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)

20th Conference of Czech and Slovak Physicists, Prague, 7.9.2020

Topics

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

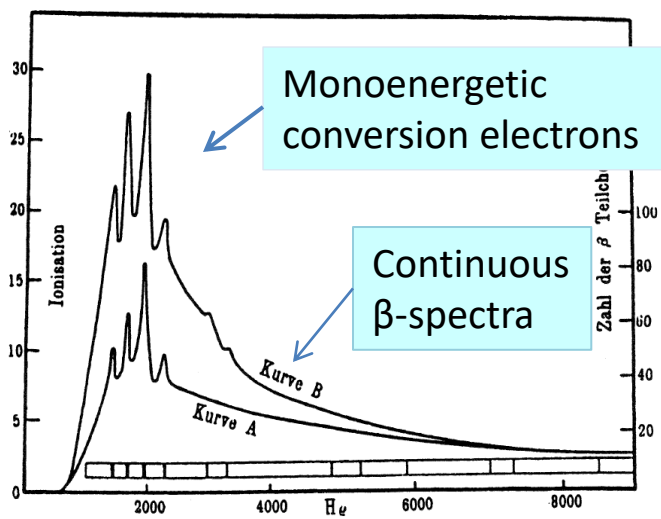
1. Mysterious shape of β-ray spectra

The laws of energy and momentum conservation:

Decay in two parts → discrete energy spectra

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

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



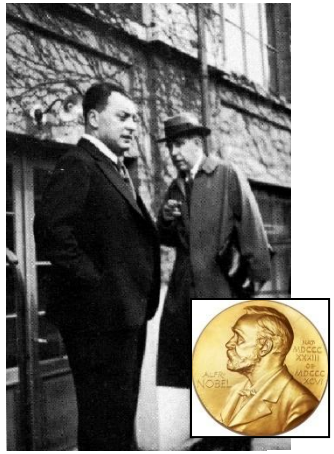
James Chadwick

1914:

1935

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

β-spectrum is continuous! WHY?



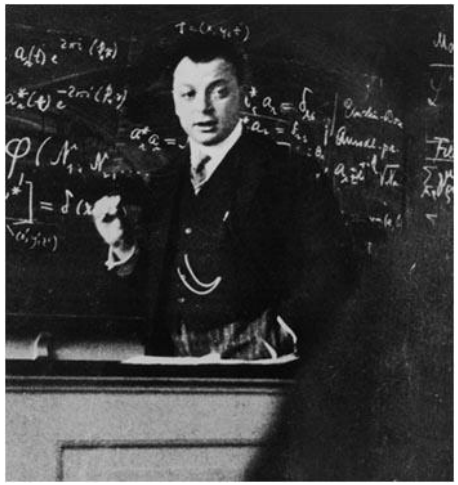
Wolfgang Pauli and Niels Bohr

1928

The neutrino hypothesis

Wolfgang Pauli

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



1945

Proposed on 4th December 1930:

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

$^{35}S \rightarrow {}^{35}Cl + e^- + \tilde{\nu}_e$ $\quad$ $^{3}H \rightarrow {}^{3}He + e^- + \tilde{\nu}_e$

Decay in three parts → continuous energy spectra
Assumed neutrino properties: <u>light, neutral, penetrating</u>

Only protons and electrons were known at that time

Enrico Fermi

(33 years old experimental and theoretical physicist,
also future Nobel prize winner)

1938

Developed <u>the β-decay theory</u> incorporating the Pauli's neutrino already in 1934:

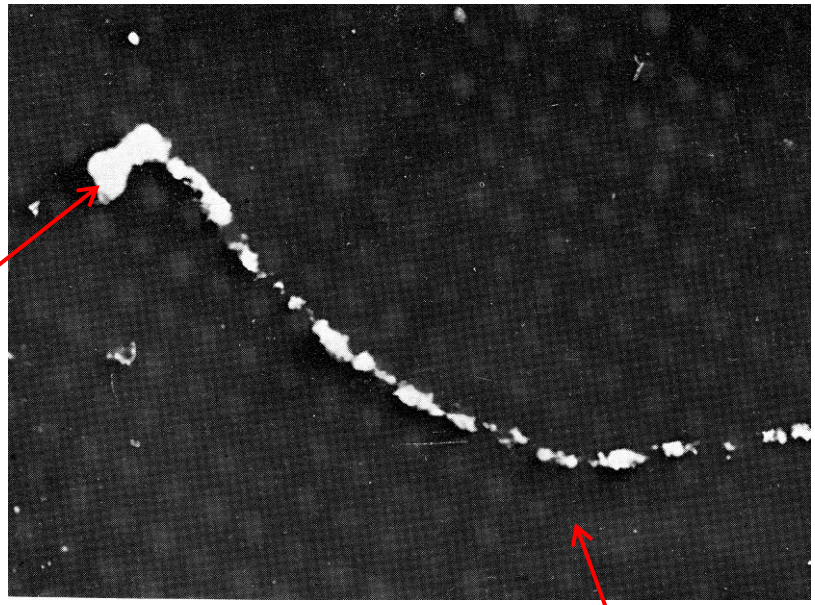
$^{35}S \rightarrow {}^{35}Cl + e^- + \tilde{\nu}_e$ $\qquad$ $^{3}H \rightarrow {}^{3}He + e^- + \tilde{\nu}_e$

Calculated β-spectrum shape <u>agreed with the experiment:</u>
"*the neutrino mass is smaller than the electron mass, most probably zero*"

β-decay of $^6He \rightarrow {}^6Li + e^- + \tilde{\nu}_e$ 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: $^6He \rightarrow {}^6Li + e^-$
This is not a two-particle decay

2. Neutrinos – the most abundant massive articles

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

We already know:

- Three kinds of neutrinos: ν_e , ν_μ , ν_τ
- Neutrinos are electrically neutral particles
- Penetrability ($\sigma_\nu \approx 10^{-20}\ \sigma_{\text{nucl. phys.}}$)
- 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**

ν mixing matrix

i =1,2,3 **mass eigenstates**

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

- All experiments and cosmological observations up to now:

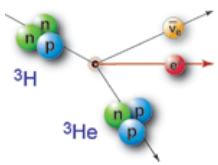
Only upper limits on m_i

β-ray spectroscopy – the only model independent method

70 years of searching for massive neutrinos in β-ray spectra

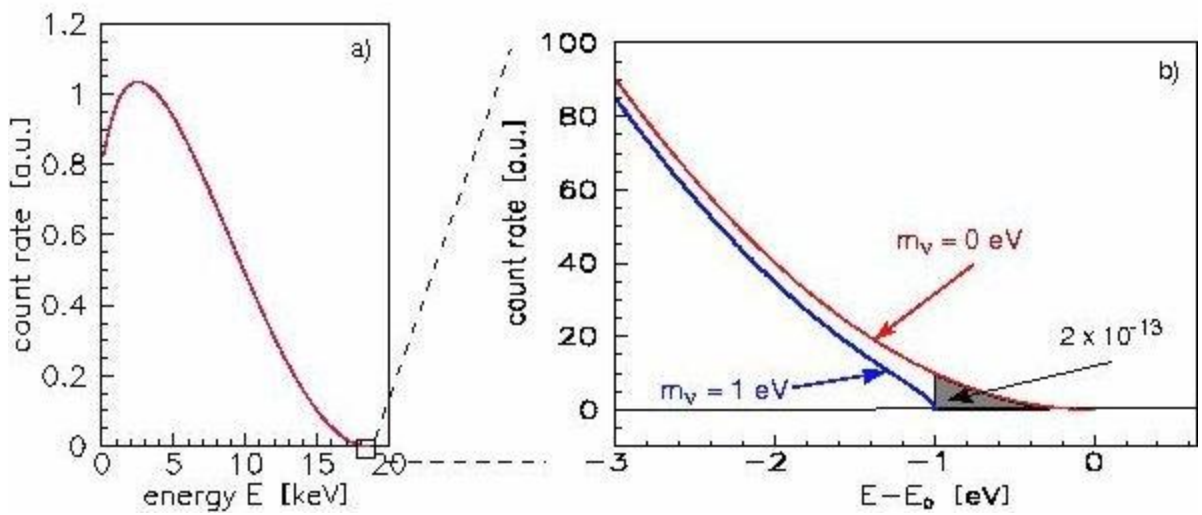
$$dN/dE = K \times F(E,Z) \times p \times E_{tot} \times (E_0-E_e) \times [\,(E_0-E_e)^2 - m_\nu^2\,]^{1/2}$$

