Searching for active and sterile neutrinos in β-ray spectra

Otokar Dragoun

Nuclear Physics Institute ASCR,
Řež near Prague

Supported by the GACR,
P203/12/1896

Karlsruhe Tritium Neutrino Experiment

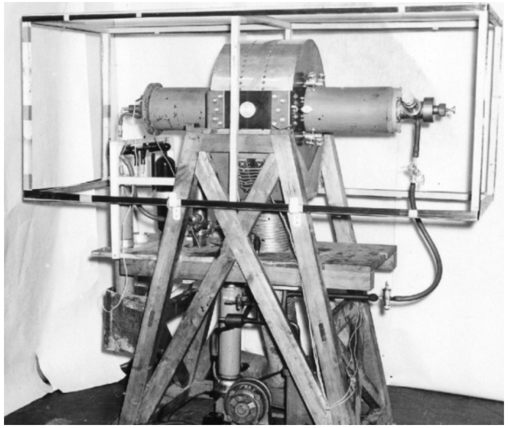
Division of Elementary Particle Physics, Institute of Physics ASCR, 28.4.2016

Topics

1. Electron spectroscopy at NPI
2. Methods for m_ν determination
3. *m_ν* from β-spectroscopy
4. KATRIN experiment
5. New approaches
6. Sterile neutrinos
7. Perspectives

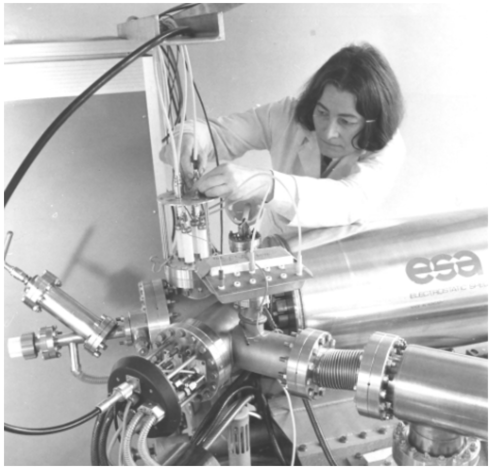
1. Electron spectroscopy of radioactive nuclei at NPI

1955 –1990: for structure of the atomic nucleus
1990 – now: for neutrino mass determination



First Czechoslovak β-ray spectrometer (1956)

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



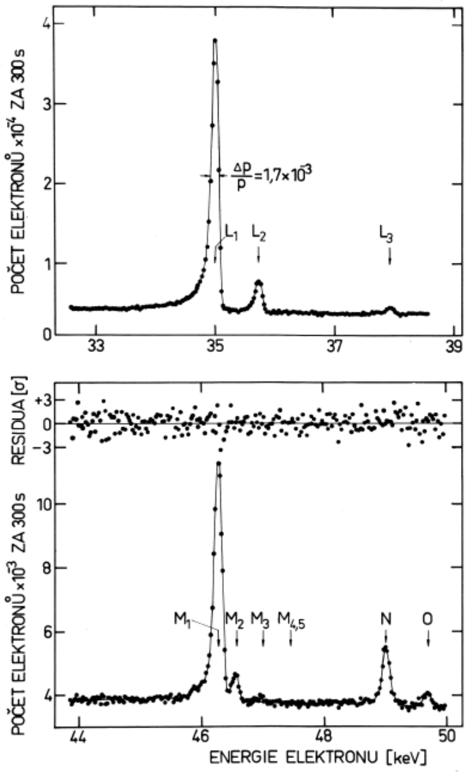
Elektrostatic spectrometer of keV electrons (1983)

best resolution ΔE ≤ 1 eV
at low transmission

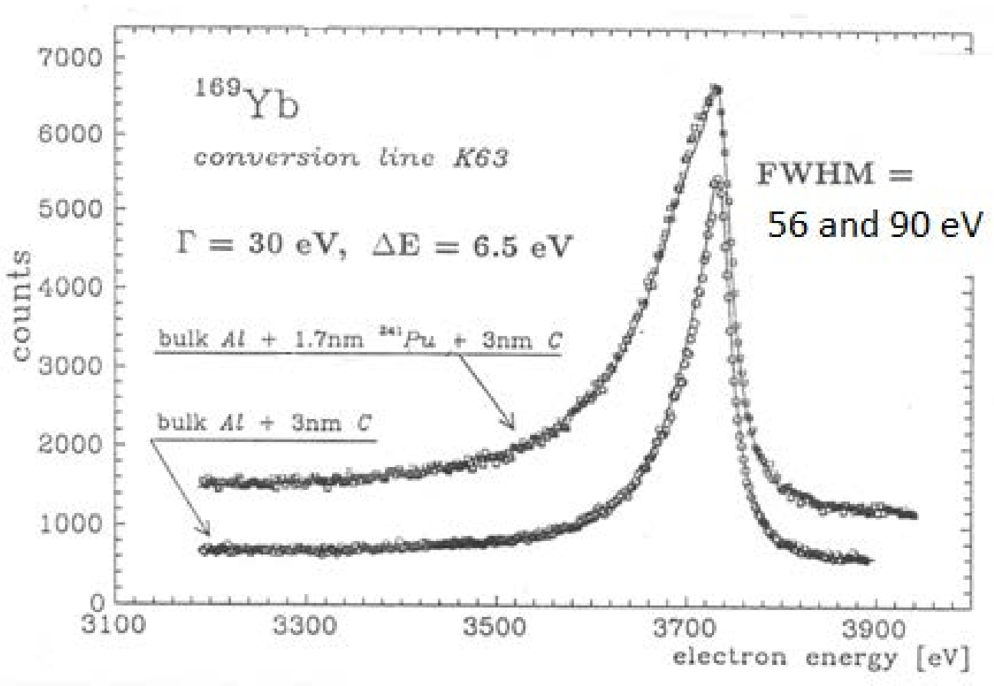
Internal conversion electrons

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

Examples of our measurements and calculations



Conversion electrons
of elmag. transitions in ^{199}Hg



First extensive calculations of internal conversion coefficients for outer atomic shells

