Understanding the Particle Nature of Neutrinos

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Particle Properties

Interactions

Flavors & States

Charge

Spin

Particle Type

Mass
\[ N \rightarrow N' + e^- \text{ some nuclei emit electrons!} \]

\[ M_{\text{parent}}c^2 \Rightarrow E_{\text{daughter}} + E_{\text{electron}} \]

\[ KE_{\text{electron}} = M_{\text{parent}}c^2 - M_{\text{daughter}}c^2 - m_{\text{electron}}c^2 \]

**Fig. 5.** Energy distribution curve of the beta-rays.
Wolfgang Pauli proposed that an undetectable particle shared the energy of beta decay with the emitted electron.
Neutrinos Don’t Matter to Chemists

can be represented by a nuclear equation. For example,

\[ ^{238}_{92}\text{U} \rightarrow ^{4}_{2}\text{He} + ^{234}_{90}\text{Th} \]

\[ \alpha\text{-particle} \]

In balancing nuclear equations, notice that both the total charge and the total mass must balance.

The thorium produced in the decay of \(^{238}_{92}\text{U}\) is itself radioactive and decays by beta emission. The nuclear equation for the change is

\[ ^{234}_{90}\text{Th} \rightarrow ^{0}_{-1}\text{e} + ^{234}_{91}\text{Pa} \]

\[ \beta\text{-particle} \]

Thus beta emission increases the atomic number by one unit, but has (essentially) no effect on the mass.

Gamma radiation, as we learned in Chapter 4, is really nothing more than a very energetic form of electromagnetic radiation. Its emission from a nucleus doesn’t change the charge or mass number, so gamma radiation is often omitted from nuclear equations.
Fermi’s Theory of Beta Decay

Enrico Fermi
Univ. of Chicago

Fermi’s Theory of Beta Decay based on Pauli’s Letter of Regrets

Experiment: \[ M_n c^2 \neq E_p + E_e \]

Conjecture: \[ M_n c^2 = E_p + E_e + E_\nu \]

Consistency requires that \( E_\nu \) is not observable!

Fermi’s theory still stands (parity violation added in the 50s).
Weak Interactions in the Standard Model

The weak gauge bosons $W^\pm$ act on left-handed doublets
(charged-current interaction)

$\beta$-decay

Since $m_w=80.4$ GeV $>> m_p$, decay is governed by Fermi coupling $G_F$

Fermi coupling

$$G_F = \frac{g_2^2}{\sqrt{2}} \frac{1}{8m_W^2}$$

g_2 = W$ gauge coupling

Weinberg angle

$$\frac{e}{g_2} = \sin\theta_W = 0.48$$
Fermi’s Idea for Measuring $m_\nu$

Fig. 5. Energy distribution curve of the beta-rays.

Fig. 1.2. Graph from Fermi's famous paper on the theory of beta decay, showing how the shape of the emitted electron's energy spectrum varies with neutrino mass.
First Direct Detection of the (Anti)Neutrino

Reines and Cowan 1956

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
Discovery of Muon Neutrino

1962

\[ \bar{\nu}_\mu + p \rightarrow n + \mu^+ \]

\[ \nu_\mu + n \rightarrow p + \mu^- \]

Lederman, Schwartz, Steinberger

\(10^4 \nu_\mu \) and \( \bar{\nu}_\mu \)

\(\mu\) produce nice tracks as they go through the chamber (29 events)

\(e\) produce showers as they cross Al (0 events)
Muon Neutrino Mass Studies

Current best limit from studies of the kinematics of $\pi \rightarrow \mu \nu$ decay

$$p_\mu^2 + m_\mu^2 = \left(m_\pi^2 + m_\mu^2 - m_\nu^2\right)^2 / 4m_\pi^2$$

Can use $\pi$-decay:
- **At Rest:** Mass of $\pi$ is dominate uncertainty
- **In Flight:** Resolution on $p_\pi - p_\mu$ limited experimentally

Best mass limit is from $\pi$-decay at rest

$$< 170 \text{ keV at 95\% CL} \quad \text{(Assamagan et al., PRD 1996)}$$

New BNL Experiment using $g$-2 setup (sensitivity for $> 8$ keV)
Proposed BNL “NuMass” Experiment

**BNL g-2 Neutrino Mass Experiment**

\[ m(\nu_\mu) < 8 \text{ keV}/c^2 \]

**Forward-going decay muons**

- Orbit a larger diameter by \( \Delta D \)
- \( q = 29.7 \text{ MeV}/c \)

**Diagram:**

- Undecayed pions
- Decay \( \mu \)'s
- \( \Delta D \) depends on \( m(\nu) \)

**Equations:**

\[
\frac{\Delta D}{D} = \frac{p_\mu - p_\pi}{p_\pi} = \frac{0.7 \text{ MeV}/c}{3 \text{ GeV}/c} = \frac{3.26 \text{ mm}}{14 \text{ m}}
\]

