Seeking the Origin of Asymmetry

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Outline

• The Big Question:
  – Why is there much more matter than anti-matter in our universe?
  – Is neutrino the key to this question?

• The Overall Strategy:
  – Neutrino vs. Antineutrino oscillations
  – Will there be a signal?

  – Will the detector technology be viable?

• The Experimental Design and Future Challenges
Where is all the anti-matter?

$$\eta := \frac{N_{\text{baryon}}}{N_\gamma} = \begin{cases} (6.0 \pm 0.1) \times 10^{-10} & \text{(BBN)} \\ (6.0 \pm 0.07) \times 10^{-10} & \text{(CMB)} \end{cases}$$
CP Violation: Asymmetry between Matter and Anti-matter

Parity (P): \( \begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} \)

Charge (C): \( q \rightarrow -q \)

Time (T): \( t \rightarrow -t \)

CP violation \( \rightarrow \) physics laws governing the interaction of matter are different from those governing anti-matter
Is there CP violation (CPV) in the Standard Model of Particle Physics?

- Yes, CPV exists in the quark sector, but not enough to explain the observed asymmetry
- What about the lepton (neutrino) sector?
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Some Facts about the Neutrino

- Neutrinos interact through weak interaction
  - It takes a wall thicker than our galaxy to stop a neutrino
- Neutrinos have non-zero mass
  - Physics beyond the standard model
- The smallness of neutrino mass also suggests a new mechanism of the mass generation

Energy Budget of the Universe:
- Dark Energy ~73%
- Dark Matter ~23%
- Visible Matter ~4%
- Neutrino >~ 0.3%
Some Facts about the Neutrino

- Neutrino Flavor Eigenstate ≠ Mass Eigenstate
Neutrino Oscillation

Neutrino Flavor Eigenstate $\neq$ Neutrino Mass Eigenstate

$$\begin{align*}
\begin{pmatrix}
\nu_\alpha \\
\nu_\beta
\end{pmatrix} &= \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix} \cdot \begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix} = \begin{pmatrix} m_1 \\
m_2
\end{pmatrix}
\end{align*}$$

Neutrino are produced and detected by weak interaction, but propagate as mass eigenstates.

$$|\nu_\alpha(t)\rangle = \cos \theta \cdot e^{-i(P_1 \cdot r - E_t)} |\nu_1(0)\rangle + \sin \theta \cdot e^{-i(P_2 \cdot r - E_t)} |\nu_2(0)\rangle$$

\begin{align*}
\text{Appearance} \\
P(\nu_\alpha \rightarrow \nu_\beta) &= \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2_{21} \left[\frac{eV^2}{E[GeV]}\right] \frac{L[km]}{E[GeV]}\right) \\
\text{Survival} \\
P(\nu_\alpha \rightarrow \nu_\alpha) &= 1 - P(\nu_\alpha \rightarrow \nu_\beta) = \left(\Delta m^2_{ij} = m_i^2 - m_j^2\right)
\end{align*}
\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\theta_{23} \sim 45^\circ\]

\[\theta_{13} \text{ and } \delta_{CP}\]

\[\theta_{12} = \sim 32^\circ\]

CP-violation: \[P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)\]
Available Neutrino Sources

CP-violation: \[ P \left( \nu_\mu \rightarrow \nu_e \right) \neq P \left( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \right) \]
Periodic Summary

• To find the origin of matter-anti-matter asymmetry, we decide to look at the neutrino sector

• With all available channels and practical constraints, we decide to search for new CP violation

\[
P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)
\]

• Is this approach viable?

