Measuring the Mass Scale of Neutrinos

J.A. Formaggio
Massachusetts Institute of Technology
The phenomena of neutrino oscillations is now firmly established.
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**Reactor & Long Baseline**

\[ \sin^2(\theta_{13}) = 0.0241 \pm 0.0025 \]

\[ \Delta m_{12}^2 = (7.54 \pm 0.26) \times 10^{-5} \text{ eV}^2 \]

**Solar**

\[ \sin^2(\theta_{12}) = 0.307 \pm 0.016 \]

\[ \Delta m_{23}^2 = (2.43 \pm 0.09) \times 10^{-3} \text{ eV}^2 \]

**Atmospheric**

\[ \sin^2(\theta_{23}) = 0.386 \pm 0.022 \]


More Questions

What We Don’t Know

1. What is the absolute scale of neutrinos?
2. What is the mass hierarchy?
3. What is the nature of neutrino mass?

![Diagram of neutrino mass spectrum with bounds from MAINZ and TROITSK.](image)
More Questions

**What We Don’t Know**

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What We Don’t Know

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3. What is the nature of neutrino mass?

Diagram showing the mass hierarchy with labels for normal and inverted cases.
More Questions

What We Don’t Know

(1) What is the absolute scale of neutrinos?

(2) What is the mass hierarchy?

(3) What is the nature of neutrino mass?
Neutrino Masses from Cosmology

- Cosmology looks at the sum of neutrino masses (gravitational effect)

\[ \Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_{i}^{n_{\nu}} m_{\nu,i}}{\rho_{\text{critical}}} \]
The Strategy
(a naive view)

WMAP Temperature Map

CMB, Polarization

Surveys (galaxy, weak)

Lyman $\alpha$

CMB Polarization

Galaxy Surveys

Weak lensing

Max Tegmark, 2005
Current Limits

- Limits for neutrino masses depend in part on:
  - Which data is used, and...
  - ...what assumptions are made.

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Komatsu et al. 2010
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Komatsu et al 2010

Gonzales-Garcia
arXiv: 1006.3795 v2
(and many others)
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v2

(and many others)
Planck alone can push neutrino limits down 1 eV.

Host of new experiments coming to the forefront can push even lower.
Moving Forward...

As precision demands moves to 1%, non-linear effects, degeneracies, baryons, etc. all begin to play a role.

Numerical simulations and semi-analytical techniques used to address.

Moving to the normal hierarchy scale now requires 1% precision on the power spectrum.

\[ \frac{\Delta P}{P} \approx -12 \frac{\Omega_\nu}{\Omega_m} \approx 1\% \]
Direct Probes

If massive, the neutrino takes away some energy...

\[ ^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \nu_e \]

...from the electron (which we detect)

Beta decay allows a kinematic determination of the neutrino mass

No dependence on cosmological models or matrix elements
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\[ m_\beta = \sqrt{\sum_{i=1}^{n_\nu} |U_{ei}|^2 m_i^2} \]
KATRIN is currently the prominent experiment for beta decay measurements.

New techniques being explored in the future:

MARE and Project 8
MAC-E Filter Technique

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

**Spectroscopic: MAC-E Filter**

Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution \((\Delta E/E = B_{\text{min}}/B_{\text{max}} = 0.93 \text{ eV})\)
The KATRIN Experiment

Tritium Beta Decay

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \nu_e \]

Electron Beta Decay Spectrum

Tritium retention system

\[ 10^{10} \text{ e}^-/s \]

Pre & Main spectrometers

\[ 10^3 \text{ e}^-/s \]

Detector

\[ 1 \text{ e}^-/s \]

Windowless Gaseous Tritium Source

\[ 5 \times 10^{19} \text{T}_2/s \]
The Windowless Gaseous Tritium Source (WGTS)

• Gaseous tritium source provides source of beta-decay electrons.

• Use of injection + differential pumping to provide well-controlled gas column density.

• In-situ monitoring of purity of gas via laser Raman spectroscopy.

