Experimental Paths in Neutrino Mass Measurements

Fundamental Symmetries & Neutrinos
NSAC Chicago Meeting

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MIT
Neutrino mass measurements have a long history in physics, predating the Standard Model itself.

It should therefore be no surprise that our quest to understand this fundamental property continues; both for its own right as well as its theoretical implications.
With oscillations firmly in place, we at least understand that the neutrino has a mass.

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Reactor & Long Baseline

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

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

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

Solar

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

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

Atmospheric

Measuring Neutrino Masses

\[ M = \sum_{i} m_{\nu,i} \]

Cosmological Measurements

\[ \langle m_{\beta\beta}^{2} \rangle = \left| \sum_{i} U_{ei}^{2} m_{\nu,i} \right|^{2} \]

0νββ Measurements

\[ \langle m_{\beta}^{2} \rangle = \sum_{i} \left| U_{ei} \right|^{2} m_{\nu,i}^{2} \]

Beta Decay Measurements
The Neutrino Mass Scale

- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.

- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.
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<td>m_3 &gt; 2 eV (eV scale, current)</td>
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Ruled out by β-decay experiments

Neutrinos ruled out as dark matter
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$m_\nu > 2 \text{ eV (eV scale, current)}$

Neutrinos ruled out as dark matter

$m_\nu > 0.2 \text{ eV (degeneracy scale)}$

Impact on cosmology and $0\nu\beta\beta$ reach
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<td>$m_\nu &gt; 0.01$ eV (normal hierarchy)</td>
<td>Oscillation limit; possible $C\nu B$ detection</td>
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Direct Probes

Beta Decay

A kinematic determination of the neutrino mass
No model dependence on cosmology or nature of mass
Direct Probes

Electron Energy

\[ \dot{N} \sim p_e (K_e + m_e) \sum_i |U_{ei}|^2 \sqrt{E_0^2 - m_{\nu_i}^2} \]

Beta Decay

A kinematic determination of the neutrino mass
No model dependence on cosmology or nature of mass
Techniques for the 21st Century

**Spectroscopy (KATRIN)**

Magnetic Adiabatic Collimation with Electrostatic Filtering

State-of-the-Art technique

\[ T_2 \rightarrow (T \cdot {^3\text{He}}^+) + e^- + \bar{\nu}_e \]

**Calorimetry (HOLMES, ECHO & NUMECS)**

Technique highly advanced.

New experiment(s) planned to reach \( \sim \text{eV} \) scale.

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

**Frequency (Project 8)**

Radio-frequency spectroscopy for beta decay

R&D phase (new results)

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

Spectroscopic: MAC-E Filter

Inhomogeneous magnetic guiding field.
Retarding potential acts as high-pass filter
High energy resolution

\[ \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} = 0.93 \text{ eV} \]

KATRIN

\[ T_2 \rightarrow (T \cdot ^3\text{He}^+) + e^- + \bar{\nu}_e \]

adiabatic transformation of e\(^-\) momentum

Inhomogeneous magnetic guiding field.
Retarding potential acts as high-pass filter

\[ (T \cdot ^3\text{He}^+) + e^- + \bar{\nu}_e \]
Adiabatic transport ensures high retention of phase space for decay

\[ \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \rightarrow 0.93 \text{ eV} \]

Energy resolution scales as the ratio of minimum / maximum fields
The KATRIN Setup

10^{11} \text{ Bq “Windowless” gaseous T}_2 \text{ Source (High field)}

Adiabatic transport ensures high retention of phase space for decay

\[ \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \to 0.93 \text{ eV} \]

Energy resolution scales as the ratio of minimum / maximum fields
The KATRIN Setup

10^{11} Bq “Windowless”
gaseous T_2 Source

(High field)

Tritium retention system
(10^7 tritium flow reduction)

10^{11} e^- / second

1 e^- / second

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The KATRIN Setup

10^{11} Bq “Windowless” gaseous T_{2} Source

10^{11} e^{-} / second

(High field)

Tritium retention system
(10^{7} tritium flow reduction)

High resolution electrostatic filter
(3G low field)

Detector System (High Field)

Adiabatic transport ensures high retention of phase space for decay

\[ \Delta E \bigg/ E = \frac{B_{\text{min}}}{B_{\text{max}}} \rightarrow 0.93 \text{ eV} \]

Energy resolution scales as the ratio of minimum / maximum fields
WGTS Demonstrator

Provides \( \sim 2 \times 10^{11} \) Bq of activity (with tritium activity extruded from system).

- Monitoring of tritium purity, pressure & temperature.
- Temperature stability of \( \pm 3.6 \text{ mK} \) recently achieved (x10 better than specification).
A 10 m diameter analyzing spectrometer with 1:2000 energy resolution (0.93 eV)

- Extremely stable high voltage of main vessel.
- Few ~ppm precision divider and monitoring spectrometer.
Summer 2013 saw “first light” from the KATRIN. Spectrometer and detector system fully integrated. Allowed for test of transmission function and background levels.
Commissioning showed excellent behavior of MAC-E Filter response.  
Next commissioning (now) should show greater background suppression. 

At -18.6 keV, better than 100 meV resolution
Sharpest transmission function for a MAC-E filter

Background rate of order Hz (radon-dominated)
Greater reduction of backgrounds to come
Projected Sensitivity

Neutrino Mass Goals

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

Data taking to commence in 2016.
Can we push further?

