NEUTRINOS: Masters of Surprise

R. D. McKeown
UVa Physics Colloquium
Nov. 22, 2013
Outline

- Introduction to neutrinos and oscillations
- Reactor antineutrino experiments
- KamLAND
- Daya Bay
- Future experiments
- Conclusions
Nuclear Beta Decay

• Since 1920’s physicists have observed beta decay (e.g. $^{14}\text{C} \rightarrow ^{14}\text{N} + \text{e}^-$)

• But the electron energy distribution is continuous:

• Where did the energy go??
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li⁶ nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lightened by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
W. Pauli

“I have done a terrible thing, I have postulated a particle that cannot be detected.”
Surprise: Detectable after all!

Discovery of the Neutrino – 1956
Reines and Cowan

Finally, we chose to look for the reaction $\bar{\nu}_e + p \rightarrow n + e^+$. If the free neutrino exists, this inverse beta decay reaction has to be there.

F. Reines, Nobel Lecture, 1995
August 11, 1967

Dear Willy,

I do have a preliminary result from our first good run…
This limit is quite low…

Please regard these results as very preliminary. There are several points that must be checked before we are certain this is a bonafide observation. I will collect another sample in September—we are ready now, turn on the sun.

Standard Solar Model Calculation
Subsequent History

- 60’s and 70’s – n’s studied in accelerator-based production:
  \[ n_e \neq n_m \]

- 1980-present: the quest for neutrino mass and oscillations - n’s as dark matter??

"All you have to do is imagine something that does practically nothing. You can use your son-in-law as a prototype."
1998: Surprise!

Super-Kamiokande reports first evidence for neutrino oscillations!
Two Generation Model

\[
|\nu_e\rangle = \cos \theta \, |\nu_1\rangle + \sin \theta \, |\nu_2\rangle
\]

\[
A_e |\nu_e\rangle + A_\mu |\nu_\mu\rangle
\]

\[
|\nu_1, \nu_2\rangle \quad \text{mass eigenstates} \quad m_1, m_2
\]

\[
\Delta m^2 = m_1^2 - m_2^2
\]

\[
P_\mu = |A_\mu|^2 = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right)
\]

\[
P_e = |A_e|^2 = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right)
\]

Requires:
- Neutrinos have nonzero mass
- Flavor mixing
Three Generations of Neutrinos
Pontecorvo Maki – Nakagawa – Sakata Matrix

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

\[
= \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\times
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

3\textsuperscript{rd} mixing angle

CP violation

\[
\Delta m^2, \text{eV}^2
\]

SuperK atmospheric

Solar + KamLAND

\[
\sin^2 2\theta
\]
More Solar Neutrino Results

(Bahcall, Krastev and Smirnov, 2001)
2002: SNO finds missing solar neutrinos!!

Measured neutral current process:

\[ n_x + d \rightarrow n_x + p + n \]

\[ \phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}^{(stat)}^{+0.36}_{-0.34}^{(syst)} \times 10^6 /\text{cm}^2\text{s} \]

\[ f_{SSM} = 5.15 \times 10^6 /\text{cm}^2\text{s} \]
• $\bar{n}_e$ from n-rich fission products
• detection via inverse beta decay ($\bar{n}_e + p \rightarrow e^+ + n$)
• Measure flux and energy spectrum
Nuclear Reactors make Antineutrinos

\[ Z = N \]

\[ (n \rightarrow p + e + \bar{n}) \times 6 \]

Fission (200 MeV)

Uranium
The Reactor Neutrino Flux and Spectrum

- $^{235}$U, $^{239}$Pu, $^{241}$Pu from $b$ measurements
- $^{238}$U calculated
- Time dependence due to fuel cycle

~ 200 MeV per fission
~ 6 $\nu_e$ per fission
~ $2 \times 10^{20}$ $\nu_e$ /GWth sec

Reactor Isotopes
Detection Signal

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

Coincidence signal:

- **Prompt**: \( e^+ \) annihilation \( \rightarrow E_n = E_{\text{prompt}} + E_n + 0.8 \text{ MeV} \)
- **Delayed**: \( n+p \) 180 \( ms \) capture time, 2.2 MeV
  \( n+Gd \) 30 \( ms \) capture time, 8 MeV
The $\bar{\nu}_e$ energy spectrum

$\nu_e + p \rightarrow n + e^+$
cross section
($\sim 10^{-42}$ cm$^2$)

Calculated reactor $\bar{\nu}_e$ spectrum

Neutrinos with $E < 1.8$ MeV
are not detected
KamLAND used the entire Japanese nuclear power industry as a long-baseline neutrino source.

