Absolute neutrino mass scale and the KATRIN experiment

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Outline

1. Applied methods of m_ν measurements and current results
2. Educational role of previous β-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 4π due to β-decay of ^{40}K in your body

140 g of potassium, 0.01 % abundance of ^{40}K, $T_{1/2} = 1.2 \cdot 10^9$ y

1. Applied methods of m_ν measurements and current results

Model independent methods

also called direct or kinematic

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

Examples

- *two body decay of π^+ at rest:* $\boldsymbol{\pi^+ \rightarrow \mu^+ + \nu_\mu}$

$\sigma_{rel} = 3\cdot10^{-6}$ for m_π , $4\cdot10^{-8}$ for m_μ , $4\cdot10^{-6}$ for p_μ

$m(\nu_\mu) \leq 190$ 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_ν = 2 eV

Δt_ν is too small for terrestrial experiments

e.g. in the OPERA experiment:
$\langle E_\nu \rangle$ = 17 GeV, d = 730 km, t_c = 2.4 ms
⇒ expected time delay **$\Delta t_\nu = 2 \cdot 10^{-23}$ s**

Extraterrestrial experiments:

e.g. for 10 MeV neutrinos from SN1987a
⇒ expected time delay **$\Delta t_\nu = 0.1$ s**

BUT assumptions about the supernova explosion are needed

- *<u>β-spectrum shape in the endpoint region</u>*

where (according to Fermi theory, 1934)

$$dN/dE \sim (E_0 - E)^2 \cdot [\, 1 - \mathbf{m^2_{\nu}} /(E_0 - E)^2 \,]^{1/2}$$

E_0 is the endpoint for $m_\nu = 0$

Since neutrinos oscillate $|\nu_\alpha> \; = \Sigma\, U_{\alpha i} \cdot |\nu_i>$

and $\mathbf{|m_i - m_k| << \Delta E_{instr}}$

β-spectrum analysis yields **<u>the effective mass</u>**

$$\mathbf{m^2(\nu_e) = m^2_\beta = \Sigma\, |U_{ei}|^2 \cdot m^2_i}$$

this is <u>a weighted average</u>, no phases

thus no possible cancellations

More sensitive but model dependent methods

- search for 0νββ - 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

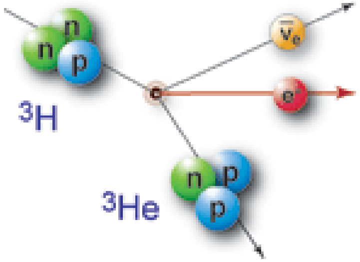
Effective ν mass from kinematic experiments:

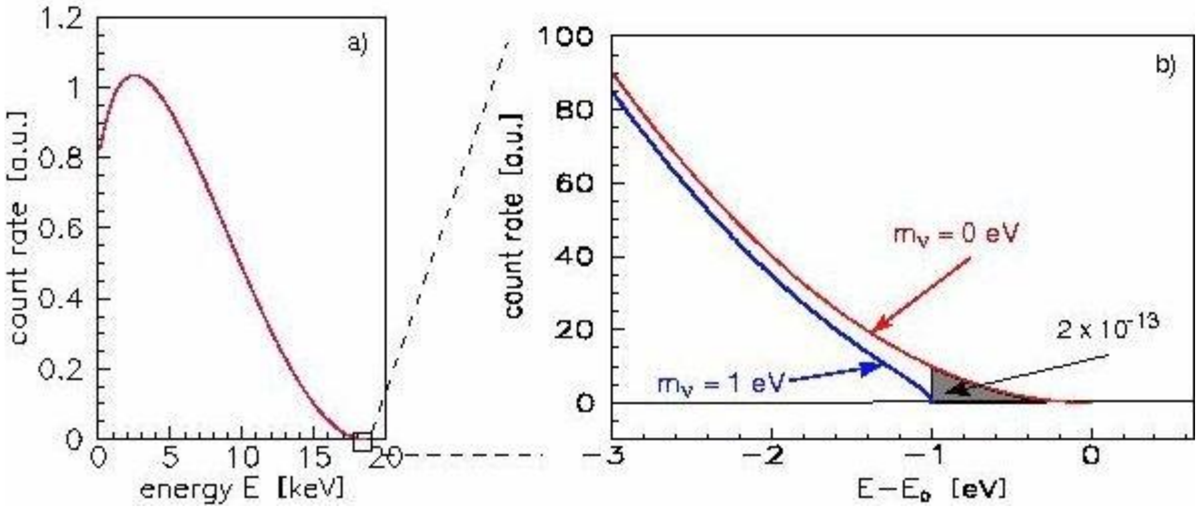
$m(\nu_e) < 2$ eV	$m(\nu_\mu) < 0.19$ MeV	$m(\nu_\tau) < 18.2$ MeV
β-decay	π^+ decay	τ^- decay

