Monitoring of the Energy Scale in the KATRIN Neutrino Experiment

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Outline

1. Introduction to topic

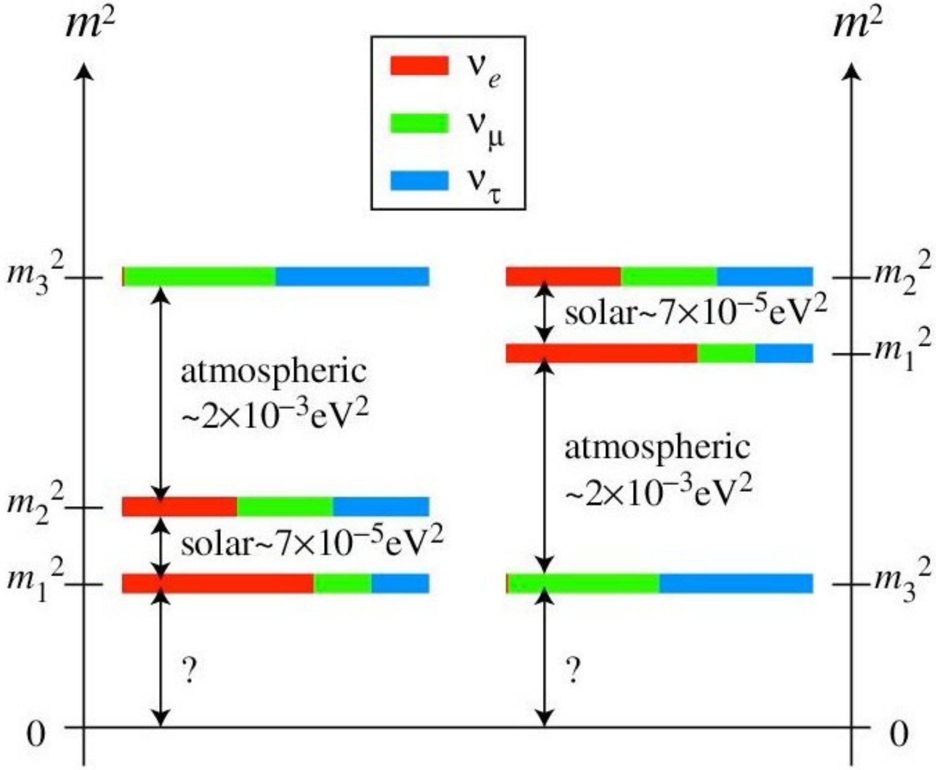
- neutrino mass
- measuring neutrino mass: KATRIN experiment
- high voltage in KATRIN - monitoring concept
- ^{83}Rb/^{83m}Kr source as nuclear & atomic standard

2. Measurement results

- investigation of new line-shape: Doniach – Sunjic function
- stability measurements

Neutrino mass

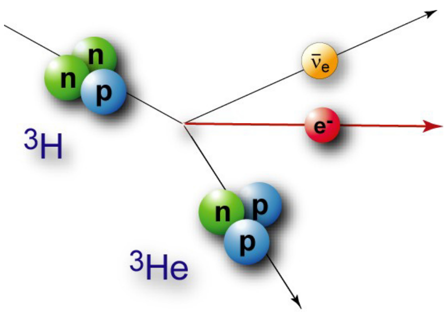
- non-zero neutrino mass confirmed by various oscillation experiments (Super-Kamiokande, SNO, Daya-Bay, …) excluding other explanations
- neutrino mass hiearchy?
- absolute mass scale?



- motivation for absolute mass scale also from cosmology (hot dark matter?)

- current accepted limit on neutrino mass (from T_2 β-decay measurements in Mainz & Troitsk):

$$m(\bar{\nu}_e) < 2\ \mathrm{eV/c}^2$$



- potential: improve sensitivity down to 0.2 eV

Measuring neutrino mass: β-decay

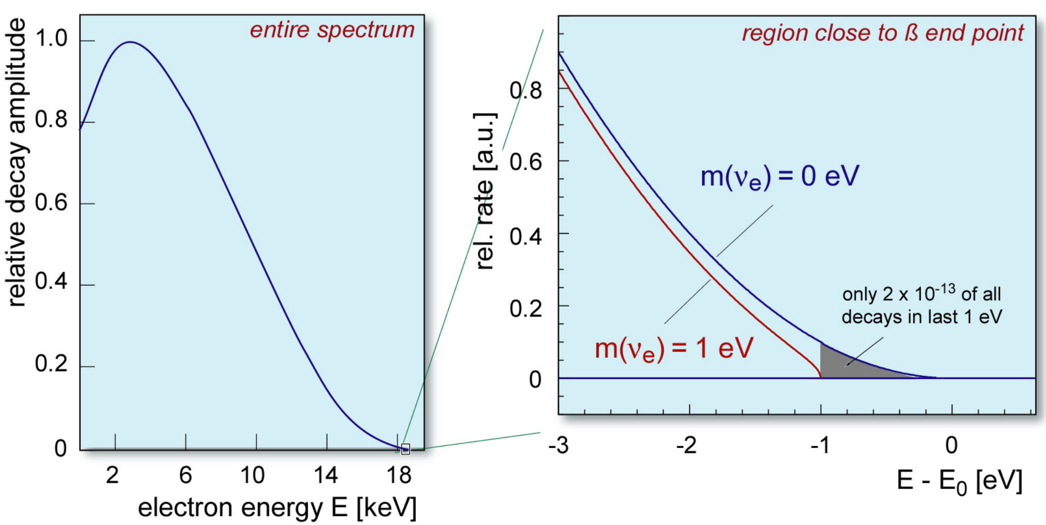
- kinematic determination of electron anti-neutrino mass from β-decay – model independent
- decay rate given by:

$$\frac{d\Gamma}{dE} = C\,p\,(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_{\nu_e}^2}\,F(Z+1,E)\,\Theta(E_0-E-m_{\nu_e})$$

$$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

- suitable β-emitter: tritium
  - E_0 = 18.6 keV, $T_{1/2}$ = 12.3 y
  - super-allowed transition
  - simple final states