- Can direct measurements push to the inverted hierarchy scale?
- To do so, they must have better scaling law.

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**KATRIN Sensitivity**

- $\Delta m^2_{31} < 0$
- $\Delta m^2_{32} > 0$
- 99% CL (1 dof)

Source column density at max

Rovibrational states of THe$^+$

- $\sigma(m_\nu)^2 \sim 0.38 \text{ eV}^2$

10 meters across

$10^{-11}$ mbar vacuum
In principle, it is possible to improve the statistical sensitivity of KATRIN by combining its energy resolution with a time-of-flight measurement.

By tagging the electron as it travels to the detector.

The improvement is substantial, over a factor of 5-6 in the statistical sensitivity. However, no realistic method to tag the electron in the KATRIN experiment appears possible.

A gated pulse is possible, but yields equivalent statistical sensitivity.
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New kid on the block: Electron Capture

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

\[ {^{163}\text{Dy}^*} \rightarrow {^{163}\text{Dy}} + \text{E.C.} \]
New kid on the block: Electron Capture
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Advantages & Challenges

**Calorimetry**

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

- Advantages:
  - Source = detector
  - No backscattering
  - No molecular final state effects.
  - Self-calibrating

- Source Activity
  - \( N_{ev} > 10^{14} \) to reach sub-eV level

- Detector Response
  - \( \Delta E_{\text{FWHM}} < 10 \text{ eV} \)
  - \( \tau_{\text{risetime}} < 1 \mu\text{s} \)

**Experimental Challenges:**

- Fast rise times to avoid pile-up effects.
- Good energy resolution & linearity
- Sufficient isotope production
Advantages & Challenges

Calorimetry

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$\Delta E_{\text{FWHM}} < 10 \text{ eV}$
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The ECHo Experiment

Metallic Magnetic Calorimeters

- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at $2.80 \pm 0.08$ keV.
The HOLMES Experiment

Technologies:

- Transition Edge Sensors
- Superconducting Resonators

MARE-HOLMES

- MARE (Phase I) explored various technology approaches, such as Transition-Edge Sensors (TES) and Microwave Kinetic Inductance Detectors (MKIDs).
- Successful extraction of Ho$^+$ ions for metal production and implantation onto detectors.
- Successful funding received for one thousand channel Ho detector experiment (the HOLMES experiment).
The NuMECS Experiment

Technologies:

- Transition Edge Sensors
- Superconducting Resonators

- New effort in the US (Los Alamos) for using transition-edge sensor technology for electron capture characterization.

- Concentration on high purity $^{163}$Ho production via FRIB. Recent high purity production at the 0.1 mg level and energy resolution (6 eV @ 6 keV with $^{55}$Fe surrogate).

See position paper (link here) for details.
The NuMECS Experiment

Technologies:

- Transition Edge Sensors
- Superconducting Resonators

NuMECS (Next 5 years)

Example spectrum in target energy range for $^{163}\text{Ho}$ ECS

- Critically assess entire electron capture method and validate all component technologies.
- Show scalability through a demonstrator experiment with $4 \times 10^24$ TES array of Ho-implanted detectors with RF-SQUID multiplexing.
- Aim mass sensitivity of demonstrator to $\sim 1$ eV scale.

See position paper [link here] for details.
Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

"Never measure anything but frequency."

I. I. Rabi

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

- Use cyclotron frequency to extract electron energy.
- Non-destructive measurement of electron energy.

B. Monreal and JAF, Phys. Rev D80:051301

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

- **Source = Detector**
  (no need to extract the electrons from the tritium)

- **Frequency Measurement**
  (can pin electron energies to well-known frequency standards)

- **Full Spectrum Sampling**
  (full spectrum measured at once, large leverage for stability and statistics)

Simulation of beta (frequency) spectrum

100,000 tritium decays in 30μs
Initial Demonstration: $^{83m}$Kr

Phase I: Use mono-energetic source to determine single electron detection.

Use of standard gaseous $^{83m}$Kr source allows quantification of energy resolution and linearity.
The Apparatus

Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

Magnetic bottle allows for trapping of electron within cell for measurement.
First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.
First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.
Cyclotron Radiation Emission Spectroscopy (CRES) allows extraction of many details from trapped electrons (energy, resolution, confinement time, etc.)

Reduces to an image analysis for event characterization.
Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)
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Moving Beyond the Degeneracy 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 rotational-vibrational states of T₂. 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.
- The trapping conditions necessary for electrons also lends itself for atomic trapping of atomic tritium (R. G. H. Robertson)

Inherent 0.36 eV final state smearing
Projected Sensitivity (Molecular & Atomic)

Systematics include final state interactions, thermal broadening, statistical uncertainties, and scattering.

See position paper (link here) for details.
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Degeneracy and Beyond...

**Spectroscopy (KATRIN)**

Technique PROVEN. State-of-the-art.

Experiment soon to commence with 0.2 eV reach.

Integral measurement with TOF possibility.

\[ T_2 \rightarrow (T \cdot ^3\text{He}^+) + e^- + \bar{\nu}_e \]

**Calorimetry (HOLMES, ECHO & NuMECS)**

Technique advanced.

New experiment(s) planned to reach ~1 eV scale.

Statistics & systematics next hurdle.

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

**Frequency (Project 8)**

Technique DEMONSTRATED.

Potential of scalability and exploring atomic sources to inverted scale.

Next to establish the scalability of the technique.

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