Puzzles in Neutrinos

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The basic facts

- Three flavors, each associated with a charged lepton
- Weak interactions only
- Very small masses

<table>
<thead>
<tr>
<th>Quarks</th>
<th>(u)</th>
<th>(c)</th>
<th>(t)</th>
<th>(\gamma)</th>
<th>Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(d)</td>
<td>(s)</td>
<td>(b)</td>
<td>(g)</td>
<td></td>
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<tr>
<td>Leptons</td>
<td>(\nu_e)</td>
<td>(\nu_\mu)</td>
<td>(\nu_\tau)</td>
<td>(Z)</td>
<td>(W)</td>
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<tr>
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<td>(e)</td>
<td>(\mu)</td>
<td>(\tau)</td>
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\[\begin{array}{c}
\nu_l \rightarrow t + W^+ \\
\nu_l \rightarrow \nu_l + Z^0
\end{array}\]
Why is this interesting?

• Most common particle out there: $\approx 330 \text{ cm}^{-3}$

• Providing previously-unknown insights into the Standard Model

• Affect structure formation in the universe

• Just starting to look at human-scale applications
Some history


Neutrinos?

Neutrinos theorized Neutrinos detected

Number of flavors

$N_{\nu} \geq 1$ $N_{\nu} \geq 2$ $N_{\nu} \geq 3$ *

$\nu$ from nuclear reactors

First detection @ Savannah River (other exp’ts) Chooz KamLAND

$\nu$ from the sun

Homestake S/Kamiokande SNO SAGE & GNO

$\nu$ from cosmic ray showers

First detection in S.Africa and India IMB S/Kamiokande Soudan 2 MACRO

$\nu$ from a supernova

N.S. Oblath, MIT
Neutrino Sources

Terrestrial

- Nuclear Reactors
- Accelerators
- Cosmic ray showers
- The Earth

Astrophysical

- The Big Bang
- Supernovae
- The Sun
- Other astrophysical sources

Other astrophysical sources
Mass vs. Flavor

Neutrino flavor states \(\neq\) Neutrino mass states

- Flavor states are eigenstates of the weak interaction
- Mass states are eigenstates of the Hamiltonian
2-ν oscillations

In the 2-neutrino approximation

Neutrino flavor and mass states

\[
\begin{pmatrix}
\nu_e \\
\nu_{\mu\tau}
\end{pmatrix} = \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} \\
-\sin \theta_{12} & \cos \theta_{12}
\end{pmatrix} \begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

Flavor-change probability

\[
P(\nu_e \rightarrow \nu_{\mu\tau}) = |\langle \nu_{\mu\tau} | \nu(t) \rangle|^2 = \sin^2(2\theta_{12}) \sin^2 \left(1.27 \Delta m_{21}^2 \frac{L}{E} \right)
\]

\[
\Delta m_{21}^2 \equiv m_2^2 - m_1^2
\]

“Survival probability” = \[P(\nu_e \rightarrow \nu_e) = 1 - P(\nu_e \rightarrow \nu_{\mu\tau})\]
2-ν oscillations

In the 2-neutrino approximation

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\Delta m^2_{21} \equiv m_2^2 - m_1^2
\]

“Survival probability” = \(P(\nu_e \rightarrow \nu_e) = 1 - P(\nu_e \rightarrow \nu_{\mu\tau})\)
3-ν oscillations

**MNSP Matrix** - Maki, Nakagawa, Sakata, and Pontecorvo

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\times
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\times
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\phi_1} & 0 \\
0 & 0 & e^{i(\phi_2 + \delta)}
\end{pmatrix}
\times
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- \(c_{23} \equiv \cos \theta_{23}\)
- \(s_{23} \equiv \sin \theta_{23}\)

**θ**
- **θ\(_{23}\)**: cosmic ray and accelerator experiments
- **θ\(_{13}\)**: reactor and accelerator experiments
- **θ\(_{12}\)**: solar experiments and KamLAND

\(\delta\) is a CP-violating phase

- \(\theta_{23} \approx 45^\circ\)
- \(\theta_{13} < 15^\circ\)
- \(\theta_{12} \approx 34^\circ\)

Majorana Phases

- BB decay
Neutrino masses

- At least two masses are non-zero
- They are very small

We have measured two mass separations

- $\Delta m^2_{21} \approx 8 \times 10^{-5} \text{ eV}^2$
- $\Delta m^2_{32} \approx 3 \times 10^{-3} \text{ eV}^2$
Mass Hierarchy

- We know the value and sign of $\Delta m^2_{12}$
- We know the absolute value of $\Delta m^2_{23}$
Mass Hierarchy

- We know the value and sign of $\Delta m^2_{12}$
- We know the absolute value of $\Delta m^2_{23}$
Open Questions

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What is $\theta_{13}$?
Why measure $\theta_{13}$?

- Because it’s there
- $\theta_{13}$ must be measurable for us to measure
  - the CP-violating phase $\delta$
  - the mass hierarchy
• Beta decays of fission fragments release $\bar{\nu}_e$

• Look for $\bar{\nu}_e$ disappearance

• Probe $\theta_{13}$ directly

\[ P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) - \ldots \]
Accelerator Experiments

- Long-baseline = hundreds of km
- Neutrinos produced in pion decays
- Sensitive to $\theta_{13}$, CP-violating phase, and the mass hierarchy
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$
State of the art

Upcoming reactor experiments

• Double Chooz
• Daya Bay
• RENO

Figure from M. Mezzetto, 2009
Hot off the presses

T2K and MINOS have both released recent results!