**T$_2$ Specifications**

- Tritium activity: $1.7 \times 10^{11}$ Bq
- Tritium throughput: 40 g T$_2$/day
- Temp. stability: $\pm 0.03$ mK @ 30K
- Electron flux: $10^{11}$ β/s
- Column Density: $5 \times 10^{17}$ cm$^{-2}$
Recent milestone:
Demonstrator achieves $30 \pm 0.03$ K neon stability
Order of magnitude improvement

Solenoid testing

Beam alignment ($< 0.5$ mm)

Tritium Source

Transport & Pumping

Main Spectrometer

Detector
Recent milestone:

Main solenoids pass stress tests.
The Main Spectrometer

Inner wire electrodes installed for rejection of low energy particles produced from cosmic rays.

Combination of precision high voltage and low magnetic field with correction air coils.

Inherent resolution of $\Delta E = 0.93$ eV.
Recent milestones:
Air coils fully installed.
Inner wire electrodes installed.
Vessel sealed and undergoing vacuum tests.
Recent milestone:

Final pump port closed and sealed as of May 2012
Excellent progress in the simulation of the experiment on this scale.
The Detector

Final electron detection occurs on a segmented silicon detector (148 pixels for spatial resolution).

Two high-field magnets provide final focusing of tritium decay electrons onto detector.

Multiple background reduction techniques (veto, material selection, etc.) employed.
Recent milestones:

- Detector installed at KIT
- Undergoing final commissioning in conjunction with main spectrometer.
Projected Sensitivity

\[ \Delta m_{\beta,\text{stat}}^2 = 0.018 \text{ eV}^2 \]

Assumes 3 yr running

\[ \Delta m_{\beta,\text{sys}}^2 = 0.017 \text{ eV}^2 \]

Major systematics include source purity, HV stability, source stability and T2 final states

Neutrino Mass Goals

- Discovery: 350 meV (at 5\(\sigma\))
- Sensitivity: 200 meV (at 90% C.L.)

Commence Tritium Running in 2015
Can we push further?

- KATRIN will achieve 200 meV scale. Can direct measurements push lower to the normal hierarchy scale?

- Any future experiment needs to be able to (a) have a better scaling law for increased target mass and (b) improve its energy resolution.

**KATRIN Sensitivity**

![Diagram](image.png)

10 meters across

$10^{-11}$ mbar vacuum
Bolometric:

MARE

\[ ^{187}\text{Re} \rightarrow ^{187}\text{Os} + e^- + \bar{\nu}_e \]

Advantages:
- No backscattering
- No atomic or molecular final state effects.

Disadvantages:
- Extremely long half-life.
- Pileup backgrounds.

Uses \(^{187}\text{Re}\) as its beta source (one of the lowest endpoints, 2.3 keV)

Cryogenic setup in Milan
MARE & ECHO

Bolometric:

- **New Technology:**
  - Use of magnetic micro calorimeters. Minimize rise time and energy resolution.
  - MKID devices (1-10 GHz) resonating superconductors.
  - Reduces pileup, increases pixelation and energy resolution

- **New Isotopes:**
  - Also exploring $^{183}$Ho electron capture

\[ ^{187}\text{Re} \rightarrow ^{187}\text{Os} + e^- + \bar{\nu}_e \]

\[ ^{183}\text{Ho} + e^- \rightarrow ^{163}\text{Dy} + \nu_e \]

R&D to lead to eV sensitivity
Project 8

I. I. Rabi

A. L. Schawlow

“Never measure anything but frequency.”

B. Monreal and J. Formaggio, Phys. Rev D80:051301

- Use cyclotron frequency to extract electron energy.

\[
\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}
\]

- Non-destructive measurement of electron energy.

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

B. Monreal and J. Formaggio, Phys. Rev D80:051301
**The Concept**

- Coherent radiation emitted can be collected and used to measure the energy of the electron in a non-destructive manner.

\[
\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}
\]

**Radiative Power Emitted**

\[
P_{\text{tot}}(\beta_\parallel, \beta) = \frac{1}{4\pi\epsilon_0} \frac{2e^2\omega_0^2}{3c} \frac{\beta^2_\parallel}{1 - \beta^2}
\]

- Uniform B field
- Low pressure $T_2$ gas.
- Antenna array for cyclotron radiation detection.

B. Monreal and J. Formaggio
The Tritium Spectrum

- Look at a simulated tritium spectrum watched by a synthetic array (evenly spaced antennas over 10 meter uniform field).

- Low energy electrons dominate at higher frequencies.

