Year One:

Direct Neutrino Masses post PLANCK

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Year One:
Direct Neutrino Masses post PLANCK
The phenomena of neutrino oscillations is now firmly established.
Precision measurements now exist on all three mixing angles to date. As such, oscillation measurements place a lower limit on the neutrino mass scale.

**Reactors & 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

Neutrino oscillations have placed a lower bound on neutrino masses that can be experimentally accessed.

Lower bound depends on hierarchy of neutrinos (inverted or normal)

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

Cosmological Measurements

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

0νββ Measurements

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

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.

**Lightest Neutrino Mass (eV)**

- $m_\nu > 2 \text{ eV (eV scale, current)}$
  - Ruled out by $\beta$-decay experiments
  - Neutrinos ruled out as dark matter

- $m_\nu > 0.2 \text{ eV (degeneracy scale)}$
  - Impact on cosmology and $0\nu\beta\beta$ reach

- $m_\nu > 0.05 \text{ eV (inverted hierarchy)}$
  - Resolve hierarchy if null result

- $m_\nu > 0.01 \text{ eV (normal hierarchy)}$
  - Oscillation limit; possible CMB detection
Cosmology has had a similar trajectory as neutrino physics, from inception to present day.
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Neutrino Physics & Cosmology

- Two primary cosmology measurements that link directly to neutrino physics:

  1. Number of neutrino species
  2. Sum of neutrino masses

- Both large scale structure (LSS) and CMB anisotropies (CMB), particularly CMB gravitational lensing, can be used to measure these quantities.

\[
\Omega_R h^2 = \left[ 1 + N_{\text{eff}} \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \right] \Omega \gamma h^2
\]

\[
\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \sum_i^n \frac{m_{\nu,i}}{\rho_{\text{critical}}}
\]
Planck Satellite:
Launched May 14th, 2009
The Microwave sky...
**PLANCK Results**

- The basic PLANCK analysis looks at 6 main cosmological parameters. Neutrino masses are added as extensions to that model.

- Most conservative data combinations see no evidence for neutrino masses.

- Certainly tension exists with certain parameters (SZ clusters, Hubble constant, etc.) that alter the fits or in some cases favor finite masses.

<table>
<thead>
<tr>
<th>Fit</th>
<th>$\Sigma m_\nu$ (95% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck + WP + HighL</td>
<td>$&lt; 0.66$ eV</td>
</tr>
<tr>
<td>Planck + WP + HighL + BAO</td>
<td>$&lt; 0.23$ eV</td>
</tr>
<tr>
<td>Planck + SZ + BAO</td>
<td>$0.22 \pm 0.09$ eV</td>
</tr>
</tbody>
</table>
Moving Forward...

- Current cosmological limits are starting to push at the degeneracy-inverted scale.

- Future experiments (CMB-IV) could push all the way down to the normal scale.

- Model dependencies and degeneracies will still persist.

\[
\frac{\Delta P}{P} \simeq -12 \frac{\Omega_\nu}{\Omega_m} \simeq 1\%
\]

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

**Nonlinearities**

**Degeneracies**
Direct Probes

Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass
KATRIN is currently the prominent experiment for beta decay measurements.

New techniques being explored in the future:

ECHO, MARE-HOLMES and Project 8
**MAC-E Filter Technique**

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

**Spectroscopic: MAC-E Filter**

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

High energy resolution

\[ \Delta E/E = \frac{B_{\text{min}}}{B_{\text{max}}} = 0.93 \text{ eV} \]
Windowless Gaseous Tritium Source

Rear Calibration System

Tritium retention system $10^{10}$ e$^-$/s

WGTS:

- Injected tritium source with ~few Curie activity.
- Extremely stable pressure/temperature

Tritium Retention System:

- Designed to reduce tritium flow by $10^{14}$
Windowless Gaseous Tritium Source
$5 \times 10^{19}$ T$_2$/s

Rear Calibration System

Tritium retention system
$10^{10}$ e$^-$/s

Pre & Main spectrometers
$10^3$ e$^-$/s

Detector
1 e$^-$/s

Spectrometers:
- 1 eV resolution transmission function.
- Inner wire electrodes for background reduction.
- Coils to shape low field region.

Detector:
- Position-dependent beta detector.
Windowless Gaseous Tritium Source
\(5 \times 10^{19} \text{ T}_2/\text{s}\)

Rear Calibration System

Tritium retention system
\(10^{10} \text{ e}^-/\text{s}\)

Pre & Main spectrometers
\(10^3 \text{ e}^-/\text{s}\)

Detector
\(1 \text{ e}^-/\text{s}\)
Provides ~ $2 \times 10^{11}$ Bq of activity (with tritium activity extruded from system).

- Monitoring of tritium purity, pressure & temperature.
- Temperature stability of ±3.6 mK recently achieved (x10 better than specification).
Recent milestone:

Main solenoids pass stress tests.
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.
Recent milestone:

Final pump port closed and sealed.
The very last view into the spectrometer
“First Light”

First time pre-spectrometer, main spectrometer, and detector are all connected.

First electrons in this combined system now recorded.

Background at 1 Hz, appears to be radon-dominated.

Will be reduced when cold baffles & screening potential are applied.