- Non-zero \( m_\nu \) shrinks \( \Delta D \)

\[
\frac{\delta D}{D} = \frac{-m_\nu^2}{2 q m_\pi}
\]

- 0.04 mm for current limit
Number of Active Neutrinos

Precision studies of Z-line shape, determine number of active light neutrinos

Each separate \( (\nu_l)_L \) adds to total Z-width.

\[
N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \left( \frac{\Gamma_\ell}{\Gamma_\nu} \right)_{\text{SM}}
\]

From LEP, one finds:
\[
N_\nu = 2.984 \pm 0.008
\]
which argues strongly for only having 3 generations

Big bang nucleosynthesis gives a constraint on the effective number of light neutrinos at \( T \sim 1 \) MeV:

\[
1.2 < N_\nu^{\text{eff}} < 3.3 \quad [99\% \text{ CL}]
\]

Because mixing effects are likely to bring sterile neutrinos into equilibrium, above suggests that the number of \( (\nu_l)_R \) is also limited to 3.
Search for tau Neutrino

Discovery of $\tau$ lepton at SLAC

$\rightarrow$ there should be a corresponding neutrino.

In 1989, indirect evidence for the existence of $\nu_\tau$ in measurement of Z-width

$\rightarrow$ no one had directly observed the tau neutrino.

The tau neutrino interact and form a tau that has an 18% probability of decaying to

- a muon and two neutrinos (long event)
- an electron and two neutrinos (short event)

86% of all tau decays involve only 1 charged particle (a kink) which is the particle physicists are looking for in DONUT experiment
Discovery of tau Neutrino

2000

An 800 GeV beam of protons from the TeVatron collides with a block of tungsten

Experimental Challenges:
- Very short lifetime of the $\tau$.
- $\nu_\tau$ is extremely non-interacting (detector must have a very fine resolution).

Detecting a $\tau$ Neutrino

$D_s$ decay into $\tau$ and $\nu_\tau$ neutrino

\[ D_s \rightarrow \nu_\tau + \tau \]
\[ \tau \rightarrow \nu_\tau + X \]

6,000,000 candidate events on tape
4 clean tau events
A $\nu_\tau$ interacted with a nucleon in a steel layer, producing a $\tau$.

**Long tau decay** because it decays to one charged particle, the electron, and the decay vertex occurs several sheets downstream from the neutrino interaction vertex.

**Short tau decay** to an electron in less than the distance it takes to traverse an emulsion layer.
Direct $\nu_\tau$ Mass Limits

Look at tau decays near the edge of the allowed kinematic range

$\tau^- \rightarrow 2\pi^- \pi^+ \nu_\tau$ and $\tau^- \rightarrow 3\pi^- 2\pi^+ (\pi^0) \nu_\tau$

Fit to scaled visible energy vs. scaled invariant mass (e.g. hep-ex/9906015, CLEO)

Best limit is $m(\nu_\tau) < 18.2$ MeV at 95% CL (Aleph, EPJ C2 395 1998)

Massive $\nu_\tau$ shifts edge of the kinematic distribution

Outer lines: $m_{\nu_\tau} = 0$
Inner lines: $m_{\nu_\tau} = 30$ MeV
“Standard Model” Neutrino Physics

1914  Electron Spectrum in $\beta$ decay is continuous
1930  Pauli postulates that a new particle is emitted
1933  Fermi names the new particle neutrino and introduces four-fermion interaction
1956  Reines and Cowan discover the neutrino
1962  At least two neutrinos: $\nu_e \neq \nu_\mu$
1973  Discovery of neutral currents at CERN
1983  Discovery of the W and Z
1989  Measurement of Z width at CERN $\rightarrow N_\nu=3$
2002  tau neutrino discovered.
the standard model contains 3 left-handed lepton doublets
\[
\begin{pmatrix}
\nu_e \\
e
\end{pmatrix}_L
\begin{pmatrix}
\nu_\mu \\
\mu
\end{pmatrix}_L
\begin{pmatrix}
\nu_\tau \\
\tau
\end{pmatrix}_L
\]
and 3 times 3 (color) left handed quark doublets
\[
\begin{pmatrix}
u \\
d
\end{pmatrix}_L
\begin{pmatrix}
e \\
\mu
\end{pmatrix}_L
\begin{pmatrix}
t \\
\tau
\end{pmatrix}_L
\]
all these fermions have right handed partners, except neutrinos, which are always left handed
\[
e_R, \mu_R, \tau_R, u_R, d_R, c_R, s_R, t_R, b_R
\]
interactions are mediated by gauge bosons
\[
\gamma, g(8), W^\pm, Z
\]
fermions acquire mass by interacting with the Higgs field
\[
\langle H \rangle
\]
no right handed neutrinos
\[
m_\nu = 0 \text{ in the standard model}
\]
Elementary Particles

3 \( \nu \) flavors

Only upper limits on \( m_\nu \) from kinematic studies.