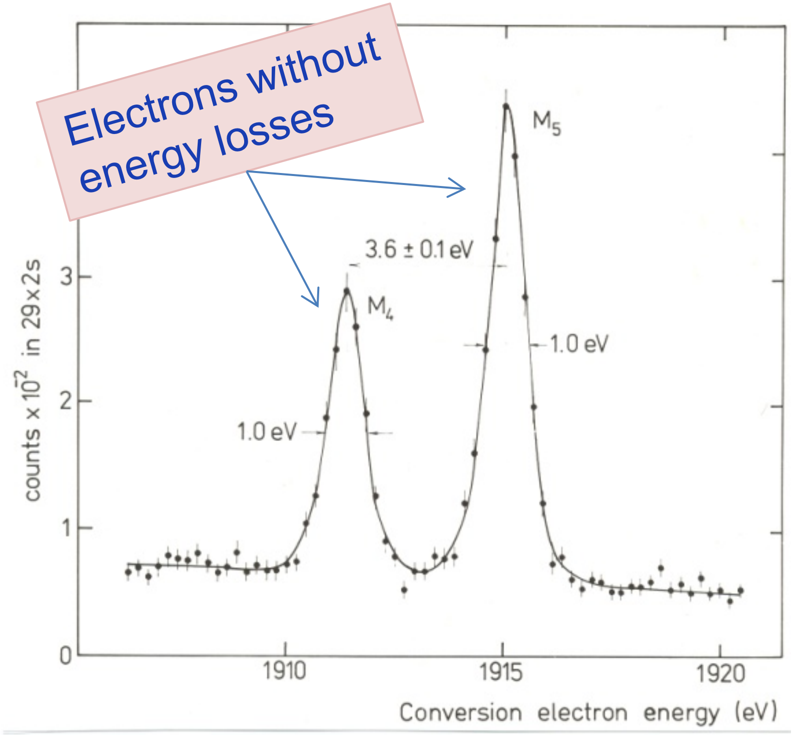
MC calculations of individual elastic and inelastic scattering of electrons in radioactive sources

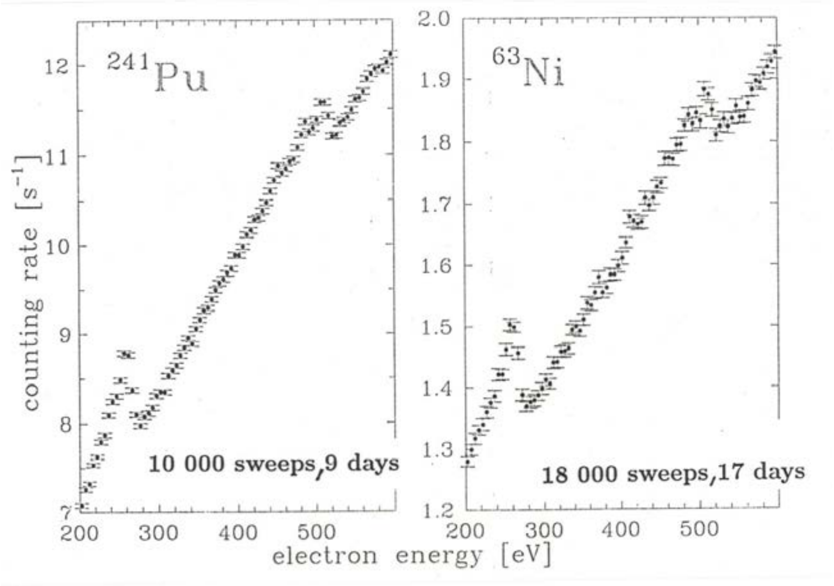
Next examples of our measurements

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

2 keV conversion electrons of ^{99m}Tc

Lines of KLL Auger electrons of carbon and oxygen on continuous β-spectra


Electrons without energy losses



$(\Delta E)_{instr} < 1$ eV

$\Gamma_{nat} < 0.3$ eV

$$g(E) = \int R(E, E')\, f(E')\, dE'$$

Measured spectrum

Instrumental response function

True spectrum

2. Methods for m_ν determination

$$\boxed{|\nu_\alpha\rangle = \sum_{1}^{n} U_{\alpha i}|\nu_i\rangle}$$

$$m_{\nu_\alpha} = \sqrt{\sum_{1}^{3} |U_{\alpha i}|^2 m_{\mathrm{i}}^2}$$

Effective masses due to insufficient instrumental resolution

- **Two body decay at rest:** **$\pi^+ \rightarrow \mu^+ + \nu_\mu$**

  $\sigma_r(\pi) = 3\cdot10^{-6}$, $\sigma_r(\mu) = 5\cdot10^{-8}$, $\sigma_r(p_\mu) = 4\cdot10^{-6}$

  $$m_{\nu_\mu}^2 = -(0.016 \pm 0.023)\mathrm{MeV}^2 \qquad m_{\nu_\mu} \leq 190\,\mathrm{keV} \qquad E_{\mathrm{tot}}^2 = p^2 + m^2$$

Phys. Rev. D53 (1996)6065

Model independent methods

- **Neutrino oscillations:**

  $$m_2^2 - m_1^2 = (7.50 \pm 0.20) \times 10^{-5} eV^2$$
  $$|m_3^2 - m_2^2| = (2.32 \pm 0.12) \times 10^{-3} eV^2$$

$m_1 < m_2 < m_3$	$m_3 < m_1 < m_2$
$m_1 \geq 0$	**$m_1 \geq$ 48 meV**
$m_2 \geq$ 8 meV	**$m_2 \geq$ 49 meV**
$m_3 \geq$ 49 meV	**$m_3 \geq 0$**

- **β-ray spectroscopy:** $m_{\nu_e} = \sqrt{\sum_{1}^{3} |U_{ei}|^2 \cdot m_i^2}$ **< 2 eV**

Model dependent methods

- **Time-of-flight : SN 1987A**

  d = 168 000 ly, $t_\gamma = 5\cdot10^{12}$s

  Observed ≈ 20 ν within $\Delta t \approx 10$ s

  Assuming $\Delta t_{\mathrm{SN}} = 0$: $m_{\nu_e} \leq 20\,\mathrm{eV}$

  BUT $\Delta t_{\mathrm{SN}} > 0$

  including assumptions on SN dynamics $m_{\nu_e} \leq 5.7\,\mathrm{eV}$

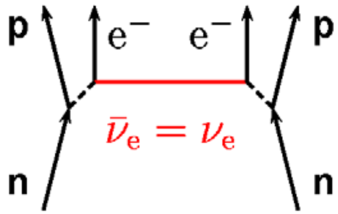
- **0νββ-decay:** $m_{\beta\beta} = \left|\sum_{1}^{3} m_k \cdot \left|U_{ek}\right|^2 \cdot e^{i\phi(k)}\right|$ < (0.2 –0.7) eV

- **Cosmology**: $\sum_{1}^{3} m_i$ < (0.12 – 1.7) eV

JCAP 11(2015)011

Effective neutrino mass from 0νββ decay

Indirect method depending on nuclear models



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G\left(E_{tot}, Z\right)\cdot\left(M^{0\nu}\right)^{2}\cdot m_{\beta\beta}^{2}$$

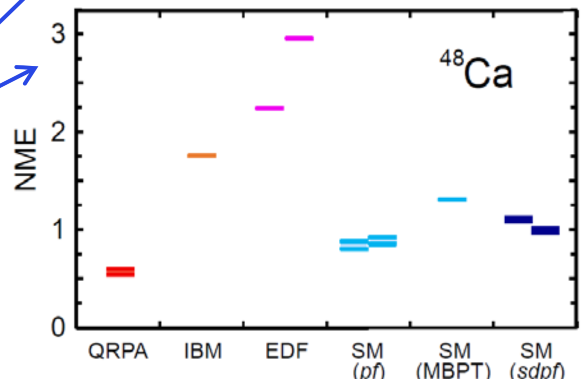
$$m_{\beta\beta} = \left|\sum_{j=1}^{3}\left|U_{ej}\right|^{2}\cdot e^{i\alpha_j}\cdot m_j\right|$$

Experiment

Theorie: *factor 2-3 !*

Effective ν_e mass

unknown phases!

