Weighing Neutrinos

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What we will cover:

The role that neutrinos play.

Measuring neutrinos from the Heavens

Measuring neutrinos on Earth

Connecting back?
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Connecting back?
Within the Framework

Binds nuclei; mediated by gluons; only couples to quarks

Couples to charge; mediated by photons; felt by quarks and leptons

Common to all particles; mediated by the $W^\pm/Z^0$ bosons.

Spin 1/2

Spin 1
Unlike all the other particles, neutrinos can only interact via with the weak force.

The number of interactions, therefore, is quite limited.

Common to all particles; mediated by the $W^\pm/Z^0$ bosons.
Experiments, in particular oscillation experiments carried out over the last forty years, have revealed that neutrinos do possess a small and finite mass.

Neutrino mass has provided the first contradiction in the Standard Model. What else can we learn from neutrino masses?
Neutrino mass can be measured using several different but complimentary techniques.
Neutrino mass can be measured using several different but complimentary techniques.

How do we measure masses?
The Perfect Quantum Mechanics Problem...

- At heart, neutrino oscillations is an interference problem between different states.
- Allows one to probe extremely small mass differences.
Neutrino Oscillations

- In general, we have a $3 \times 3$ matrix that describes neutrino mixing (the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP mixing matrix):

- However, the picture simplifies if one of the mixing angles is small...

- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha/2} & 0 \\
0 & 0 & e^{i\alpha/2 + i\beta}
\end{pmatrix}
\]

- atmospheric, long baseline
- reactor, accelerator
- solar, KamLAND
- $0\nu\beta\beta$

\[
\mathcal{P}_{\text{surv}} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4E_\nu} L\right)
\]
A Rich History...
Solar Sector

- Ray Davis begins construction of Homestake
- Bahcall provides solar flux predictions
- Solar puzzle begins
- Homestake ($^{37}\text{Cl}$) measurements
- SAGE ($^{71}\text{Ga}$) begins operations
- MSW mechanism proposed
- GALLEX ($^{71}\text{Ga}$) online
- Super-K (H$_2$O) online
- GNO operational
- SNO (D$_2$O) takes data
- Solar puzzle SOLVED
- Borexino!
- 1st results from KAMLAND
Fit Results:

\[ \sin^2 \theta_{12} = 0.304^{+0.022}_{-0.016} \]

\[ \Delta m_{12}^2 = 7.65^{+0.23}_{-0.20} \times 10^{-5} \text{ eV}^2 \]

Schwetz et al, NJP 10 (2008) 113011
A Rich History... Atmospheric Sector

First observations at East Rand and Kolar Gold Mines

IMB & Kamioka Experiment

Atmospheric Deficit Problem

Kamioka Experiment begins

Frejus & NUSEX begin taking data

MACRO & Soudan2

Directional oscillations measured!

Super-Kamiokande constructed

K2K confirms signal

Atmospheric puzzle SOLVED

1st results from MINOS

T2K!
Fit Results:

\[ \sin^2 \theta_{23} = 0.50^{+0.07}_{-0.06} \]

\[ |\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{ eV}^2 \]

Schwetz et al, NJP 10 (2008) 113011
What We Know

(1) Neutrinos do have mass (and we measure these mass differences very well).

(2) Neutrinos mix (and we know most of those mixing constants very well)
**Q & A**

**What We Don’t Know**

1. What is the absolute scale of neutrinos?
2. What is the hierarchy (normal or inverted)?
3. What is the nature of neutrino mass?

Generally...

Know << Don’t Know
What we will cover:

The role that neutrinos play.

Measuring neutrinos from the Heavens

Measuring neutrinos on Earth

Connecting back?

“...the ancient of days” W. Blake
The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.

Neutrinos leave their imprint on each of these processes.
The Cosmic Microwave Background

- Mapping the cosmic microwave background has reached unprecedented precision and, along with that, great predictive power.
Primordial Nucleosynthesis

- Eventually neutrinos also decouple from neutrons and protons (below 1 MeV).

- This governs the production rate of light elements. These include elements such as $^2\text{H}$, $^3\text{He}$, $^4\text{He}$, and $^7\text{Li}$.

\[ \rho_x = \rho_\gamma + \rho_\nu = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma \]

- These abundances depend on the baryon density ratio, $\eta_{10}$, and the expansion rate of the universe.

\[ \eta_{10} \equiv 10^{10} \left( \frac{n_B}{n_\gamma} \right) \]

This quantity is unchanged at BBN, recombination, and now.
Large Scale Structure

- Neutrinos can also affect the clustering of galaxies (affected both by the number of neutrino species and the mass of the neutrinos)

\[
\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_i n_\nu m_{\nu,i}}{\rho_{\text{critical}}}
\]
Neutrino Mass Sensitivity

Cosmology places constraints on the energy density of neutrinos.

\[ \Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \sum_i^{n_\nu} \frac{m_{\nu,i}}{\rho_{\text{critical}}} \]
Limits & Datasets

- Strong limits can be further achieved by combining data collected from WMAP, Sloan Digital Sky survey (SDSS), and others.

- Tensions in data highlighted by change in limits.