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



E_0 = 18.6 keV

$T_{1/2}$= 12.3 y



Simultaneously:
- high resolution
- high luminosity
- low background

m_ν < 5 keV (1948)

m_ν < 2,3 eV (2005)

m_ν < 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 ν mass-state, daughter in ground state (*Fermi, 1934*)

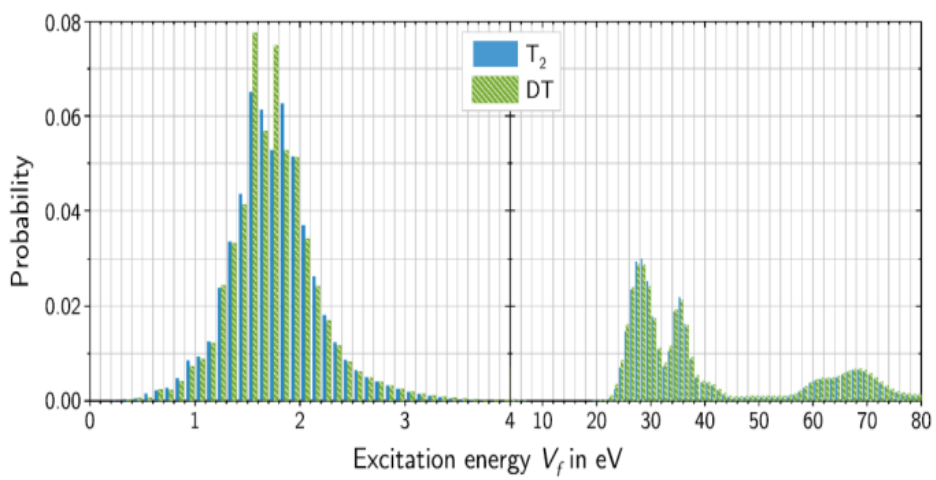
$$\frac{dN}{dE} = A \cdot F \cdot p \cdot (E + m_e) \cdot \varepsilon \cdot \sqrt{\varepsilon^2 - m_{\nu_e}^2} \qquad \varepsilon = E_0 - E$$

b) one ν mass-state, daughter also in excited states (*Bergkvist, 1972*)

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

Excitation probability

Excitation energy



<u>Observed spectrum</u>:
Sum of many with various endpoints

c) three ν mass-states, daughter also in excited states (*ν oscillations, 1998-2001*)

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

Elements of ν-mixing matrix

ν-masses

- Future β-spectroscopy might provide all $|U_{ei}|^2$ and m_i
- Present ΔE does not allow to distinguish individual m_i

The effective mass of the electron neutrino

$$m_{\nu_e}^{eff} = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

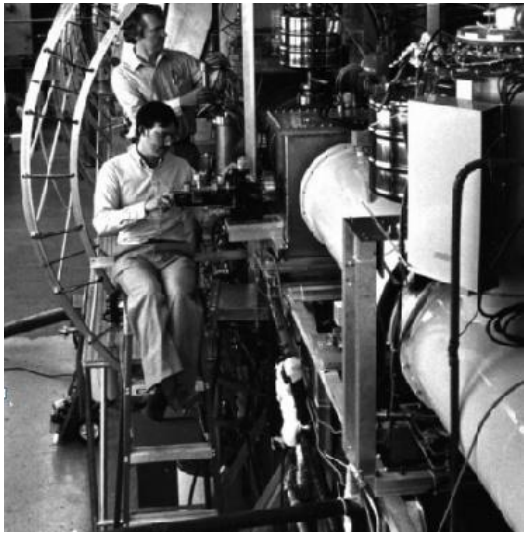
Analysis of present β-spectra: one effective ν mass-state
daughter also in excited states

3. The Karlsruhe Tritium Neutrino Experiment

Aim: improvement of the ν-mass sensitivity from 2 eV to 0.2 eV

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

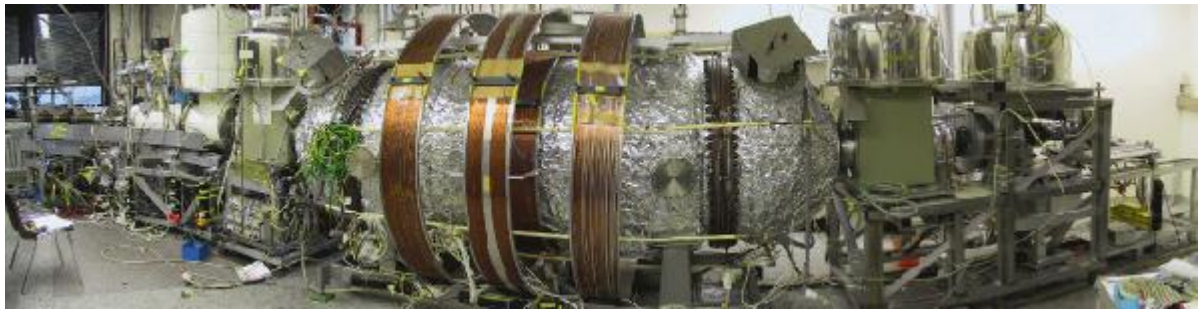
Gaseous T_2 Source at Los Alamos, USA



New β-spectrometer type: MAC-E-Filter

at Troitsk, Russia

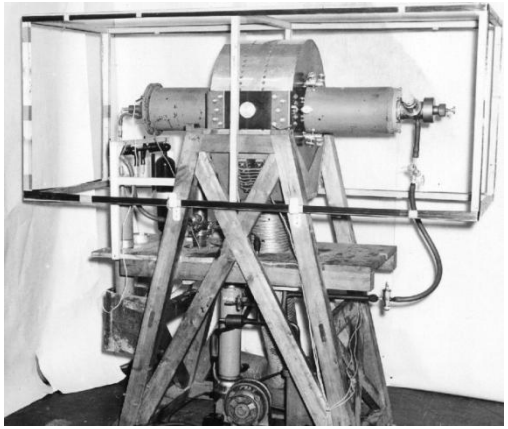
at Mainz, Germany



Electron spectroscopy of radioactive nuclei at NPI

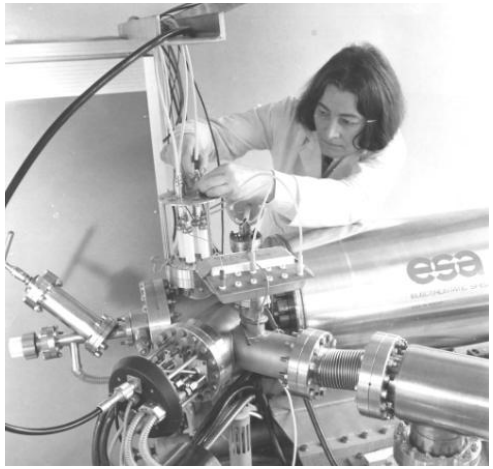
1955 –1990: internal conversion electrons
1990 – now: neutrino mass determination