Other methods:

$T_{1/2}(0\nu\beta\beta)$	$\langle m_\nu \rangle_{\beta\beta} < 0.1 - 0.9$ eV,	one claim for 0.4 eV
TOF (SN1987a)	$m(\nu_e) < 5.7$ eV	
cosmology	$\Sigma\, m_i < 0.6 - 1.7$ eV	
ν oscillations	$m_i \geq 0.05$ eV at least for the heaviest mass state	

2. Educational role of previous β-decay experiments





Requirements for a β-ray spectrometer:

Simultaneously: - high energy resolution ΔE_{instr}

- large solid angle Ω_{input}
- low background

Neutrino mass from the β-spectrum shape

milestones

$m_\nu < 5$ keV **1948**

- β-spectrum of ^{35}S (E_0=167 keV)
- magnetic spectrometer

$m_\nu < 1$ keV **1949**

- β-spectrum of gaseous tritium (E_0=18.6 keV)
- proportional counter

***$m_\nu <$* 60 eV** **1972**

- β-spectrum of implanted tritium
- magnetic spectrometer with <u>100 x increased source area</u>
- part of Q_β goes into <u>excited states</u> of daughter $^3He^+$ ion

  ⇒ measured spectrum is a sum of partial β-spectra with various $E_{0,\,i}$

$m_\nu \approx 30$ eV ? 1980 - 1987

8 eV relic neutrinos would create all dark matter

- excellent toroidal magnetic spectrometer
- but tritium in complicated organic compound
- underestimated energy losses of β-particles
- wrong fitted E_0 supported by wrong Q_β from mass spectrometry

$m^2_\nu < 0$? 1991 - 1996

- 7 laboratories, 3 types of magnetic spectrometers
- various solid and gaseous tritium sources
- none of them $\mathbf{m^2_\nu}$ positive, two of them 6σ negative
- wrong theoretical spectrum of final states? NO
  but mostly underestimated energy losses of β-particles

$m_\nu \approx 0$ + up to 3% of $m_\nu = 17$ keV ? 1985-1994

- from β-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

$m_\nu < 2.3$ eV Mainz neutrino mass experiment 2005

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

Similar results reported the **Troitsk neutrino mass experiment** in 2003

- spectrometer of the same type
- gaseous tritium source
- $m^2_\nu = (-2.3 \pm 2.5_{stat} \pm 2.0_{syst})\ \mathrm{eV}^2$
  but only after artificial correction of β-spectrum
  with two additional fitting parameters

Final Troitsk result in 2011

- enlarged data set
- removed runs with unstable tritium density

$m^2_\nu = (-0.67 \pm 1.89_{stat} \pm 1.68_{syst})\ \mathrm{eV}^2$
without any artificial correction

$m_\nu < 2.0$ eV 2011

weighted average of Mainz (2005) and Troitsk (2011)
$m^2_\nu = -0.6 \pm 1.9$ eV^2

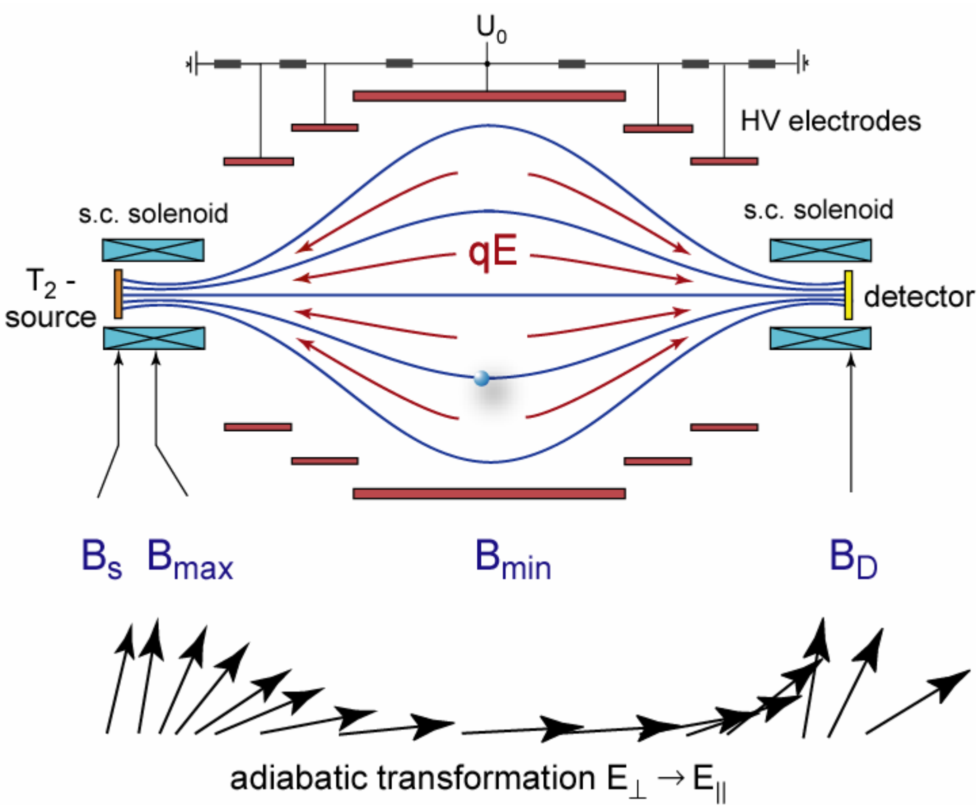
$\Rightarrow m_\nu < 2.0$ eV at 95% C.L. using the conservative approach