- Relaxation of certain assumptions also highlights string model dependencies.

\[
\Sigma m_\nu < 2.3 \text{ eV (WMAP5)}
\]

\[
\Sigma m_\nu < 1.2 \text{ eV (WMAP5+SDSS)}
\]

\[
\Sigma m_\nu < 0.8 \text{ eV (WMAP5+SDSS+SN+BBN)}
\]

\[
\Sigma m_\nu < 0.6 \text{ eV (CMB+LSS+SN}^{\text{Ia}}+\text{BAO)}
\]

\[
\Sigma m_\nu < 0.2 \text{ eV (CMB+LSS+SN}^{\text{Ia}}+\text{Ly-}\alpha)
\]

\[
\text{Equation of state (w)}
\]
Planck Satellite:
Launched May 14th, 2009
New Frontiers

- Enhanced sensitivity to the microwave background should provide stronger constraint on neutrino mass from cosmological sources:

- Should be able to push down to $\sum m_\nu \sim 100$ meV at 95% C.L. by combining with other observations.
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Connecting back?

“...down they fell, driven headlong from the pitch of heaven, down into this deep...”, Paradise Lost
Direct Probes

Beta decay allows a *kinematic* determination of the neutrino mass

No dependence on cosmological models or matrix elements

$$m_\beta = \sqrt{\sum_{i=1}^{n_\nu} |U_{ei}|^2 m_i^2}$$
\[
\begin{align*}
\text{Source} &= \text{Detector} \\
{^{187}\text{Re}} &\rightarrow {^{187}\text{Os}} + e^- + \bar{\nu}_e \\
\text{Source} &\neq \text{Detector} \\
{^3\text{H}} &\rightarrow {^3\text{He}^+} + e^- + \bar{\nu}_e
\end{align*}
\]
Direct Neutrino Probes: MARE

- Use bolometers to measure the full energy deposit from beta decay.

- Use $^{187}$Re as beta decay isotope ($T_{1/2} = 4.3 \times 10^{10}$ y, $Q = 2.46$ keV)

- Main advantages: measures all deposited energies (no final state issues).

- Main disadvantage: the long half-life of $^{187}$Re. Many detectors needed.

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

$m_{\nu}^2 = (-112 \pm 207 \pm 90)$ eV$^2$

Timeline

MARE-1 will push limits to 2 eV by ~2010.

Upgrade (MARE-2) will push to 0.2 eV by ~2018.
The KATRIN Experiment

- KATRIN uses the beta decay from (gaseous) tritium to probe the absolute neutrino mass scale.

Tritium Beta Decay

\[ ^3\text{H} \rightarrow ^3\text{He} e^- \nu_e \]
Magnetic Adiabatic Collimation:
- Use adiabatic guiding to move $\beta$-particles along B-field lines.
- Field constrained by 2 s.c magnets.

Electrostatic Filter:
- Use retarding potential to remove $\beta$-particle below threshold.
- High pass filter (variable potential)
KATRIN = Liouville’s Theorem + Jackson problem

Figure 17: The 70 m long KATRIN reference setup with its major components: a) the windowless gaseous tritium source WGTS, b) the transport elements, consisting of an active pumping part and a passive cryotrapping section, c) the two electrostatic spectrometers, and d) the detector for β-counting. What is not shown is the monitor spectrometry.

- The reference experimental configuration is a linear setup which minimizes the overall magnetic inhomogeneities due to stray fields.
- The monitor spectrometer with its separate beam line.

These modifications as well as corresponding design work for better scanning procedure and reduction of systematic effects during a two year long optimization phase have improved the neutrino mass sensitivity of KATRIN from the initial estimate of $m_{\nu} = m_{\nu}^0 \text{eVmc}^2$ to the new reference value of $m_{\nu} = m_{\nu}^0 \text{eVmc}^2$ for details see section [pl]. In the following, we give an overview of the new reference setup of KATRIN, which supersedes the earlier outlines reported in [oj pl].

3.1 Experimental overview

The Karsruhe Tritium Neutrino (KATRIN) experiment will be performed on the site of Forschungszentrum Karlsruhe (FZK). Locating the KATRIN experiment at FZK allows the use of the unique expertise of the onsite Tritium Laboratory Karlsruhe (TLK), which is the only scientific laboratory equipped with a closed tritium cycle and licensed to handle the required amount of tritium ($\approx 16 \text{Bq}$).

A further unique advantage of choosing TLK as host laboratory is the possibility to operate the tritium related parts and in particular the tritium source of KATRIN within the existing TLK building close to the tritium handling facilities. The non-tritium related parts of KATRIN, in particular the electrostatic spectrometers, will be housed in new buildings at the ‘greenfield’ site north of TLK.

The reference setup of KATRIN shown in figure corresponds to a ∼70 m long linear configuration with about 16 superconducting solenoids which adiabatically guide β-decay electrons from source to detector. The experimental configuration of KATRIN can be grouped into four major functional units:

- a) High luminosity Windowless Gaseous Tritium Source (WGTS) delivering on average $1 \times 10^9$ β-decay electrons during the standard operation mode of the experiment.

$\Delta \theta$ determines the energy resolution.