Monoenergetic
$E_{ce} = E_{\gamma} - E_{bin}$



First Czechoslovak
β-ray spectrometer
(1956)

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



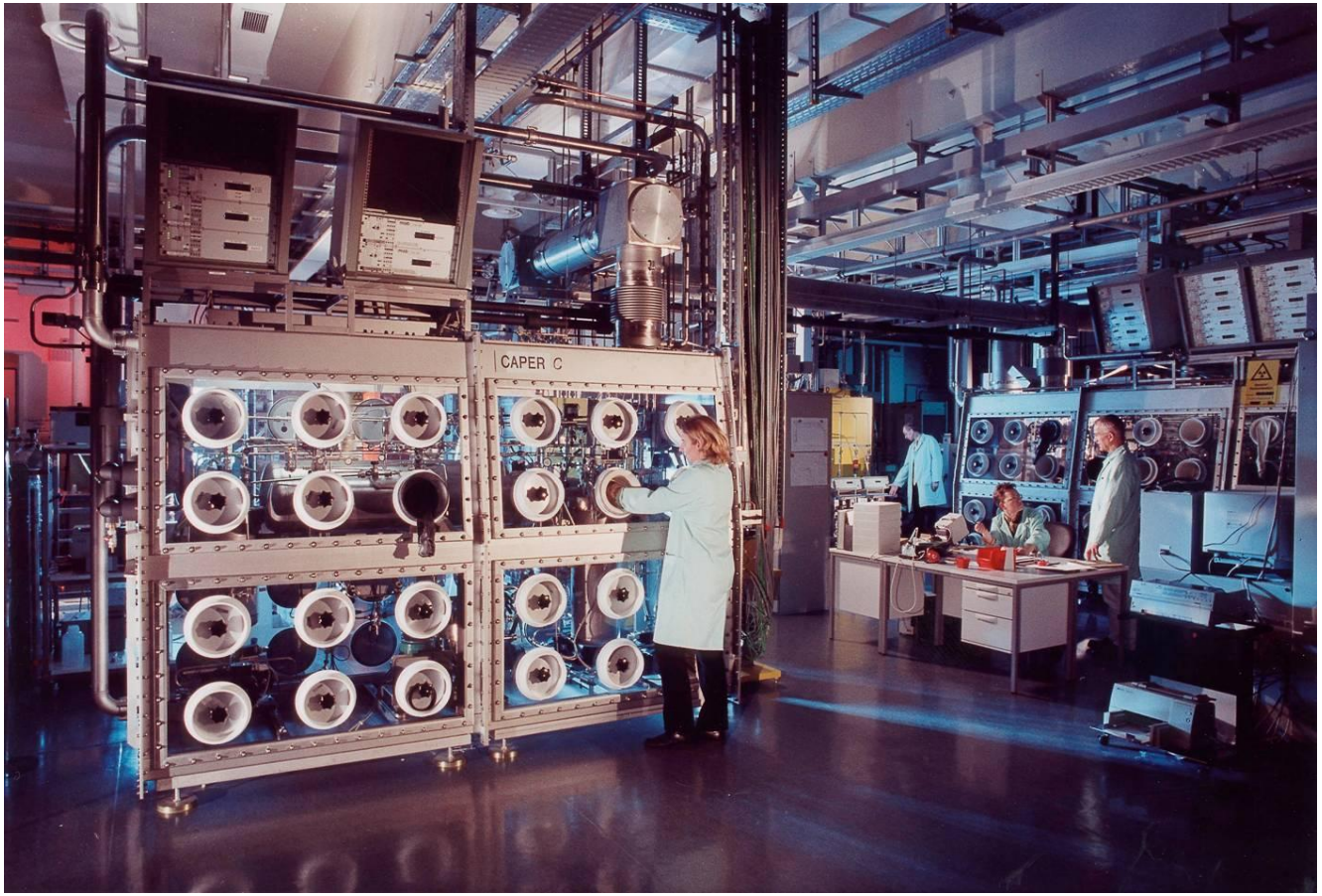
Elektrostatic spectrometer
of keV electrons
(1983)

best resolution $\Delta E \leq 1$ eV
at low transmission

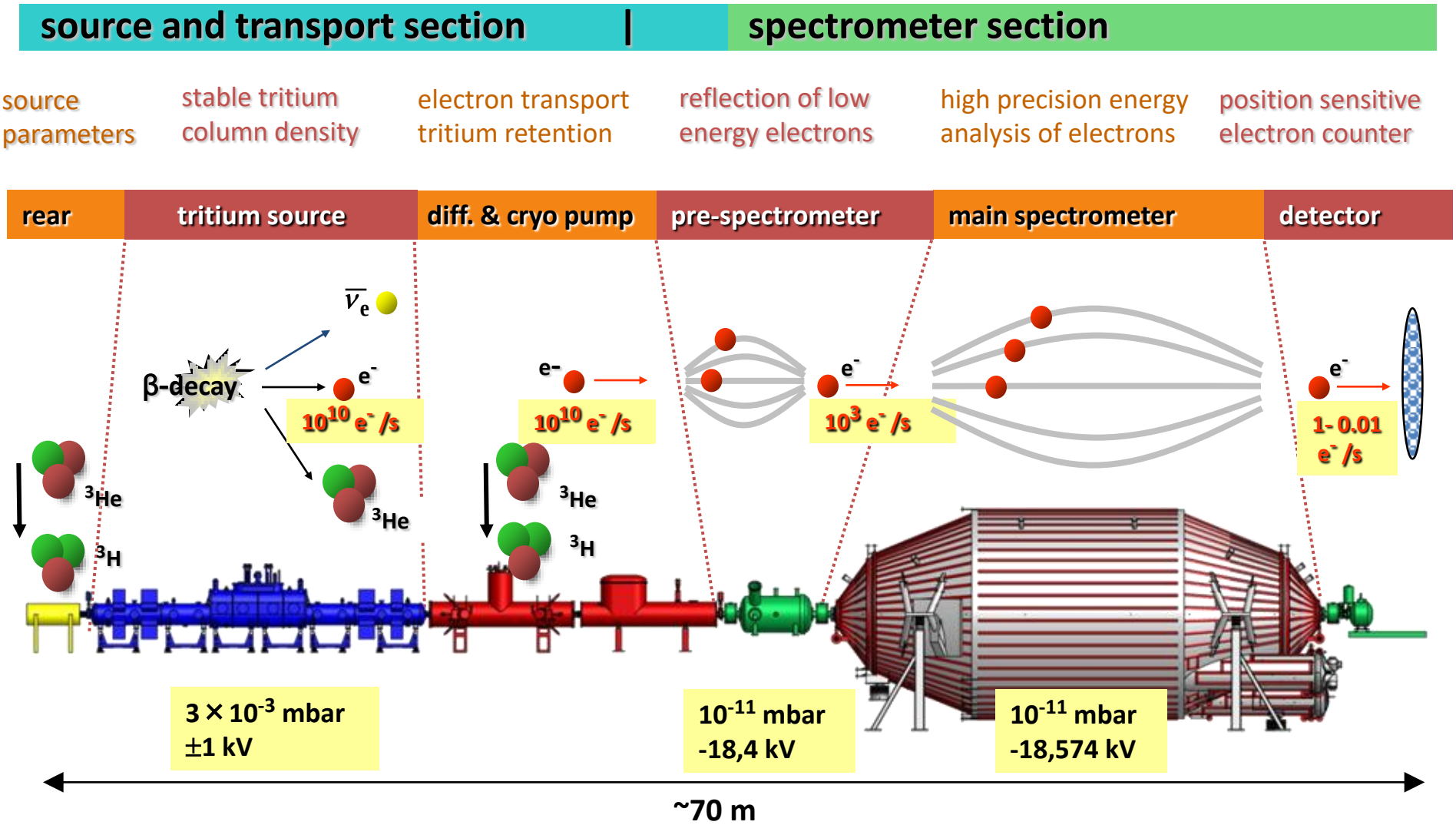
Tritium Laboratory Karlsruhe

<u>The only one in Europe</u>:

