Direct Neutrino Mass Measurement with KATRIN

Sanshiro Enomoto (University of Washington) for the KATRIN Collaboration

Don’t know Dirac or Majorana?
No problem!!
Neutrino Mass Measurement with Single Beta Decay

Use Kinematics only, look at the end-point shape

$$\frac{dN}{dE_e} = C \cdot F(E, Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e) \sqrt{(E_o - E_e)^2 - m_{\nu_e}^2}$$

$$\sum_i |U_{ei}|^2 \cdot m_i^2 \sim m^2$$
in degenerated region

$$^3\text{H} \rightarrow ^3\text{He} + e^- + \nu_e$$
Neutrino Mass Measurement with Single Beta Decay

Use **Kinematics only**, look at the end-point shape

\[
\frac{dN}{dE_e} = C \cdot F(E, Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e) \sqrt{(E_o - E_e)^2 - m_{\nu_e}^2}
\]

\[\sum_i |U_{ei}|^2 \cdot m_i^2 \sim m_{\nu_e}^2 \quad \text{in degenerated region}\]

\[\beta \rightarrow \nu + e^- \quad \beta \rightarrow \bar{\nu} + e^+\]

**Tritium as beta-source**

- **low end-point** (18.6 keV)
  - relatively large deformation
  - electro-statically reachable
- **short life** (12.3 y):
  - small source amount
  - less scattering in source
- **super-allowed** transition
  - matrix element reliably calculable
- **simplest molecular**:
  - molecular states calculable

\[\beta \rightarrow \nu + e^- \quad (18.6 \text{ keV})\]

\[\beta \rightarrow \bar{\nu} + e^+ \quad (12.3 \text{ y})\]
Neutrino Mass Measurement with Single Beta Decay

Use Kinematics only, look at the end-point shape

\[
\frac{dN}{dE_e} = C \cdot F(E, Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e) \sqrt{(E_o - E_e)^2 - m_{\nu_e}^2}
\]

\[\sum_i |U_{ei}|^2 \cdot m_i^2 \sim m_e^2\]
in degenerated region

\[\^3\text{H}\to^3\text{He} + e^- + \bar{\nu}_e\]

Tritium as beta-source

- low end-point (18.6 keV)
  - relatively large deformation
  - electro-statically reachable
- short life (12.3 y):
  - small source amount
  - less scattering in source
- super-allowed transition
  - matrix element reliably calculable
- simplest molecular:
  - molecular states calculable

only \(2 \times 10^{-13}\) of all beta in last 1 eV

Needs:

- strong source
- high precision spectroscopy
Electron Spectroscopy with Electro-Static Filter

Problem: only small fraction of electrons reach this → guiding magnetic field
Electron Spectroscopy with Electro-Static Filter

Problem: only $E_{\parallel}$ is measured

$E_{\parallel}/E_{\perp}$ depends on initial emission angle

$\rightarrow$ adiabatic collimation
Electron Spectroscopy with Electro-Static Filter

reduce magnetic field adiabatically

⇒ magnetic moment conserves: $\mu = \frac{E}{B} = \text{const}$ ⇒ collimation
MAC-E (Magnetic-Adiabatic-Collimation Electro-static) Filter

\[ \mu = \frac{E}{B} = \text{const} \]

Energy resolution is determined by B-Ratio

\[ \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{source}}} \]
Present Mass Limit and KATRIN Experiment

Mainz (2005, final result)
\[ m(\nu_e) < 2.3 \text{ eV (95\%CL)} \]

Triosk (2011, re-analysis)
\[ m(\nu_e) < 2.05 \text{ eV (95\%CL)} \]

KATRIN
design sensitivity: \[ m(\nu_e) < 0.2 \text{ eV (90\%CL)} \]

1/10 sensitivity on \( m_e \)
\[ \Rightarrow 1/100 \text{ sensitivity on } m_e^2 \]
\[ \Rightarrow x100 \text{ statistics, 1/100 systematics} \]
KATRIN Experiment