• What about the detector technology?
Will the signal be non-zero? $\theta_{13}$

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \propto 1 - \sin^2 2\theta_{13}$

$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13}$

- $\theta_{13}$ is one of three neutrino mixing angles
- Its value was unknown prior to 2012
- Do a new experiment to measure $\theta_{13}$: Daya Bay
Reactor Neutrinos

- Pure anti-$\nu_e$ source
- $\sim 6$ anti-$\nu_e$ per fission
- $\sim 2 \times 10^{20}$ anti-$\nu_e$/GW$_{th}$/sec
- At 1 km, $\sim 1$ event/day/ton/GW
The largest, deepest reactor $\Theta_{13}$ experiment in Town
Keys to High Precision

• Statistics $\rightarrow$ Precision
  Powerful reactors (17.6 GW) + Large Mass (80 ton)

Far/Near $v_e$ Ratio  
Distances from reactor  
Oscillation deficit

$$\frac{N_{far}}{N_{near}} = \left( \frac{L_n}{L_f} \right)^2 \cdot \left( \frac{P_{survival}(E, L_f)}{P_{survival}(E, L_n)} \right)$$

• Systematics $\rightarrow$ Accuracy
  – Reactor: using near/far to form ratio + baseline (near $\sim$0.4 km, far $\sim$1.7 km)
  – Detector: “identical detectors” + “precise detector calibration”
  – Background: deep underground + active/passive shielding
Daya Bay Anti-$\nu_e$ Detector

Reflectors at top/bottom of cylinder

192 Photomultipliers on the outside wall

Steel tank
40 ton mineral oil

Inner acrylic tank
20 ton Gd-loaded liquid scintillator

Outer acrylic tank
20 ton liquid scintillator

Automated calibration system

5 m diameter
Detectors in 3 Sites

Experimental Hall 1: Data taking began Aug. 15, 2011

Experimental Hall 2: Began 1 detector operation on Nov. 5, 2011

Experimental Hall 3: Began 3 detectors operation on Dec. 24, 2011
The Hunting Race for $\theta_{13}$ Since 2011

March 2012, Daya Bay reported the discovery of non-zero value of $\theta_{13}$ with a statistical significance $> 5\sigma$.
A Top-10 Scientific Breakthrough of 2012

The Discovery of the Higgs Boson

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is in high-energy physics. The discovery of the Higgs boson, after more than 40 years of searching, completes the standard model of physics and is arguably the key to the exploration of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Runners-Up

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

Science 338, 1527

2015 Sambamurti Lecture: Xin Qian
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\text{CP-violation: } P\left(\nu_\mu \rightarrow \nu_e\right) \neq P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)
\]

• Is this approach viable?

Yes, \(\theta_{13}\) is non-zero \(\sim 8.4^\circ\)

• What about the detector technology?
Signal: $\nu_\mu \rightarrow \nu_e$

Appearance

- Oscillation patterns are very sensitive to the $\delta_{\text{CP}}$ and the mass hierarchy
Accelerator Neutrino Experiment

- Accelerator Neutrino Beam
- Far Detector to measure Neutrino Oscillation
- Near Detector to categorize Neutrino beam

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu (~100\%) \]

...
Recent Accelerator Neutrino Beams

**NUMI @ FNAL**
- Target
- Horns
- Decay Pipe
- Absorber
- Hadron Monitor
- Muon Monitors
- 10 m
- 30 m
- 675 m
- 5 m
- Rock
- 12 m
- 18 m

**BNB @ FNAL**
- Protons (8 GeV)
- Target and horn

**CNGS**
- Target beam instrumentation downstream (TBD)
- Hadron stop
- Target in Gran Sasso
- 100 m
- 992 m
- 18.2 m
- 5 m
- 67 m
- 5 m

**J-PARC**
- Near Detectors
- Beam Dump
- Decay Volume
- Target Station
- Target
- Protons

2015 Sambamurti Lecture: Xin Qian
Signal and Background

\[ \begin{align*}
\nu_e + A & \to e^- + X \\
\bar{\nu}_e + A & \to e^+ + X \\
\nu_\mu + A & \to \mu^- + X \\
\bar{\nu}_\mu + A & \to \mu^+ + X \\
\nu_\tau + A & \to \tau^- + X \\
\bar{\nu}_\tau + A & \to \tau^+ + X \\
\end{align*} \]

Neutral-Current: \( \nu + A \to \nu + X \)