- **large amount of tritium**
- **high chemical and isotopic purity.**

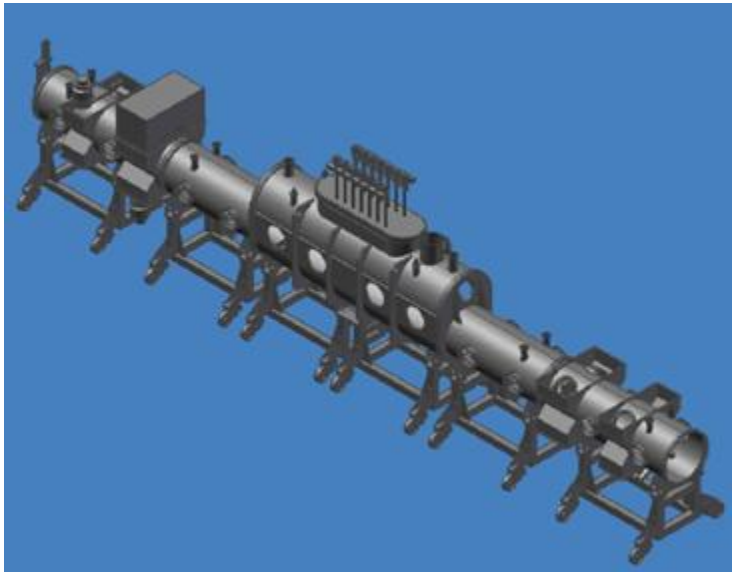


KATRIN main components:



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 %



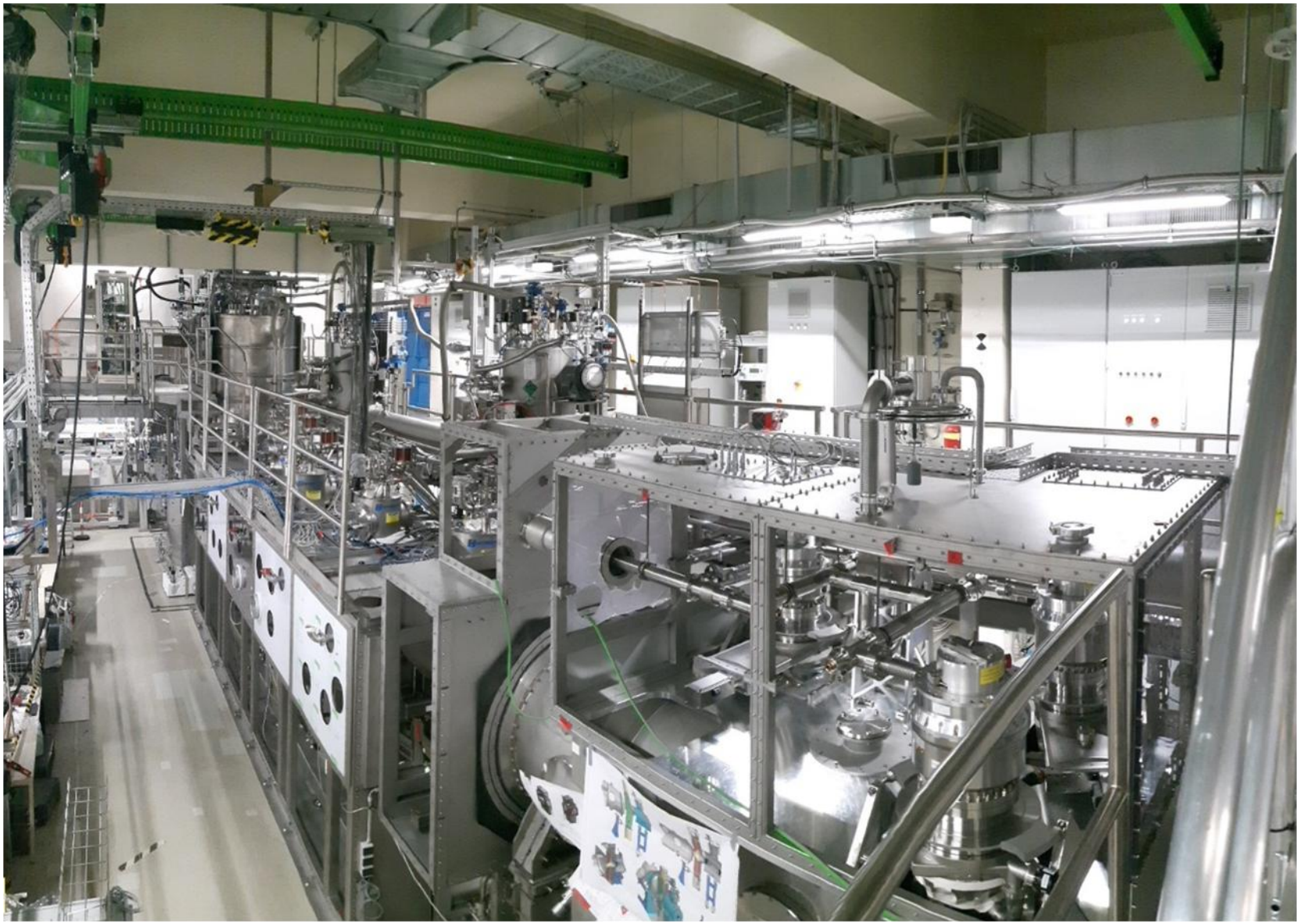
- Continuously filled in the middle with molecular tritium at $3 \cdot 10^{-3}$mbar
- Continuously pumped at both ends

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

- Column density of 5×10^{17} tritium molecules per cm^2
- **$5.7 \times 10^{10} \pm 0.1$ % of β-particles** for energy analysis

