Particle Physics: Neutrinos – part I

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Week 8: March 25, 2017
Columbia University Science Honors Program
Course Policies

**Attendance**
Up to four absences
Send email notifications of all absences to
shpattendance@columbia.edu.

Please, no cell phones

**Please, ask questions!**

**Lecture materials**
https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram
Schedule

1. Introduction (Inês)
2. History of Particle Physics (José)
3. Special Relativity (José)
4. Quantum Mechanics (Inês)
5. Experimental Methods (Cris)
6. The Standard Model—Overview (Cris)
7. The Standard Model—Limitations (Cris)
8. Neutrinos – part I (José)
9. Neutrinos – part II (José)
10. LHC and Experiments (Inês)
11. The Higgs Boson and Beyond (Inês)
12. Particle Cosmology (Cris)
Neutrinos in the Standard Model

- Only left-handed neutrinos (and right-handed antineutrinos) in the Standard Model.
- Initially implemented as massless particles.
  - **Neutrino oscillations** show neutrinos have mass!
- Why neutrino masses are so different from the other fermions?
  - Are neutrinos acquiring mass through the same mechanism (Higgs) or from something else?
Neutrino oscillations (2-neutrino example)

- Consequence of neutrino mixing (quantum superposition, as in Schrödinger's cat): the neutrinos that interact are not the same as the neutrinos that propagate.

- Two flavor approximation:

\[
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_x\rangle
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle
\end{pmatrix}
\]

- Transition probability (derivation in blackboard):

\[
P_{lx(x \neq x)}^{2\nu}(L, E) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
\]

- **Survival** probability:

\[
P_{ll}^{2\nu}(L, E) = 1 - P_{lx(x \neq x)}^{2\nu}(L, E)
\]

- Neutrino oscillation implies neutrinos are massive and non-degenerated.
3 neutrino mixing

- **Flavor eigenstates** \((\nu_e, \nu_\mu, \nu_\tau) \neq \text{mass eigenstates} \, (\nu_1, \nu_2, \nu_3)\).
- Related by **Pontecorvo-Maki-Nakagawa-Sakata mixing matrix**:
  3 neutrinos → 3 angles \((\theta_{12}, \theta_{23}, \theta_{13})\) + 1 CP-violating phase \((\delta)\).

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U
\begin{pmatrix}
1 \\
c_{23} & s_{23} \\
-s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & s_{13} e^{-i\delta} \\
-s_{13} e^{i\delta} & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} \\
-s_{12} & c_{12}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\rightarrow
\begin{pmatrix}
m_1 \\
m_2 \\
m_3
\end{pmatrix}
\]

\(c_{ij} = \cos \theta_{ij}, \quad s_{ij} = \sin \theta_{ij}\)

- CP violation only possible if all three angles are not zero.
Measurement of $\theta_{12}$ and $\Delta m^2_{21}$
Solar experiments
Solar neutrinos: pp chain

- 98.4% of Sun's fusion energy.

\[(pp) \quad p + p \rightarrow ^2\text{H} + e^+ + \nu_e \quad (99.6\%)\]

\[p + e^- + p \rightarrow ^2\text{H} + \nu_e \quad (0.4\%)\]

\[^2\text{H} + p \rightarrow ^3\text{He} + \gamma \]

\[^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \quad (85\%)\]

\[^4\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \quad (15\%)\]

\[^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \quad (99.87\%)\]

\[^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \quad (0.13\%)\]

\[^7\text{Li} + p \rightarrow ^4\text{He} \quad (pp\text{II})\]

\[^8\text{B} \rightarrow ^6\text{Be}^* + e^+ + \nu_e \quad (8^\text{B})\]

\[^8\text{Be}^* \rightarrow ^4\text{He} \quad (pp\text{III})\]
Solar neutrinos: CNO cycle

- 1.6% of Sun's fusion energy.
Solar neutrinos: energy spectrum
Homestake experiment
Homestake experiment

- Detection of solar neutrinos using the reaction:
  \[ \nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar} \]

- Ratio of observed to predicted:
  \[ \frac{R_{\text{Cl}}}{R_{\text{SSM}}} = 0.301 \pm 0.027 \]

- Missing neutrinos!
Kamiokande
Kamiokande

- Detection of solar neutrinos using the reaction:

\[ \nu_l + e^- \rightarrow \nu_l + e^- \]

