Direct neutrino mass measurement

16th International Conference on Topics in Astroparticle Physics and Underground Physics (TAUP)
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Guido Drexlin, Institute of Experimental Particle Physics ETP, Department of Physics

- introduction
- electron capture on holmium
- beta-decay of tritium
- first $\nu$-mass result of KATRIN
- keV-sterile neutrinos
- conclusion
assessing neutrino masses: the three-fold way

0νββ-decay
- ββ-decay: $^{76}\text{Ge}, ^{130}\text{Te}, ^{136}\text{Xe}$
- model-dependent: Majorana-ν

kinematics weak decays
- β-decay: $^3\text{H}$
- EC: $^{163}\text{Ho}$
- model-independent: conservation of E,p

$\langle m_{0\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{e_i}^2 \cdot m_i \right|$  
$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{e_i}|^2 \cdot m_i^2}$

LSS: CMB, GRS, lensing
- model-dependent: $\Lambda$CDM

$\sum_{i=1}^{3} m_i = m_{tot}$

Eligio Lisi
Neutrino Theory

Fedor Simkovic
0νββ Theory

Yong-Hamb Kim
0νββ Experiment

Ofer Lahav
Cosmology Overview
ν-masses from kinematic studies – the challenge

- **setting the stage:** experimental observables $m(\nu_e)$ in β-decay & EC $m_{\beta\beta}$ in 0νββ-searches (Majorana/CP-phases)

![Diagram showing experimental observables and neutrino mass hierarchy]

- **Normal hierarchy**
  - $\Sigma m(\nu_i)$ (eV)
  - $m^2$ from kinematic studies

- **Inverted hierarchy**
  - $\Sigma m(\nu_i)$ (eV)
  - $m^2$ from kinematic studies

![Diagram showing normal and inverted hierarchies]
Moore’s law* of direct $\nu$-mass sensitivities

- **setting the stage:** experimental progress over past decades due to **new technologies**

![Graph showing the decline in neutrino mass limit over time](image)

- **gaseous molecular tritium source:** Los Alamos
- **MAC-E filters:** Mainz, Troitsk
- $m(\nu_e) < 2$ eV (95% CL)

*courtesy of JF Wilkerson*
EC ON HOLMIUM-163: ECHO, HOLMES

$m(v_e) < 225 \text{ eV (1987)}$
electron capture: $Q$-value

**EC-process of $^{163}$Ho:** $^{163}$Ho + $e^{-} \rightarrow \nu_{e} + ^{163}$Dy* ($t_{1/2} = 4570$ yr)

1. After EC: $\nu_{e}$ carries away energy & momentum

$Q_{EC}$: Penning trap mass spectroscopy

$M(^{163}$Ho) − $M(^{163}$Dy)

$Q_{EC} = (2833 \pm 30_{stat} \pm 15_{syst})$ eV

- agrees with MMC-value from Ho-spectrum

$Q_{EC} = (2858 \pm 10_{stat} \pm 50_{syst})$ eV

$Q_{EC} \Rightarrow$ no EC from K, L shells possible

electron capture: de-excitation

- **EC-process of $^{163}$Ho**: $^{163}$Ho + e$^{-}$ → $\nu$e + $^{163}$Dy* (only from s$_{\frac{1}{2}}$ or p$_{\frac{1}{2}}$ orbitals)

- atomic hole state de-excites to atomic g.s. ⇒ Auger & Koster-Kronig electrons, X-rays

![Diagram of de-excitation spectrum](image)

$T_C$: **calorimetric energy** from atomic de-excitations

$\frac{1}{\lambda} \cdot \frac{d\lambda}{dE_C}$ (keV$^{-1}$)

$T_C$ (keV)

finite hole $\tau$: Breit-Wigner resonance ($\Gamma_i$)