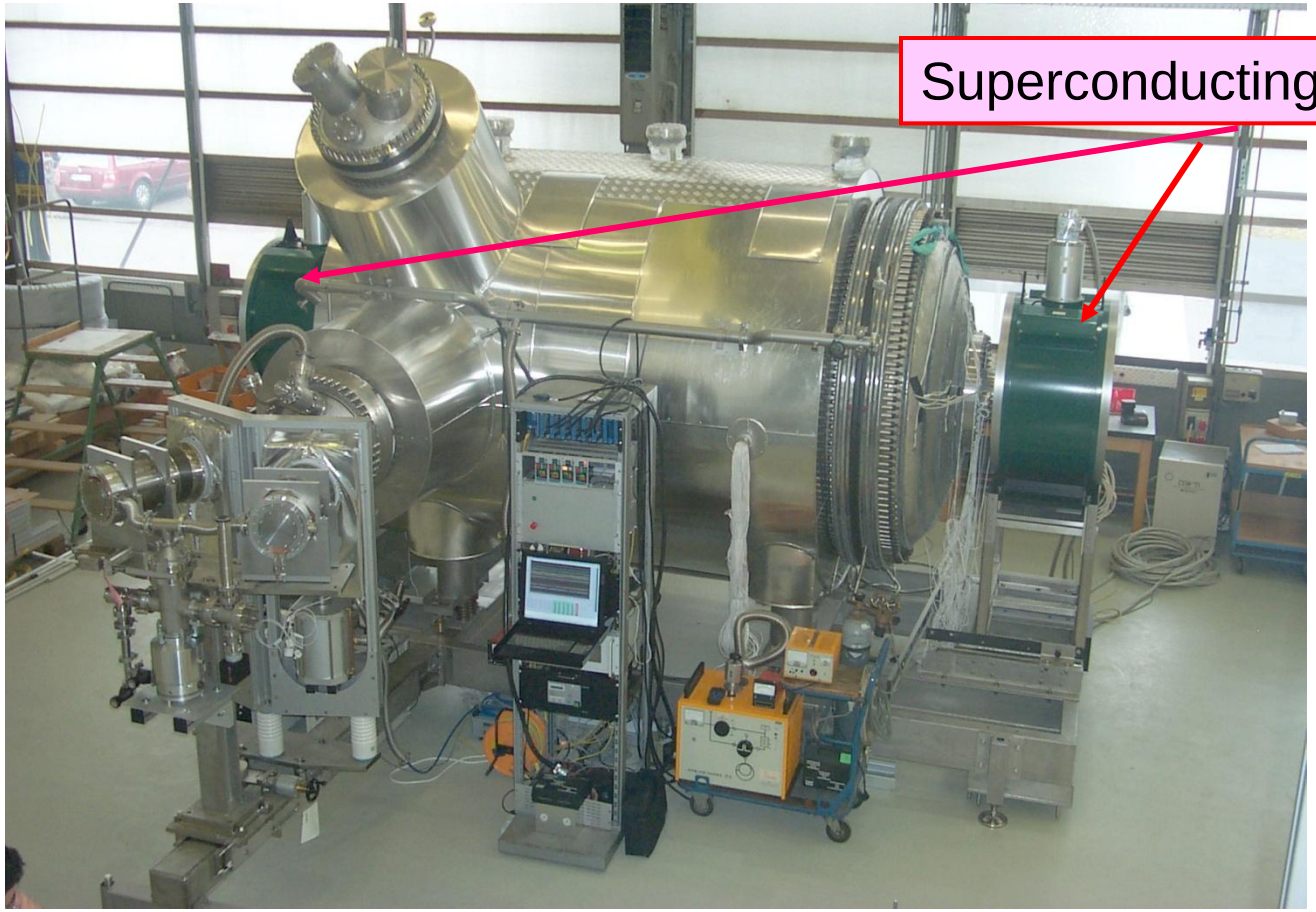
One of the most complex cryostats ever built

Source and transport system of KATRIN inside TLK



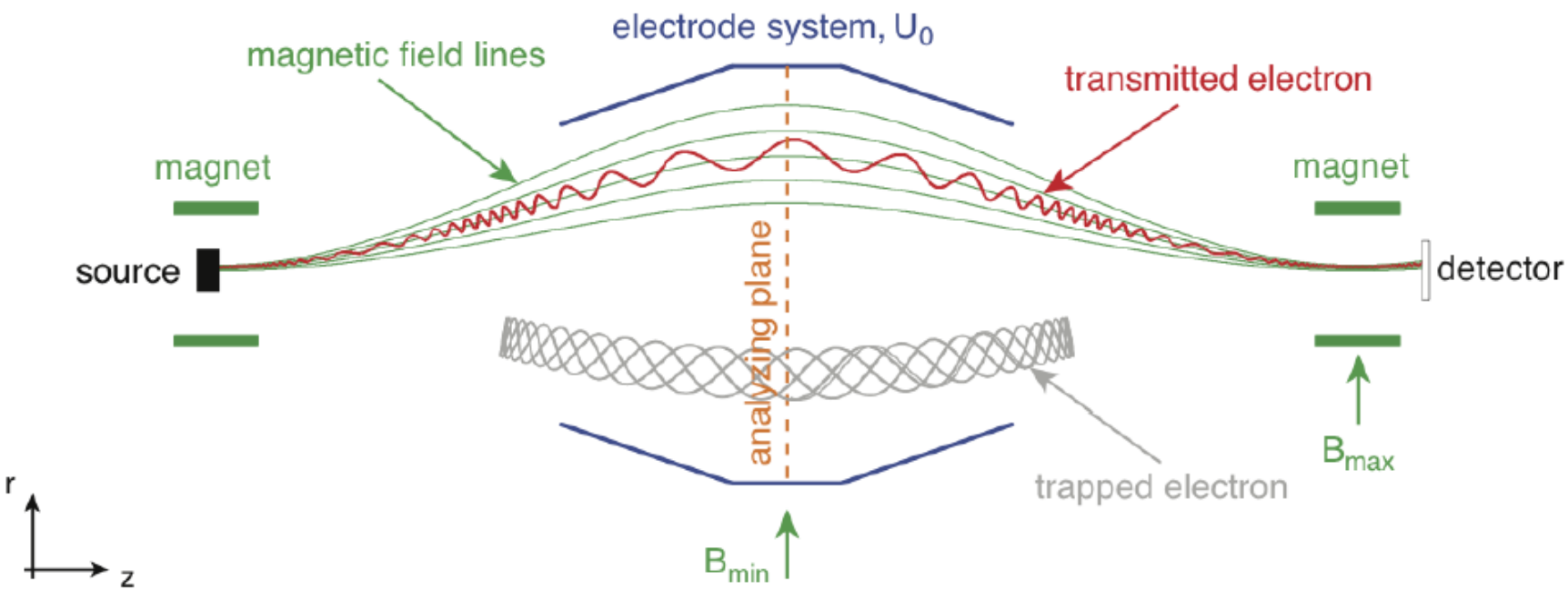
KATRIN electron pre-spectrometer

Vacuum chamber: 1.7 m in diameter
3.7 m in length



KATRIN main electron spectrometer

- Magnetic adiabatic collimation with electrostatic retardation
- Large Ω_{input} and narrow line width ΔE_{instr} simultaneously
- No electron scattering on slits
- Danger of magnetic traps (UHV of 10^{-11} helps)

