Neutrino Mass Limits from Direct Measurements of the Beta-Decay Endpoint

Roger Huang

10/10/2018

Outline

- Neutrino Masses
- Measuring neutrino masses with β-decay endpoint measurements
- The spectrometer-based approach to β-decay endpoint measurements, and current best limits
- The KATRIN experiment

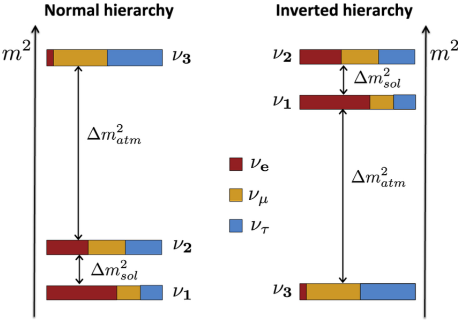
Neutrino Masses

- Observations of neutrino oscillations have confirmed that the neutrino mass eigenstates and flavor eigenstates are not the same

$$|\nu_\ell\rangle = \sum_j U_{\ell j} |\nu_j\rangle$$

$$\ell = e, \mu, \tau, j = 1, 2, 3$$

- 2 of the mass splittings have been measured by neutrino oscillation experiments, but this gives no information about their absolute mass scale



Neutrino Mass Limits

- Searches for neutrino-less double beta decay are sensitive to an effective Majorana mass $m_{\beta\beta} = |\sum_i U_{ei}^2 \cdot m_{\nu_i}|$, but this is related to the mass eigenstates through unknown Majorana phases and requires that neutrinos possess a Majorana nature
  - Current limits at $m_{\beta\beta} < 0.33$ eV (subject to uncertainties in nuclear matrix element calculations)
- Cosmological observations let us set limits on the sum of the masses of the neutrino mass eigenstates, but are also model-dependent
  - Current limits at $\sum m_\nu < 0.59$ eV
- Single β-decay offers a direct, model-independent way to measure the absolute neutrino mass, measuring

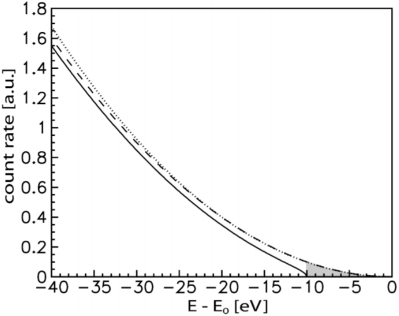
$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

Measuring Neutrino Mass with Beta-Decays

- In single-beta decay, the decay energy Q is almost entirely shared between the β-particle and neutrino

$$(A, Z) \rightarrow (A, Z+1)^{+} + e^{-} + \bar{\nu}_e + Q$$

- A nonzero neutrino mass shifts the endpoint of the β energy spectrum
- Precisely measuring the β energy spectrum lets us set limits on $m(\nu_e)$

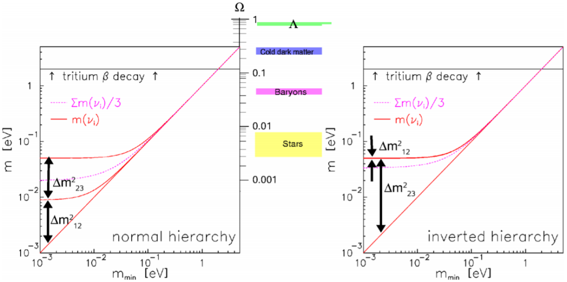


β-spectrum close to the endpoint E_0. Dotted line is for $m(\nu_e) = 0$, solid line for $m(\nu_e) = 10$ eV

Current Limits from Beta-Decay Measurements

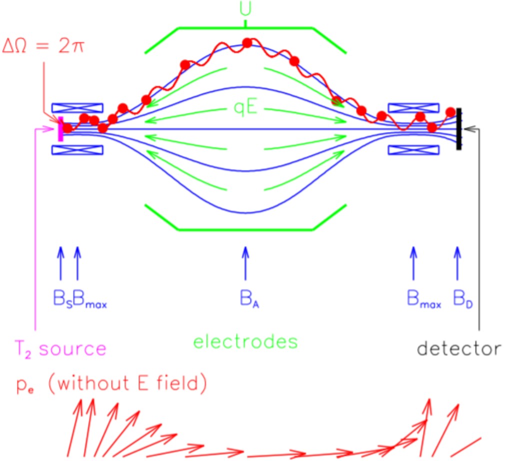
- Primary candidate isotopes for neutrino mass measurements through β-decay are ^{187}Re and tritium
    - ^{187}Re has a very low end-point at 2.47 keV, but low activity due to its half-life of 4.3×10^{10} years (MARE experiment using this isotope in calorimetric approach)
    - Tritium still has a relatively low end-point at 18.6 keV, and high activity due to a half-life of 12.3 years