Are \( \nu \) massless?

(\textit{ad hoc} assumption in SM)
Neutrino Interactions

$W$ exchange gives Charged-Current (CC) events and $Z$ exchange gives Neutral-Current (NC) events.

In CC events the outgoing lepton determines if neutrino or antineutrino.

\[ l^- \rightarrow \nu \]

\[ l^+ \rightarrow \bar{\nu} \]
Neutrino Cross Section is Very Small

Weak interactions are weak because of the massive W and Z boson exchange

\[ \sigma^{\text{weak}} \propto G_F^2 \propto \left( \frac{1}{M_W \text{ or } Z} \right)^4 \]

\[ M_W \sim 80 \text{ GeV} \]
\[ M_Z \sim 91 \text{ GeV} \]

\[ G_F = \frac{\sqrt{2}}{8} \left( \frac{g_W}{M_W} \right)^2 = 1.166 \times 10^{-5} / GeV^2 \quad (g_W \approx 0.7) \]

For 100 GeV neutrinos:

\[ \sigma(\nu e) \sim 10^{-40} \quad \sigma(\nu p) \sim 10^{-36} \text{ cm}^2 \]
\[ \sigma(pp) \sim 10^{-26} \text{ cm}^2 \]

Mean free path length in steel \( \sim 3 \times 10^9 \text{ m} \)

→ Need big detectors and lots of \( \nu \)'s

At Hera see W and Z propagator effects
- Also weak \( \sim \) EM strength

\[ \sigma^{\text{EM}} \propto \frac{1}{Q^4} \]
Neutrinos Are Left-Handed - Helicity and Handedness

**Helicity** is projection of spin along the particles direction. Frame dependent (if massive)

The operator: $\sigma \cdot \mathbf{p}$

Handedness (or chirality) is Lorentz invariant. Only same as helicity for massless particles.

If neutrinos have mass then left-handed neutrino is:

- mainly left-helicity
- But also small right-helicity component $\propto m/E$

Neutrinos only interact weakly with a $(V-A)$ interaction

All neutrinos are left-handed

All antineutrinos are right-handed

Only left-handed charged-leptons ($e^-, \mu^-, \tau^-$) interact weakly but mass

$$R_{\text{theory}} = \frac{\Gamma(\pi^\pm \rightarrow e^\pm \nu_e)}{\Gamma(\pi^\pm \rightarrow \mu^\pm \nu_\mu)}$$

$$= \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2$$

$$= 1.23 \times 10^{-4}$$
• we can define **chirality** (L/R) projections

\[ \psi_{L,R} = P_{L,R} \psi = \frac{1}{2} (1 \pm \gamma_5) \psi \]

and **helicity** projections

\[ \psi_{\pm} = H_{\pm} \psi = \frac{1}{2} (1 \pm \vec{\Sigma} \cdot \hat{p}) \psi \]

helicity = projection of spin on the direction of motion

• for a massless particle

  helicity = chirality

• also note that

\[ (\psi_L)\dagger \gamma_0 \equiv \bar{\psi}_L = \bar{\psi} P_R \]

The anti-particle of a left-handed neutrino \( \nu_L \) is a right-handed anti-neutrino.

• the W boson only interacts with left handed fields

\[ \mathcal{L} = g_2 \bar{\psi}_L \gamma_\mu \bar{\psi}_L \gamma^\mu \bar{\psi}_L \]

right handed neutrinos do not couple to \( W, Z \)
• Dirac mass ($\bar{\psi} = \psi^\dagger \gamma_0$)

$$\mathcal{L} = m(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$

\begin{align*}
\langle H \rangle & \quad \langle H \rangle \\
\nu_L & \quad \nu_R & \quad \bar{\nu}_R & \quad \bar{\nu}_L
\end{align*}

Lepton number conserved

• Majorana mass ($\psi^c = \bar{\psi}^T C$)

$$\mathcal{L} = m(\bar{\nu}_L^c \nu_L + h.c.) = m(\nu_L C \nu_L + h.c.)$$

\begin{align*}
\langle H \rangle & \quad \langle H \rangle \\
\nu_L & \quad \nu_L & \quad \nu_L
\end{align*}

Lepton number violated

• how to tell the difference? $0\nu2\beta$ decay
Dirac and Majorana Neutrinos

Dirac Neutrinos
\[ \nu \neq \bar{\nu} \]

Majorana Neutrinos
\[ \nu \neq \bar{\nu} \]

only difference is “handedness”
\[ \nu \text{ are left-handed } \nu \rightarrow \mu^- \]
\[ \bar{\nu} \text{ are right-handed } \nu \rightarrow \mu^+ \]

Lepton number conserved
- Neutrino \( \rightarrow \mu^- \)
- Antineutrino \( \rightarrow \mu^+ \)

Lepton number not conserved
- Neutrino \( \leftrightarrow \) Antineutrino with spin flip

Dirac Mass Term
\[ -m_D \left( \bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L \right) \]

Majorana Mass Term
\[ -\frac{1}{2} m_M^L \left( \bar{\nu}_L (\nu_L)^c + (\nu_L)^c (\nu_L) \right) - \frac{1}{2} m_M^R \left( \bar{\nu}_R (\nu_R)^c + (\nu_R)^c (\nu_R) \right) \]
No fundamental reason why neutrinos must be massless. But why are they much lighter than other particles?