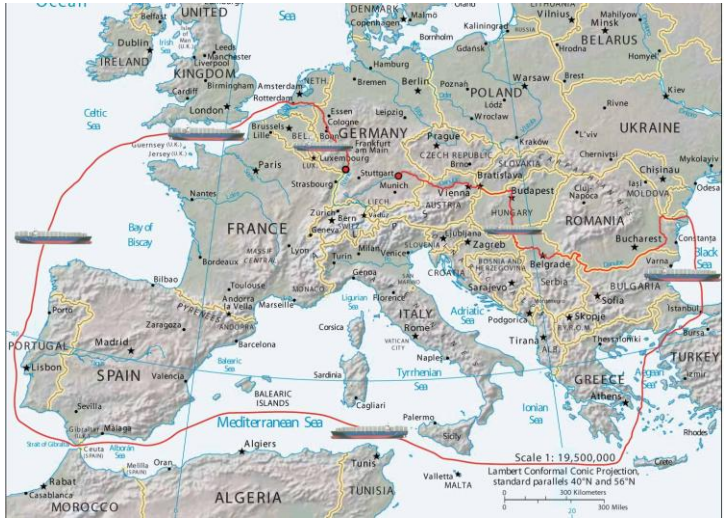


Vacuum test of the spectrometer chamber at a factory

- 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

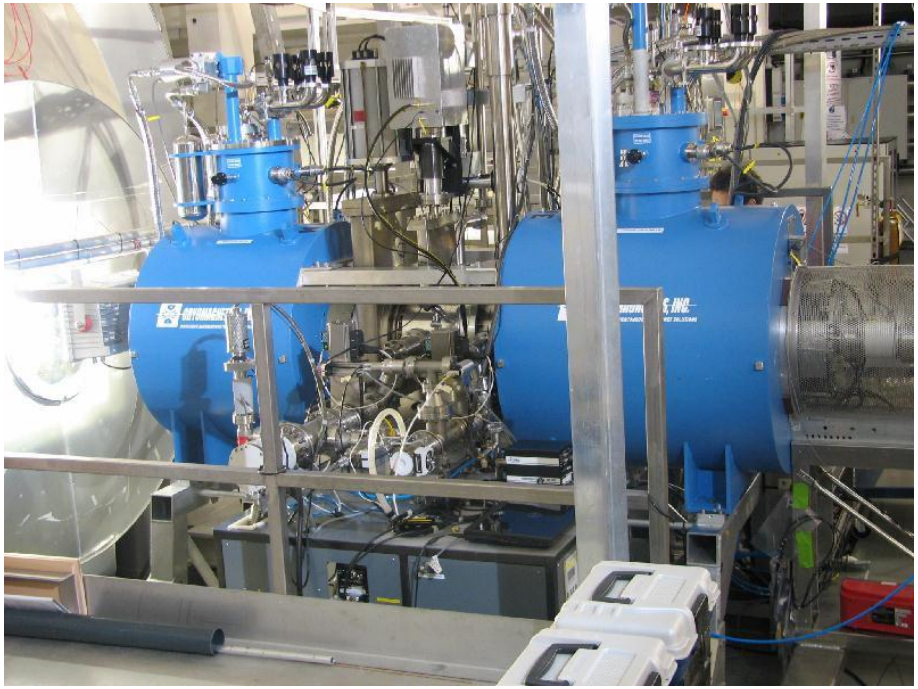


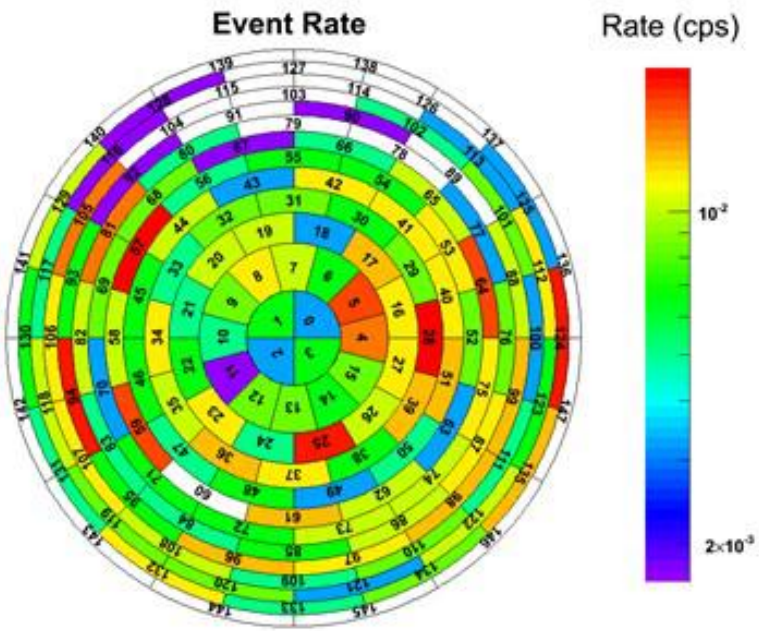
8800 km around Europe

Last 7 km

Placing at KIT

Focal plane detector





***Si PIN diode**, 9 cm diam.*
148 independent pixels

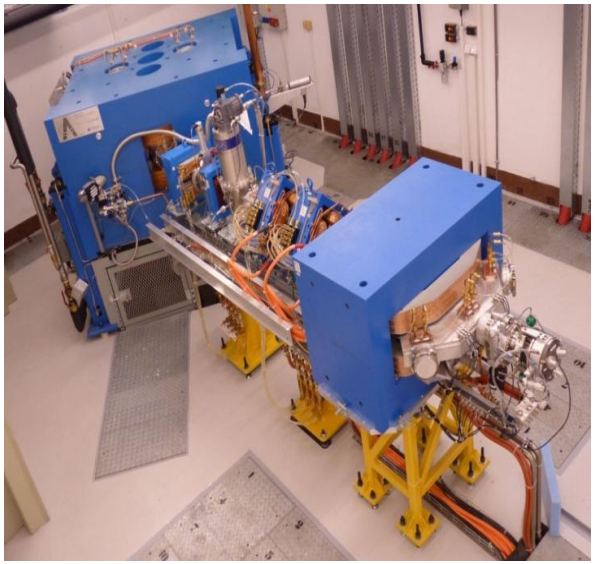
Tasks of the NPI at Řež for KATRIN

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

in three NPI laboratories

^{83}**Rb** (86d) → ^{83m}**Kr** (1.8h) → ^{83}**Kr**

p (24 MeV, 45 μA) → ^{nat}**Kr**



New cyclotron TR-24

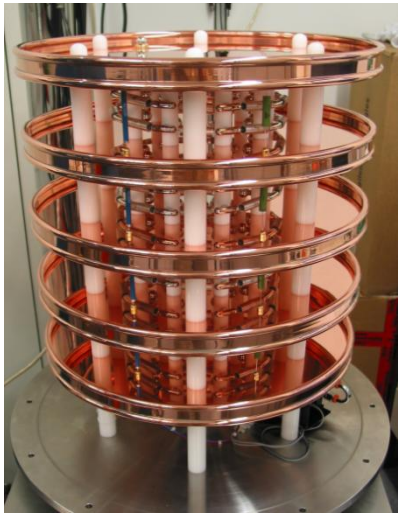
Installation of krypton target at the TR-24

New radiochemical laboratories

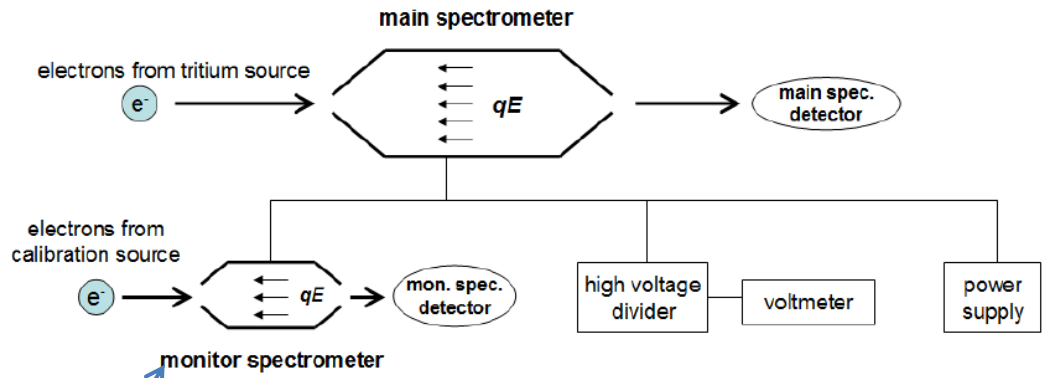
The first NPI task for KATRIN : monitor high voltage stability

In collaboration with the Mass-separator group at Bonn University

Precision HV divider



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



KATRIN monitor spectrometer

<u>Standard of stable electron energy</u>

at 17.8 keV: ^{83}Rb/^{83m}Kr 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