Commissioning program of the main spectrometer well underway!
Projected Sensitivity

**Neutrino Mass Goals**

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

**Partial Loading in 2014.**

**Full Tritium Running in 2015**

- Statistical
- Final-state spectrum
- T^- ions in T_2 gas
- Unfolding energy loss
- Column density
- Background slope
- HV variation
- Potential variation in source
- B-field variation in source
- Elastic scattering in T_2 gas
Can we push further?

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

\[ 10 \text{ meters across} \]
\[ 10^{-11} \text{ mbar vacuum} \]
Calorimetric Techniques

The use of low temperature calorimetry for beta decay has focused on isotopes with the lowest endpoint energy.

Particularly, $^{187}$Re as beta source (one of the lowest endpoints, 2.3 keV).

More recently, $^{163}$Ho electron capture (De Rujula and Lusignoli, 1982) has been the subject of R&D over the past several years.

$^{187}$Re $\rightarrow$ $^{187}$Os + $e^-$ + $\bar{\nu}_e$

$m_\nu < 15.2 \pm 2.0$ eV (90 % C.L.)

\[ \dot{N} \sim (Q_{EC} - E_C)^2 \sum_i |U_{ei}|^2 \sqrt{1 - \frac{m_{\nu i}^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \psi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_{EC} - E_H)^2 + \frac{\Gamma_H^2}{4}} \]

New kid on the block: Electron Capture
Advantages & Challenges

Isotopes of Interest:

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

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

Source Activity

\[ N_{ev} > 10^{14} \text{ to reach sub-eV level} \]

Detector Response

\[ \Delta E_{FWHM} < 10 \text{ eV} \]
\[ \tau_{\text{risetime}} < 1 \mu s \]

Experimental Challenges:
- Fast rise times to avoid pile-up effects.
- Good energy resolution & linearity
- Abundant isotope production
The ECHo Experiment

Technology:

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 ECHo Experiment

Technology:

- Metallic Magnetic Calorimeters

Future Steps

- Collaboration moving toward multi-pixel experiments to increase sensitivity.
- Studies of solid state effects and further investigation of holmium endpoint.
The HOLMES Experiment

Technologies:

Superconducting Resonators

Transition Edge Sensors

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).
Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

Project 8

Never measure anything but frequency.

I. I. Rabi

A. L. Schawlow

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

• Use cyclotron frequency to extract electron energy.

• Non-destructive measurement of electron energy.

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

Frequency Approach

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

- **Source = Detector**
  (no need to separate 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)
A Phased Approach

Initial Demonstration Source: $^{83m}$Kr

Collaboration taking a phased approach to understand scaling and systematics of the experiment.

First phase (single electron detection) underway.

Design for second stage well under way.
Status of Phase I (Single Electron Detection)

Main Superconducting Magnet
1 T field (27 GHz)

~100 G Trapping coil

Magnet Cooldown

Using 0.93 Tesla field, where signal occurs at ~26 GHz with trapping coil
About 0.5 fW of radiated power.

Waveguides designed for 26 GHz signal with low noise amplifiers and full digitization

First data in January with rather large (~150 K) temperatures as initial test of system.
Status of Phase I (Single Electron Detection)

Using 0.93 Tesla field, where signal occurs at ~26 GHz with trapping coil
About 0.5 fW of radiated power.

Waveguides designed for 26 GHz signal with low noise amplifiers and full digitization

First data in January with rather large (~150 K) temperatures as initial test of system.
**Status of Phase I (Single Electron Detection)**

New run will improve the noise temperature down to $\sim 35K$.

System undergoing commissioning now.

Analysis & simulation show signal efficiency of $>90\%$ for electrons down
Sensitivity of $< 0.1 \text{ fW}$ and $>50 \mu s$ trapping time.

Use electron spin resonance (ESR) for in-situ calibration of magnetic field.

<table>
<thead>
<tr>
<th>System</th>
<th>Specification</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field</td>
<td>1 T Field</td>
<td>$&lt; \text{ few } 10^{-5}$ DPPH Monitoring</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$ accuracy</td>
<td></td>
</tr>
<tr>
<td>Gas System</td>
<td>$10^{-6}$ Torr</td>
<td>$&lt; 10^{-7}$ Torr PIPS detector</td>
</tr>
<tr>
<td>Noise Temperature</td>
<td>$T_{\text{sys}}&lt; 50 \text{ K}$</td>
<td>$T_{\text{sys}} \sim 35 \text{ K}$</td>
</tr>
<tr>
<td>Sensitivity Analysis</td>
<td>SNR $&gt; 12$ for $0.4 \text{ fW}$ signal</td>
<td>SNR $&gt; 10 \text{ dB}$ for $0.5 \text{ fW}$ @ room temp.</td>
</tr>
</tbody>
</table>
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 $T_2$. 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.

- 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)

Sensitivity for both molecular and atomic tritium are shown.

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

Can calibrate against frequency standards.
It is rare in our field that two systems are completely orthogonal except for only a few key quantities.

Direct probes may provide a robust test of cosmology (and vice-versa).

Disagreement on a signal would point to new physics; agreement would be an outstanding triumph.

It should truly be an exciting decade!
Thank you for your attention
Special thanks to Loredana Gastaldo, Flavio Gatti, Angelo Nunciotti, Klaus Blaum, Guido Drexl, and my Project X and KATRIN collaborators.