KArlsruhe TRItium Neutrino Experiment

- located at Karlsruhe Institute of Technology, Karlsruhe, Germany
- design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL, 3 years)

Calibration E-Gun etc

Tritium Retention (electrons guided by B)

Electron Counter (~10 mHz)

$10^{11}$ Bq Gaseous Tritium Source

0.93 eV Resolution MAC-E Filter
Windowless Gaseous Tritium Source

- 100 GBq Gaseous Tritium Source
- 40 g/day circulation

Cooled at 30 ± 0.003 K

Two Phase (LNe/GNe) Cooling

• 0.1% Pressure Stability
• 0.1% Temperature Stability
Gas Composition Monitoring

Laser Raman Spectroscopy (in embedded the tritium loop)

- 0.1 % precision in 60 sec
Tritium Retention

Injection 1.8 mbar l/s
differential pumping
cryo-absorption

DPS

CPS

10^{-7} mbar l/s

10^{-14} mbar l/s

Differential Pumping Section

Cryo-Pumping Section

Ar frost for large surface

Beam Tube at 3 K
Tritium Retention: ion blocking and removal

- No straight path for molecules
- Electrons adiabatically guided by B-field

Remove ions by $E \times B$ drift

Reflect positive ions

Dipole Electrodes

Ring Electrodes
Main Spectrometer (MAC-E Filter)

KATRIN MAC-E Filter

- $B_{\text{max}}$: 6 T by super conducting magnets
- $B_{\text{min}}$: 3 G (=0.0003 T) by $24 \times 9$ m UHV vessel
  $\Rightarrow \Delta E = 0.93 \text{ eV} @ 18.6 \text{ keV}$

- 1240 m$^3$ UHV vessel
- $10^{-11}$ mbar pressure (6 TMP and 3 km NEG strips)

- ppm-level precision retarding high-voltage (control and monitor)
Field Shaping & EM Shielding

- satisfy transmission condition (adiabatic guidance, precise retarding)
- avoid penning traps

Air Coils

- B-field shaping
- magnetic shielding
- background removal (B-pulsing)
- geomagnetism compensation

Inner Wire Electrodes

- E-field shaping
- electric shielding
- background removal (dipole mode)
- vessel HV noise screening
Electron Detector

Post-Acceleration Electrode shifts electrons to lower background region

148 pixel Si PIN diode

Position sensitivity on flux-tube cross section

\[ \Delta E = \sim 1.5 \text{ keV} \]

\[ E_{\text{thresh}} : \sim 4 \text{ keV} \]
Spectrometer Construction and Commissioning

Aug 2006

Air Coils Installed

Oct 2006

Inner Wire Electrode Installed (2012)
EGun-Spectrometer-Detector Commissioning (2013~)

- MAC-E filter transmission characterization
- Background measurements
- HV stability test
- and more (alignment, active background removal, detector characterization, …)
MAC-E Transmission Characteristics

Transmission depends on pitch angle

Transmission Function Measurement

Pitch-angle dependence
**MAC-E Characteristics (potential penetration)**

- **E-Gun**
  - $E$ fixed
  - $\Theta = 0$
  - $(x,y)$ varied

- **Spectrometer**
  - $U$ varied

Measure transmission function at various points

---

**Analyzing Plane Potential Structure**

- Measurement
- Monte Carlo Simulation
- Transmission probability

---

Graph showing:
- Potential punch trough in $V$
- Residual in $\sigma$
- Analysis point in $y$-axis (m)

Lower, Center, Upper

M. Erhard
Time-of-flight Measurements

E-Gun: start
- Pulsed
- Position varied

Detector: stop

Spectrometer

Scanning outer region

Simulation

Simulation / Data Comparison

J. Barrett
Potential Background Source: Trapped Particles

MAC-E filter is a magnetic bottle for particles generated inside (w/ large angle)

- Stored particles could be a major background source
  - stay in the vessel for ~min ~hours
  - ionize residual gas, generating low-energy secondary electrons
  - the secondaries reach the detector, just look like signals