Now also for energy calibration in dark matter searches

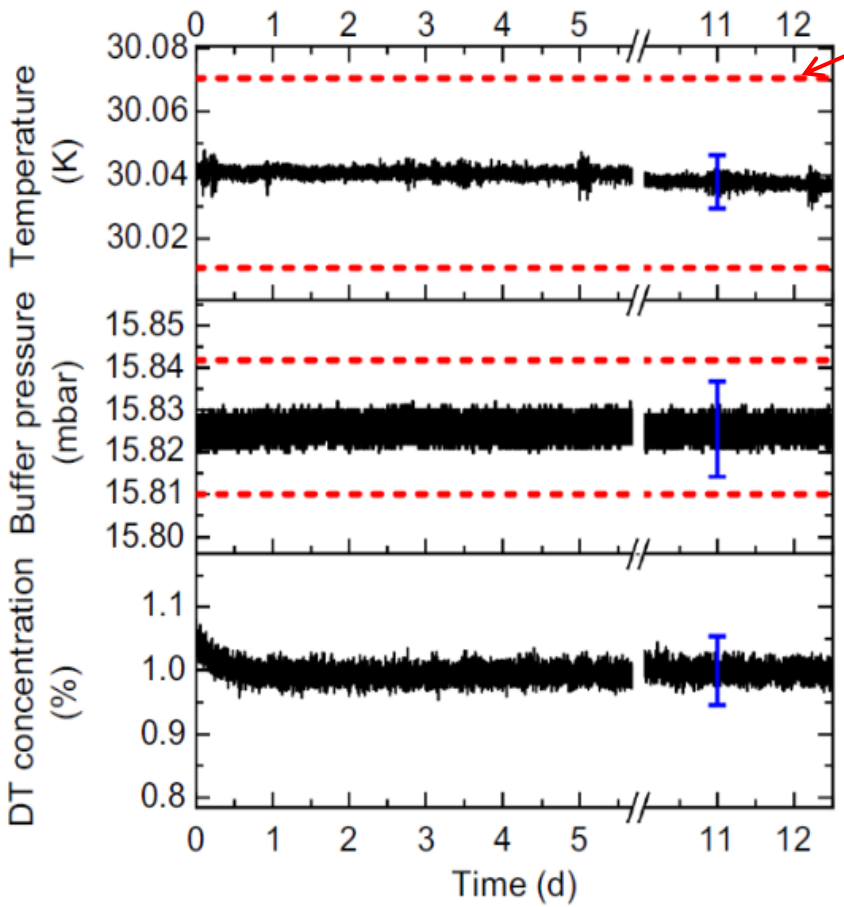
^{83m}Kr (E_{ce} = 9 – 32 keV)

- *Based on deposition of ^{83}Rb into zeolit*
- *Activity of 1.5 GBq*

Gaseous ^{83m}Kr source at Tritium Laboratory Karlsruhe

Transport container

Temporal stability of the KATRIN setup during first tests with tritium



KATRIN specification

Temperature of the source tube

Pressure in the tritium buffer tank

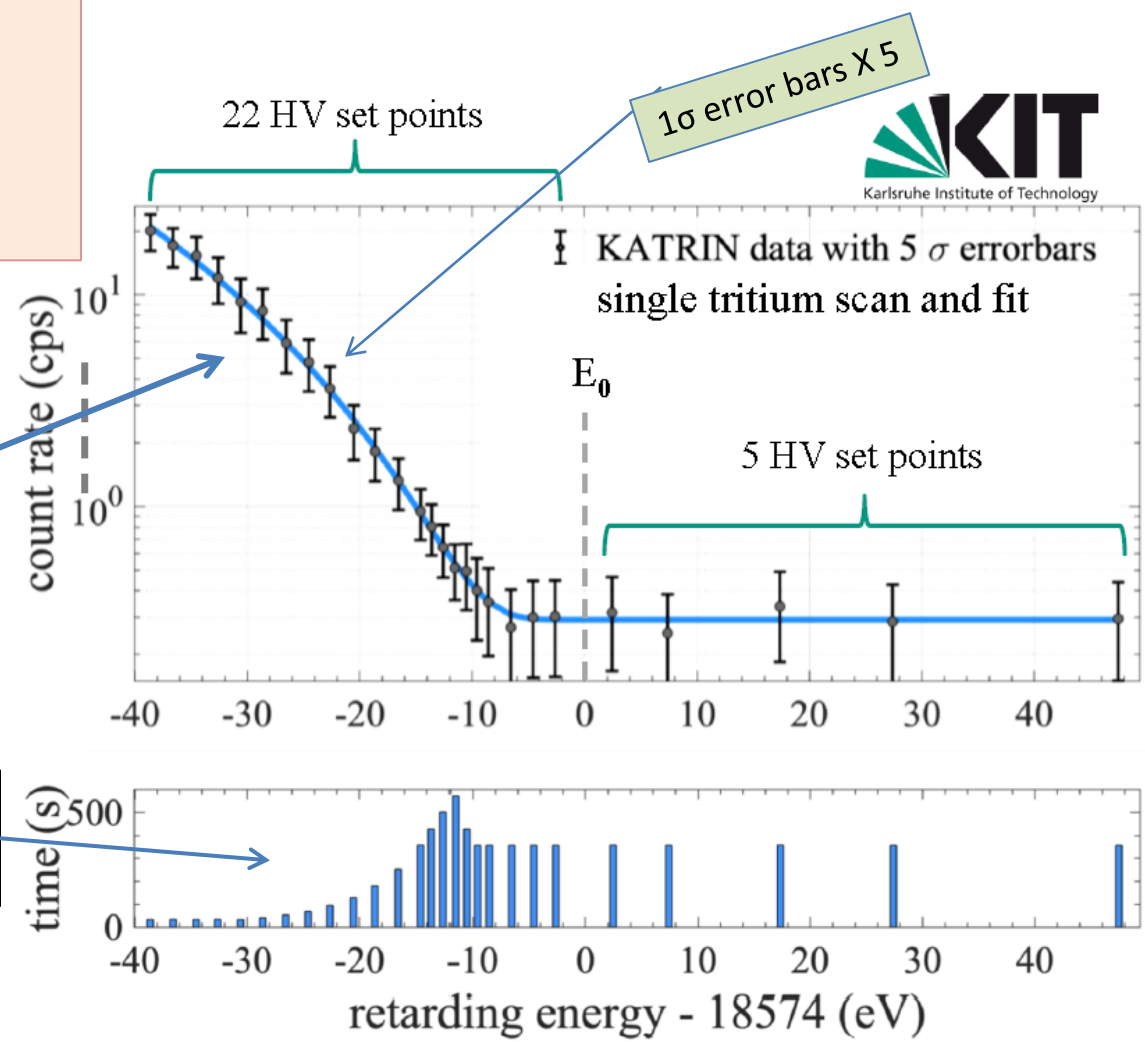
DT concentration in front of the beam tube

4. The first scientific run of KATRIN

- **22 % of nominal T_2 column density**
  radiochem. reactions of T_2 with previously unexposed steel

