Neutrino Masses and Mixing

\[
\begin{align*}
\nu_3 & \quad 0.058 \\
\nu_2 & \quad 0.050 \\
\nu_1 & \quad 0.009 \\
\text{Atmospheric} & \\
\text{Solar} & \\
\end{align*}
\]
Neutrino Mixing versus Quark Mixing

Leptons

\[
U_\ell = \begin{pmatrix}
0.85 & 0.52 & <0.053 \\
0.33 & 0.62 & -0.72 \\
-0.40 & 0.59 & 0.70
\end{pmatrix}
\]

Why so different???

Quarks

\[
V_q = \begin{pmatrix}
0.976 & 0.22 & 0.003 \\
-0.22 & 0.98 & 0.04 \\
0.007 & -0.04 & 1
\end{pmatrix}
\]

Tri-bimaximal neutrino mixing:

\[
U_{TBM} = \begin{pmatrix}
\sqrt{2/3} & 1/\sqrt{3} & 0 \\
-\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\
-\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2}
\end{pmatrix}
\]

(Harrison, Perkins, Scott 1999)
The Mass Puzzle

fermion masses

(large angle MSW)

\( \nu_1 \rightarrow \nu_2 \rightarrow \nu_3 \)

"Seesaw mechanism"

\[
m \quad \frac{m_D^2}{M} \quad m_D
\]

\( \mu \) (GeV) \( \rightarrow \) MSSM

\( \alpha^{-1} \)
Heavy Majorana Neutrino

- Connection with high mass scales
- With CP violation provides a basis for “leptogenesis”
- Majorana neutrinos ($\nu = \bar{\nu}$)
Goals for the future

- Determine mass values
- Is neutrino = antineutrino?
- Establish $\theta_{13}$ non-zero
- Measure CP violation
  (matter-antimatter difference)
Double-beta decay:
a second-order process
only detectable if first
order beta decay is
ergetically forbidden

Candidate nuclei with Q>2 MeV

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Q (MeV)</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca$\rightarrow^{48}$Ti</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}$Ge$\rightarrow^{76}$Se</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}$Se$\rightarrow^{82}$Kr</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{96}$Zr$\rightarrow^{96}$Mo</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}$Mo$\rightarrow^{100}$Ru</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}$Pd$\rightarrow^{110}$Cd</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>$^{116}$Cd$\rightarrow^{116}$Sn</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}$Sn$\rightarrow^{124}$Te</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>$^{130}$Te$\rightarrow^{130}$Xe</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}$Xe$\rightarrow^{136}$Ba</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}$Nd$\rightarrow^{150}$Sm</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>
There are two varieties of $\beta\beta$ decay

2$\nu$ mode: a conventional 2nd order process can happen only if:

- $\nu = \bar{\nu}$ (Majorana)
- $|\Delta L| = 2$
- $|\Delta (B-L)| = 2$
- $M_\nu \neq 0$ (helicity flip)

![Diagram of 2$\nu$ $\beta\beta$ decay](image)

![Diagram of 0$\nu$ $\beta\beta$ decay](image)
Background due to the Standard Model $2\nu\beta\beta$ decay

The two can be separated in a detector with good energy resolution
Neutrinoless $\beta\beta$ Decay

Whatever processes cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term and thus would represent New Physics: Schechter and Valle,82

By adding only Standard model interactions we obtain

\[(\bar{\nu})_R \rightarrow (\nu)_L\] *Majorana mass term*

→ Observing the $0\nu\beta\beta$ decay implies that $\nu$ are massive Majorana particles.
Majorana Phases