G. Drexlin – direct neutrino mass measurement
electron capture: $\nu$-mass

\[ \frac{d\lambda_{EC}}{dT_C} \sim \left( Q_{EC} - T_C \right) \cdot \sqrt{(Q_{EC} - T_C)^2 - m^2(\nu_e)} \cdot \sum_i n_i \cdot C_i \cdot \beta_i^2 \cdot B_i \cdot \frac{\Gamma_i}{2\pi} \cdot \frac{1}{(T_C - E_i)^2 + \Gamma_i^2 / 4} \]

shape: $M_1, M_2, \ldots$

finite hole $\tau$: Breit-Wigner resonance ($\Gamma_i$)

$T_C$ (keV)

$\frac{1}{\lambda} \cdot \frac{d\lambda}{dE_C}$ (keV$^{-1}$)

$10^{-3}$ $10^{-2}$ $10^{-1}$ $1$ $10$ $10^2$

$1/\lambda, d\lambda/dE_C$ (keV$^{-1}$)

spectrum close to $Q_{EC}$

$m(\nu_e) = 0$ eV

$m(\nu_e) = 0.5$ eV

$T_C - Q_{EC}$ (eV)
calorimeters to measure $^{163}$Dy* atomic de-excitation

- **MMC**: metallic magnetic calorimeters with paramagnetic sensor Au:Er

\[ \delta T \text{ in absorber from EC-decay} \quad \Rightarrow \text{change in magnetism } \delta M \text{ of param. sensor} \]

signal: \[ \delta \Phi_s \sim \frac{\partial M}{\partial T} \cdot \Delta T \sim \frac{\partial M}{\partial T} \cdot \frac{1}{C_{tot}} \cdot \delta E \]

- **thermal micro-calorimeters with TES read-out**

\[ \delta T \text{ in absorber from EC-decay} \quad \Rightarrow \text{change in temperature } \delta T \text{ of TES thermistor} \]

calorimeter signal: \[ \Delta T = \frac{\delta E}{V \cdot C_V} \]
calorimeters to measure $^{163}\text{Dy}^*$ atomic de-excitation

- **ECHo Collaboration:**
  - 8 institutions ~ 50 scientists
  - ECHo 1-k detector array (working horse)
    - 64 pixels implanted at RISIKO (Uni Mainz)
  - activity per pixel: $A_{\text{pix}} \sim 1 \text{ Bq}$ ($A_{\text{tot}} \sim 50 \text{ Bq}$)

- **HOLMES Collaboration:**
  - 6 institutions ~ 40 scientists
  - first pixels now being characterized:
    - $\Delta E = 4.5 \text{ eV} @ 2.6 \text{ keV}$
    - $\Delta t \sim 2.8 \mu\text{s}$
  - ion implanter being tested (Genova)
EC on holmium – challenges

- **challenges in reaching a sub-eV sensitivity**
  - good statistics in endpoint region:
    \[ N_{\text{ev}} > 10^{14} \rightarrow \text{overall } A \sim 1 \text{ MBq} \]
  - limit unresolved pile-up (\( f_{\text{pu}} \sim a \cdot \tau_r \))
    \[ f_{\text{pu}} < 10^{-6} \]
    for \( \tau_r < 1 \mu s \Rightarrow \text{limit pixel } a \sim 10 \text{ Bq} \)
  - very good energy resolution at endpoint
    \[ \Delta E (\text{FWHM}) < 3 \text{ eV} \]
  - detailed understanding of spectral features:
    2-hole excitations, line broadening
  - very low background level
    \[ R_{\text{bg}} < 10^{-5} \text{ events/eV/pixel/day} \]
**ECHO – final LSM result**

- **final results from a first MMC-measurement phase at Modane (LSM)**

  - 4 pixels over 4 days (275,000 counts)

  \[
  A_{\text{pix}} = 0.2 \text{ Bq} \quad \Delta E_{\text{FWHM}} = 9.2 \text{ eV}
  \]

- profile log-likelihood ratio test:

  \[
  Q_{EC} = (2838 \pm 14) \text{ eV}
  \]

  \[
  m(\nu_e) < 150 \text{ eV (95\% C.L.)}
  \]
from ECHo-1k to ECHo-100k

1. **ECHo-1k**: 2015 - 2020
   - demonstrate scalability of arrays ✓
   - MMC: $\Delta E_{\text{FWHM}} < 5$ eV
   - total activity $A \sim 100$ Bq
   - 1 y measurement phase:
     ⇒ limit $m(\nu_e) < 10$ eV (90% CL)