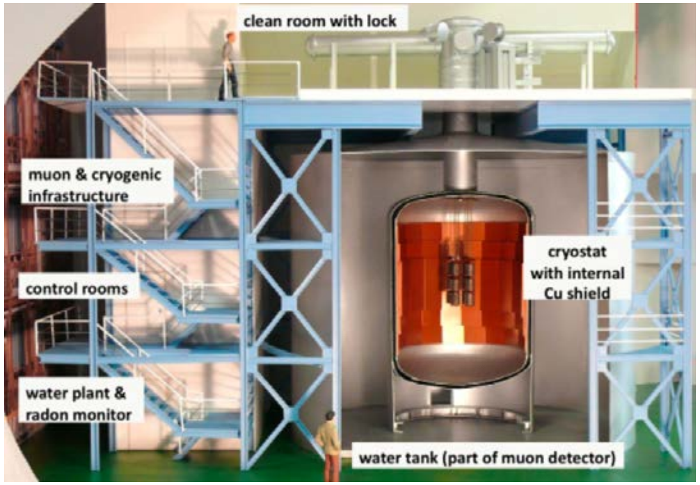


- Klapdor, ^{76}Ge (2006) **$m_{\beta\beta}$ = (0.32 ± 0.03) eV**

  claimed existence of 0νββ at 6σ (for particular $M^{0\nu}$)
- KamLAND-Zen + EXO-200, ^{136}Xe (2012):

  $m_{\beta\beta}$ < (0.12 – 0.25) eV

- GERDA measuring ^{76}Ge : comparison with Klapdor without $M^{0\nu}$



3. m_ν from β-spectroscopy

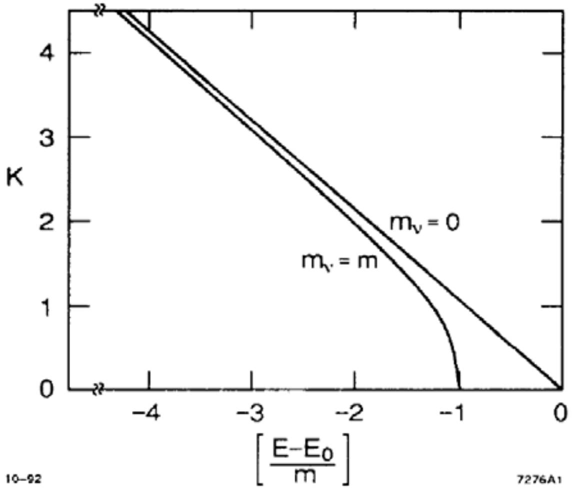
Theory of β-decay assuming existence of both neutrino of W. Pauli and weak interaction (***E. Fermi, 1934***):

$$\frac{dN}{dE} = A \cdot F(E, Z+1) \cdot p \cdot (E+m) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \boxed{m_\nu^2}}$$

Theoretical corrections in
- JCAP 1502(2015)020
- ArXiv 1603.08690

Kurie graph

$$K = \left[(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}\right]^{1/2}$$



E. Fermi from measured β-spectra of that time:

$m_\nu \ll m_e$, probably $m_\nu = 0$

From $m_{\nu_e} < 5\,\mathrm{keV}$ to $m_{\nu_e} < 2\,\mathrm{eV}$

1948: β-spectrum of ^{35}S

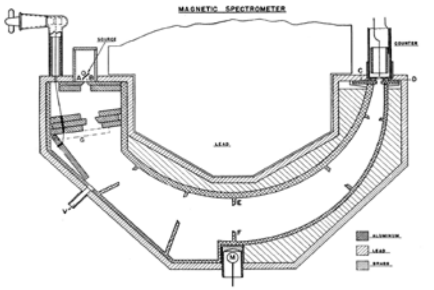
Cook et al. Phys. Rev. 73,1395.

Iron magnetic β-ray spectrometer

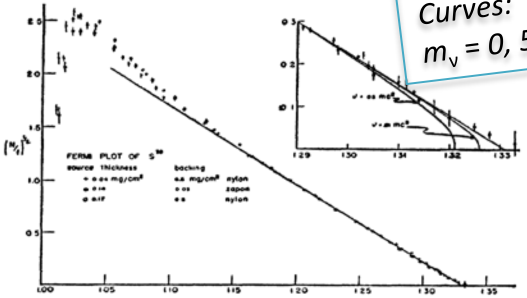
r_0 = 40 cm, source 0.4 x 2.5 cm^2

ΔE_{instr} = 1.5 keV at E = 167 keV

$\Omega/4\pi = 1 \cdot 10^{-3}$



Kurie plot (Q_β = 167 keV)