- Current best limits come from the Mainz and Troitzk experiments, using tritium in a spectrometer-based approach



The MAC-E Filter

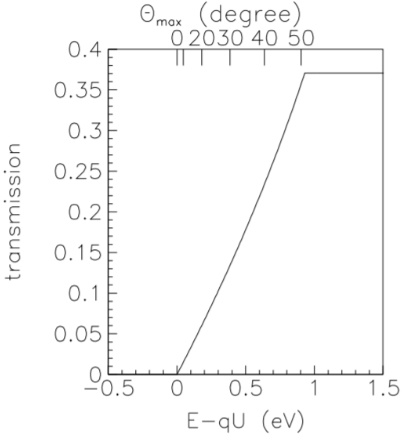
- The MAC-E Filter (Magnetic Adiabatic Collimation with Electrostatic filter) is used in the most sensitive tritium β-decay experiments
- β-particles emitted from the tritium source are guided in cyclotron motion along the magnetic field lines into the spectrometer



The MAC-E Filter

- Smoothly decreasing the magnetic field B towards the center of the spectrometer converts most of the cyclotron energy into longitudinal motion
- An electrostatic barrier applied across the spectrometer then allows only electrons exceeding a certain energy to pass through the spectrometer
- The sharpness of the barrier is given by

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

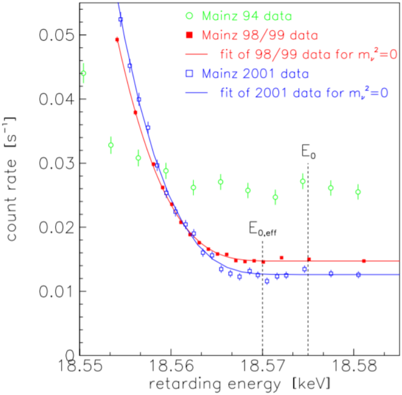


Transmission Function using KATRIN experiment specs

Results Using MAC-E Filters

- The Mainz/Troitsk experiments achieved 4.8 eV/3.5 eV energy resolution at the decay endpoint of 18.6 keV
- The β-spectrum is measured by varying the electrostatic barrier potential and counting βs that reach the detector
- Best fit to Mainz results

$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\ \mathrm{eV}^2$$

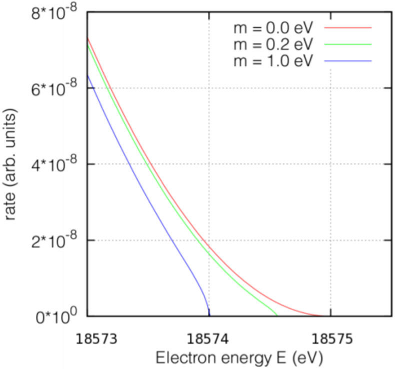


Results from Mainz Experiment

The KATRIN Experiment

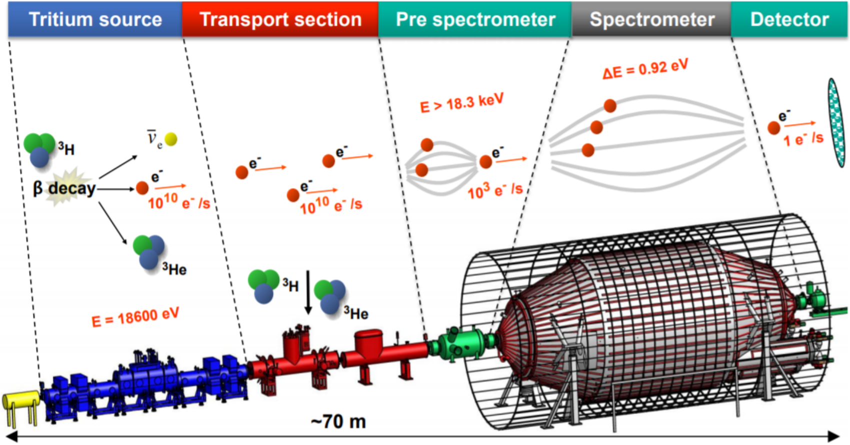
The KATRIN Experiment

- KATRIN (KArlsruhe TRItium Neutrino experiment) uses the same MAC-E filter principles but aims to improve the $m(\nu_e)$ sensitivity by a factor of 10, reaching 200 meV
- This requires increased source strength and measurement time, better energy resolution, low backgrounds, and decreased systematic uncertainties