Fermion Masses

PDG 2000

\[ \nu_3 < \nu_1 < \nu_2 < (\nu_3) \]

PDG 2000 + SNO + SK

\[ \nu_3 < \nu_1 < \nu_2 < (\nu_3) \]
Neutrino Mass: Theoretical Ideas

No fundamental reason why neutrinos must be massless.
But why are they much lighter than other particles?

\[ \nu_1 < \nu_2 < \nu_3 \]

PDG 2000 + SNO + SK

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Grand Unified Theories
- Dirac and Majorana Mass
- See-saw Mechanism

Modified Higgs sector to accommodate neutrino mass

Extra Dimensions
- Neutrinos live outside of 3 + 1 space

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Many of these models have at least one Electroweak isosinglet $\nu$

Right-handed partner of the left-handed $\nu$
Mass uncertain from light ($< 1$ eV) to heavy ($> 10^{16}$ eV)

Would be “sterile” – Doesn’t couple to standard W and Z bosons
See-Saw Mechanism

Dirac Neutrinos

\[-m_D (\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)\]

Majorana Neutrinos

\[-\frac{1}{2} m_M^L (\bar{\nu}_L (\nu_L)^c + (\nu_L)^c (\nu_L)) - \frac{1}{2} m_M^R (\bar{\nu}_R (\nu_R)^c + (\nu_R)^c (\nu_R))\]

See-Saw Mechanism with Both Majorana and Dirac Terms:

\[\mathcal{M} = \begin{pmatrix} m_M^L & m_D \\ m_D & m_M^R \end{pmatrix} \quad m_M^R = M \gg m_D \gg m_M^L = \mu\]

\[\mathbf{M}_{NH} \xrightarrow{m_N} m_N \approx M, \quad m_\nu \approx \left| \mu - \frac{m_D^2}{M} \right|\]
Direct Neutrino Mass Experiments

Techniques

**Electron neutrino**
Study $E_e$ end point for $^3\text{H} \rightarrow ^3\text{He} + \nu_e + e^-$

**Muon neutrino**
Measure $P_m$ in $\pi \rightarrow \mu \nu_\mu$ decays

**Tau neutrino**
Study $n\pi$ mass in $t \rightarrow (n\pi) \nu_\tau$ decays

(Also, information from supernova time-of-flight)
Direct Neutrino Mass Searches

Model-Independent Neutrino Masses from $\beta$-decay Kinematics

\[ N(E_e) \propto p_e E_e \left( E_0 - E_e \right) \sqrt{(E_0 - E_e)^2 - m_\nu^2 c^4} \]

Current best limit $m_\nu < 2.2 \text{ eV}$

Search for a distortion in the shape of the $\beta$-decay spectrum in the end-point region

![Graph showing the entire spectrum and close to $\beta$ endpoint]

- $m_\nu = 0 \text{ eV}$
- $m_\nu = 1 \text{ eV}$
- $\sim 2 \times 10^{-13}$
Mainz Neutrino Mass Experiment
Past Tritium Beta Decay Experiments

<table>
<thead>
<tr>
<th>Location</th>
<th>Method Description</th>
<th>Result (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITEP</td>
<td>$T_2$ in complex molecule, magn. spectrometer (Tret'yakov)</td>
<td>17-40 eV</td>
</tr>
<tr>
<td>Los Alamos</td>
<td>gaseous $T_2$ - source, magn. spectrometer (Tret'yakov)</td>
<td>&lt; 9.3 eV</td>
</tr>
<tr>
<td>Tokio</td>
<td>$T$ - source, magn. spectrometer (Tret'yakov)</td>
<td>&lt; 13.1 eV</td>
</tr>
<tr>
<td>Livermore</td>
<td>gaseous $T_2$ - source, magn. spectrometer (Tret'yakov)</td>
<td>&lt; 7.0 eV</td>
</tr>
<tr>
<td>Zürich</td>
<td>$T_2$ - source impl. on carrier, magn. spectrometer (Tret'yakov)</td>
<td>&lt; 11.7 eV</td>
</tr>
<tr>
<td>Troitsk (1994-2001)</td>
<td>gaseous $T_2$ - source, electrostat. spectrometer</td>
<td>&lt; 2.2 eV</td>
</tr>
<tr>
<td>Mainz (1994-2001)</td>
<td>frozen $T_2$ - source, electrostat. spectrometer</td>
<td>&lt; 2.2 eV</td>
</tr>
</tbody>
</table>
Motivation for a Next-Generation T$_2$ Experiment