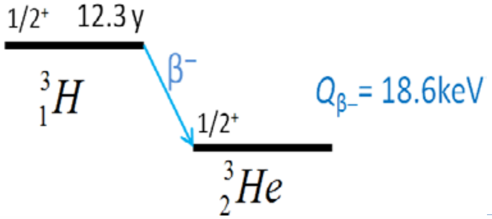


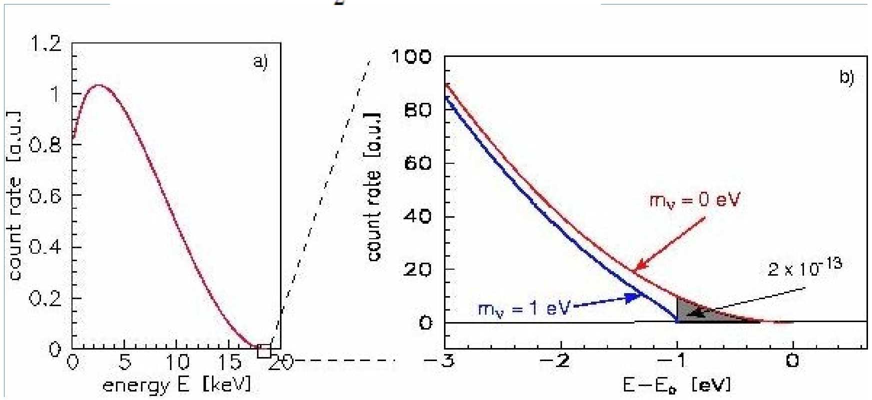
Curves:
m_ν = 0, 5, 10 keV

2005: β-spectrum of ^3H

Kraus et al. Eur. Phys.J. C40,447

Confirmed
at NRI Troitsk
in 2011





MAC-E filter at Mainz Uni.
Now: KATRIN monitor
spectrometer

4. KATRIN experiment

The tritium β-decay experiment aiming at 0.2 eV ν-mass sensitivity

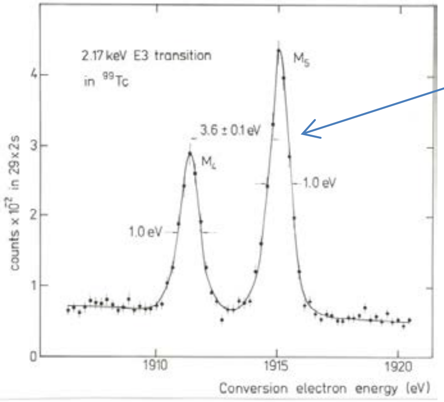
KATRIN
Karlsruhe Tritium Neutrino Experiment

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

Now: 130 researchers
from 16 institutions

Our NPI: precision electron spectroscopy of radionuclides

Tritium laboratory at KIT:
10 kg/year of high-purity tritium
scale equivalent to ITER fusion plant



$E_{ce} = E_{\gamma} – E_{bin}$

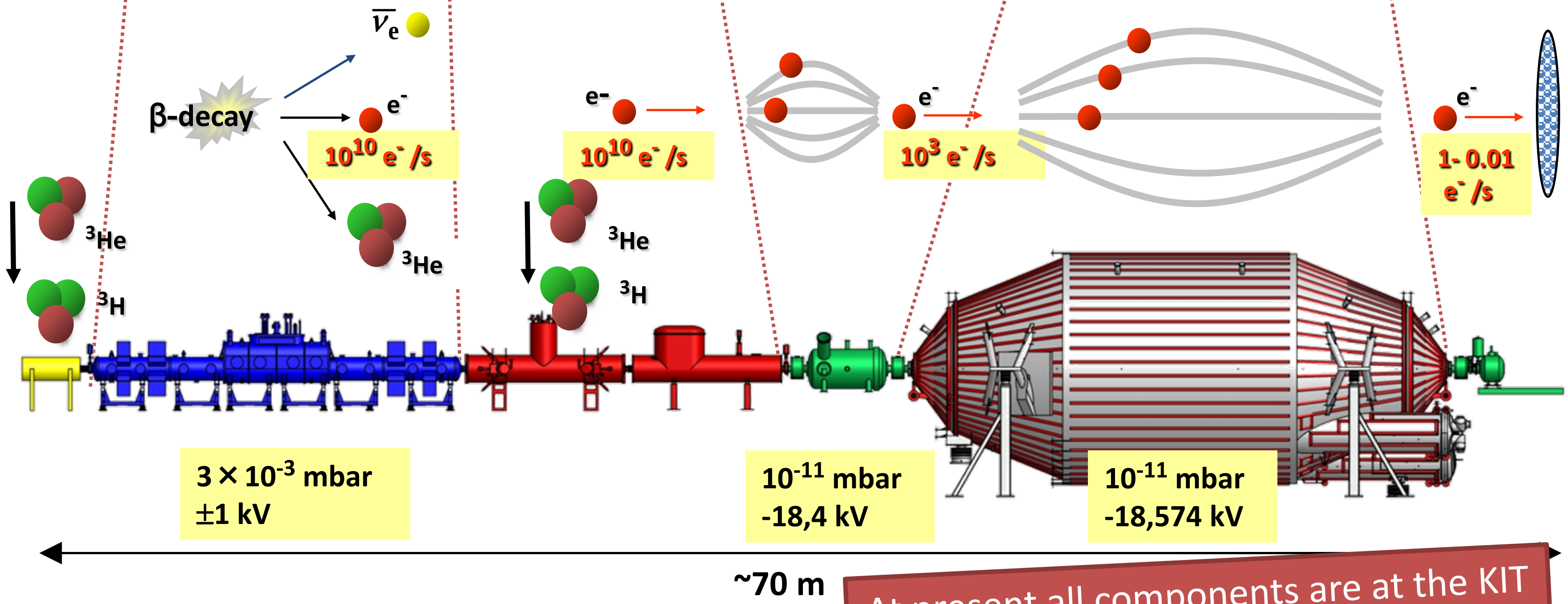
ΔE_{FWHM} < 1 eV

but low transmission

KATRIN main components:

source and transport section | spectrometer section

source parameters	stable tritium column density	electron transport tritium retention	reflection of low energy electrons	high precision energy analysis of electrons	position sensitive electron counter
rear	**tritium source**	**diff. & cryo pump**	**pre-spectrometer**	**main spectrometer**	**detector**



At present all components are at the KIT in installation or upgrade phase

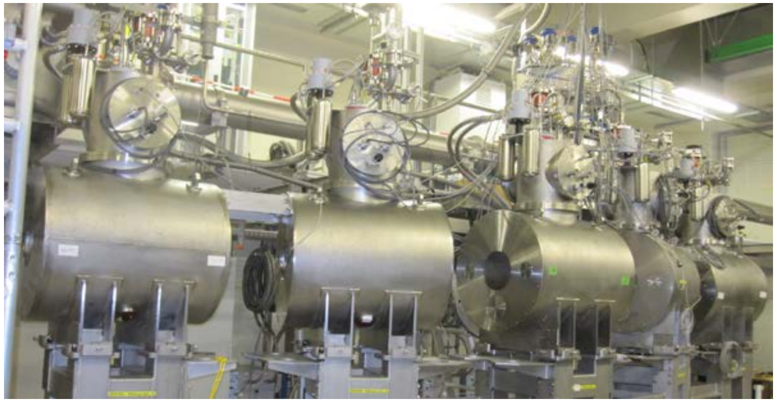
Tritium source

A *=10^{11} Bq,* ***B*** *= 3.6 T,* ***T= 30K±0.1%***
6 cryogenic liquids, 500 sensors