Most general form for 3 generation flavor mixing:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
=
\begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} & s_{12}s_{23}s_{13}e^{i\delta} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha_1/2} & & \\
& e^{i\alpha_2/2} & \\
& & e^{i\alpha_3/2}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- \(\alpha\)'s are CP violating phases (as is \(\delta\))
- \(\alpha\)'s do not contribute to oscillations
$0\nu\beta\beta$ Theory

$$[T_{1/2}^{0\nu}(0^+ \to 0^+)]^{-1} = G^{0\nu}(E_0, Z) \left| M_{GT}^{0\nu} - \frac{g_Y^2}{g_A^2} M_F^{0\nu} \right|^2 \langle m_{\beta\beta} \rangle^2 , \quad (37)$$

where $G^{0\nu}$ is the exactly calculable phase space integral, $\langle m_{\beta\beta} \rangle$ is the effective neutrino mass and $M_{GT}^{0\nu}, M_F^{0\nu}$ are the nuclear matrix elements.

The effective neutrino mass is

$$\langle m_{\beta\beta} \rangle = \left| \sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i} \right| , \quad (38)$$

where the sum is only over light neutrinos ($m_i < 10$ MeV)$^4$. The Majorana phases $\alpha_i$ were defined earlier in Eq.(9). If the neutrinos $\nu_i$ are $CP$ eigenstates, $\alpha_i$ is either 0 or $\pi$. Due to the presence of these unknown phases, cancellation of terms in the sum in Eq.(38) is possible, and $\langle m_{\beta\beta} \rangle$ could be smaller than any of the $m_{\nu_i}$. 
The nuclear matrix elements, Gamow-Teller and Fermi, appear in the combination

\[
M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \equiv \langle f | \sum_{lk} H(r_{lk}, \bar{E}_m) \tau_l^+ \tau_k^+ \left( \vec{\sigma}_l \cdot \vec{\sigma}_k - \frac{g_V^2}{g_A^2} \right) | i \rangle .
\]  (39)

The summation is over all nucleons, \(|i\rangle, (|f\rangle)\) are the initial (final) nuclear states, and \(H(r_{lk}, \bar{E}_m)\) is the ‘neutrino potential’ (Fourier transform of the neutrino propagator) that depends (essentially as \(1/r\)) on the internucleon distance. When evaluating these matrix elements the short-range nucleon-nucleon repulsion must be taken into account due to the mild emphasis on small nucleon separations.
Much progress made recently in accuracy of nuclear matrix elements. (e.g. was found that main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface. → Can use the measured 2νββ T_{1/2} to make a correction.)

Still, if/once 0νββ decay is discovered, the T_{1/2} in more than one nucleus will be needed to pin down neutrino masses.
A Recent Claim for $^{76}\text{Ge}$

$\beta\beta$ is the search for a very rare peak on a continuum of background.

~70 kg-years of data
13 years

The “feature” at 2039 keV is arguably present.
~100kg class experiments

Klapdor et al. 0.24 - 0.58 eV

Ton-scale experiments: the near future

$\beta\beta$ Decay Experiments

$10$ ton $\rightarrow$ $10$ meV

CUORE  EXO  Majorana  GERDA
### Future experiments (a very broad brush, personal view)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Main principle</th>
<th>Fid mass</th>
<th>Lab</th>
<th>Main US funding</th>
<th>Lead continent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>Majorana†</td>
<td>Eres, 2site tag, Cu shield</td>
<td>30-60kg</td>
<td>SUSEL</td>
<td>DoE-NP NSF</td>
<td>N America</td>
</tr>
<tr>
<td></td>
<td>Gerda†</td>
<td>Eres, 2site tag, LAr shield</td>
<td>34.3 kg</td>
<td>G Sasso</td>
<td></td>
<td>Europe</td>
</tr>
<tr>
<td></td>
<td>MaGe/GeMa</td>
<td>See above</td>
<td>~1ton</td>
<td>DUSEL? GS?</td>
<td>DoE-NP NSF</td>
<td>EU? NAm?</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>SNO+</td>
<td>Size/shielding</td>
<td>56 kg</td>
<td>SNOlab</td>
<td></td>
<td>N America</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$ or $^{82}\text{Se}$</td>
<td>SuperNEMO‡</td>
<td>Tracking</td>
<td>100 kg</td>
<td>Canfranc Frejus</td>
<td></td>
<td>Europe</td>
</tr>
<tr>
<td>$^{130}\text{Te}$*</td>
<td>CUORE</td>
<td>E Res.</td>
<td>204 kg</td>
<td>G Sasso</td>
<td>DoE-NP NSF</td>
<td>Europe</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>EXO</td>
<td>Tracking</td>
<td>150 kg</td>
<td>WIPP</td>
<td>DoE-HEP</td>
<td>N America</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ba tag, Track</td>
<td>1-10ton</td>
<td>DUSEL?</td>
<td>DoE-HEP NSF</td>
<td></td>
</tr>
</tbody>
</table>