- **T_2 (95.3%) HT (3.5%) DT (1.1%)**
  laser Raman spectroscoopy

One of 274 single scans
measured within 2 hours



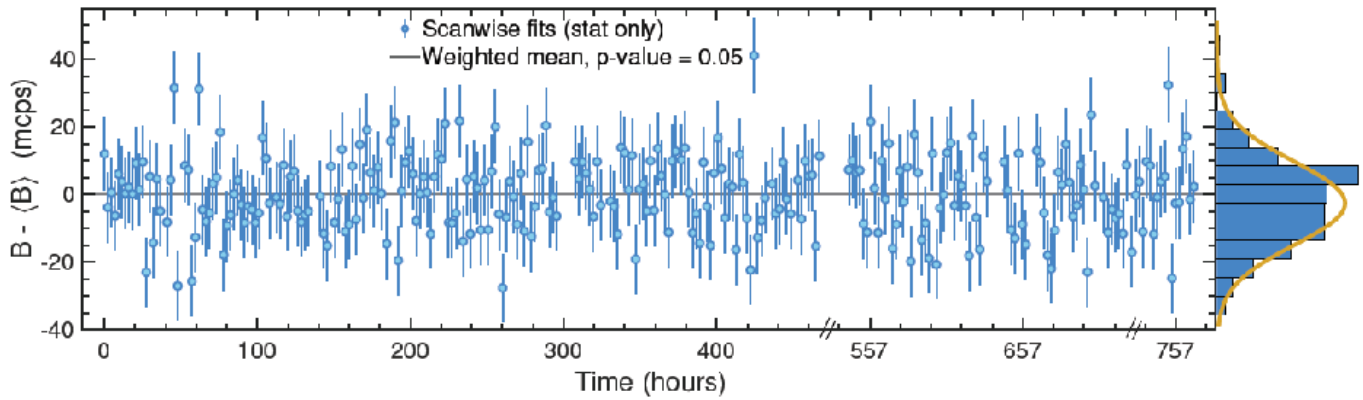
Time and energy distribution
of measurement points around E_0

Temporal stability during the first scientific run

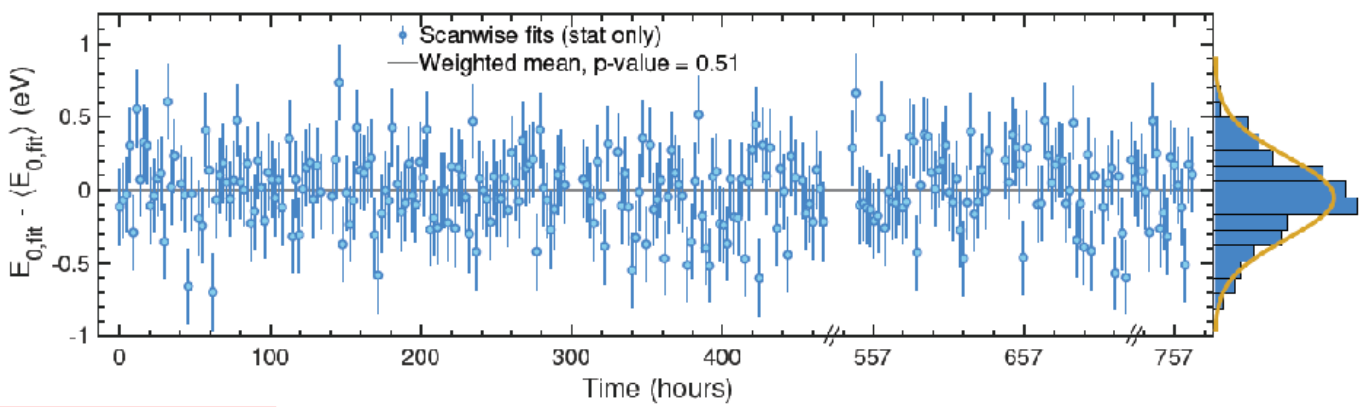
β-scan Fit Parameters Stability over 780 hours (Data)

274 single β-scan fits

Stable Background



Stable Endpoint



$$\sigma\left(E_0^{fit}\right) = 0.25\ eV$$

Analysis of measured β-spectra

Inspection of slow-control parameters:

- 274 two-hours scans in stable conditions
- 117 perfect detector pixels
- Stable high-voltage: σ = 34mV at 18.6 kV

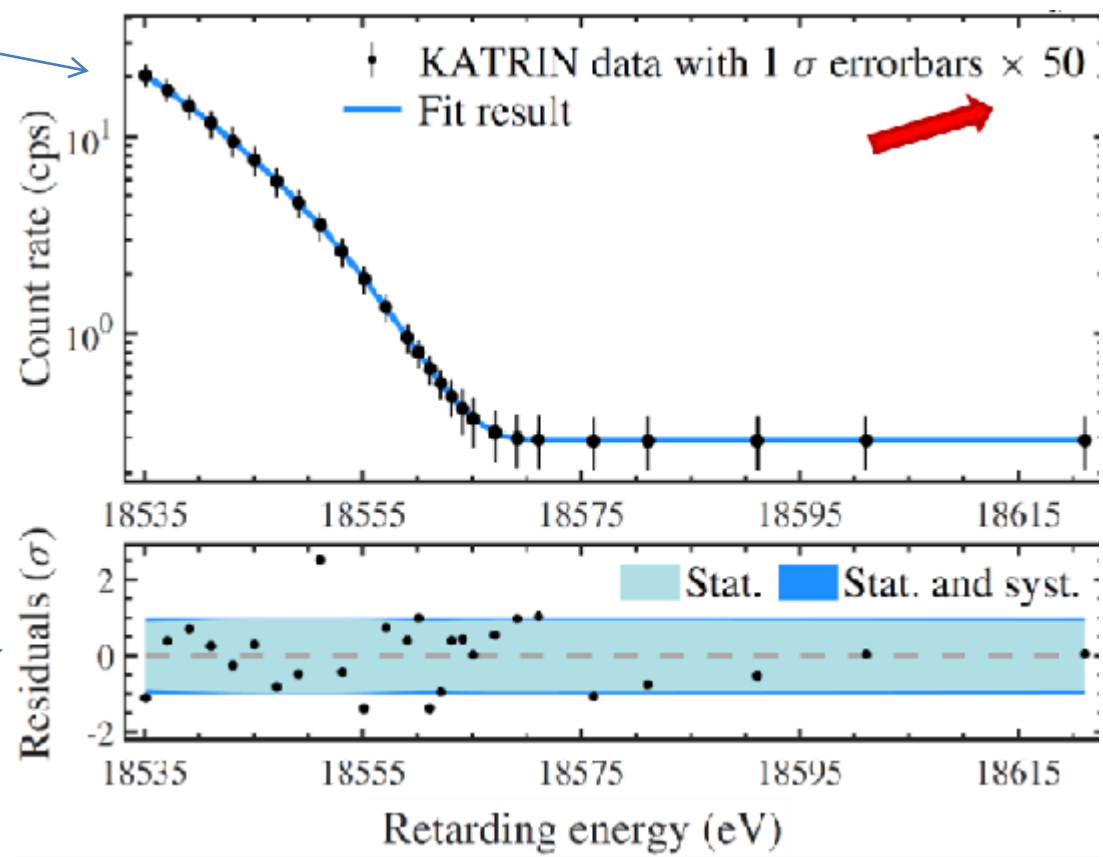
32 058 correct particial β-spectra **merged into one single spectrum**

1.5×10^6 events below E_0

Four fitted parameters:
A, E_0, m_ν^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

$$m_\nu^2 = (-1.0^{+0.9}_{-1.1})\ eV^2 \quad \text{(90 \% CL)}$$

m_ν < 1.1 eV (90% CL)

E_0 = 18 573.7 ± 0.1 eV → Q_β = 18 575.2 ± 0.5 eV

$Q_\beta[\Delta(^3H,^3He)]$ = 18 575.72 ± 0.07 eV

4 week KATRIN data:

$\sigma(m_\nu^2)_{stat}$ = 0.94 eV^2 2×

$\sigma(m_\nu^2)_{syst}$ = 0.32 eV^2 6×

(improvement on Mainz and Troitsk)

5. The KATRIN perspectives

a) 0.2eV 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