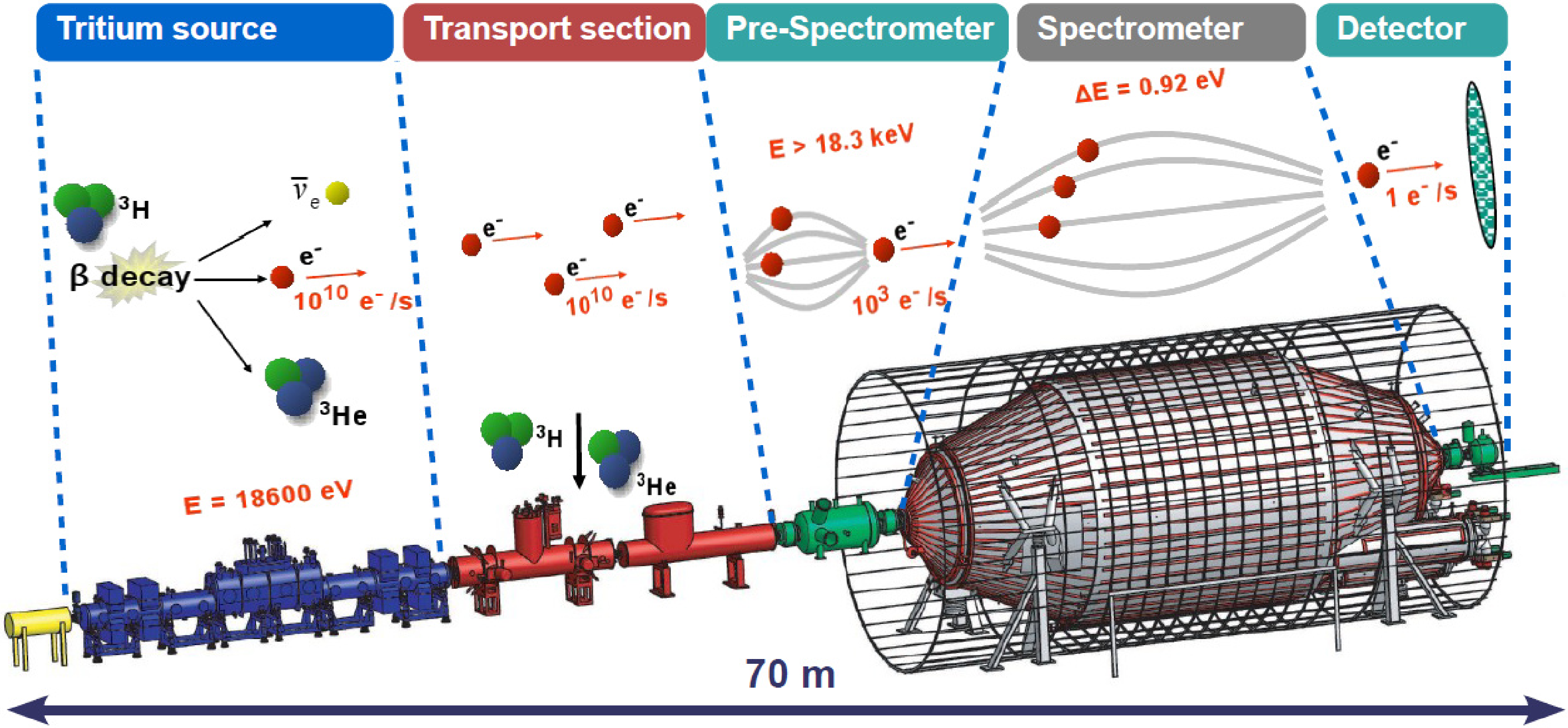
    (KATRIN experiment)



- other option:
  - ^{187}Re, E_0 = 2.47 keV, $T_{1/2}$ = 43 Gy

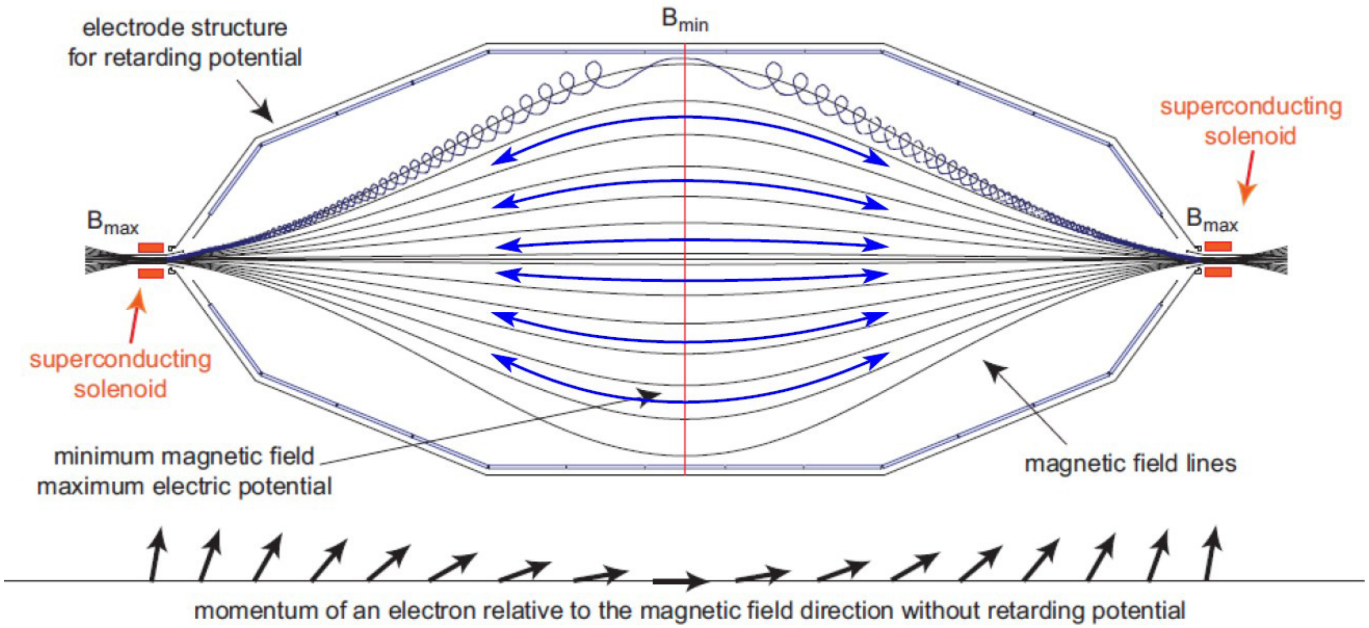
    (MARE experiment)