2. **ECHo-100k**: 2020 ff
   - ECHo-100k chip in fabrication
   - 12000 pixels ($A_{\text{pix}} \sim 10$ Bq)
   - microwave SQUID multiplexing
   - 3 y measurement phase
     ⇒ limit $m(\nu_e) < 1.5$ eV (90% CL)
$\beta$-DECAY OF TRITIUM: PROJECT8, KATRIN

M. Tanabashi et al. (PDG), PRD 98 (2018) 030001
tritium $\beta$-decay: kinematics

- continuous $\beta$-spectrum described by Fermi´s Golden Rule, measurement of effective mass $m(\nu_e)$ based on kinematic parameters & energy conservation

\[
\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E, Z) \cdot \theta(E_0 - E - m_i)
\]

\[
m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}
\]
β-spectroscopy: molecular & atomic tritium

- Molecular source ($T_2$) – sensitivity limit $\sim 100$ meV
- Atomic source (T) – sensitivity limit $\sim 40$ meV (?)

Diagram:
- $^3\text{HeT}^+$ reaction
- $e^{-}$ emission

Graph:
- Calculated final state distribution of $T_2$
- Excited electronic states
- Excitation energy (eV)

$T_2$ molecule: $e^{-}$ and $\nu_e$ emissions

FSD (Final State Distribution)
Project 8 – a novel spectroscopic approach

Cyclotron Radiation Emission Spectroscopy (CRES)
- CRES of trapped electrons from tritium β-decay in homogeneous strong magnetic field B

\[ \omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{e \cdot B}{m_e + E_{e,\text{kin}}} \]

- B = 1 T
- \( E_{e,\text{kin}} = 18.57 \text{ keV} \)
- \( f_0 = \frac{\omega_0}{2\pi} \approx 27 \text{ GHz} \)

⇒ precise measurement of \( \omega \) yields electron kinetic energy \( E_{e,\text{kin}} \)

\( \Delta \omega \sim 1/t_s \)
- sampling time \( t_s \sim \text{several } \mu \text{s} \)
- (magnetic bottle)

Project 8 – single electron history

- First detection of cyclotron radiation from a single keV electron

**Electron loses energy on scattering off residual gas:** energy loss & change of pitch angle

\[ \Delta E = 14 \text{ eV} \]

Onset \( \omega \) in initial \( ^{83}\text{mKr} \) electron \( E_\perp (30 \text{ keV}) \)

Synchrotron energy loss: 1 fW

**PRELIMINARY**
- Krypton line from tritium-ready system
- 17.8 keV
- 18.0 keV
Project 8 – a staged approach

1. Phase – I: 2010-2016 – proof-of-principle test measurements with $^{83m}$Kr
   CRES observed for first time

   first tritium data 2018
   several days of runs
   fitted $\beta$-decay endpoint:
   $E_0 = (18.526 \pm 0.09)$ keV
   new 2019 campaign to begin soon (100 d)
Project 8 – the future

3 Phase – III: … – a large volume demonstrator based on multi-antenna array in MRI tritium spectrum for $m(\nu_e) \sim 2$ eV

4 Phase – IV: … – towards an atomic tritium source
R&D for an atomic tritium source (Ioffe trap) goal: inverted mass hierarchy for $m(\nu_e)$

200 cm³

cracking  cooling  low-field seekers
decay volume
KATRIN overview: 70 m long beamline

Windowless Gaseous Tritium Source cryostat

differential
cryogenic

Main Spectrometer

3H

RS

G. Drexlin – direct neutrino mass measurement
MAC-E principle: high-resolution tritium $\beta$-spectroscopy

- **Magnetic Adiabatic Collimation & Electrostatic Filter:** adiabatic conversion $E_\perp \rightarrow E_\parallel$

\[ \mu = \frac{E_\perp}{B} = \text{const.} \]
response to quasi-monoenergetic electrons