Mounting in KIT

Differential pumping section

Test of sc magnets at 5.5 T



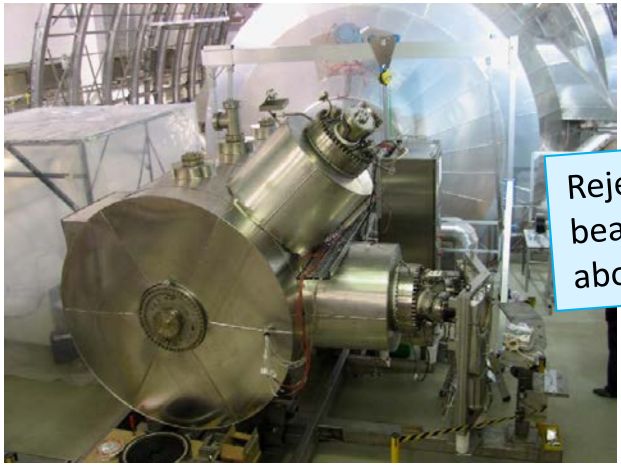
Together will reduce a T_2 flux into the main spectrometer by a factor of ***10^{14}***

≤ 1 mBq of tritium inside the main spectrometer

Cryogenic pumping section

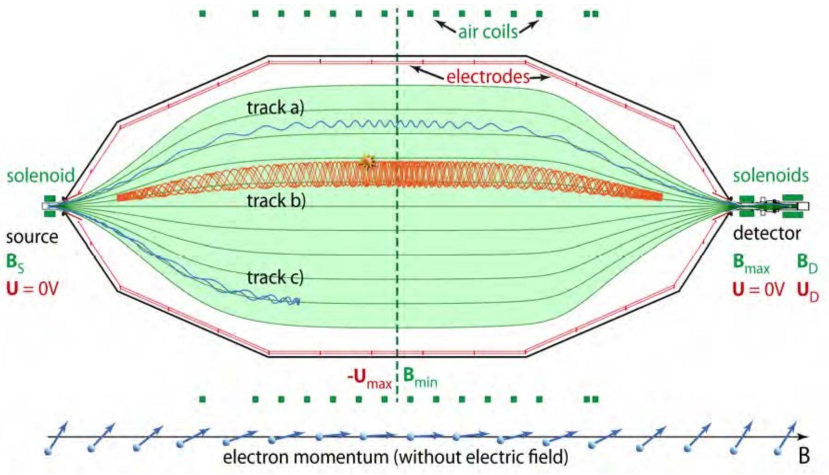
Argon snow at 3 K

Pre-spectrometer



Rejects all β-particles bearing no information about neutrino mass

KATRIN main spectrometer



23 m length, 10 m diam, 200 ton

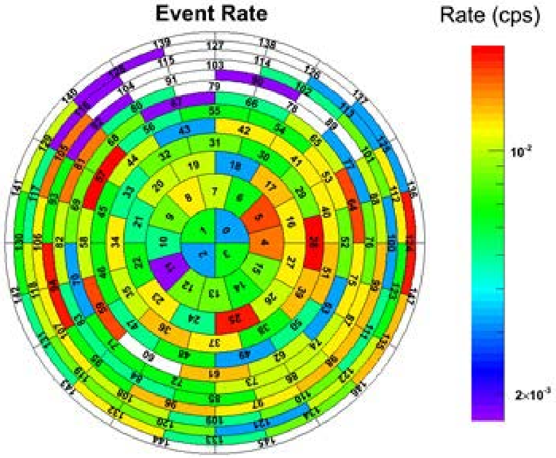
Electron tracks:

a) $E > e \cdot U_{max}$

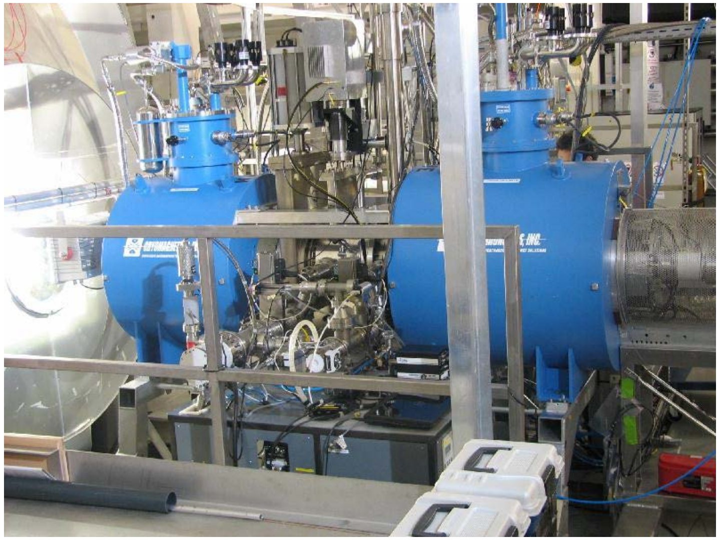
c) $E < e \cdot U_{max}$

b) electron released inside spectr.
*and **magnetically trapped !***

Focal plane detector

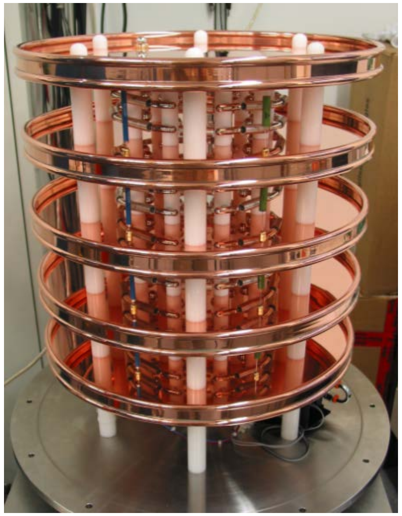


Si PIN diode, 9 cm diam.
148 independent pixels

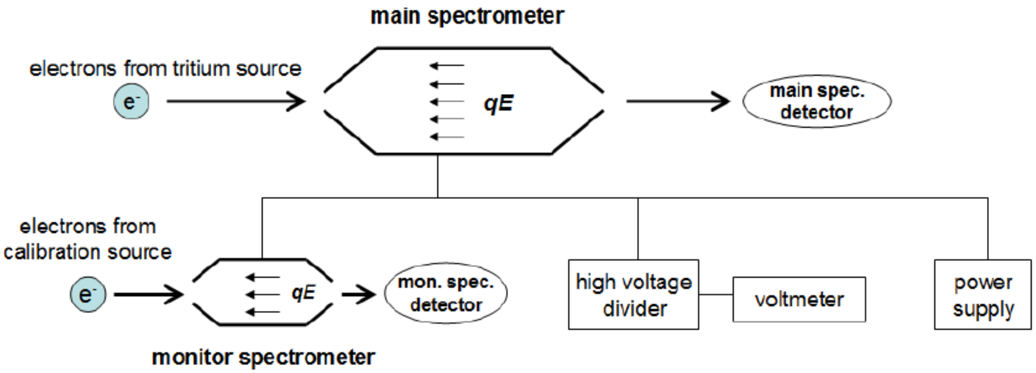


Our task for KATRIN : monitor high voltage stability ± 60 mV at 18.6 kV in 2 months