Each exp above has a US component and some US funding. Funding source listed only if “major”. Experiments in red are US led.

* No isotopic enrichment in baseline design

† Plan to merge efforts for ton-scale experiment

‡ Non-homogeneous detector
Back to Neutrino Mixing...
Maki – Nakagawa – Sakata Matrix

\[ U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \]

\[ = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \]

Future Reactor Experiment!

CP violation

[Graph showing distribution of neutrino fluxes with labels SuperK atmospheric, Solar + KamLAND]
Reactor $\theta_{13}$ Neutrino Experiments

- Chooz, France
- RENO, Korea
- Daya Bay, China
- Angra, Brazil

Under construction.

Proposed and R&D.
\( P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \right) \)

- "Clean" measurements of \( \theta, \Delta m^2 \)
- No CP violation
- Negligible matter effects
Daya Bay Nuclear Power Plant

- 4 reactor cores, 11.6 GW
- 2 more cores in 2011, 5.8 GW
- Mountains provide overburden to shield cosmic-ray backgrounds
- Baseline ~2km
- Multiple detectors → measure ratio
### Experiment Layout

- **Multiple detectors per site cross-check detector efficiency**
- **Two near sites sample flux from reactor groups**

**Total Tunnel length ~ 3000 m**

<table>
<thead>
<tr>
<th></th>
<th>DYB</th>
<th>LA</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>DYB cores</td>
<td>363</td>
<td>1347</td>
<td>1985</td>
</tr>
<tr>
<td>LA cores</td>
<td>857</td>
<td>481</td>
<td>1618</td>
</tr>
<tr>
<td>LA II cores</td>
<td>1307</td>
<td>526</td>
<td>1613</td>
</tr>
</tbody>
</table>
Antineutrino Detector

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

n capture on Gd (30 \(\mu\)s delay)

- 192 8” PMT’s
- 20 T Gd-doped liquid scintillator
- Gamma catcher
- Buffer oil

- 3 zone design
- Uniform response
- No position cut
- 12%/\(\sqrt{E}\) resolution

From Bemporad, Gratta and Vogel

Observable \(\bar{\nu}\) Spectrum

\(E, (\text{MeV})\)
Muon Veto System

Water Cerenkov (2 layers) → Redundant veto system → 99.5% efficient muon rejection
Site Preparation

Daya Bay Near Hall construction (100m underground)

Assembly Building

Tunnel lining

Portal of Tunnel
Hardware Progress

SSV Prototype

4m Acrylic Vessel Prototype

Transporter

Calibration Units
Detector Assembly

Delivery of 4m AV

SS Tank delivery

Clean Room

March 2009: Assembly building occupancy
Summer 2009: Near Hall occupancy
Sensitivity to $\sin^2 2\theta_{13}$

90% CL, 3 years

- Experiment construction: 2008-2011
- Start acquiring data: 2011
- 3 years running
Project Schedule

- October 2007: Ground breaking
- August 2008: CD3 review (DOE start of construction)
- March 2009: Surface Assembly Building occupancy
- Summer 2009: Daya Bay Near Hall occupancy
- Fall 2009: First AD complete
- Summer 2010: Daya Bay Near Hall ready for data
- Summer 2011: Far Hall ready for data