KArlsruhe TRItium Neutrino experiment



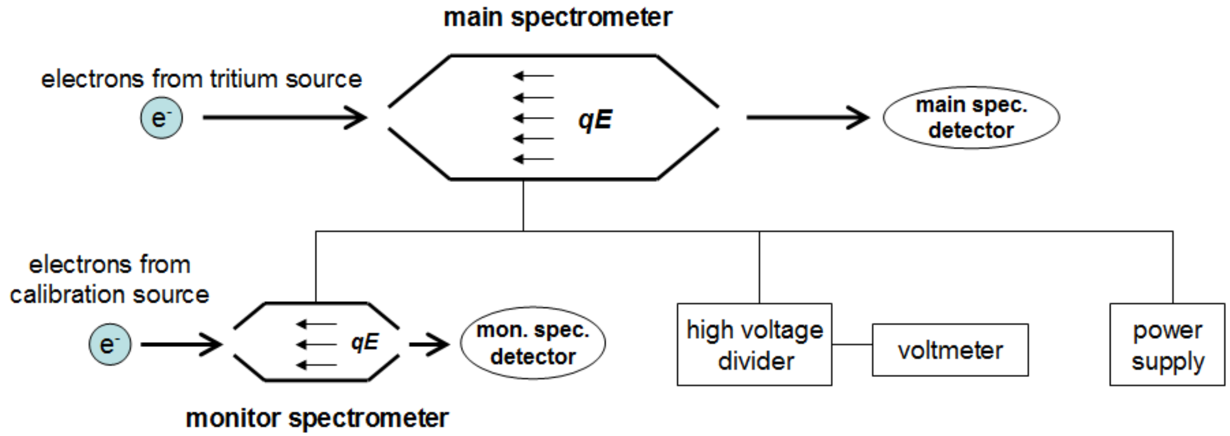
- β-electrons are transported along magnetic field lines from the T_2 source through the transport and pumping sections and spectrometers to the detector
- T_2 pumped out by TMP's and cryosorption pumps (flow reduction factor of 10^{14})
- most of electrons pre-filtered at pre-spectrometer
- low background at main spectrometer, extreme high vacuum (10^{-11} mbar)

Measuring neutrino mass: MAC-E filter for KATRIN



- principle: adiabatic guidance of electrons from T_2 source along magnetic field lines to a plane where their energy is analysed using an electrostatic potential = MAC-E filter
- adiabatic transport: $\mu = E_{\perp} / B = \text{const.}$
- B-field drops by 4 orders of magnitude from solenoid to the analysing plane: $E_{\perp} \rightarrow E_{\parallel}$
- only electrons with $E_{\parallel} > eU$ can pass the retardation potential → integral spectrum
  - acquired by recording electron countrate for particular retarding voltages U in discrete voltage steps
- superior energy resolution: $\Delta E = E_{\perp,\text{max,start}} \cdot B_{\text{min}} / B_{\text{max}} = 0.93\,\text{eV}$