Both experiments exclude $\theta_{13} = 0$

- T2K (June 14): @ 2.5σ
- MINOS (June 24): @ 1.7σ
- (assuming $\delta_{CP}=0$)

Figure from M. Mezzetto, 2009
Bleeding edge

Global Fit Result

\[ \sin^2 2\theta_{13} = 0.098 \pm 0.026 \]

\[ \theta_{13} \approx 9.1^\circ \]

Central value and 90% CL uncertainty from G.L. Fogli, et al, 2011

Original figure from M. Mezzetto, 2009
\( \theta_{13} \) experiment talks

- Reactor
  - Double Chooz: 1E
  - Daya Bay: 3E

- Long Baseline
  - T2K: 1E, 2E
  - NO\( \nu \)A: 3E
  - MINOS: 5F
What is the absolute mass scale?
Absolute Mass Scale

- We know the mass differences ...
- ... but not the absolute mass scale
- Can measure with single beta decay isotopes
  - $^3$H or $^{187}$Re
- Can also measure with cosmology

\[ |\Delta m^2_{32}| \]

\[ \Delta m^2_{21} \]
$^3$H Beta Decay

...from which one detects the electron
Energy Spectrum

The shape is modified by neutrino mass, squared

Use a large spectrometer to filter out the high-energy electrons
The KATRIN Spectrometer
Mass Limits from $^3$H

- Predecessors: Mainz and Troitsk
  - Current limit: $m_\nu < 2.2 \text{ eV}$

- Under construction: KATRIN
  - Sensitivity down to $m_\nu < 0.2 \text{ eV}$
  - Talk in session 3E

- Future experiment: Project 8
  - Talk in session 5E
To sum up . . .

• We have known about neutrinos for ~80 years

• In the past 15 years neutrino physics has been revolutionized

• The current generation of experiments continues to make amazing progress

• There are plenty of intriguing questions left to answer

• Check out sessions 1E, 2D, 2E, 3E, 4E, 5E and 5F, and Plenary 2 for the latest neutrino news!
\( \nu \) mass limit: \( b \) decay

- \(^3\text{H}\) beta decay
  - Current limit: \( m_\nu < 2.2 \text{ eV} \)
  - Goal for KATRIN: \( m_\nu < 0.2 \text{ eV} \)
  - Beyond KATRIN: Project 8

- \(^{187}\text{Re}\) beta decay
  - Goal for MARE: \( m_\nu < 2 \text{ eV} \)

- Single beta decay talks:
  - KATRIN (3E), Project 8 (5E)
Neutrino Mass Models

- See-saw mechanism
- mention other models
Does $\bar{\nu} = \nu$

- If yes, then the $\bar{\nu}_i$ are “Majorana” neutrinos
  - The SM Lagrangian has Majorana mass terms, e.g. $m_L \bar{\nu}_L \nu_L^c$
  - Lepton number is not conserved

- Dirac masses are the analogues of the SM quark and charged lepton masses
  - Dirac mass terms: $m_D \bar{\nu}_L \nu_R$
Zero-ν Double Beta Decay

- Observation of zero-neutrino double-beta (0νββ) decay implies Majorana neutrinos
State of the art: $0\nu\beta\beta$

- [limits from Neutrino2010]
- Check out session 4E for the latest news
CP Violation

- Through leptogenesis would result in the baryon asymmetry observed in the universe
- Outgrowth of the see saw mechanism
- Heavy neutrinos created at the big bang would decay into +/- charged leptons
- If nu interactions violate CP, then heavy nu interactions would too
- Would have had different rates of decays $N \rightarrow l^- + higgs^+$ and $N \rightarrow l^+ higgs^-$
- sphaeleron process takes lepton asymmetry and turns it into a baryon asymmetry
CP Violation

• There is a CP-violating phase in the MNSP matrix

\[
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\]

• If any mixing angle is too small, CP violation won’t be seen in the neutrinos

• Lepton CP violation could explain the matter/antimatter asymmetry in the universe
Observing CP Violation

- Use accelerators at different baselines
- look for $P(\bar{\nu}_a \rightarrow \bar{\nu}_b) \neq P(\nu_a \rightarrow \nu_b)$
- See the talk on the DAEdALUS experiment ()
Sterile Neutrinos?

• Evidence from LSND
• $Z$ width gives 3 active flavors ($Z \rightarrow \nu \bar{\nu}$)
• if $>3$ flavors, the extra must not couple to the $Z$
From oscillations . . .

- We know that there are at least two mass separations
  - $Dm^2_{21} \approx 7.58 \times 10^{-5} \text{ eV}^2$
    (solar & KamLAND)
  - $Dm^2_{32} \approx 2.35 \times 10^{-3} \text{ eV}^2$
    (atmospheric & accelerator)
- And we know two of the three mixing angles
  - $q_{12} = 0.306 \pm 0.017$
  - $q_{23} = 0.42 \pm 0.08$
Sterile Neutrinos?

• Discuss recent results from MiniBooNE and new reactor flux information