- MAC-E filter characteristics well understood (also used to study plasma)

![Diagram with decay scheme and energy levels]

- $^{83}\text{Rb}$, $T_{1/2} = 86.2$ d
- $^{83}\text{mKr}$, $T_{1/2} = 1.83$ h
- $\gamma$, $E_\gamma = 32.15$ keV
- $\gamma$, $E_\gamma = 9.4$ keV

![Energy spectrum graph with L3-32 line at 30.47 keV]

- Filter width: $\frac{\Delta E}{E} \approx \frac{B_{\text{min}}}{B_{\text{max}}}$
- L3-32 line: 30.47 keV

- G. Drexlin – direct neutrino mass measurement
First Tritium:  

- low tritium concentration:  
  ~1% DT and ~99% D2  
- functionality of all system components \( \checkmark \) at nominal \( \rho_d \) \( (5\times10^{17} \text{ cm}^{-2}) \)

\[ \chi^2 = 13.8 \text{ for 18 dof} \]

KATRIN Collab., “First operation of the KATRIN experiment with tritium”, to be subm. to Eur. Phys. J. C
KATRIN neutrino mass campaign #1

- 4-week long measuring campaign in spring 2019 with high-purity tritium

- April 10 – May, 13 2019 780 h
- high-purity tritium ($\varepsilon_T = 97.5\%$) laser-Raman
- high source activity: $2.45 \cdot 10^{10}$ Bq
- high-quality data collected
- full analysis chain using two independent methods
- target: first neutrino mass result at TAUP 2019
KATRIN neutrino mass campaign #1

- 22% of nominal source activity (column density)
  ⇒ limits effects due to radiochemical reactions of T_2 (initial "burn in" effect)
- high isotopic tritium purity
  ⇒ T_2 (95.3%), HT (3.5%), DT (1.1%)

4.9 g / day

\[ \pm 2.4 \% \]
tritium scanning – strategy

- 274 scans of tritium β-decay spectrum:
  - alternating up- / down- scans
  - 2 h net scanning time
  - analysis: 27 HV set points
  - [E_0 – 40 eV, E_0 + 50 eV]

MTD maximises ν-mass sensitivity
  - focus on region close to E_0

22 HV set points
modelling of experimental data

**β-spectrum ⊗ response function**

\[ R_\beta(E, m^2(\nu_e)) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E - qU) \, dE + R_{bg} \]
tritium scanning – fitting of spectrum

- fit of integrated experimental energy spectrum to theoretical model with 4 free parameters
  - leave parameters $A_s$ and $E_0$ unconstrained 
    'shape-only' fit

- merged data set
  - combine all 274 scans: excellent stability of all fitted $\beta$-decay endpoints $E_0$ ($\sigma = 0.25$ eV)
    $\Rightarrow$ “stacking” of events at mean HV set-point (excellent reproducability: RMS = 34 mV)
Integral tritium $\beta$-decay spectrum

- **High-statistics $\beta$-spectrum**
  
  - 2 million events in 90-eV-wide interval (522 h of scanning)
  
  - excellent goodness-of-fit
  \[ \chi^2 = 21.4 \text{ for 23 d.o.f.} \]
  \[ (p\text{-value} = 0.56) \]

- **bias-free analysis**
  - blinding of FSD
  - full analysis chain first on MC data sets
  - final step: unblinded FSD for experimental data
analysis chain & υ-mass result

- two independent analysis methods
to propagate uncertainties & infer parameters
  - Covariance matrix:
    covariance matrix + $\chi^2$-estimator
  - MC propagation:
    $10^5$ MC samples + likelihood (-2 ln $\mathcal{L}$)
  - both methods agree to a few percent

- υ-mass and $E_0$: best fit results

$$m^2(\nu_e) = \left( -1.0 + 0.9 \right) \text{eV}^2 \ (90\% \text{ CL})$$

$E_0 = (18573.7 \pm 0.1) \text{ eV} \ \Rightarrow \ Q\text{-value : } (18575.2 \pm 0.5) \text{ eV} \quad Q\text{-value } [\Delta M(\text{^3H},\text{^3He})]: (18575.72 \pm 0.07) \text{ eV}$
systematics breakdown