(3 years of data taking to reach goal sensitivity)
$P(\nu_\mu \rightarrow \nu_\tau) = 4c_{13}^2s_{13}^2s_{23}^2 \sin^2 \Delta_{31}$

$+ 8c_{13}^2s_{13}s_{23}c_{23}s_{12}c_{12} \sin \Delta_{31} \cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta \sin \Delta_{21}$

$- 8c_{13}^2s_{13}^2s_{23}^2s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$

$+ 4c_{13}^2s_{12}^2(c_{23}^2s_{12}^2 + s_{12}^2s_{23}^2s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13} \cos \delta) \sin^2 \Delta_{21}$

$- 8c_{13}^2s_{13}s_{23}^2(1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[ \cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right].$
Future US Program:
The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOvA’s sensitivity to the mass ordering.

L = 810 km
$\nu_e$ Appearance at DUSEL

1300 km

$\nu_e$ Unoscillated WBB120 1300km
$\nu_e$ Oscillated WBB120 1300km
$\nu_e$ Signal W68120 1300km
Water Cerenkov vs. Liquid Argon TPC
Mass Hierarchy and CP Violation


Taipei, June 2009
Large Underground Detector

- Long Baseline Neutrino Oscillations
- Nucleon decay (B violation, Mass scale $< M_{\text{GUT}}$?)
- Supernova neutrino detection ($\theta_{13}$, r-process?)
The Lifecycle of Stars

Sun-Like Stars (up to 1.5 times the mass of the Sun) → Red Giant

Stellar Nursery

Red Giant → Planetary Nebula → White Dwarf

Huge Stars (from 1.5 to 3 times the mass of the Sun) → Red Supergiant

Stars form in a nebula, from collapsing clouds of interstellar gas and dust.

Giant Stars (over 3 times the mass of the Sun) → Red Supergiant

Black Dwarf

Supernova → Neutron Star

Black Hole
Evolution of 18 solar mass star

The diagram illustrates the evolution of a star with 18 solar masses, highlighting key stages such as core hydrogen exhaustion, nitrogen burning, core helium exhaustion, carbon ignition, and supernova explosion. It includes timelines for significant events, such as 11 million years B.C. (Ape men emerge), 700,000 B.C. (Homo erectus), and 46,000 B.C. (Homo sapiens). The diagram also marks the transition from gaseous to solid masses, with Earth's orbit and Jupiter's orbit depicted. The diagram uses a Hertzsprung-Russell diagram to show luminosity and surface temperature, with milestones such as Sk-69 202 born 850,000 B.C. (Fire and tool making).
Neutrino spectra

The gravitational energy of the collapsed core (a few $10^{53}$ ergs) is radiated away in neutrinos of all types. There is a large luminosity in neutrinos ($L_\nu > 10^{52}$ ergs/s) for nearly 10 seconds, before it decreases. The luminosity is nearly the same for all neutrino types and is maintained by mass accretion onto the proto-neutron star where the kinetic energy of infall is converted into thermal energy. The neutrinos have approximately the Fermi-Dirac spectra with zero chemical potential. Then

$$\langle E_\nu \rangle = \pi T_\nu; \quad \langle E_\nu^2 \rangle \approx 6 T_\nu^2$$

The average energy of the emitted neutrinos ($\sim 15$ MeV) is much less than the energy of neutrinos produced in the high-density core ($\sim 150$ MeV). When the neutrinos diffuse out of this core, they are down-scattered in energy. As they carry away the entire energy, there are about 10 neutrinos emitted for every one produced in the center.
Supernova Neutrino Detection

SN1987A:
~ 20 $\bar{\nu}_e p \rightarrow e^+ n$ events

SN200??:
~ $10^4$ CC events
~ $10^3$ NC events
Spectrum modification due to neutrino mixing