Validate/rule out models with quasi-degenerate masses

Role of $\nu$’s as hot dark matter, constrain $\Omega_\nu$
Next Generation $T_2$ $\beta$-decay Experiment ($m_e < 0.35$ eV)

Main challenge: XHV conditions $p < 10^{-11}$ mbar
Neutrinoless Double Beta Decay (0νββ)

The Next Frontier in Neutrino Physics

- **2ν mode**: conventional 2nd order process in nuclear physics
- **0ν mode**: hypothetical process only if \( M_\nu \neq 0 \) AND \( \nu = \bar{\nu} \)

\[
\Gamma_{2\nu} = G_{2\nu} \ | M_{2\nu} |^2
\]
\[
\Gamma_{0\nu} = G_{0\nu} \ | M_{0\nu} |^2 \left( \langle m_{\beta\beta} \rangle \right)^2
\]

- \( G \) are phase space factors
- \( G_{0\nu} \sim Q^5 \)

*important physics*
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The Next Frontier in Neutrino Physics

2ν mode: conventional 2nd order process in nuclear physics

0ν mode: hypothetical process only if $M_\nu \neq 0$ AND

The only known practical approach to discriminate Majorana vs Dirac $\nu$
Neutrino Masses: What do we know?

The results of oscillation experiments indicate $\nu$ do have mass, set the relative mass scale, and a minimum for the absolute scale.

$$m_i > \sqrt{\Delta m^2_{atm}} \approx 50\,\text{meV}$$

$\beta$ decay experiments set a maximum for the absolute mass scale.

$$50\,\text{meV} < m_\nu < 2200\,\text{meV}$$

For the next experiments $\langle m_\beta \rangle$ in the range of 10 - 50 meV is very interesting.
Distinguishing the Mass Hierarchy in $0\nu\beta\beta$
Several Proposed Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Material Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COBRA</td>
<td>Te-130</td>
<td>10 kg CdTe semiconductors</td>
</tr>
<tr>
<td>DCBA</td>
<td>Nd-150</td>
<td>20 kg Nd layers between tracking chambers</td>
</tr>
<tr>
<td>NEMO</td>
<td>Mo-100, Various</td>
<td>10 kg of $\beta\beta$ isotopes (7 kg of Mo)</td>
</tr>
<tr>
<td>CAMEO</td>
<td>Cd-114</td>
<td>1 t CdWO&lt;sub&gt;4&lt;/sub&gt; crystals</td>
</tr>
<tr>
<td>CANDLES</td>
<td>Ca-48</td>
<td>Several tons CaF&lt;sub&gt;2&lt;/sub&gt; crystals in liquid scint.</td>
</tr>
<tr>
<td>CUORE</td>
<td>Te-130</td>
<td>750 kg TeO&lt;sub&gt;2&lt;/sub&gt; bolometers</td>
</tr>
<tr>
<td>EXO</td>
<td>Xe-136</td>
<td>1 ton Xe TPC (gas or liquid)</td>
</tr>
<tr>
<td>GEM</td>
<td>Ge-76</td>
<td>1 ton Ge diodes in liquid nitrogen</td>
</tr>
<tr>
<td>GENIUS</td>
<td>Ge-76</td>
<td>1 ton Ge diodes in liquid nitrogen</td>
</tr>
<tr>
<td>GSO</td>
<td>Gd-160</td>
<td>2 t Gd&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;5&lt;/sub&gt;:Ce crystal scint. in liquid scint.</td>
</tr>
<tr>
<td>Majorana</td>
<td>Ge-76</td>
<td>500 kg Ge diodes</td>
</tr>
<tr>
<td>MOON</td>
<td>Mo-100</td>
<td>Mo sheets between plastic scint., or liq. scint.</td>
</tr>
<tr>
<td>Xe</td>
<td>Xe-136</td>
<td>1.56 t of Xe in liq. Scint.</td>
</tr>
<tr>
<td>XMASS</td>
<td>Xe-136</td>
<td>10 t of liquid Xe</td>
</tr>
</tbody>
</table>
Selected Proposals for $0\nu\beta\beta$ Experiments

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Proposed ton-year $= M \times T \times \epsilon$</th>
<th>Anticipated $&lt;m_{ee}&gt;$, (QRPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE</td>
<td>$0.21 \times 5 \times 1 = 1$</td>
<td>60 meV</td>
</tr>
<tr>
<td>EXO</td>
<td>$6.5 \times 10 \times 0.7 = 45$</td>
<td>13 meV</td>
</tr>
<tr>
<td>GENIUS</td>
<td>$1 \times 2 \times 1 = 2$</td>
<td>20 meV</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>$0.5 \times 10 \times 1 = 5$</td>
<td>25 meV</td>
</tr>
<tr>
<td>MOON</td>
<td>$3.3 \times 3 \times 0.14 = 1.4$</td>
<td>30 meV</td>
</tr>
</tbody>
</table>