During 63 years, β-ray spectroscopists improved the model independent limit of experimentally observable $\mathbf{m}^2_\nu$ by 6 orders of magnitude.

Next improvement by 2 orders of magnitude is expected from KATRIN

Electrostatic retardation spectrometer with adiabatic magnetic collimation of electrons (MAC-E-filter)

Developed independently
at Mainz and Troitsk



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

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

Ω_{input} up to 50% of 4π

Advantages:
- Large Ω_{input} and narrow line width ΔE_{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 β-spectroscopy

λ_{inel} (Al) = 30 nm for E_e = 20 keV

⇒ large source area S

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

large spectrometer dimensions

3. Principle and technique of the KATRIN experiment

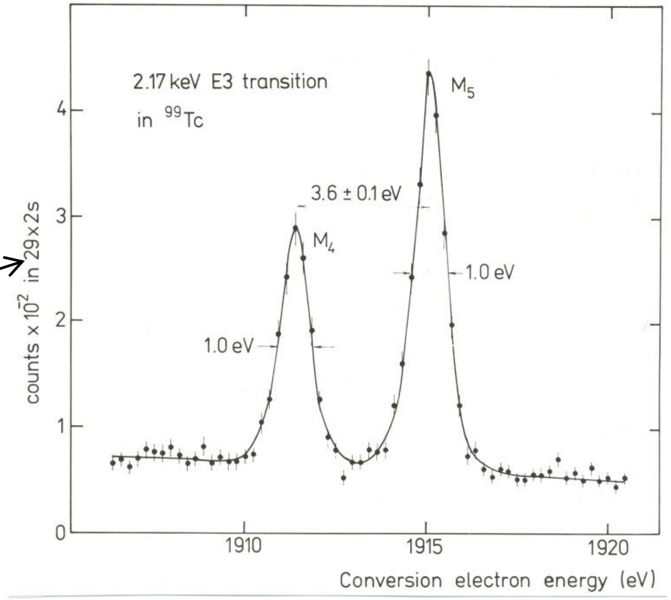
at the Karlsruhe Institute of Technology (KIT = FZK + Tech. Uni.)

The next generation tritium β-decay experiment measuring m_ν 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

