only upper limits on $m_i$
  \( \beta \)-ray spectroscopy – the only model independent method
70 years of searching for massive neutrinos in $\beta$-ray spectra

dN/dE = K \times F(E,Z) \times p \times E_{\text{tot}} \times (E_0-E_e) \times \left[ (E_0-E_e)^2 - m_\nu^2 \right]^{1/2}

$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$

$E_0 = 18.6$ keV
$T_{1/2} = 12.3$ y

Simultaneously:
- high resolution
- high luminosity
- low background

$m_\nu < 5$ keV (1948)
$m_\nu < 2.3$ eV (2005)
$m_\nu < 1.1$ eV (2019) KATRIN

For interesting history and perspectives see e.g. Open Phys. J. 3 (2016) 73-113

PMFA 52(2007)100-121, in Czech
The effective mass of the electron neutrino

a) one \( \nu \) mass-state, daughter in ground state  \( (\text{Fermi, 1934}) \)

\[
\frac{dN}{dE} = A \cdot F \cdot p \cdot (E + m_e) \cdot \varepsilon \cdot \sqrt{\varepsilon^2 - m_{\nu_e}^2} \quad \varepsilon = E_0 - E
\]

b) one \( \nu \) mass-state, daughter also in excited states  \( (\text{Bergkvist, 1972}) \)

\[
\frac{dN}{dE} = A \cdot F(E, Z + 1) \cdot p \cdot (E + m_e) \cdot \sum_j P_j(\varepsilon - V_j) \cdot \sqrt{(\varepsilon - V_j)^2 - m_{\nu_e}^2} \cdot \Theta(\varepsilon - V_j - m_{\nu_e})
\]

Observed spectrum:

Sum of many with various endpoints
c) three \( \nu \) mass-states, daughter also in excited states \((\nu \text{ oscillations, 1998-2001})\)

\[
\frac{dN}{dE} = A \cdot F \cdot p \cdot (E + m_e) \cdot \sum_j P_j (\varepsilon - V_j - m_i) \cdot \sum_i |U_{ei}|^2 \sqrt{(\varepsilon - V_j)^2 - m_i^2} \cdot \theta(\varepsilon - V_j - m_i)
\]

- Future \( \beta \)-spectroscopy might provide all \( |U_{ei}|^2 \) and \( m_i \)

- Present \( \Delta E \) does not allow to distinguish individual \( m_i \)

**The effective mass of the electron neutrino**

\[
m_{\nu e}^{\text{eff}} = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}
\]

Analysis of present \( \beta \)-spectra: one effective \( \nu \) mass-state daughter also in excited states
3. The Karlsruhe Tritium Neutrino Experiment

Aim: improvement of the $\nu$-mass sensitivity from 2 eV to 0.2 eV

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

Gaseous $T_2$ Source at Los Alamos, USA

New $\beta$-spectrometer type: MAC-E-Filter

at Troitsk, Russia

at Mainz, Germany
Electron spectroscopy of radioactive nuclei at NPI

1955 –1990: internal conversion electrons
1990 – now: neutrino mass determination

First Czechoslovak β-ray spectrometer (1956)

Magnetic β-ray spectrometer. One of the first Czech instruments operated by a computer (1971)

Elektrostatic spectrometer of keV electrons (1983)

Monoenergetic

\[ E_{ce} = E_v - E_{bin} \]

best resolution \( \Delta E \leq 1 \text{ eV} \) at low transmission
Tritium Laboratory Karlsruhe

The only one in Europe:
• large amount of tritium
• high chemical and isotopic purity.
KATRIN main components:

**source and transport section**
- source parameters
- stable tritium column density
- electron transport tritium retention

**spectrometer section**
- reflection of low energy electrons
- high precision energy analysis of electrons
- position sensitive electron counter

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**Source and Transport Section**

**Rear**
- **Tritium Source**
  - \(\beta\)-decay: \(e^-\) production
  - \(10^{10} e^-/s\)

**Diffuser and Cryo Pump**
- \(10^{10} e^-/s\)

**Pre-Spectrometer**
- \(10^3 e^-/s\)

**Main Spectrometer**
- \(10^{-11} \text{ mbar} \), -18.574 kV

**Detector**
- \(1-0.01 e^-/s\)

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**Source Parameters**
- \(3 \times 10^{-3} \text{ mbar} \pm 1 \text{ kV}\)

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**Energy Levels**
- \(10^{-11} \text{ mbar} \), -18.4 kV

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**Distance**
- \(~70 \text{ m}\)
Windowless gaseous tritium source

- Stainless steel tube of 10 m length and 9 cm diameter
- Cooled to 30 K ± 0.1 %
- In magnetic field of 3.6 T ± 2 %
- Continuously filled in the middle with molecular tritium at 3·10⁻³ mbar
- Continuously pumped at both ends

- Activity of 114 GBq
- Tritium flow of 170 GBq/s
- Isotopic purity 95 %

- Column density of 5×10¹⁷ tritium molecules per cm²
- 5.7×10¹⁰ ± 0.1 % of β-particles for energy analysis