High voltage in KATRIN - monitoring concept

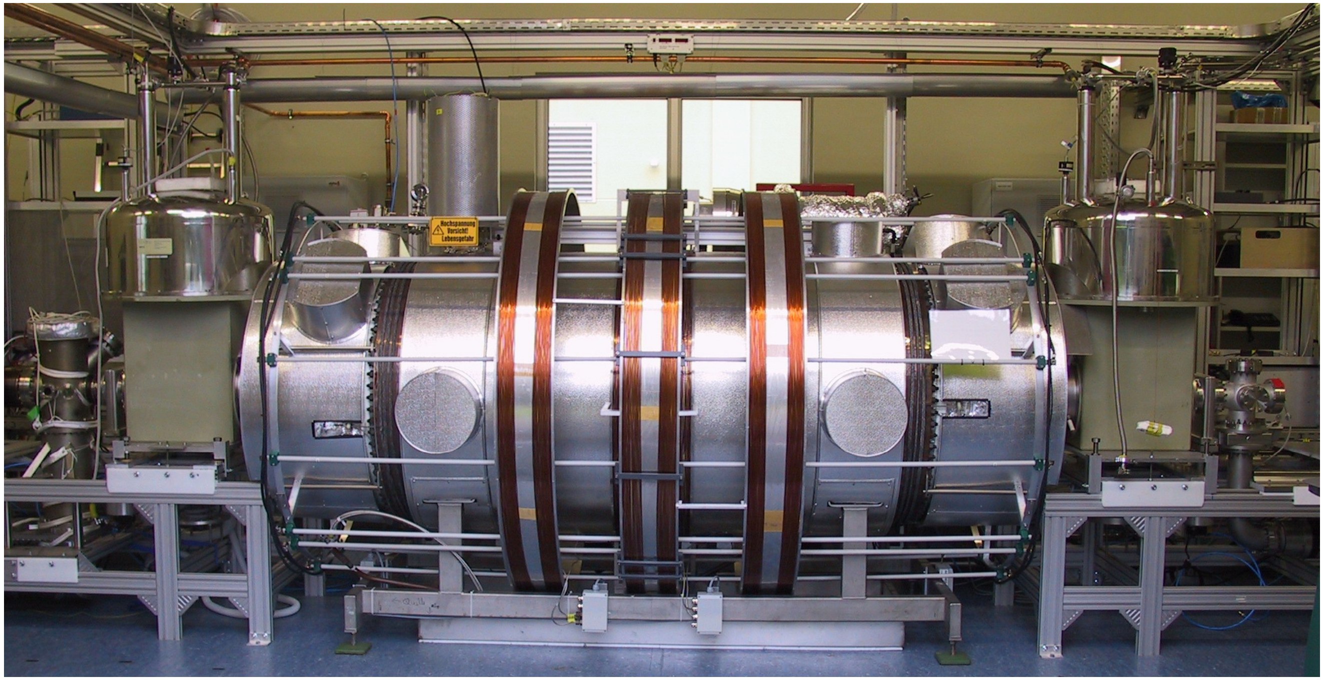


- retardation potential depends on high voltage applied to the spectrometer
- for precise analysis of electron energy by retardation potential the high voltage has to be known to very high precision
  - to achieve desired ν mass sensitivity HV has to be stable within ± 60 mV over 2-month KATRIN run → for U ~ 18.6 kV: **± 3 ppm !**

Two methods of monitoring the HV:

- reduce HV by a high-precision divider and measure it directly with a precise voltmeter
- apply the same HV on another MAC-E filter (= Monitor spectrometer) and measure time-stable conversion electron line by varying potential on the source
  - any change in line position points to instability of the divider-voltmeter setup

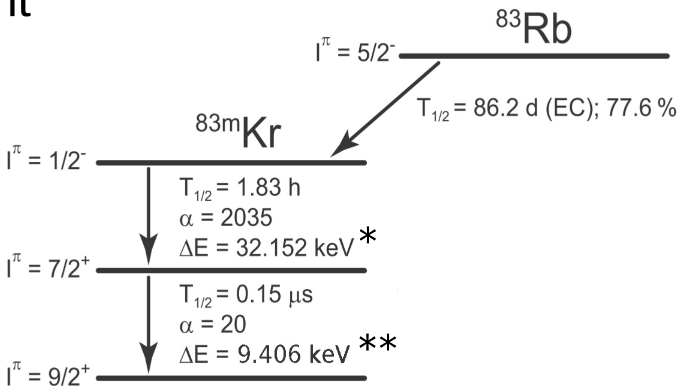
KATRIN Monitor spectrometer



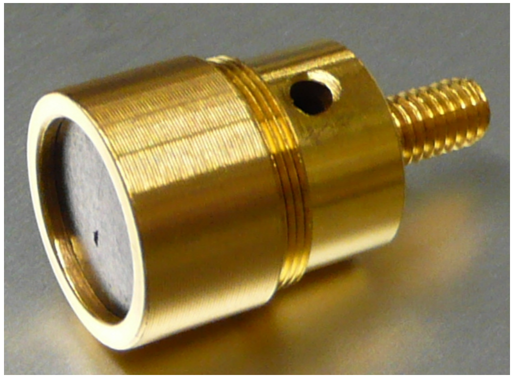
- former Mainz spectrometer, rebuilt in KIT Karlsruhe
- in practice: smaller version of the Main spectrometer
  - energy resolution 0.93 eV @ 18.6 keV
  - Earth & low magnetic field compensation system
  - ultra-high vacuum ~ 10^{-9} mbar in the tank, ~ 10^{-10} mbar in the source and detector chambers
  - 3D positioning of source and detector

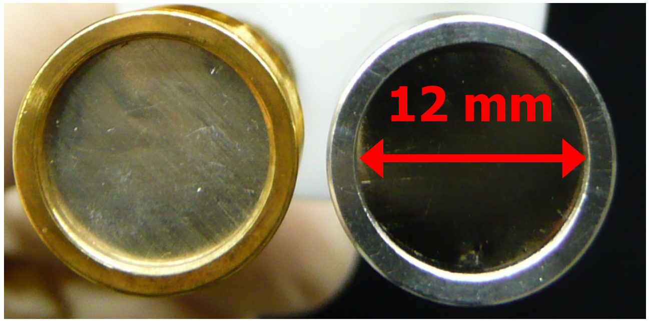
Solid ^{83}Rb/^{83m}Kr conversion electron source

- best suited for monitoring of HV in KATRIN: K-32 conversion electron line from ^{83m}Kr – energy 800 eV below tritium endpoint
- $T_{1/2}$ of ^{83m}Kr only 1.8 hours
  → replenishment from ^{83}Rb with $T_{1/2}$ = 86 days
- method: to capture ^{83m}Kr atoms in Pt substrate before they decay
  → solid sources
- production: implantation of ^{83}Rb atoms into pure platinum substrate at ISOLDE mass separator (CERN)
- under investigation: implantator at HISKP Bonn