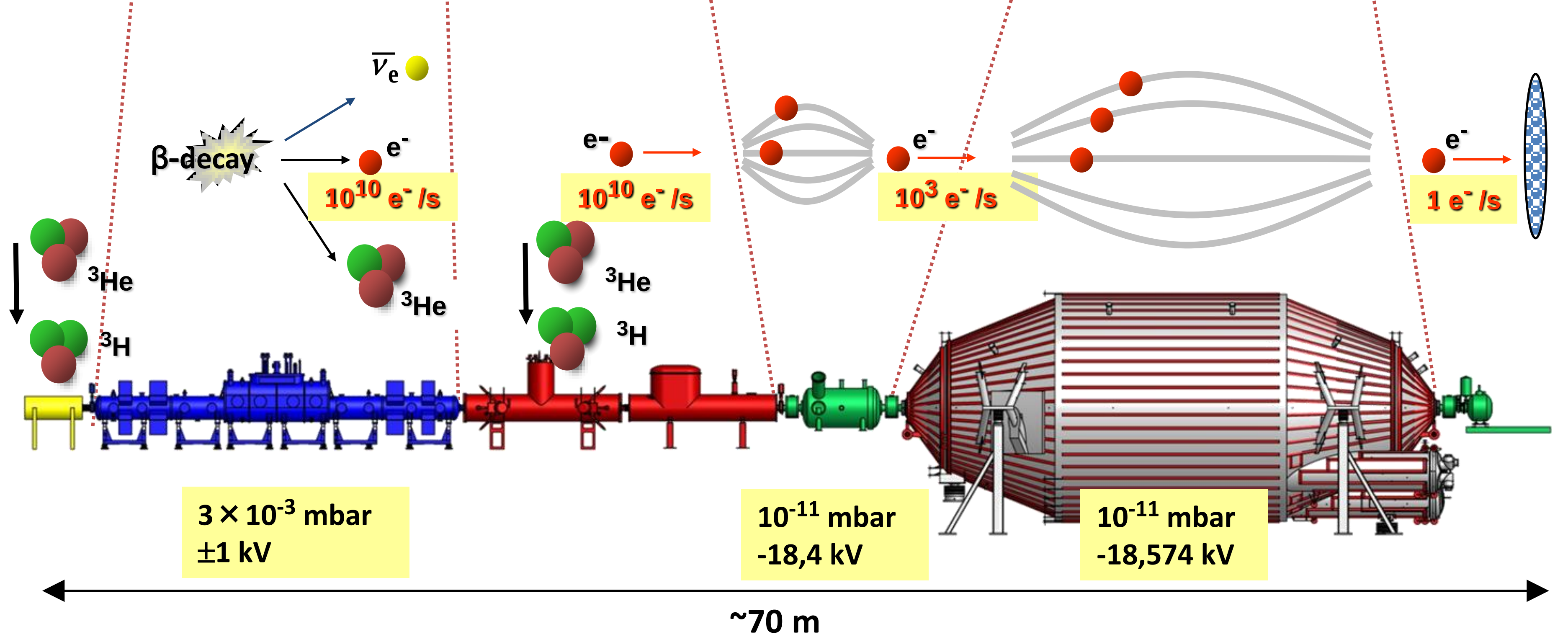
electron transport tritium retention

reflection of low energy electrons

high precision energy analysis of electrons

position sensitive electron counter

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



10^{10} e^-/s

10^{10} e^-/s

10^3 e^-/s

1 e^-/s

3×10^{-3} mbar
±1 kV

10^{-11} mbar
-18,4 kV

10^{-11} mbar
-18,574 kV

~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

- **± 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

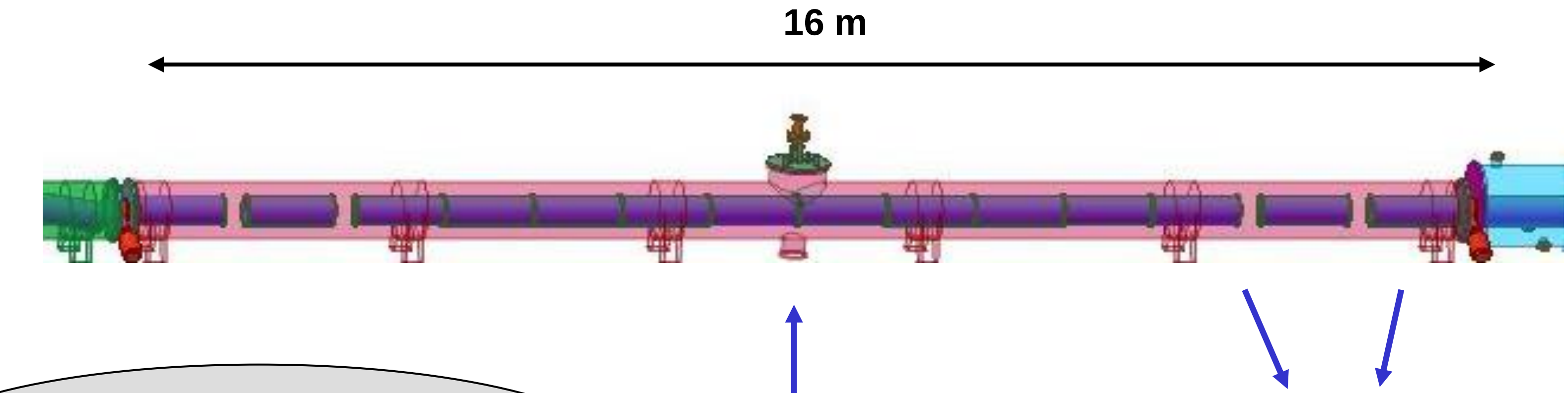
- **± 60 mV** long-term stability of high voltage at 18.6 kV
  unrecognized shift by 50 mV ⇒ 0.04 eV error in fitted m_ν

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)