- Ratio of observed to predicted:

\[ \frac{\Phi_{\text{Kamiokande}}}{\Phi_{\text{SSM}}} = 0.484 \pm 0.066. \]

- Missing neutrinos again!
Super-Kamiokande
Super-Kamiokande

- Detection of solar neutrinos using the reaction:
  \[ \nu_l + e^- \rightarrow \nu_l + e^- \]
- Ratio of observed to predicted:
  \[ \frac{\Phi_{SK-I}}{\Phi_{SSM}} = 0.406 \pm 0.014 \]
- Improved result over Kamiokande, neutrinos still missing!
Super-Kamiokande
Super-Kamiokande

- NEUTRINOGRAPHY of the Sun. 500 days exposure!
SNO
SNO

- Detection of solar neutrinos using the reaction:
  \[ \nu_l + e^- \rightarrow \nu_l + e^- \quad \text{(ES)} \]
  \[ \nu_e + D \rightarrow e^- + p + p \quad \text{(CC)} \]
  \[ \nu_l + D \rightarrow \nu_l + p + n \quad \text{(NC)} \]

- Ratio of observed to predicted:
  \[ \frac{\Phi^{ES}_{SNO}}{\Phi_{SSM}} = 0.406 \pm 0.046 \]
  \[ \frac{\Phi^{CC}_{SNO}}{\Phi_{SSM}} = 0.290 \pm 0.017 \]
  \[ \frac{\Phi^{NC}_{SNO}}{\Phi_{SSM}} = 0.853 \pm 0.075 \]
\[ \Phi^{\nu_e}_{\text{SNO}} + r^{\text{ES}} \Phi^{\nu_{\mu,\tau}}_{\text{SNO}} = \Phi^{\text{ES}}_{\text{SNO}} \]

\[ r^{\text{ES}} \equiv \frac{\sigma^{\text{ES}}_{\nu_{\mu,\tau}}}{\sigma^{\text{ES}}_{\nu_e}} \approx 0.1553. \]

\[ \Phi^{\nu_e}_{\text{SNO}} = \Phi^{\text{CC}}_{\text{SNO}} \]

\[ \Phi^{\nu_e}_{\text{SNO}} + \Phi^{\nu_{\mu,\tau}}_{\text{SNO}} = \Phi^{\text{NC}}_{\text{SNO}} \]
KamLAND

![Diagram of the KamLAND detector system, including a liquid scintillator vessel, containment vessel, outer detector, and calibration device.](image)
KamLAND

C.-E. Wulz

Wien, Mai 2005
$\bar{\nu}_e$ production at nuclear reactors

- Fission of nuclear fuel ($^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$) produces neutron rich fission products.

- $\beta^-$ decay of fission products:
  \[ \frac{A}{Z}X \rightarrow \frac{A}{Z+1}Y + e^- + \bar{\nu}_e \]

- Average per fission:
  - 200 MeV released.
  - 6 antineutrinos.

- Nuclear power plants: greatest man-made antineutrino source.

- Need to consider nuclear fuel evolution.
KamLAND

- Detection of reactor neutrinos using the inverse beta-decay reaction:
  \[
  \bar{\nu}_e + p \rightarrow e^+ + n
  \]
Solar + KamLAND results
Measurement of $\theta_{23}$ and $\Delta m^2_{\text{atm}}$
Atmospheric neutrinos
Super-Kamiokande results

![Graphs showing the number of events for different energy categories (Sub-GeV e-like, Sub-GeV μ-like, Multi-GeV e-like, Multi-GeV μ-like + PC)]
IceCube
Accelerator neutrinos
T2K & MINOS experiments

Super-Kamiokande

J-PARC

Near Detector
280 m

295 km

1000 m

Neutrino Beam

The MINOS Experiment

Fermilab

Near Detector: 980 tons

Far Detector: 5400 tons

Soudan

Duluth

Lake Superior

Madison

Lake Michigan

Fermilab

MN

WI

MI

IA

IL

IN

MO
T2K & MINOS experiments
Measurement of $\theta_{13}$
Measurement of $\theta_{13}$ with reactors

- For baselines of \(~ 1\) km, the probability can be approximated by:

$$P_{ee}(L, E) 
\approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right)
\approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( 1.27 \frac{\Delta m_{31}^2 [eV^2] L [m]}{E [MeV]} \right)$$