One of the most complex cryostats ever built
Source and transport system of KATRIN inside TLK
KATRIN electron pre-spectrometer

Vacuum chamber: 1.7 m in diameter
3.7 m in length

Superconducting magnets
KATRIN main electron spectrometer

- Magnetic adiabatic collimation with electrostatic retardation
- Large $\Omega_{\text{input}}$ and narrow line width $\Delta E_{\text{instr}}$ simultaneously
- No electron scattering on slits
- Danger of magnetic traps (UHV of $10^{-11}$ helps)
Vacuum test of the spectrometer chamber at a factory

- Helium test O.K.
- $p < 6 \cdot 10^{-8}$ mbar without baking
Challenging transport of the spectrometer chamber

23 m length, 10 m diam, 200 ton

8800 km around Europe

Last 7 km

Placing at KIT
Focal plane detector

Si PIN diode, 9 cm diam.
148 independent pixels
Tasks of the NPI at Řež for KATRIN

Ultra-stable and high-purity radioactive sources of monoenergetic electrons

$^{83}\text{Rb} \ (86\text{d}) \rightarrow ^{83}\text{mKr} \ (1.8\text{h}) \rightarrow ^{83}\text{Kr}$

$p \ (24\text{ MeV}, 45\mu\text{A}) \rightarrow ^{\text{nat}}\text{Kr}$

Installation of krypton target at the TR-24

New radiochemical laboratories

New cyclotron TR-24
The first NPI task for KATRIN: **monitor high voltage stability**

**In collaboration with the Mass-separator group at Bonn University**

Precision HV divider

**unrecognized shift by 50 mV ⇒ 0.04 eV error in fitted mν!!**

KATRIN monitor spectrometer

**Standard of stable electron energy at 17.8 keV:** $^{83}\text{Rb}/^{83}\text{mKr} \text{ source}$

\[
E_{ce} = E_\gamma - E_{bin}
\]

**drift 0.6 ppm /2 months**

3 times better than requested
The second NPI task for KATRIN: gaseous source of monoenergetic electrons for WGTS

\( ^{83m}Kr \) \( (E_{ce} = 9 - 32 \text{ keV}) \)

- Based on deposition of \(^{83}\text{Rb}\) into zeolit
- Activity of 1.5 GBq

Now also for energy calibration in dark matter searches

Gaseous \(^{83m}\text{Kr}\) source at Tritium Laboratory Karlsruhe

Transport container
Temporal stability of the KATRIN setup during first tests with tritium

- Temperature of the source tube
- Pressure in the tritium buffer tank
- DT concentration in front of the beam tube
4. The first scientific run of KATRIN

- 22% of nominal T₂ column density
  radiochem. reactions of T₂ with previously unexposed steel
- T₂ (95.3%) HT (3.5%) DT (1.1%)
  laser Raman spectroscopy

One of 274 single scans measured within 2 hours

Time and energy distribution of measurement points around $E_0$
Temporal stability during the first scientific run

**β-scan Fit Parameters Stability over 780 hours (Data)**

274 single β-scan fits

Stable Background

Stable Endpoint

\[ \sigma(E_0^{\text{fit}}) = 0.25 \text{ eV} \]
Analysis of measured $\beta$-spectra

**Inspection of slow-control parameters:**
- 274 two-hours scans in stable conditions
- 117 perfect detector pixels
- Stable high-voltage: $\sigma = 34\text{mV}$ at 18.6 kV

32 058 correct partial $\beta$-spectra merged into one single spectrum

1.5×10$^6$ events below $E_0$

Four fitted parameters: $A, E_0, m^2, R_{bcg}$

Excellent goodness-of-fit:
$X^2 = 21.4$ for 23 d.o.f.
$p$-value = 0.56

Statistical uncertainties dominate
The best fit values

\[ m^2_\nu = \left(-1.0^{+0.9}_{-1.1}\right) \text{eV}^2 \quad (90\% \text{ CL}) \]

\[ m_\nu < 1.1 \text{ eV} \quad (90\% \text{ CL}) \]

\[ E_0 = 18\,573.7 \pm 0.1 \text{ eV} \quad \rightarrow \quad Q_\beta = 18\,575.2 \pm 0.5 \text{ eV} \]

\[ Q_\beta[\Delta(3\text{H},3\text{He})] = 18\,575.72 \pm 0.07 \text{ eV} \]

4 week KATRIN data:

\[ \sigma(m^2_\nu)_{\text{stat}} = 0.94 \text{ eV}^2 \]

\[ \sigma(m^2_\nu)_{\text{syst}} = 0.32 \text{ eV}^2 \]

\[ 2 \times \left(\text{improvement on Mainz and Troitsk}\right) \]
5. The KATRIN perspectives

a) $0.2\text{eV}$ neutrino-mass sensitivity after 1000 measuring days

b) Search for **sterile** neutrinos in the **eV** mass region

c) Search for **sterile** neutrinos in the **keV** mass region

KATRIN setup with TRISTAN multi-pixel detector for high electron rates

**Upper limits of a sterile neutrino admixture to active neutrinos**

From $\beta$-spectroscopy