The $<m_{\beta\beta}>$ limits depend on background assumptions and matrix elements which vary from proposal to proposal.
Cosmological Information on Neutrino Mass

Neutrinos’ contribution to the Universe’s energy density

\[ \Omega_{\nu}h^2 = \sum m_i / 95.3 \text{ eV} \]

Combining WMAP and large scale structure

\[ \Omega_{\nu}h^2 < 0.0076 \text{ eV (95\% CL)} \]

If \( m_{\nu_e} \sim m_{\nu_\tau} \) (degenerate neutrino species)

\[ m_{\nu} < 0.23 \text{ eV} \]

Cosmological neutrino mass limits probe Dirac and Majorana \( \nu \) masses!

Mass limits comparable to 0\( \nu \beta\beta \) experiments.
Supernova Neutrinos

In a supernova explosion

- Neutrinos escape before the photons
- Neutrinos carry away \( \sim 99\% \) of the energy
- The rate of escape for \( \nu_e \) is different from \( \nu_\mu \) and \( \nu_\tau \)
  (Due extra \( \nu_e \) CC interactions with electrons)

Neutrino mass limit can be obtained by the spread in the propagation time

\[-t_{\text{obs}} - t_{\text{emit}} = t_0 \left( 1 + \frac{m^2}{2E^2} \right)\]

- Spread in arrival times
  if \( m \neq 0 \) due to \( \Delta E \)

- For SN1987a assuming
  emission time is over 4 sec
  \( m_\nu < \sim 30 \text{ eV} \)

All arrived within about \( \sim 13 \text{ s} \) after traveling 180,000 light years with energies that differed by up to a factor of three.

Neutrinos arrived about 18 hours before the light was seen.
What about a Neutrino Magnetic Moment?

Weak Interactions

Magnetic Moment

\[ \frac{d\sigma}{dT_e} = \text{weak int} + \frac{\pi \alpha^2 \mu^2_{\nu}}{m_e^2} \left( \frac{1}{T_e} - \frac{1}{E_{\nu}} \right) \]

Overline of electron recoiling from a reactor

Electron Recoil \( T \) (MeV)
Low Electron Recoil Energy Experiment

Experiment at Nuclear Reactors (low energy source of $\bar{\nu}_e$)

Time Projection Chamber

- Anode (20 μm)
- Grid (1 cm, potential 100 μm)
- Cathode (-45 kV)
- 3 bar CF$_4$ gas

High density, relatively low Z, good drifting properties

- Volume ($V$) = 1 m$^3$
- Length ($L$) = 1.6 m
- Diameter ($D$) = 0.9 cm
Neutrino Magnetic Moment

Experimental Results

Reactor Experiments

- UC Irvine: $\mu_{\nu}^{\text{reac}} < 2-4 \times 10^{-10} \mu_B$
- Kurchatov: $\mu_{\nu}^{\text{reac}} < 2.4 \times 10^{-10} \mu_B$
- Rovno: $\mu_{\nu}^{\text{reac}} < 1.9 \times 10^{-10} \mu_B$
- MUNU: $\mu_{\nu}^{\text{reac}} < 1.0 \times 10^{-10} \mu_B$ (90% CL)

Solar (Anti)Neutrino Experiments

- Super-Kamiokande: $\mu_{\nu}^{\text{sol}} < 1.5 \times 10^{-10} \mu_B$
- KamLAND
Experimental Indications for Neutrino Oscillations

**LSND Experiment**

- $L = 30\text{m}$
- $E = \sim 40\text{ MeV}$

- $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\Delta m^2 = 0.3\text{ to }3\text{ eV}^2$
Prob$_{\text{OSC}} = 0.3\%$

**Atmospheric Neutrinos**

- $L = 15 - 15,000\text{ km}$
- $E = 300 - 2000\text{ MeV}$

- $\nu_\mu \rightarrow \nu_x$

$\Delta m^2 = \sim 1\text{ to }7 \times 10^{-3}\text{ eV}^2$
Prob$_{\text{OSC}} = \sim 100\%$

**Solar Neutrinos**

- $L = 10^8\text{ km}$
- $E = 0.3\text{ to }3\text{ MeV}$

- $\nu_e \rightarrow \nu_x$

$\Delta m^2 = \sim 2\text{ to }8 \times 10^{-5}\text{ eV}^2$
Prob$_{\text{OSC}} = \sim 100\%$
Discovery of Massive Neutrinos through Oscillations

- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that neutrinos oscillate
Neutrino Mixing Matrix/Leptonic Unitarity Triangle

Global Fit of Oscillation Data (3σ)

\[ U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 0.78 - 0.88 & 0.47 - 0.62 & 0.0 - 0.23 \\ 0.18 - 0.55 & 0.40 - 0.73 & 0.57 - 0.82 \\ 0.19 - 0.55 & 0.41 - 0.75 & 0.55 - 0.82 \end{pmatrix} \]

Can we reconstruct the triangle?
Can we use it to determine the CP-violating phase?

\[ |U_{e3}| = 0.16 \]

nearly best fit values of other angles

\[ J = s_{12} c_{13} s_{13} c_{23} s_{23} c_{23} \sin \delta \]

Problem: coherence (we deal with coherent states and not mass eigenstates of neutrinos)

Ref: Gonzalez-Garcia
Ref: Farsan, Smirnov
Quarks and Leptons

<table>
<thead>
<tr>
<th>Mixing</th>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2, $\theta_{12}$</td>
<td>13°</td>
<td>32°</td>
</tr>
<tr>
<td>2-3, $\theta_{23}$</td>
<td>2.3°</td>
<td>45°</td>
</tr>
<tr>
<td>1-3, $\theta_{13}$</td>
<td>$\sim$ 0.5°</td>
<td>&lt;13°</td>
</tr>
</tbody>
</table>

$\theta_{12} + \theta_{C} = \theta_{23} \sim 45°$

Hierarchy of Mass

- Neutrinos: $|m_2/m_3| > 0.18$
- Charged leptons: $|m_\mu/m_\tau| = 0.06$
- Down quarks: $|m_s/m_b| \sim 0.02 - 0.03$
- Up-quarks: $|m_c/m_t| \sim 0.005$

Ref: Smirnov
Other oscillations? Sterile Neutrinos?

\[ \nu_\mu \Rightarrow \nu_\tau \]
\[ \nu_e \Rightarrow \nu_\mu, \tau \]

Cannot be explained by 3 active neutrinos!

Will be checked by MiniBoone at FNAL (2005)
The LSND Experiment

800 MeV proton beam from LANSCE accelerator

Water target
Copper beamstop

LSND Detector

87.9 ± 22.4 ± 6.0 events.
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.
3.8 σ evidence for oscillation.

Oscillations?

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \]

LSND took data from 1993-98
- 49,000 Coulombs of protons
- L = 30m and 20 < E_\nu < 53 MeV

Saw an excess of:

L/E_\nu (meters/MeV)

Beam Excess

\[ p(\nu_\mu \rightarrow \nu_e, e^n)n \]
\[ p(\nu_e, e^n)n \]
[other]
Too Many $\nu$-Oscillation Signals

Three known neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$ cannot explain three different $\Delta m^2$ values.

$\Delta m_{solar}^2 = m_2^2 - m_1^2 = 5 \times 10^{-5} \text{eV}^2$

$\Delta m_{atmos}^2 = m_3^2 - m_2^2 = 3 \times 10^{-3} \text{eV}^2$

then

$\Delta m_{LSND}^2 = m_3^2 - m_1^2 = \sim 5 \times 10^{-3} \text{eV}^2$  \hspace{1cm} \text{But LSND sees } \sim 1 \text{eV}$

Experimental ideas
- Not all 3 signals are neutrino oscillations
- Unknown uncertainties give false signals

Theoretical ideas
- Neutrinos and antineutrinos have different masses
- More than three types of neutrinos – extra “sterile” neutrino types

with $\Delta m^2 > 0.1 \text{eV}^2$

$m(\nu)$ in cosmologically relevant region?
LSND Oscillation Parameters

$\nu_\mu \rightarrow \nu_\tau$

$\nu_e \rightarrow \nu_\mu$,

$\nu_e \rightarrow \nu_\tau$
MiniBoone Experiment at Fermilab
Estimates of the MiniBoone Signal

goal: $10^{21}$ p on target to cover LSND at $5\sigma$

- ~500k $\nu_\mu$C CC events
- ~50K $\nu_\mu$C NC

**Intrinsic $\nu_e$ background:**
- events: 1,500

**$\mu$ mis-ID background:**
- events: 500

**$\pi^0$ mis-ID background:**
- events: 500

**LSND-based $\nu_\mu \rightarrow \nu_e$:**
- events: 1,000
New Surprises Beyond Mixing of 3 Massive States?

Sterile Neutrinos
- Are they light enough that we can see them?
- They would give a whole new spectrum of mass states and mixings
  ⇒ MiniBooNE and follow-ups are key