It is important to have a detector which can pick up the electron-neutrinos.
It is important to have a detector which can differentiate these reactions.
Requirements on Detector Technology

- Capability to have excellent differentiation power between signal and background for various reactions
- Detector needs to be able to scale to several 10s of ktons economically

Answer: Liquid Argon Time Projection Chambers
3D Image of Neutrino Interaction
Excellent new opportunity with high res. LArTPC

- Argon: most abundant noble gas (1.3% by weight)
- Electron drift $v$: 1.6 km/s
- Position resolution $\sim$ mm
- PID: $dE/dx$ through charge collection + event topology

First proposed by C. Rubbia, 1977 $\rightarrow$ ICARUS; time

dE/dx of 1 MIP: 2.1 MeV/cm

First proposed by C. Rubbia, 1977 $\rightarrow$ ICARUS; time
For 3D demo, visit http://www.phy.bnl.gov/wire-cell/examples/mvd/nue-cc-v2/#/1

Electron Shower

Hadronic Shower
For 3D demo, visit
http://www.phy.bnl.gov/wire-cell/examples/list/

Neutral pion

Neutrino interaction buried under cosmics
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\]

- Is this approach viable?
  
  Yes, $\theta_{13}$ is non-zero $\sim 8.4^\circ$

- What about the detector technology?
  
  LArTPC is a very promising, but complicated detector technology. It is crucial to gradually scale up and practice this new technology $\rightarrow$ MicroBooNE an 80 tons LArTPC
Fermilab’s Booster Neutrino Beam (BNB)

Linac
Length: 150m
Proton Energy: 400 MeV

Booster
Circumference: 468m
Proton Energy: 8 GeV

Fermilab’s low-energy neutrino beam
$\langle E_{\nu} \rangle \approx 700$ MeV

Target and Horn
Accelerates protons to 8 GeV

Dirt
Decay tunnel
$E \approx 800$ MeV

MicroBooNE detector
MicroBooNE LArTPC

- Time Projection Chamber
  - 3 wire planes
  - 8256 channels
  - 1.6 ms drift time
- Optical system
  - 32 cryogenic PMTs
- Laser-based Calibration System
- High Voltage System
- Many innovative technologies

10.3 x 2.3 x 2.5 m
Uniform field of 500 V/cm
170 tons of purified LAr
Moving day!
June 23rd, 2014

Data is coming!
The Experimental Design and Future Challenges
Deep Underground Neutrino Experiment

- A horn-produced broad band beam with 60-120 GeV protons at 1200 kW (upgradable to 2.3 MW) from FNAL
- A baseline of 1300 km towards the Sanford Underground Research Facility in Lead, South Dakota
- A 40 kt fiducial volume Liquid Argon Time Projection Chamber located at the 4850 ft level
- A high resolution near detector at FNAL
- This configuration will be achieved in phases according to $ constraints

Aim for CPV, MH, precision measurements of $\Delta m^2_{32}$, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, and $\delta_{\text{CP}}$
One 10 kton LArTPC
There are many challenges ahead

• How to scale up the detector to 40 kt?
• How to achieve high purity argon at this scale?
• How to properly reconstruct neutrino interaction events to maximize the potential of this technology?
• How to properly control the systematics for precision measurements?
• How to collect enough resources for construction?
• How to maintain a healthy field with such a long-term project?
• …
Summary

• We are lucky that $\theta_{13}$ is non-zero

• LArTPC technology is promising and under healthy development

• Design of next-generation long-baseline accelerator neutrino experiment is sound

• It has been a long journey to search for new CP violation to explain why we are made of matter

• Our patience will be rewarded, exciting decades to come!
In Memorium

Aditya Sambamurti
1961-1992
Physics Program Of MicroBooNE

- MicroBooNE
  - ~eV Sterile Neutrino?
- LAr-ND/T600
  - (Anti)-Neutrino-Argon Cross Section
- LBNF
  - MH, CPV Unitarity Test

μBooNE