Neutrinos were “free of charge”!
2003: KamLAND Surprise

LMA:
\[ Dm^2 = 5.5 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 2Q = 0.833 \]

KamLAND Result (2008)

Best combined fit values:
\[ Dm^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta = 0.47^{+0.06}_{-0.05} \]

PRL 100, 221803 (2008)
The Mass Puzzle

 fermion masses

(large angle MSW)

$\nu_1 \rightarrow \nu_2 \rightarrow \nu_3$

$\nu_L \rightarrow \nu_R$

$m_{\nu} = \frac{m_D^2}{M} \ll m_D$

“Seesaw mechanism”

$m_D \ll m_{\nu}$

$\alpha_i^{-1}$

$\mu$ (GeV)

MSSM

$U(1)$

$SU(2)$

$SU(3)$
Pontecorvo Maki – Nakagawa – Sakata Matrix

\[ U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \]

Gateway to CP Violation!

\[ s_{13} e^{-i\delta} \]

CP violation

SuperK atmospheric

Solar + KamLAND

Jefferson Lab

R. McKeown  Nov. 22, 2013  25
Neutrino vs. Quark Mixing

Leptons

\[ U_\ell = \begin{pmatrix} 0.85 & 0.52 & \text{sin } q_{13} \\ 0.33 & 0.62 & -0.72 \\ -0.40 & 0.59 & 0.70 \end{pmatrix} \]

Quarks

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

Why so different???

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)
CHOOZ/Palo Verde limits for $\nu_{13}$

(2001-3)

2008 MINOS result:

$$|Dm^2_{32}| = 2.43 \pm 0.13 \times 10^{-3} \text{eV}^2$$

$$\sin^2 2\theta_{13} < 0.15$$

(90% CL)
Recent Reactor Flux Analysis (2011)

- PRD 83, 073006 (2011)
- 0.943 ± 0.023
$\bar{n}_e$ Survival Probability
(3 generations)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2 \left( \frac{\Delta m_{ee}^2 \cdot \frac{L}{E}}{E} \right) - \cos^4 \theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2 \left( \frac{\Delta m_{21}^2 \cdot \frac{L}{E}}{E} \right)$$

$$| \Delta m_{ee}^2 | \sim | \Delta m_{32}^2 | \approx | \Delta m_{31}^2 | >> | \Delta m_{21}^2 |$$

- “Clean” measurements of $q$, $Dm^2$
- Far/near ratio to cancel uncertainty in reactor flux
New Reactor $\theta_{13}$ Neutrino Experiments

- Chooz, France
- RENO, Korea
- Daya Bay, China
Daya Bay Collaboration
An International Effort

Asia (20)
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (16)

Europe (3)
Charles Univ., Dubna, Kurchatov Inst.

~240 collaborators
Daya Bay - A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing $17.4 \text{ GW}_{th}$ ($6 \times 2.95 \text{ GW}_{th}$)
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

Reactors produce $\sim 2 \times 10^{20}$ antineutrinos/sec/GW
Daya Bay Experiment Layout

6 antineutrino detectors in 3 underground experimental halls

6 reactor cores

<table>
<thead>
<tr>
<th></th>
<th>Overburden</th>
<th>$R_\mu$</th>
<th>$E_\mu$</th>
<th>D1,D2</th>
<th>L1,L2</th>
<th>L3,L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>280</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
<td>1307</td>
</tr>
<tr>
<td>EH2</td>
<td>300</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
<td>528</td>
</tr>
<tr>
<td>EH3</td>
<td>880</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
<td>1548</td>
</tr>
</tbody>
</table>
Daya Bay Experiment Layout

Hall 1: began 2AD operation on Sep. 23, 2011

Hall 2: began 1 AD operation on Nov. 5, 2011

Hall 3: began 3AD operation on Dec. 24, 2011
Antineutrino Detectors

6 ‘functionally identical’ detectors:
Reduce systematic uncertainties

3 nested cylinders:
Inner: 20 tons Gd-doped LS (d=3.1m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

Each detector:
192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides (7.5 / \sqrt{E} + 0.9)% energy resolution
Detector Filling and Target Mass Measurement