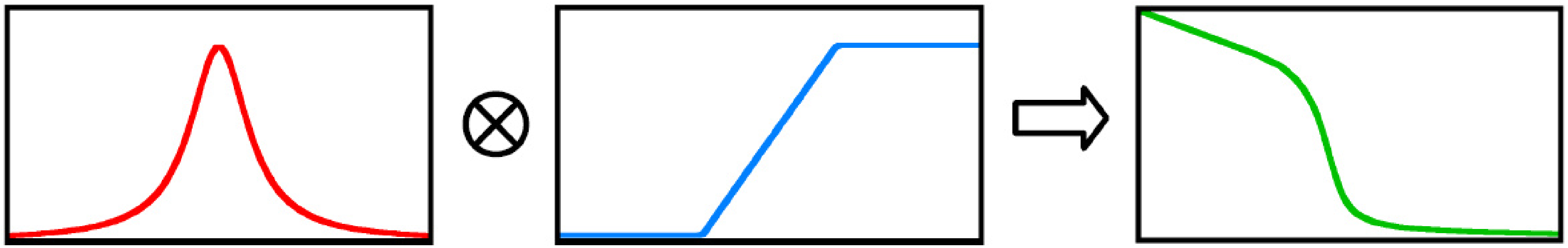


* D. Vénos et al., NIM A 560 (2006) 352
** M. Slezák et al., EPJ A 48 (2012) 12





Integral spectrum of the MAC-E filter: analysis

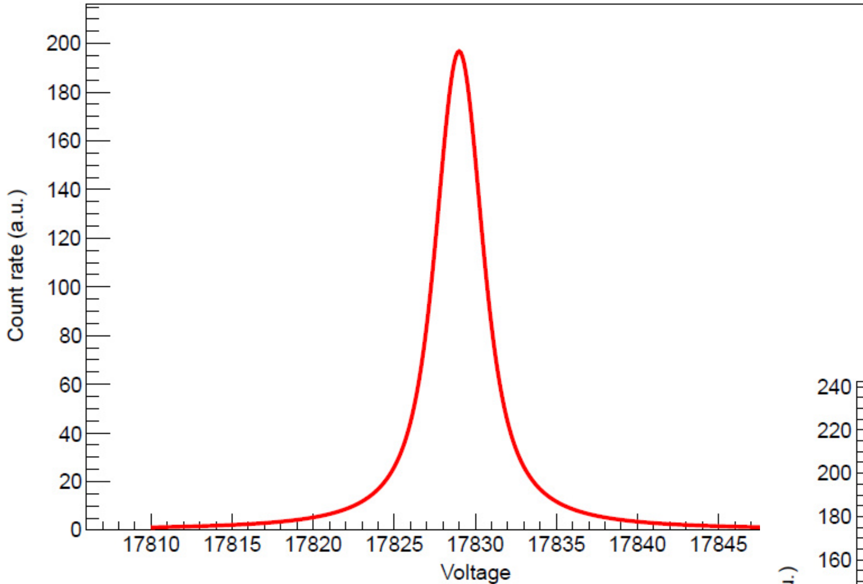


conversion line shape transmission function integral spectrum

- the integral spectrum is analysed by means of many-parameter fit (search of chi-square minimum via Minuit routine under ROOT)
- expected conversion line shape: Lorentzian function
- observed conversion line shape: Lorentzian ⊗ Gaussian & asymmetrical shape at lower energy side (Lor. ⊗ Gaus. = Voigt shape)

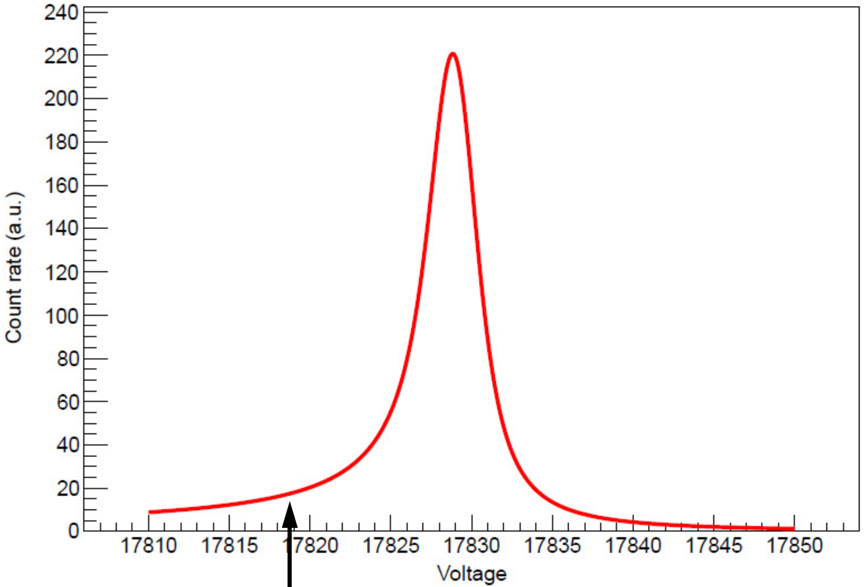
- previously used description: two Voigt lines (motivation: ^{83}Rb atoms sitting in two different environments in the substrate)
- new approach: single Doniach & Sunjic asymmetrical line shape convoluted with Gaussian (motivation: interaction of conversion electrons with conduction electrons in the metal)
  - S. Doniach, M. Sunjic, J. Phys. C 3 (1970) 285

Line shapes – differential form examples



Voigt (symmetrical)

Doniach-Sunjic (conv. with Gauss.) (asymmetrical)