$\Delta x$ is the size of the vacuum tank.

Source area $\Delta \theta \Delta x$ determines amount of $T_2$. $\Delta \theta$ determines the energy resolution.

$\Delta x$ is the size of the vacuum tank.

$\Delta \theta$ determines the energy resolution.
Detector
Main Spectrometer
Transport & Pumping
Tritium Source
**Pre-Spectrometer**

Fixed potential.

- $E = 18.3$ keV
- $\Delta E = 80$ eV

Filters most low energy electrons from beta spectrum

**Main Spectrometer**

Variable retarding potential.

- $E = 18.4-18.6$ keV
- $\Delta E = 0.93$ eV

24 m long, 10 m wide vacuum region.

Precision MAC-E filter.
The long journey....
KATRIN Lands!
KATRIN Lands!
Final Sensitivity

- Slotted to begin taking data in 2012. Will achieve sub-eV sensitivity after just a few months of operation.

- Final sensitivity at the 200 meV level (90% C.L.)
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.

- We propose a new approach: use frequency as a means to measure the electron energy in a non-destructive way.
Measuring Energy with Frequency

• Take advantage of cyclotron radiation created by a relativistic electron moving in a uniform magnetic field.

• This provides a non-destructive means of measuring the electron energy. As such, it escapes the limitations of Louiville’s theorem.

“Never measure anything but frequency.”

I. I. Rabi

A. L. Schawlow
Measuring Energy with Frequency

• In a uniform magnetic field, an electron will undergo cyclotron motion.

• Emitted frequency is independent of pitch angle of the electron and depends solely on the relativistic boost.

Cyclotron Frequency

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

Radiative Power Emitted

\[ P_{\text{tot}}(\beta, \theta) = \frac{1}{4\pi\epsilon_0} \frac{2e^2\omega_0^2}{3c} \frac{\beta^2 \sin (\theta)^2}{1 - \beta^2} \]
Measuring Energy with Frequency

- In a uniform magnetic field, an electron will undergo cyclotron motion.

- *Emitted* frequency is independent of pitch angle of the electron and depends solely on the relativistic boost.

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Project 8

- Uniform B field
- Low pressure T$_2$ gas.
- Antenna array for cyclotron radiation detection (26 GHz at 1 Tesla)

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“Never measure anything but frequency.”

I. I. Rabi

A. L. Schawlow

B. Monreal and J. Formaggio

“...and Prometheus was punished for giving fire back to mankind...”

What we will cover:

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Connecting back?
We have a good track record...

- Neutrinos from reactors. Detected (1950s)
- Neutrinos from the sun. Detected (1960s)
- Neutrinos from the atmosphere. Detected (1960s)
- Neutrinos from accelerators. Created & detected (1960s)
- Neutrinos from supernovae. Detected (1980s)
- Neutrinos from the Earth. Detected (2000s)
- Neutrinos from galactic sources. Not yet (but close!)
- Neutrinos from the Big Bang. Not even close...
Why is it so hard???

- Cosmological neutrinos comprise the most intense natural source of neutrinos available to us from nature.

- The cosmological photon background has been measured incredibly well. The noise from the early big bang still rings today.

So??

What’s the problem?!
Why is it so hard?

• Actually, the problem is THRESHOLD.

• Consider, for example, ordinary inverse beta decay.

\[ E_\nu + m_p \geq m_e + m_n \]

• But here the kinetic energy from relics is very small.

\[ \langle K \rangle \simeq 1.95 \text{ K} \ (0.17 \text{ meV}) \]

• Since energy is conserved, you need the neutrino to have enough energy to initiate the process.

• For most nuclei, you just do not have enough energy. You need a threshold-less process.

“Choice. The problem is choice.”
“About every neutrino physicist goes through a phase in his or her career and asks ‘There’s got to be a way to measure the relic neutrino background...’”  

P. Fisher
Neutrino Capture

Instead of beta decay...

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

The process is energetically allowed even at zero momentum.

This threshold-less reaction allows for relic neutrino detection.

References

Detecting the Impossible

- Has three main advantages:

  (i) The process is exothermic. There is enough energy for the decay to occur (because beta decay will happen anyway). Thus, it is threshold-less.

  (ii) Electron energy is almost mono-energetic, after the endpoint energy.

  (iii) For tritium, 100 g corresponds to 10 events/year.
Some More Quotes....

“About every neutrino physicist goes through a phase in his or her career and asks ‘There’s got to be a way to measure the relic neutrino background...’”  P. Fisher

“...In all fairness, this method [neutrino capture] appears to have survived the longest.”  P. Fisher

“Anyone who can measure relic neutrinos via neutrino capture will have made an amazing neutrino mass measurement...”  G. Drexlin

“If it were easy, we’d be done by now...”  my translation
Neutrino masses provide a unique window into the world of particle physics, offering a first glimpse of where new physics might begin.

Over the next decade, many experiments will push to determine the absolute neutrino mass scale, from a variety of approaches.

Certain techniques used to measure neutrino mass can even be extended, providing a glimmer of hope of extending back to cosmology.
Thank you for your attention
“Balance...”

Backup slides