- well-understood systematics budget $\sigma_{\text{syst}}$ (with $\sigma_{\text{syst}} < \sigma_{\text{stat}}$)
  - total statistical uncertainty budget $\sigma_{\text{stat}} = 0.97$ eV$^2$
  - total systematic uncertainty budget $\sigma_{\text{syst}} = 0.32$ eV$^2$

- non-Poisson bg. part
- background slope
- B-field values
- HV „stacking“
- inelastic scattering
- final state distribution
- energy loss distribution

$1-\sigma$ uncertainty on $m_\nu^2$ (eV$^2$)
systematics breakdown

- well-understood systematics budget $\sigma_{\text{syst}}$ based on only 4 weeks of data
  - total statistical uncertainty budget $\sigma_{\text{stat}} = 0.97 \text{ eV}^2$
  - total systematic uncertainty budget $\sigma_{\text{syst}} = 0.32 \text{ eV}^2$

improves on Mainz/Troitsk by

factor 2

factor 6

non-Poisson bg. part 0.298
background slope 0.066
B-field values 0.049
HV „stacking“ 0.044
inelastic scattering 0.052
final state distribution
energy loss distribution

$1-\sigma$ uncertainty on $m_\nu^2$ (eV^2)
KATRIN result and expectation

- best-fit result corresponds to a 1-σ statistical fluctuation to negative $m^2(\nu_e)$

- p-value is derived from 13 000 MC samples with $m^2(\nu_e) = 0$ and properly fluctuated $\sigma_{\text{stat}}$ and $\sigma_{\text{syst}}$

p-value = 0.16
neutrino mass upper limit

- **confidence belts**: procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC)

- for this first result we follow the robust LT method
- LT yields experimental sensitivity by construction for $m^2(\nu_e) < 0$

- **KATRIN upper limit on neutrino mass**:

  - LT  $m(\nu) < 1.1$ eV (90% CL)
  - FC  $m(\nu) < 0.8$ eV (90% CL)
  - < 0.9 eV (95% CL)

M. Aker et al. (KATRIN Collab.), *An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN*, to be subm. to PRL today
KATRIN – future plans

- **KATRIN near- and long-term future:**
  - **Further reduction of background**
    - from decays of Radon & Rydberg atoms
    - spectrometer bake-out successful ✅
    - upgraded aircoil system ✅
    - „shifted analysis plane“ (SAP)
    - bg-studies & tritium scans soon
  - **Further reduction of systematics**
    - energy loss via egun in ToF modus, …

- **1000 days of measurements** at
  - nominal $\rho_d (5 \cdot 10^{17}$ molecules cm$^{-2}$)
  - 3 tritium campaigns (65 days each)
  - per calendar year

- **Sensitivity** $m(v_e) = 0.2 \text{ eV (90\% CL)}$
  - $0.35 \text{ eV (5}\sigma)$
future Moore’s law of direct $\nu$-mass sensitivities

- **KATRIN 2019 – 2024:** a new, much steeper slope for Moore’s law

![Graph showing neutrino mass sensitivity over calendar year](graph.png)

- **KATRIN 2019:** $m(\nu_e) < 1.1$ eV (90% CL)
- **KATRIN 2024:**
  - $m(\nu_e) < 0.2$ eV (90% CL)
  - or $= 0.35$ eV (5 $\sigma$)
SEARCH FOR KEV STERILE NEUTRINOS
Tritium β-decay and dark fermions

- **BSM particles (sterile neutrinos, light fermionic DM)**
  - cover entire phase space (masses up to 18 keV)
  - cover tiny couplings (~10^-7) ⇒ left-right couplings (Rodejohann)

\[
\frac{dn}{dE} = \cos^2 \theta_s \cdot \frac{dn}{dE}(m_{\text{active}}) + \sin^2 \theta_s \cdot \frac{dn}{dE}(m_{\text{sterile}})
\]