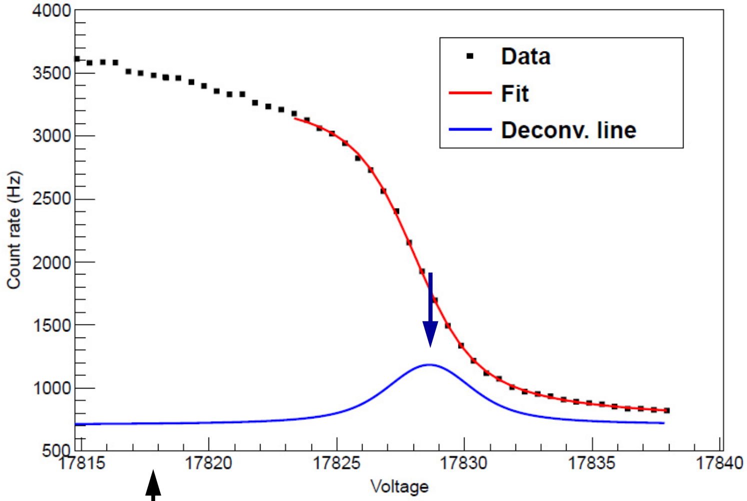


asymmetrical part, for zero asymmetry merges into Voigt

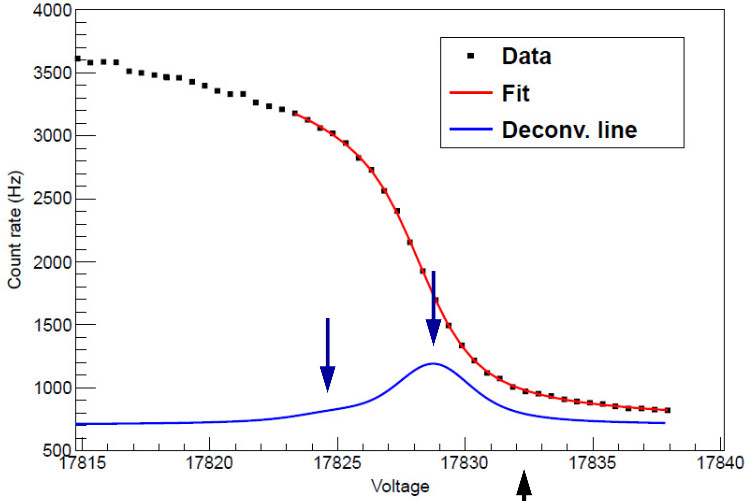
- no asymmetry was observed in Mainz for vacuum evaporated solid sources
→ has to be a solid-state effect
- one source was annealed up to 400 ℃
→ no change in line shape

Line shapes – integral form examples (1)

One Voigt fit:



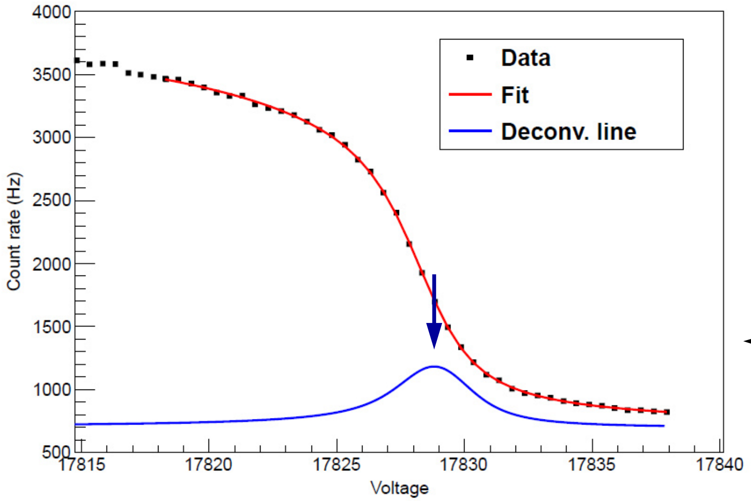
Two Voigt fit:



× does not work at all, data are not described well

• works well, but only on limited space
• left peak tends to fluctuate
• no. of free parameters: 6

One Doniach-Sunjic fit:

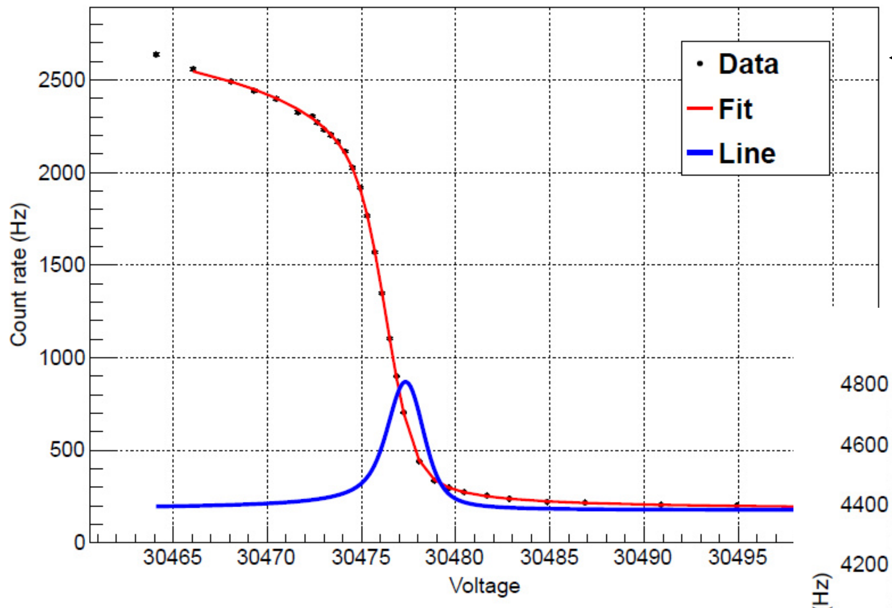


✓ works perfectly
✓ can describe more data
✓ no. of free parameters: 5

Line shapes – integral form examples (2)