- Rare, high energy electrons give a clean signature near endpoint.
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100,000 tritium decays in 30μs
Project 8
Collaboration

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University of Washington, Center for Experimental Nuclear Physics and Astrophysics

D.M. Asner, J. Fernandes, A.M. Jones, J.F. Kelly, B.A. VanDevender
Pacific Northwest National Lab
Prototype Status

Monolithic assembly inserted into 2-in diameter vertical bore of 1T s.c. magnet.

Source gas flows directly through waveguide fiducial volume.

Cyclotron power transported in both directions to low-noise 30 GHz amplifiers loaned by NRAO.

Signal mixed down to lower frequency (250 MHz bandwidth) and fully digitized.
Magnetic Trapping

Magnetic bottle
1 T field (27 GHz)

Trapping coil

Trapping field

Use 0.93 Tesla field, where signal occurs at ~26 GHz with quadrupole trapping coil.

System monitors field in-situ using DPPH ESR monitoring.

Overall stability of prototype $\frac{\Delta B}{B} \sim 1 \times 10^{-5}$

$\Delta E = 1 \text{eV} \Rightarrow \frac{\Delta f}{f} = 2 \times 10^{-6} \Rightarrow t_{\text{min}} = 30 \mu\text{s}$

Implies path length ~km. Trapping will be needed.
Environmental Interference (now eliminated)

Tickler

split-ring resonator

$f_0 = 2.07 \, \text{GHz}, \, Q \sim 10^4$

Upcoming Plans

Did first test run in Sep 2011, a more intense run set for later this fall.

System with greater monitoring of vacuum, temperature, and calibration of fields.

In future, also exploring tuned RF cavities, at weaker fields and larger volumes for tritium running.
Moving Beyond the Inverted Scale

- Most effective tritium source achieved so far involves the use of gaseous molecular tritium.

- Method will eventually hit a resolution “wall” which is dictated by the roto-vibrational states of $T_2$. This places a resolution limit of 0.36 eV.

- One needs to either switch to (extremely pure) atomic tritium or other isotope with equivalent yield.

- High intensity sources of tritium might be achievable using similar techniques as employed in H/D production.

- Main challenge is achieving the purity and transport of atomic tritium. Requires heavy R&D.

---

Electronic excitation of $^3\text{HeT}^+$ (43%)

![Spectrum of rot-vib-excitations in electronic ground state (57%)](image)

Spectrum of rot-vib-excitations in electronic ground state (57%)
Jerzierski B et al., 1985 Phys. Rev. A 32 2573

$T_2$ source

1.7 eV

2$\sigma \approx 0.7$ eV

FIG. 1. Probability histogram for transitions to the first (ground) electronic state of the $^3\text{HeT}^+$ molecular ion. The energy “zero” is the energy of the ground-state He atom and the $T^+$ nucleus at infinity. This energy is 1.89742 eV above the ground rovibronic state of $^3\text{HeT}^+$. 

---

ortho-hydrogen

para-hydrogen
The next generation of beta decay experiments will provide greater sensitivity to the neutrino mass scale. **KATRIN** is the current next-generation experiment designed to reach this level of sensitivity. Future experiments, such as **Project 8, MARE and ECHO**, are also being developed using calorimetric and frequency techniques.
Thank you for your attention
Upcoming Data

• Planck alone can push neutrino limits down 1 eV.

• Host of new experiments coming to the forefront.
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KATRIN sensitivity goal requires 60 mV precision at 18.6 kV.

System monitored with high precision HV divider (10^{-6} stability).

In-situ monitoring of $^{83m}$Kr line using refurbished Mainz spectrometer.

**Recent milestones:**

- Monitor spectrometer installed.
- HV stabilization $\sim x3$ better than specification.
**Main Spectrometer**

E = 18.4-18.6 keV  
ΔE = 0.93 eV  
24 m long, 10 m wide vacuum region.  
Precision MAC-E filter.

---

**Pre-Spectrometer**

E = 18.3 keV  
ΔE = 80 eV  
Filters most low energy electrons from beta spectrum
Next Steps

• Continue prototype tests:
  - Next $^{83m}$Kr run scheduled in 2 weeks.
  - Provide measurement of Kr line width.
  - Insert small amount of tritium as test

• Continue study of resonant cavities for enhanced detection.

• Begin “scalable design” for few eV precision mass measurement.

• Proposal for large experiment, for 2014.

$\sim 40 \mu$Ci of $T_2$ (KATRIN is $\sim 3$ Ci)