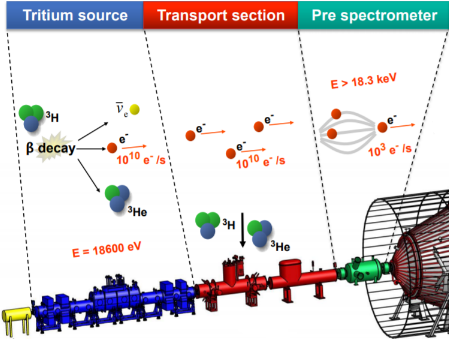
Tritium β-endpoints for different $m(\nu_e)$

The KATRIN Setup



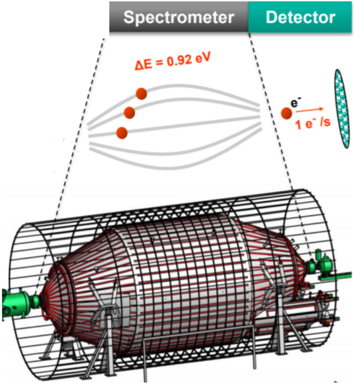
KATRIN - Tritium Source and Pre-Spectrometer

- Design luminosity of 1.7×10^{11} Bq, requiring $5 \times 10^{19}\, T_2$ molecules injected per second at $T = 30$ K, pressure at 10^{-3} mbar
- $B = 3.6$ T in source, $B = 5.6$ T in transport section to guide the electrons
- Pre-spectrometer has 100 eV resolution and can cut out electrons more than 300 eV beneath the decay endpoint



KATRIN - Main Spectrometer

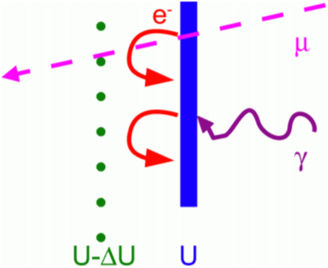
- Main spectrometer achieves 0.93 eV resolution for 18.6 keV electrons with a magnetic field ratio of 1/20000
    - Conservation of magnetic flux combined with this magnetic field ratio is the reason for the massive spectrometer size (23.8 m long, 9.8 m diameter)
- The detector is a Si-PIN diode with 1 keV resolution, divided into 148 pixels for good spatial resolution, which is used to deal with radial inhomogeneity of the electric potential in the spectrometer



KATRIN Backgrounds

- Backgrounds need to be kept to the 10^{-3} cps level
- Dominant background is from low-energy secondary electrons created near the high-potential electrodes by cosmic muons or background radioactivity
- The magnetic field inside the tube provides natural shielding that deflects most of these electrons, allowing $10^{-5} - 10^{-7}$ transmission rate

- 2 layers of nearly massless wire electrodes are placed along the vessel walls to block these remaining electrons with an electrostatic barrier



KATRIN Systematics

Systematic Uncertainty	Countermeasures
Inelastic scattering of β-particles inside the T_2 source	Energy-loss measurements done with an e-gun
Fluctuations in T_2 column density in windowless gaseous source	Temperature and pressure control of source at 10^{-3} level, laser Raman spectroscopy
Spatial inhomogeneity of transmission function	Measurements with e-gun or ^{83m}Kr source
Stability of retardation voltage	Measured to 10^{-6} precision

Summary

- Precise measurement of the β spectrum endpoint in single-β decay is a direct, model-independent method of probing the absolute neutrino mass scale
- Current best limits come from measuring tritium β-decay using MAC-E filters:

$$m(\nu_e) < 2 \text{ eV at } 95\% \text{ CL}$$

- The KATRIN experiment has taken this technology to the extreme, and was inaugurated on June 11, 2018
- KATRIN aims to push this limit to $m(\nu_e) < 0.2$ eV with 3 years of data

References

1. Neutrino mass limit from tritium β-decay. arxiv:0909.2104
2. Introduction to direct neutrino mass measurements and KATRIN. arxiv:1012.2282
3. Current Direct Neutrino Mass Experiments. arxiv:1307.0101
4. Neutrino mass sensitivity by MAC-E-Filters. arxiv:1308.0532
5. PDG Review