- Doniach-Sunjic lineshape works with other conversion electron lines in the spectrum as well:

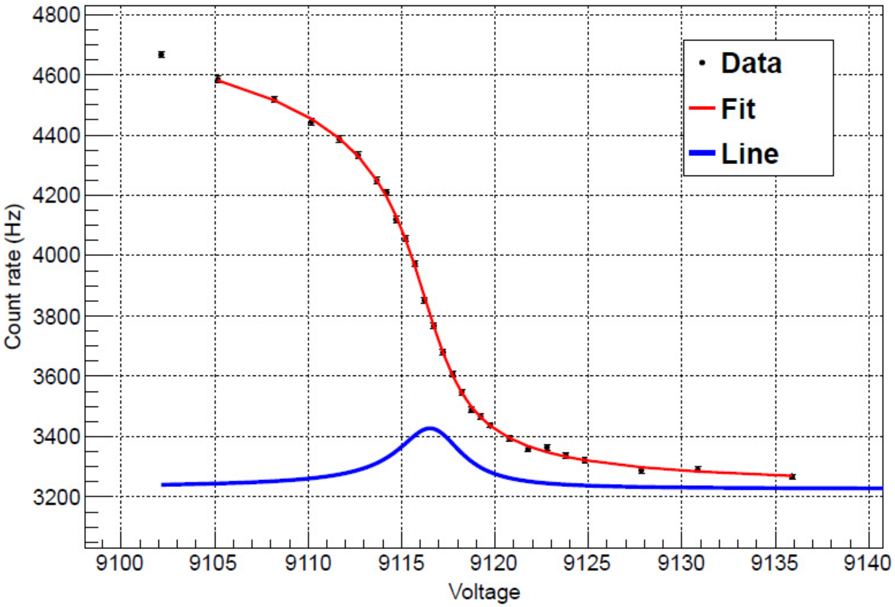
L_3-32, source Pt10-1



← sharp line (small lorentzian width)

broad line (large lorentzian width)

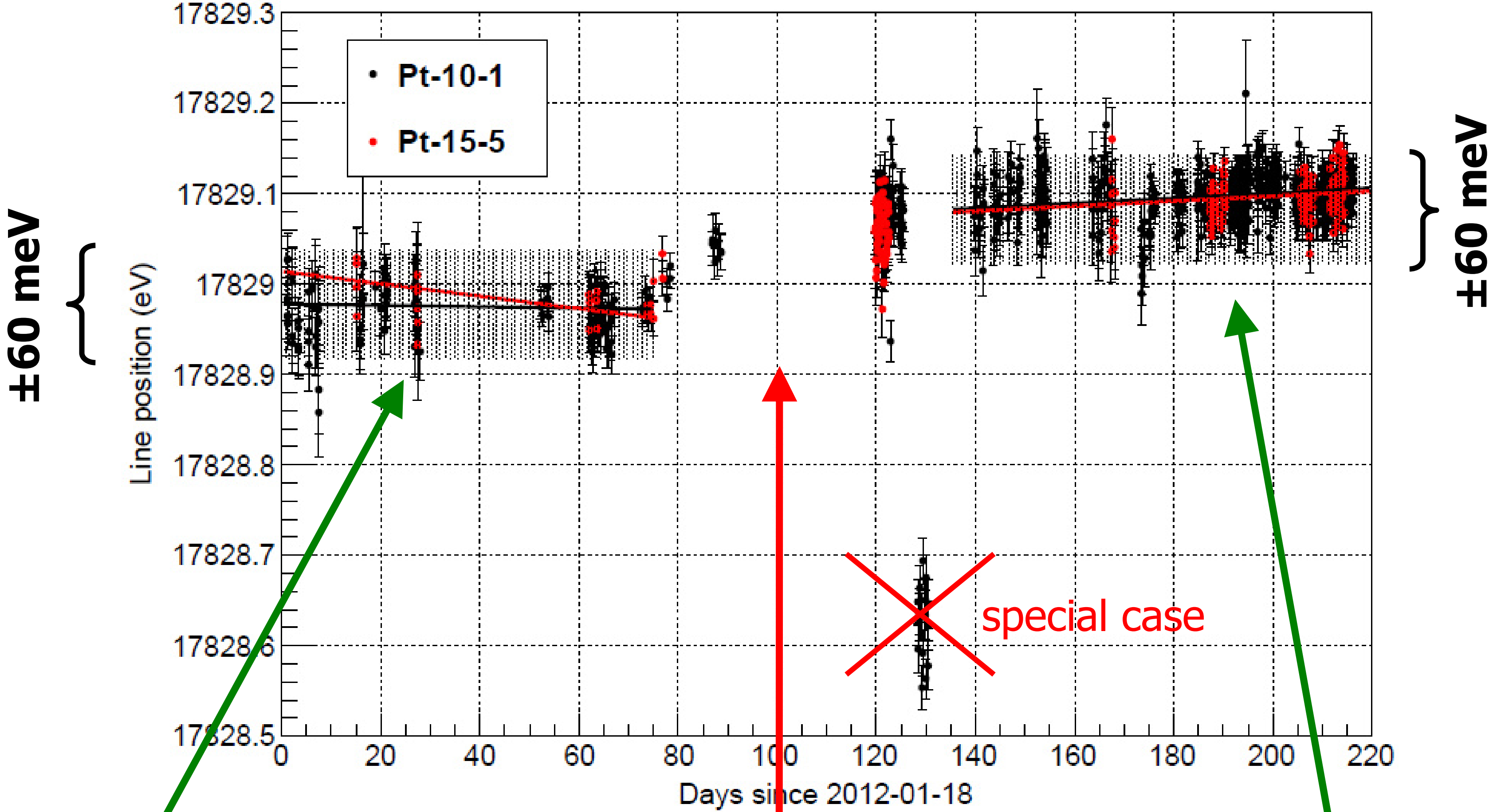
M_1-9.4, source Pt10-1



- asymmetry comparable among different lines
  - was not the case with 2 Voigt fits