Probing for CP violation
- CP violation comes about when a process has a different rate for particles and anti-particles
- Need to measure last mixing angle
  ⇒ \( \theta_{13} \)
- Then look at \( \bar{\nu} \) versus \( \nu \) oscillations to measure \( \delta \)
  ⇒ New long baseline and reactor experiments are key

\[
\begin{pmatrix}
\nu_e \\
\nu_{\mu} \\
\nu_{\tau}
\end{pmatrix} =
\begin{pmatrix}
\sim 0.7 & \sim 0.7 & \sin \theta_{13} e^{i\delta} \\
\sim -0.5 & \sim 0.5 & \sim 0.7 \\
\sim 0.5 & \sim -0.5 & \sim 0.7
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

3+2 models

LSND
Atmospheric
Solar

→ LSND primarily \( \nu_e \)

\[
P_{\text{osc}}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{\text{osc}}(\nu_\alpha \rightarrow \bar{\nu}_\beta)
\]
Experimental Program with Sterile Neutrinos

If sterile neutrinos then many mixing angles, CP phases, and $\Delta m^2$ to include

Measure number of extra masses $\Delta m_{14}^2$, $\Delta m_{15}^2$ ...

Measure mixings: could be many small angles

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s \\
\nu'_s \\
\vdots
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \ldots \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & U_{\mu5} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & U_{\tau5} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} \\
U_{s1}' & U_{s2}' & U_{s3}' & U_{s4}' & U_{s5}' \\
\vdots & \vdots & \vdots & \vdots & \vdots
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4 \\
\nu_5 \\
\vdots
\end{pmatrix}
\]

Map out mixings associated with $\nu_\mu \rightarrow \nu_e$

Map out mixings associated with $\nu_\mu \rightarrow \nu_\tau$

Compare $\nu_\mu$ and $\bar{\nu}_\mu$ oscillations $\Rightarrow$ CP and CPT violations
Theoretical Prejudices before 1995

Natural scale for $\Delta m^2 \sim 10 - 100$ eV$^2$
since needed to explain dark matter

Oscillation mixing angles must be small
like the quark mixing angles

Atmospheric neutrino anomaly must be
other physics or experimental problem
because it needs such a large mixing angle

LSND result doesn’t fit in so must not
be an oscillation signal

In 2004 we know ....
Wrong
Wrong
Wrong

???
Beyond Neutrino Mass & Mixing with Oscillation Experiments

Searching for Direct Evidence of Oscillations

Consistent with standard zenith angle analysis

Neutrino oscillation Neutrino decay Neutrino decoherence

90% allowed regions

Best-fit expectation
\( \Delta m^2 = 2.4 \times 10^{-3}, \sin^2 2\theta = 1.00 \)
\( \chi^2_{\text{min}} = 37.8/40 \text{ d.o.f} \)

First dip is observed as expected from neutrino oscillation
Interdependencies/Redundancies of Experiments

<table>
<thead>
<tr>
<th>What How</th>
<th>Absolute mass scale</th>
<th>Majorana Nature</th>
<th>Hierarchy</th>
<th>$\theta_{13}$</th>
<th>$\delta$</th>
<th>$\alpha$’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$-decay /cosmology</td>
<td>$\times$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta\beta$-decay</td>
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<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
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<td></td>
</tr>
<tr>
<td>Oscillations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

reactor + accelerator

Need all types of experiments
### Particle Properties of the Neutrino

<table>
<thead>
<tr>
<th>Interactions</th>
<th>weak (and gravitational) only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavors</td>
<td>3 active flavors</td>
</tr>
<tr>
<td></td>
<td>sterile flavors?</td>
</tr>
<tr>
<td>Charge</td>
<td></td>
</tr>
<tr>
<td>Spin</td>
<td>s=1/2</td>
</tr>
<tr>
<td>Type</td>
<td>Dirac $\nu \neq \bar{\nu}$</td>
</tr>
<tr>
<td></td>
<td>Majorana $\nu = \bar{\nu}$</td>
</tr>
<tr>
<td>Mass</td>
<td>$m_{\nu e} &lt; 2$ eV from tritium $\beta$ decay</td>
</tr>
<tr>
<td></td>
<td>$m_{\nu \mu} &lt; 170$ keV from $\pi$ decay</td>
</tr>
<tr>
<td></td>
<td>$m_{\nu \tau} &lt; 18$ MeV from $\tau$ decay</td>
</tr>
</tbody>
</table>
Open Questions in Neutrino Physics

• What are the values of $\Delta m^2$, $U_{ij}$ in (2,3)sector?
• Is $U_{13} = 0$?
• What is the level ordering of 2,3 (or 1,3)?
• Is there CP violation for neutrinos?

• Is $U$ 3-dimensional? 4? 6? $\infty$?
  or, is the 3-D version unitary?
  or, are there sterile $\nu$?

→ MiniBoone
→ Direct mass measurements -KATRIN
→ $0\nu\beta\beta$ Majorana
  Exo
  Genius
  etc.

• What are the masses?
• Are $\nu$ Dirac or Majorana particles?