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

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

drift 0.6 ppm /2 months

5 times better than requested

<u>Our next task</u>: **gaseous ^{83m}Kr source**

$T_{1/2}$ = 1.8 h

E_{ce} = 9 – 32 keV

KATRIN expected result

after 1000 days of measurement, 5-6 calendar years:

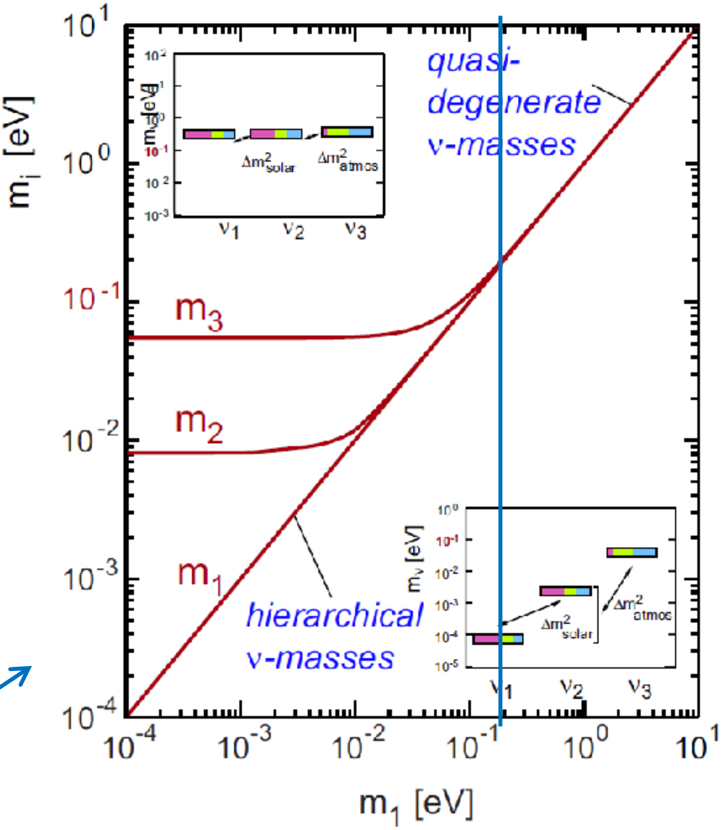
- ***If no neutrino mass is observed***

  $m(\nu_e)_{\mathrm{eff},\,\beta} < 0.2$ eV (90% C.L.)

- ***Discovery potential***

  $m(\nu_e)_{\mathrm{eff},\,\beta} = 0.35$ eV (5σ effect)

- In a model independent way
- Regardless neutrino type



Almost whole quasi-degenerate region will be explored

5. New approaches

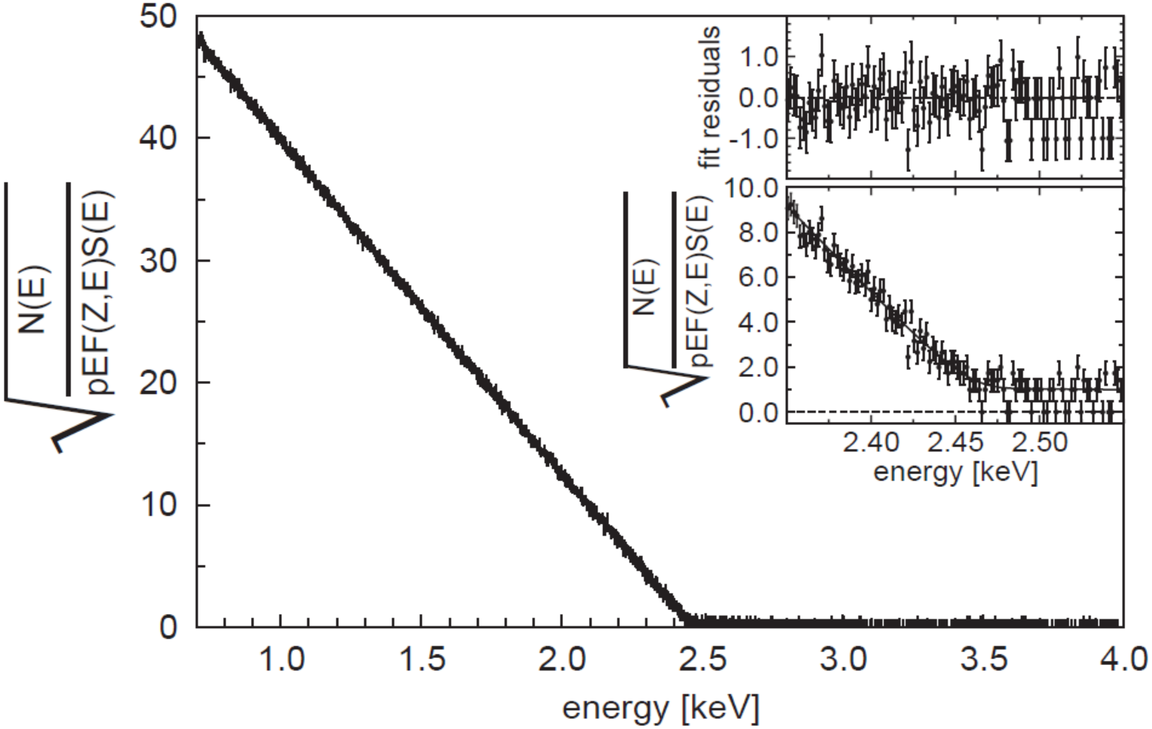
Low-temperature microcalorimeters

- β-emitter fully contained in the absorber
- all Q_β (except ν energy) transferred into heat

No troubles with
- electron energy losses
- final states after β-decay

^{187}Re (Q_β = 2.4 keV, $T_{1/2}$ = 4.3·10^{10} y

MIBETA: m_ν < 15 eV



BUT
- whole spectrum is measured
- yet too slow
- yet insufficient ΔE_{instr}
- coupling of absorber to temperature sensor