T_2 injection rate:
1.8 cm³/s (± 0.1%)

at pressure of $3.4 \cdot 10^{-3}$ mbar

T_2 injection

Isotopic
purity
>95%

T_2 pumping

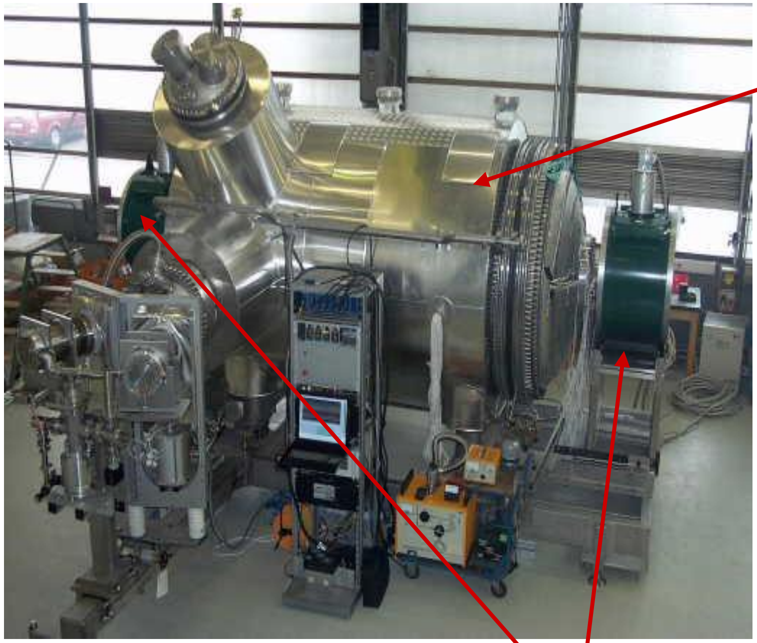
Total pumping speed:
12000 l/s

Probably the most complex cryostat ever built

KATRIN electron pre-spectrometer

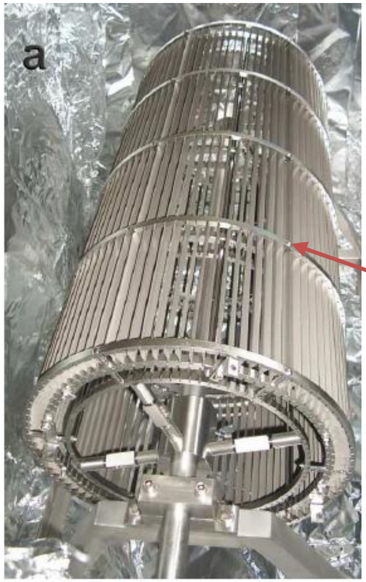
Aim: only the uppermost part of β-spectrum into the main spectrometer