- **Perseus galaxy cluster**

\[
\sin^2 \theta = 0.2 \quad m_s = 10 \text{ keV}
\]
Science reach of KATRIN with new detector array

- estimated **KATRIN sensitivity** and SDD layout of TRISTAN

\[ \sin^2 \theta \]

\[ m_{\text{sterile}} \ (\text{keV}) \]

S. Mertens et al., arXiv: 1810.06711

**TRISTAN – TRitium Investigation on STerile (A) Neutrinos**
# Conclusion

- **major experimental progress of direct kinematic methods** since NEUTRINO 2018!

**KATRIN:**
- first neutrino mass result
- $m_\nu < 1.1$ eV (90 % CL)
- 3 cycles / year

**ECHo:**
- goal: $m(\nu_e) < 20$ eV in 2020

**P8:** first tritium CRES spectrum

**HOLMES:** significant R&D progress
THANK YOU!

this talk is dedicated to V.M. Lobashev & E.W. Otten
thank you to L. Gastaldo, J. Formaggio, N. Oblath, A. Nucciotti
ADDITIONAL TRANSPARENCIES
Complementarity: tritium β-decay & EC of $^{163}$Ho

$^{3}$H$_{2}$ → $^{3}$HeT$^{+}$ + e$^{-}$ + $\bar{\nu}$$_{e}$

β-source requirements

- Kinematics: short $t_{1/2}$ & low $E_{0}$
- (super-) allowed transition
- Good understanding of final state
- High isotopic purity & source stability
- Well-established procurement method

Only two isotopes of choice: tritium & holmium

$^{163}$Ho + e$^{-}$ → $^{163}$Dy* + $\nu$$_{e}$
Complementarity: tritium $\beta$-decay & EC of $^{163}$Ho

**$\beta$-source requirements**

- **$^3$H**: super-allowed
  - $E_0 = 18.6$ keV
  - $t_{1/2} = 12.3$ y

- **$^{163}$Dy**: line width
  - $E_0 = 2.8$ keV
  - $t_{1/2} = 4570$ y

- molecular ✔
- atomic (R&D)

- only two isotopes of choice: tritium & holmium

- high isotopic purity & source stability
- well-established procurement method

- good understanding of final state

**$^{163}$Ho**-

- atomic, in solid state, embedded in (ordered) crystal

- $4 \times 10^8$ atoms for 1 Bq
- $2 \times 10^{11}$ atoms for 1 Bq
### MAC-E filter

- **Min. longitudinal β-energy** $E_{\parallel}$
  - $\Delta E = 0.9$ eV (100% transm.)

### β-detection requirements

- Cover large solid angle (~ $2\pi$)
- Very low background rate at $E_0$
- High energy resolution (~ eV)
- Short dead time, no pile up

### thermal μ-calorimeter

- Released decay-energy
  - $\Delta E \sim 5$ eV (FWHM)

### calorimeter: source ↔ detector

- Source
- Detector

### metallic magnetic calorimeter

- Released decay-energy
  - $\Delta E = 2-5$ eV (FWHM)

---

**Direct neutrino mass experiments – read-out**

- **Electron energies**
- **Cyclotron radiation**
  - Max. transversal β-energy $E_{\perp}$
    - $\Delta E = 2-3$ eV (FWHM)

---

**MAC-E filter**

- Highest energy resolution

---

**G. Drexlin – direct neutrino mass measurement**
direct neutrino mass experiments – the projects

**MAC-E filter**

- Min. longitudinal β-energy $E_{\parallel}$
- $\Delta E = 0.9$ eV (100% transm.)