For 30 years effort
see arXive 1511.00968

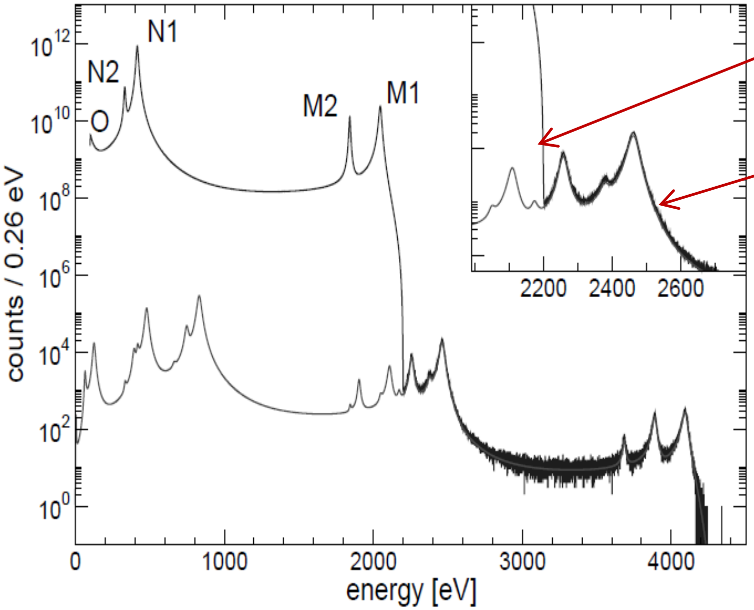
New projects HOLMES and ECHo
^{163}Ho → ^{163}Dy , electron capture

β-decay: β^-, β^+, electron capture

MC simulated spectrum of X-rays, Auger electrons and inner bremsstrahlung

for measurements with low-temperature microcalorimeters

for Q_{EC} = 2.2 keV, m_ν = 0
ΔE_{instr} = 2 eV, pile-up 10^{-6}, N_{events} = 10^{14}



part sensitive to m_ν

pile up

Suggested by DeRújula 1982, updated 2003.

Theor. spectra improved 2015 by Faessler

Project 8

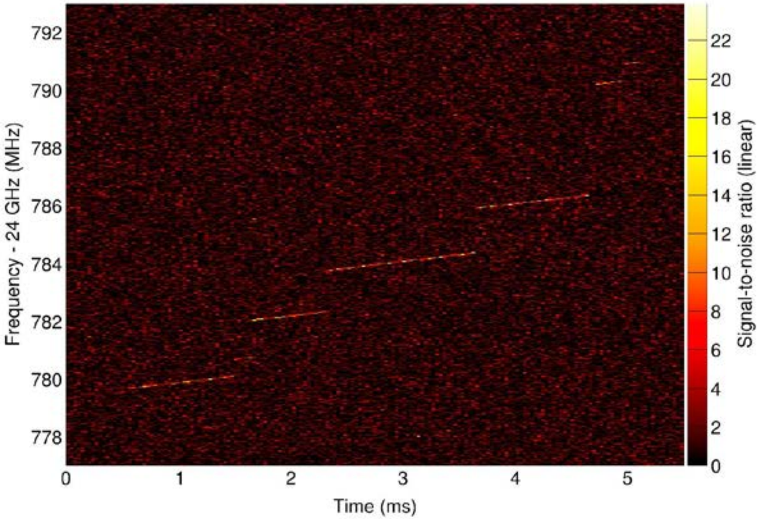
Spectroscopy of cyclotron radiation emitted by tritium decay electrons in a magnetic field

$$\omega = \frac{e\,B}{m_e\left(1+\frac{E}{m_e c^2}\right)}$$

E = 18.6 keV B = 1 T

f = ω/2π = 26.5 GHz (λ = 1.1 cm)

Aiming at atomic tritium experiment with ν-mass sensitivity < 0.06 eV to reach IH



Single electron detection proved

MC simulation:

B uniformity 0.1 ppm

1 K temperature (*Doppler effect)*

10^{12} tritium atoms/cm^3

background 10^{-6} s^{-1} eV^{-1}

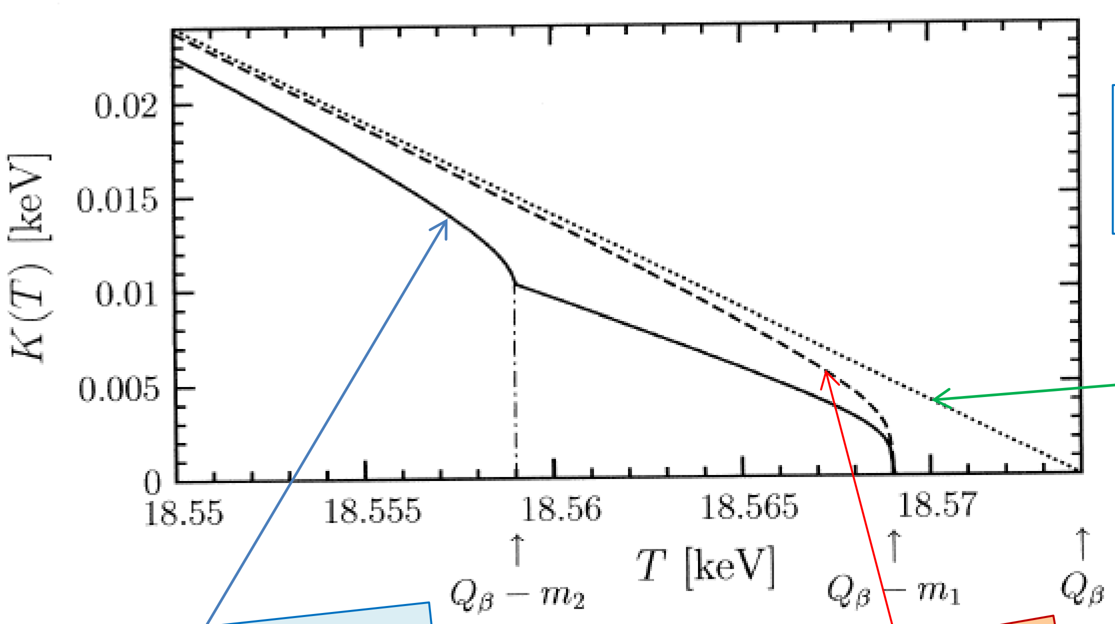
For further proposals see e.g. the review in *arXive* 1504.07496

6. Sterile neutrinos

Shrock (1980):

- search for mass states m_i in β-spectra
- the kink at $E_0 - m_i$ with amplitude $|U_{ei}|^2$
- $|U_{e4}|^2 < 0.1$ for $0.1\ \mathrm{keV} \leq m_4 \leq 3\ \mathrm{MeV}$