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



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

Superconducting magnets



turbomolecular pumps +getter strips (Zr+V+Fe alloy)
10^{-11} mbar achieved

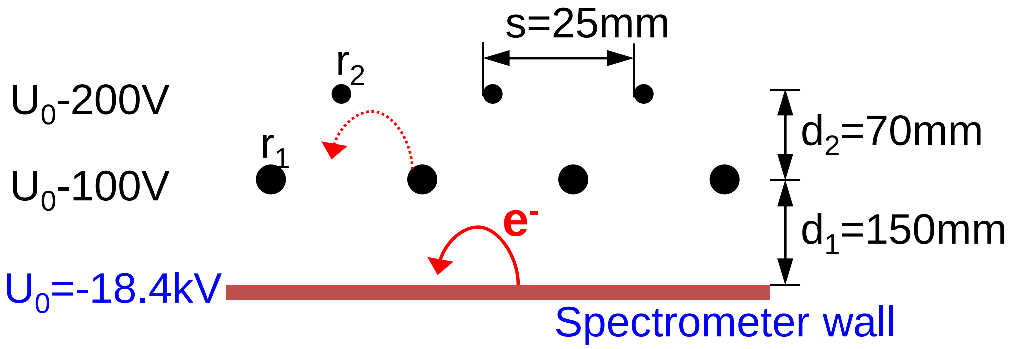
Vacuum chamber of the main spectrometer

9000 km on sea
around Europe

The last 7 km to
the KIT

diameter 10 m
length 23 m
weight 200 t

Wire electrodes of the main KATRIN spectrometer



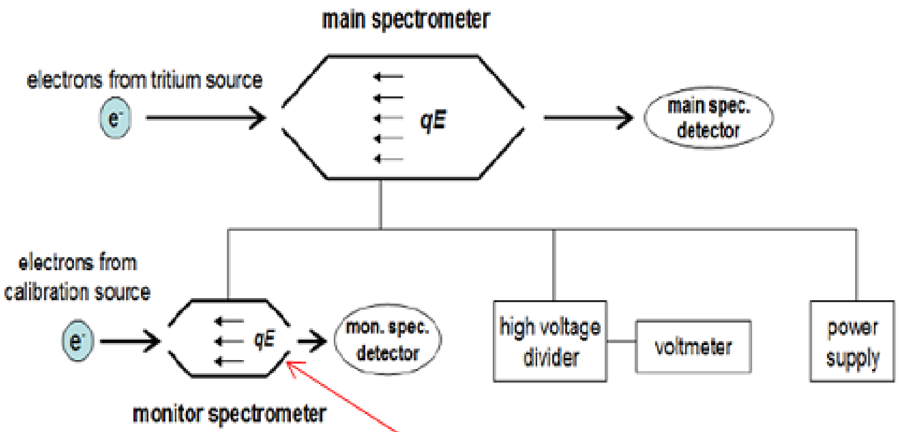
- **Reduce background** due to secondary electrons from the wall
- **Secure precise form** of the retarding electrostatic field
  no magnetic traps for e^- and ions

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



Shift of line energy will indicate a possible shift of measured voltages

^{83m}Rb/ ^{83m}Kr source of 17.8 keV electrons

- implanted ^{83m}Rb sources

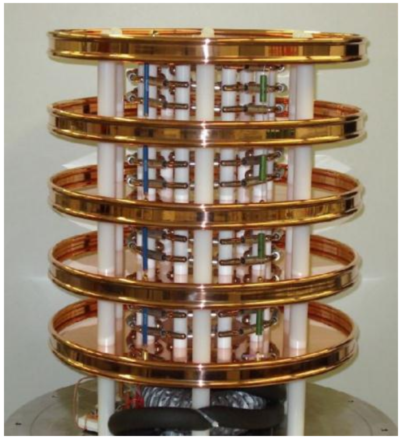
  90 % retention of ^{83m}Kr

  electron energy drift < ±3 ppm/month

- 1 GBq ^{83m}Kr source for testing the whole KATRIN setup with monoenergetic electrons

  ^{83}Rb production at the NPI cyclotron

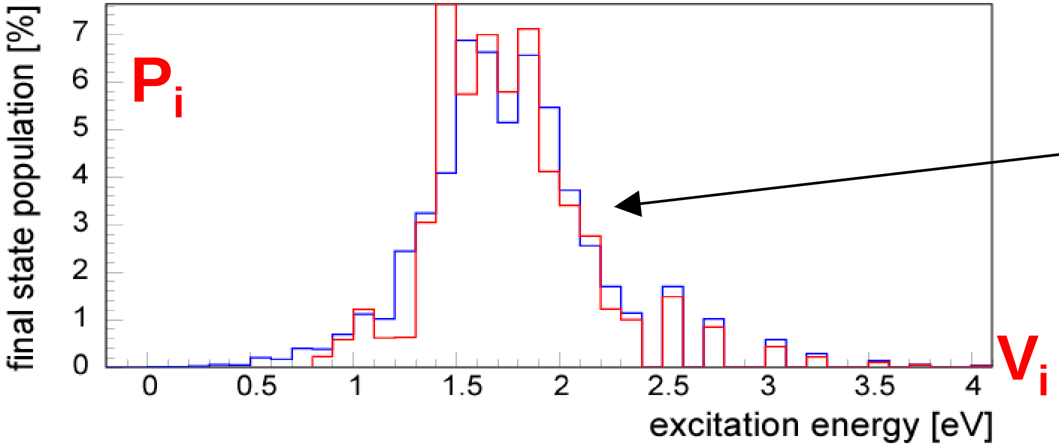
  deposition in zeolite: no escape of ^{83}Rb ($T_{1/2}$= 86d)
  high release of ^{83m}Kr ($T_{1/2}$= 1.8h)