\(E = 4\) MeV
Measurement of $\theta_{13}$ with two-detector reactor experiments

- Antineutrinos detected by inverse $\beta$-decay: $\bar{\nu}_{e} + p \rightarrow e^+ + n$
- Reactor prediction and the antineutrino detection systematics can be reduced if two identical detectors, one near and one far from the reactors, are built.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactor power (GW$_{th}$)</th>
<th>Distance (m) Near / Far</th>
<th>Depth (mwe) Near / Far</th>
<th>Target mass (ton) × detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>8.5</td>
<td>400 / 1050</td>
<td>120 / 300</td>
<td>$8 \times 2$</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>17.4</td>
<td>470, 576 / 1648</td>
<td>260 / 860</td>
<td>$20 \times 8$</td>
</tr>
<tr>
<td>RENO</td>
<td>16.5</td>
<td>294 / 1383</td>
<td>120 / 450</td>
<td>$16 \times 2$</td>
</tr>
</tbody>
</table>
Double Chooz: a two-detector experiment

Near Detector
- L ~ 400 m
- ~ 300 ν/day
- 120 mwe
- December 2014

Chooz-B reactors
- PWR N4s
- $2 \times 4.25 \text{ GW}_th$
- ~ $10^{21} \nu/s$
- 100%ν\text{e}

Far Detector
- L ~ 1050 m
- ~ 40 ν/day
- 300 mwe
- April 2011

EDF’s Chooz nuclear power plant (Ardennes, France)
Electron antineutrino detection

inverse Beta Decay (IBD):
- Reaction threshold: $E_\nu \geq 1.806$ MeV.
- Disappearance experiment.
- Well known cross-section (0.2%).
- Coincidence of 2 signals: background suppression.

Prompt signal:
- Positron kinetic energy + $\gamma$'s from annihilation.
- $E_{\text{prompt}} \approx E_\nu - 0.782$ MeV
- $E_{\text{prompt}} \sim 1 - 9$ MeV

Delayed signal:
- $\gamma$'s from radiative neutron capture.
- Gd: $\Delta T \sim 30$ $\mu$s, $E_{\text{delayed}} \sim 8$ MeV.
- H: $\Delta T \sim 200$ $\mu$s, $E_{\text{delayed}} = 2.22$ MeV.
The Double Chooz Far Detector

Inner Detector:
- **Neutrino Target**: acrylic vessel (8 mm) with 10.3 m$^3$ Gd-loaded (1 g/l) liquid scintillator.
- **Gamma-Catcher**: acrylic (12 mm) vessel with 22.5 m$^3$ of liquid scintillator.
- **Buffer**: stainless steel (3 mm) vessel supporting 390 10” PMTs, with 110 m$^3$ of non-scintillating mineral oil.

Outer Detector:
- **Inner Veto**: steel (10 mm) vessel supporting 78 8” PMTs, with 90 m$^3$ of liquid scintillator.
- **Shielding**: 15 cm steel.
- **Outer Veto**: plastic scintillator strips.
Latest measurements of $\theta_{13}$

$\theta_{13}$ unknown until 2011. Huge progress in a few years.

Double Chooz
JHEP 1410, 086 (2014)

Preliminary (Moriond)

Daya Bay
PRL 115, 111802 (2015)

RENO
Preliminary (arXiv:1511.05849)

T2K
PRD 91, 072010 (2015)

- $\Delta m^2 > 0$
- $\Delta m^2 < 0$

A. Cabrera, FNAL seminar 03/25/2016
First glimpse of $\delta$

- $\nu_\mu \rightarrow \nu_e$ depends on the mass hierarchy and CP-violating phase.

**Critical input:** Using the $\theta_{13}$ from the reactor experiments, the mass hierarchy and the CP-violating phase can be studied.
3 neutrinos: mass hierarchy

- 2 squared-mass differences
- But which is on top of which?
- The Solar + KamLAND experiments show that the mass eigenstate $\nu_2$ is heavier than $\nu_1$.

- Which is the **lightest neutrino**? Two possibilities left:
Future: $\delta$ and mass hierarchy

- Both CP-violating phase and the mass hierarchy can be measured in a long-baseline accelerator experiment.
- Need a long baseline and a broad-energy beam to disentangle CP violation caused by matter effects (Earth is made only from matter) from the intrinsic CP violation.