K-32 stability measurements (1)

- for the monitoring concept of KATRIN to work, the K-32 line energy has to be stable in time (max. drift ±1.5 ppm per month)



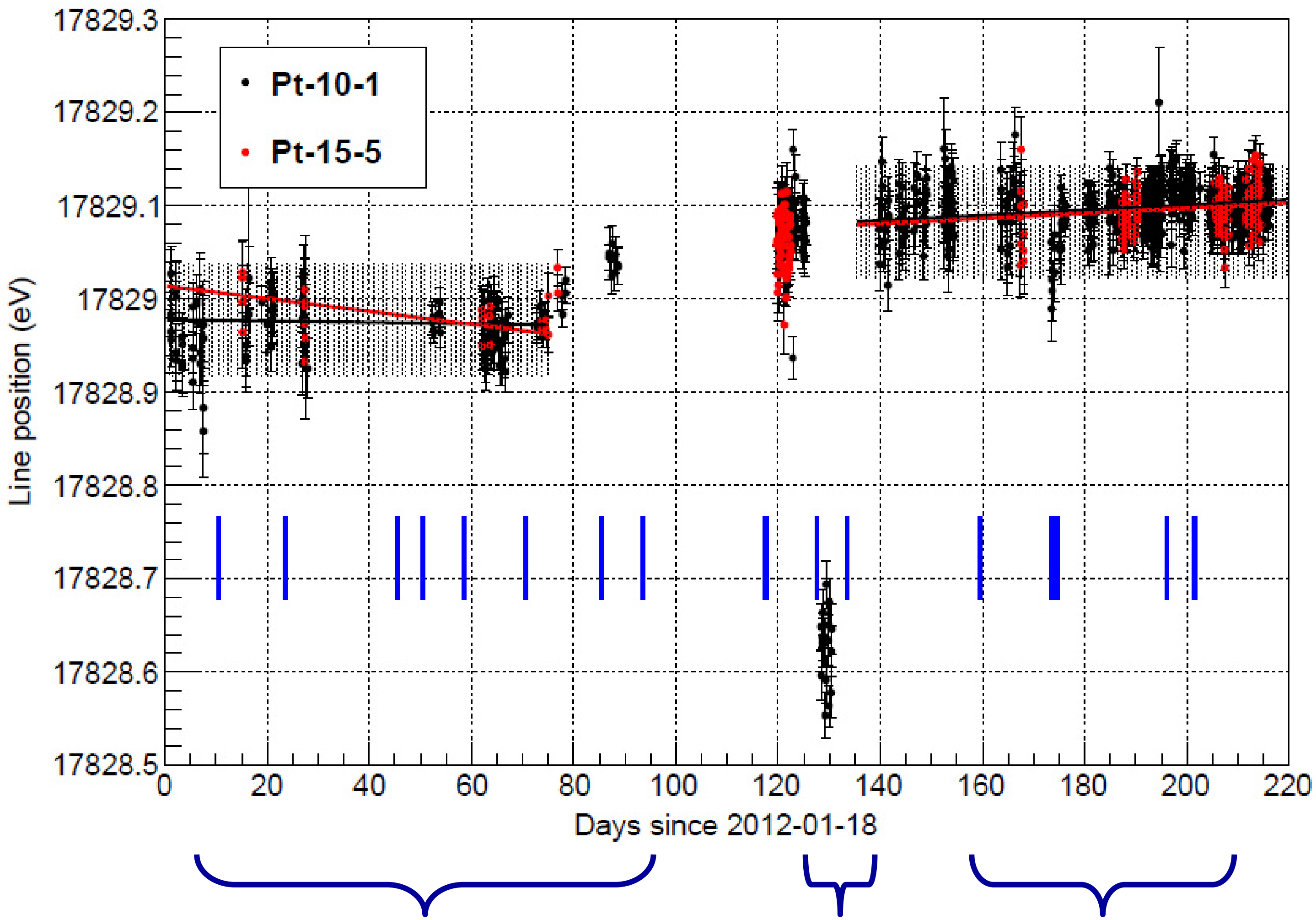
Pt10-1: -0.1(1) ppm/month
Pt15-5: -0.8(5) ppm/month

too large drift

Pt10-1: 0.3(1) ppm/month
Pt15-5: 0.5(2) ppm/month

K-32 stability measurements (2)

- possible explanation for large line drift: various experiments done at MoS introducing gases into spectrometer, discharges?



Background experiments at MoS **Venting & bake-out** **Changes to HV system**

Conclusions

- absolute mass scale of neutrinos unknown
  → measurement of the neutrino mass in the KATRIN experiment from T_2 β-decay
- monitoring of high voltage in KATRIN one of crucial points for reaching the designed sensitivity on the neutrino mass
- one method for monitoring: another spectrometer (Monitor spec.) connected to the same high voltage measuring time-stable conversion electron line from a solid ^{83}Rb/^{83m}Kr source

- Monitor spectrometer successfully running at KATRIN site at KIT
- K-32 energy stability confirmed in two time intervals, but between them the line position is not as stable as required
- possible reason: load to MoS due to various experiments performed

→ during KATRIN T_2 runs no such experiments will be done and conditions will be stable → stable K-32 energy expected

- next major task: demonstrate stability and monitoring capabilities in KATRIN mode (HV cable between spectrometers, varying potential on the source)

Thank you for attention!