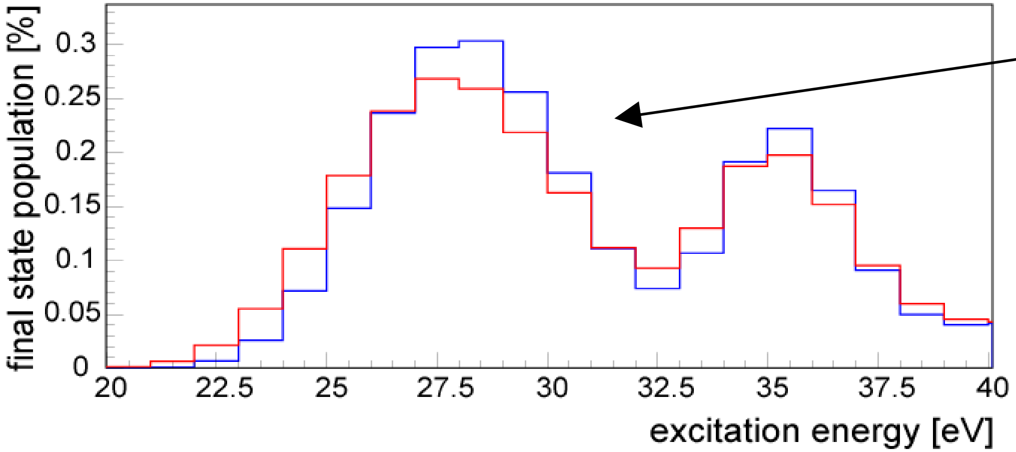
High-voltage divider
metrology precision

Analysis of measured β–spectrum: final $(THe)^+$ states

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



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)

  $\boldsymbol{m_\nu < 0.2}$ **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)

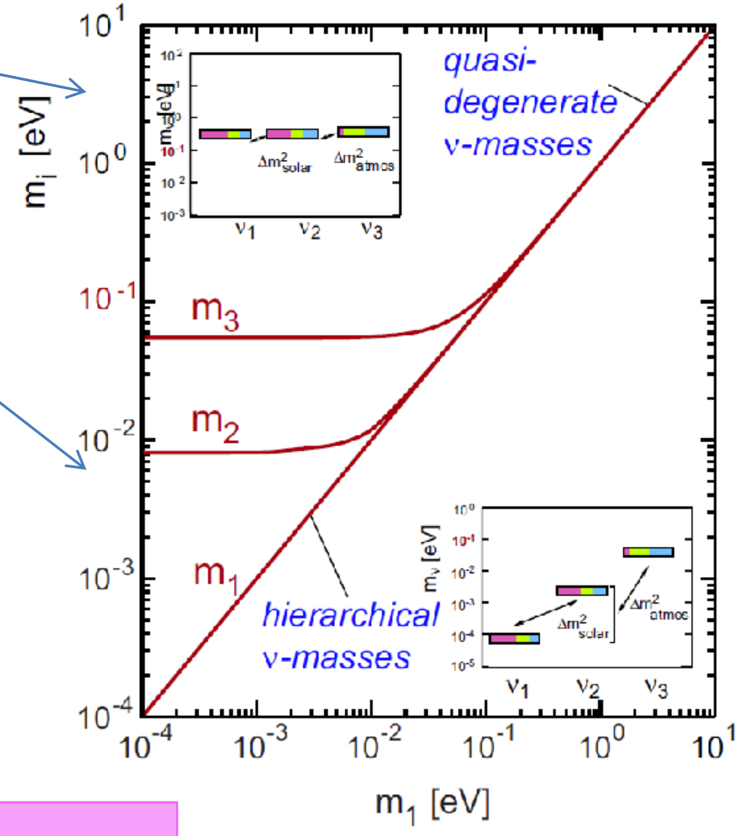
Possible unaccounted **right-handed couplings** will change the fitted m_ν by less than 10%

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

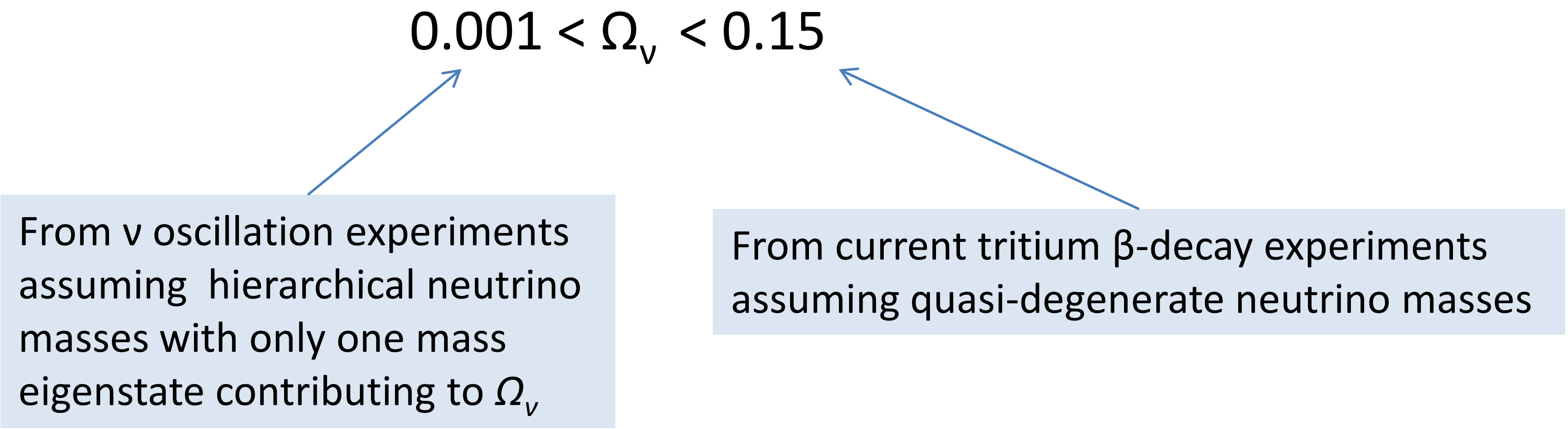
Both in accord with oscillation experiments