Large-angle particles are magnetically reflected

\[ \nabla B \times \vec{B} \text{ and } \vec{E} \times \vec{B} \]
Imaging the Stored Particles

by injecting Ar to increase residual gas (pressure: $10^{-11}$ mbar → $10^{-8}$ mbar)

storage time is reduced,
rate spikes with <200 ms duration

Ring pattern from stored particles is visible
We had known the source: it’s Radon, as always

Pumping Port 3 km of getter material (SAES St 707: Zr-V-Fe)

Cryo-Baffle is installed between NEG and Vessel

Cluster rate and total BG rate, for various Baffle configurations

Fully operational baffle almost completely removes Rn
Unexpected: 0.5 cps Electrons; from where?

Sources are in the volume (not from the wall)

Low-energy electrons (~eV) generated in the volume??

Other observations
• Dependence on temperature, cleanness of vessel wall, and inner-wire E-field
• Not correlated to cosmic muon rates
• 30 keV and 42 keV electrons observed from the vessel wall ($^{210}$Pb EC ??)

Our Best Hypothesis: Rydberg Hydrogen (neutral excited hydrogen atoms)
• Rn progeny $^{210}$Pb are embedded in the vessel wall
• Alpha-decay of $^{210}$Po ($^{210}$Po progeny) somehow excites hydrogen on the wall
• Excited H* atoms (Rydberg Hydrogen) are ionized in volume by black-body radiation
KATRIN “First Light” (Oct 2016)

Electrons traveling “end-to-end”
Final Commissioning in 2017

2017 Commissioning Plans

• Characterization of components, completion of tritium loops
• Test/calibration with gaseous Kr source
• Test with D$_2$ gas, then D$_2$+T$_2$
• Measurement of energy-loss in source with E-Gun

Measurements Started Last Week
Commissioning Measurements March 2017 ~ D$_2$+T$_2$ run by end of 2017

---

28
Scanning Optimization and Spectrum Fitting

Scanning Optimization with Toy MC

Four Parameter Fitting: $m_{\nu}^2, E_0, A_{\text{sig}}, R_{\text{bg}}$

End-point is unconstrained

Design Sensitivity: 200 meV (90% CL) in 3 yr
If the 500 mcps BG cannot be removed

Simple scaling of the design report model

Design Report 2004 (10 mcps)

558 mcps BG
Not optimized
KATRIN Sensitivity in case the BG cannot be removed

Optimization on Scanning Range

![Graph showing the relationship between observed $\beta$ rate in cps and the energy range with background $E_0$.](image1)

Optimization on Flux Volume

- Shrunk flux volume
  - Reduced BG
  - Worse $\Delta E$

Extended Analysis Interval

- More signal
- Less “clean” part

Optimized scanning analysis interval

- $E_0 = 30$ eV
- $E_0 = 45$ eV
- $E_0 = 60$ eV

Sensitivity on $m_\nu$ in meV (90% C.L.)

- $\sim 240$ meV ($\Delta E \sim 2.4$ eV)
Summary and Outlook

KATRIN: Model-Independent Neutrino Mass Measurement

- Only uses beta-decay kinematics
- 100 GBq gaseous tritium + 0.9 eV resolution MAC-E filter
- Design sensitivity 0.2 eV (90%CL) in 3 years

Status

- Main spectrometer commissioned and characterized
- “First light” last month: everything assembled
- Source section commissioning in 2017

FAQ: When will KATRIN start?

In two years → First tritium data in one year
KATRIN Collaboration

- ~130 Collaborators
- 18 Institutions
- 6 Countries
  DE, US, CZ, RU, UK, FR
KATRIN Error Budget
(KATRIN Design Report 2004)

Statistical description of final states
Tritium ion concentration
energy loss in source
column density fluctuation
background slope
HV fluctuation
Source potential variation
Source B-field variation
elastic scattering in source

\[ \times 10^{-3} \sigma(m_{\nu}^2) \quad \text{eV}^2 \]

\[ \sigma_{\text{stat}} < 0.018 \text{ eV}^2 \]
(3 years)

\[ \sigma_{\text{sys}} < 0.017 \text{ eV}^2 \]