See **White Papers**:
arXive 1204.5379
arXive 1602.04816



Kurie plots of tritium β-spectrum

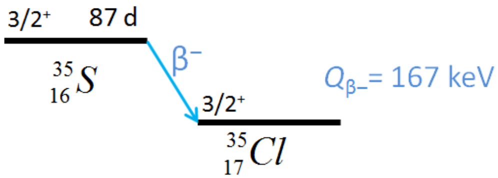
massless neutrino

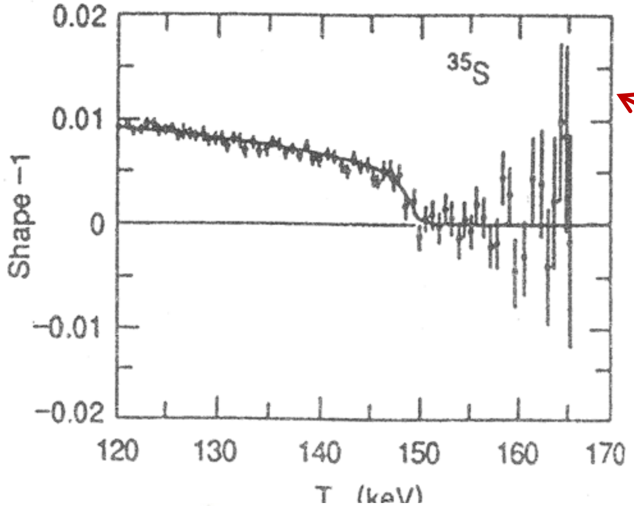
two neutrino mixing:
m_1= 5 eV, m_2= 15 eV
$|U_{e1}|^2 = |U_{e2}|^2 = 0.5$

neutrino
with m = 5 eV

An admixture of the 17 keV neutrino in β-ray spectra

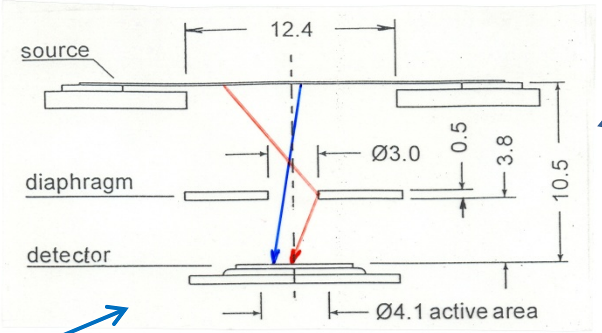
For example





NOW DISPROVED!

false$|U_{e4}|^2 \approx$ 1% found:
in 7 different experiments
at 4 different institutions
using 5 different isotopes



NPI Řež + Tech. Uni. Munich

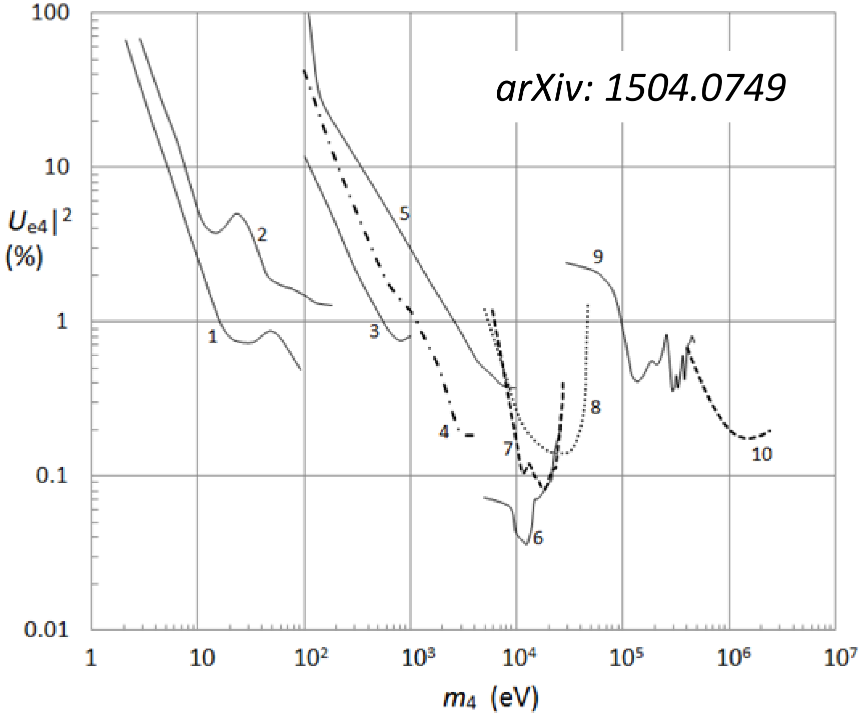
<u>False results</u> mainly caused by
- electron energy losses in sources
- electron scattering on slits
- inaccurate response function

Neglected scattering on the diaphragm
→ **false$|U_{e4}|^2 \approx$ 0.3 %**

The best upper limits on the admixture $|U_{e4}|^2$ of sterile neutrinos

Derived from measured β-ray spectra

See also Kink search in β-decay
http://pdg.lbl.gov/2015


arXiv: 1504.0749

1 – ^{3}H, MAC-E-Filter
2 – ^{3}H, MAC-E-Filter
3 – ^{187}Re, low-temp. calorim.
4 – ^{3}H, magn. spectr.
5 – ^{3}H, implant. in Si(Li) spectr.
6 – ^{63}Ni, magn. spectr.
7 – ^{63}Ni, magn. spectr.
8 – ^{35}S, Si(Li) sp. + magn. colim.
9 – ^{64}Cu, magn. spectr.
10 – ^{20}F, magn. spectr.

$|U_{e4}|^2$
$< 4 \cdot 10^{-3}$ for $m_4 = 2 - 40$ keV
$< 5 \cdot 10^{-4}$ for $m_4 = 14 - 20$ keV

MC simulations for **KATRIN:**
- highly sensitive to m_4 in **eV** range
- sensitive also in **keV** range
  (electron energy losses in tritium source!)

7. Perspectives

Current problems of neutrino physics

- Dirac or Majorana particles : $\nu \neq \bar{\nu}$ or $\nu = \bar{\nu}$?
- Hierarchy of mass states: $m_1 < m_2 < m_3$
  or $m_3 < m_1 < m_2$?
- Neutrino masses: m_i = ?
- Leptonic CP violation: δ_{CP} = ?
- Sterile neutrinos: $\nu_e + \nu_\mu + \nu_\tau + \nu_s$?

β-ray spectroscopy:
new upper limits
in the near future

… and the Czech contribution:

IP and NPI at Czech Acad. Sci.
IPNP at Charles Uni.
ITEP and FNSI at Czech Tech. Uni.

- neutrino oscillations: **Daya-Bay and NOvA**
- 0νββ decay: **SuperNEMO, TGV**
- direct ν mass measurement: **KATRIN**

Good luck!