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 ν oscillation experiments assuming hierarchical neutrino masses with only one mass eigenstate contributing to Ω_ν

From current tritium β-decay experiments assuming quasi-degenerate neutrino masses

KATRIN

- will be **sensitive to Ω_ν = 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

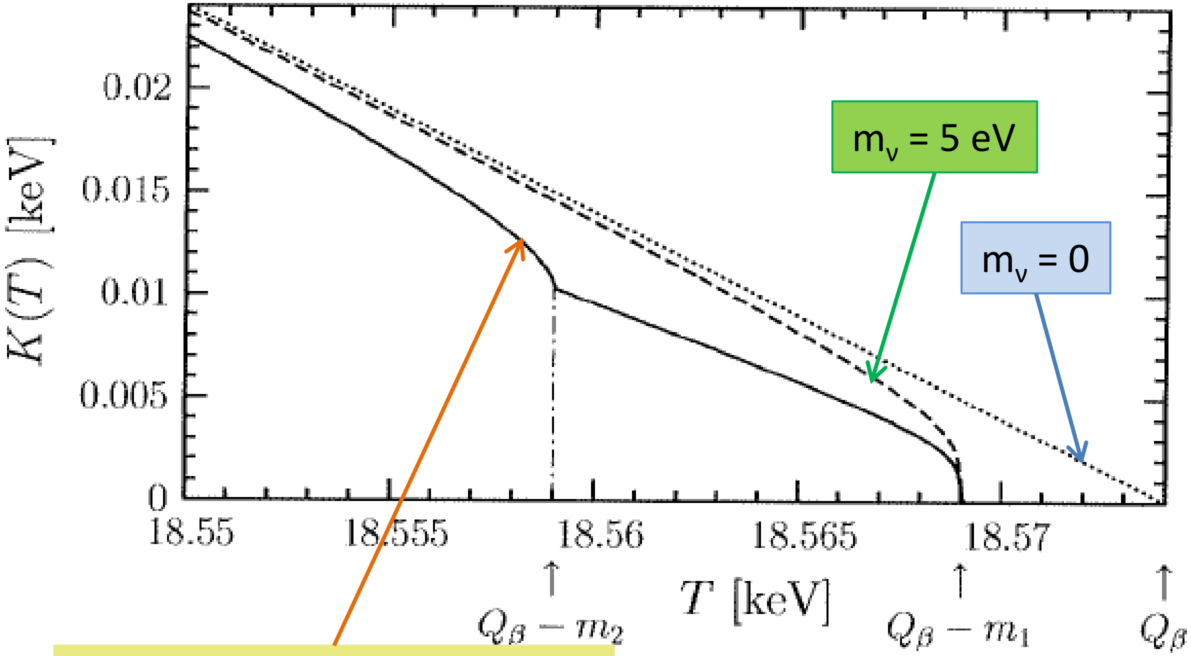
KATRIN would see sterile neutrinos

with
$\Delta m^2_{s1} = 6.49\ \mathrm{eV}^2$
$|U_{e4}|^2 = 0.12$

$\Delta m^2_{s2} = 0.89\ \mathrm{eV}^2$
$|U_{e5}|^2 = 0.11$
and similar cases.

Well separated from signal of all three light active neutrinos

Kurie plot for tritium decay



Two neutrino mixing:
$m_1 = 5$ eV, $m_2 = 15$ eV
$|U_{e1}|^2 = |U_{e2}|^2 = 1/2$

from Giunti and Kim: Fundamentals of neutrino physics and astrophysics (2011)

5) *Local density of relic neutrinos*

KATRIN tritium gaseous source as a target

$5.3 \cdot 10^{19}$ tritium atoms, mass of 0.26 g

for $\nu_e + T \rightarrow {}^3He^+ + e^-$

monoenergetic

with relic neutrinos

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

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

arXiv: 1006.1886

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

KATRIN Collaboration will do its best to fulfill these tasks