**thermal μ-calorimeter**

- Released decay-energy
- $\Delta E \sim 5$ eV (FWHM)

**PTOLEMY:**

R&D efforts to combine techniques

**cyclotron radiation**

- Max. transversal β-energy $E_{\perp}$
- $\Delta E = 2-3$ eV (FWHM)

**metallic magnetic calorimeter**

- Released decay-energy
- $\Delta E = 2-5$ eV (FWHM)
HOLMES – status & plans

- **HOLMES source production and purification:**
  
  130 MBq available for tests and experiments

- **Detector arrays - characterization:**
  
  - very good single pixel performance
  
  - $\Delta E_{\text{FWHM}} = (4.9 \pm 0.1)$ eV
  
  - operating microwave SQUID multiplexing
  
  - upcoming: loading of TES arrays with Ho-163

- **timeline**
  
  - proof-of-concept (2013-18), 64 channels, 1 month running
  
  - full scale (2019ff), 1000 channels, 3 years
estimated sensitivities (statistics only)

1 year live time

PRELIMINARY

1 σ for observable $m^2_{e\nu}$ (eV)

90% CL mass limit (eV)

insufficient e- lifetime

$3 \times 10^{11}$ $T_2$-decays

$3 \times 10^{13}$ $T_2$-decays

$3 \times 10^{12}$ $T_2$-decays

$1 \times 10^{12}$ decays of atomic $T$

$\delta B/B \sim 10^{-7}$

adopted from P8 Collab.
tritium scanning

- excellent stability of scanning over entire 4-week period
  - fits to β-decay endpoints $E_0$ of all 274 tritium scans:
    ⇒ Gaussian distribution

$\sigma = 0.254$ eV

p-value = 0.51
systematics: background

- background due to neutral, excited atoms in active flux-tube volume
  - ~50%: ionisation of Rydberg states due to BBR \( \Rightarrow \) purely Poisson component
  - ~50%: \( \alpha \)-decays of \( ^{219}\text{Rn} \) atoms from NEG pump \( \Rightarrow \) with small non-Poisson part
neutrino mass upper limit

- calculation of confidence belts

- procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC):
  no empty confidence intervals for fluctuations into region $m^2(\nu_e) < 0$

- KATRIN upper limit on neutrino mass (LT)
  $m(\nu) < 1.1$ eV (90% CL)

- KATRIN upper limit on neutrino mass (FC)
  $m(\nu) < 0.8$ eV (90% CL)
  $< 0.9$ eV (95% CL)
electron gun to measure electron energy losses

**Angular selective precision egun:** determineinelastic energy losses in source & pd

- well-defined pitch angle $\Delta \theta$
- narrow energy spread $\Delta E$
- excellent stability at high rates

egun during commissioning phase
systematics due to column density

- **column density $\rho_d$** – in situ measurement of transmission function with egun

\[
\rho_d \sigma = 0.403 \text{ with 0.6 \% uncertainty} \\
\rho_d = 1.1 \cdot 10^{17} \text{ molecules cm}^{-2} \text{ with 0.8 \% uncertainty}
\]

egun data

![Graph showing rate (kcps) vs. surplus energy (eV) and relative gas density $\rho/\rho_0$ vs. z (m)]
Concept of shifted analysis plane

- **nominal setting**
- **green**: reduced flux: as KNM1 setting
- **red**: reduced flux with shifted analysis plane

**nominal analysis plane**

**shifted analysis plane**

**wire electrodes**
EC on holmium – sensitivity

- good statistics in endpoint region:
  \[ N_{ev} > 10^{14} \rightarrow \text{overall } A \sim 1 \text{ MBq} \]

- limit unresolved pile-up (\( f_{pu} \sim a \cdot \tau_r \))
  \[ f_{pu} < 10^{-6} \]
  for \( \tau_r < 1 \mu s \) \( \Rightarrow \) limit pixel \( a \sim 10 \text{ Bq} \)

- very good energy resolution at endpoint
  \( \Delta E(\text{FWHM}) < 3 \text{ eV} \)

- very low background level
  \( R_{bg} < 10^{-5} \text{ events/eV/pixel/day} \)

\[ Q_{EC} = 2.833 \text{ keV} \]
\[ f_{pu} = 10^{-6} \]
\[ \Delta E_{\text{FWHM}} = 2 \text{ eV} \]

Based on \( \nu \text{2018 transparency by L. Gastaldo} \)