ISO tank on load cells

Detector in scintillator hall

coriolis flow meters

Target mass determination error ± 3kg out of 20,000

<0.03% during data taking period

Detectors are filled from same reservoirs "in-pairs" within < 2 weeks.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Relative</th>
<th>Absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons/kg</td>
<td>neg.</td>
<td>0.47%</td>
</tr>
<tr>
<td>Density (kg/L)</td>
<td>neg.</td>
<td>neg.</td>
</tr>
<tr>
<td>Total mass</td>
<td>0.015%</td>
<td>0.015%</td>
</tr>
<tr>
<td>Overflow tank geometry</td>
<td>0.0066%</td>
<td>0.0066%</td>
</tr>
<tr>
<td>Overflow sensor calibration</td>
<td>0.0043%</td>
<td>0.0043%</td>
</tr>
<tr>
<td>Bellows Capacity</td>
<td>0.0025%</td>
<td>0.0025%</td>
</tr>
<tr>
<td>Target mass</td>
<td>0.017%</td>
<td>0.017%</td>
</tr>
<tr>
<td>Target protons</td>
<td>0.017%</td>
<td>0.47%</td>
</tr>
</tbody>
</table>
Automated Calibration System

3 Automatic calibration units (ACUs) on each detector

Top view

3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz $^{68}$Ge (0 KE $e^+ = 2 \times 0.511$ MeV $\gamma$’s)
- 0.5 Hz $^{241}$Am-$^{13}$C neutron source (3.5 MeV n without $\gamma$) + 100 Hz $^{60}$Co gamma source (1.173+1.332 MeV $\gamma$)
- LED diffuser ball (500 Hz) for $T_0$ and gain

Three axes: center, edge of target, middle of gamma catcher
Antineutrino (IBD) Selection

Selection of Prompt + Delayed
- Reject Flashers
- Prompt Positron: $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
- Delayed Neutron: $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
- Capture time: $1 \mu s < \Delta t < 200 \mu s$
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  No other signal > 0.7 MeV
  in -200 µs to 200 µs of IBD.

Selection driven by uncertainty in relative detector efficiency

\[
\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]
\]

Uncertainty in relative $E_d$ efficiency (0.12%) between detectors is largest systematic.
March 2012: $q_{13}$ Surprise!

Compare measured rates and spectra

$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

$M_n$ are the measured rates in each detector. Weights $\alpha_i, \beta_i$ are determined from baselines and reactor fluxes.

$R = 0.940 \pm 0.011$ (stat) $\pm 0.004$ (syst)

Clear observation of far site deficit!

Spectral distortion consistent with oscillation.
March 2012 Rate Analysis

Estimate $\theta_{13}$ using measured rates in each detector.

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)}$$

$$\sin^2 2\theta_{13} = 0 \text{ excluded at } 5.2\sigma$$

Uses standard $\chi^2$ approach.

Far vs. near relative measurement. [Absolute rate is not constrained.]

Consistent results obtained by independent analyses, different reactor flux models.
July 2013: Updated result

Rate only analysis:

\[ \sin^2 2\theta_{13} = 0.089 \pm 0.009 \]
Energy Spectrum Distortion

- Clear difference at far site
- Consistent with oscillations
Rate + Shape Analysis

\[
\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}
\]

\[
|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} \text{ eV}^2
\]

\[
\chi^2/\text{N}_{\text{DOF}} = 162.7/153
\]
Global Comparison

![Graph showing global comparison of neutrino experiments]

- **Best Fit + 68% C.L.**
- **Accelerator Experiments**:
  - Normal Hierarchy
  - Inverted Hierarchy
- **Reactors Experiments**:
  - Rate only
  - Rate+Spectral
  - n-Gd
  - n-H

Parameters:
- $\delta_{CP} = 0$
- $\theta_{23} = 45^\circ$

Experiments and corresponding codes:
- Solar+KamLand [1106.6028]
- MINOS [1108.0015]
- T2K 6 Events [1106.2822]
- DC 101 Days [1112.6353]
- Daya Bay 55 Days [1203.1669]
- RENO 229 Days [1204.0626]
- T2K 11 Events [ICHEP2012]
- DC 228 Days [1207.6632]
- Daya Bay 139 Days [1210.6327]
- DC n-H Analysis [1301.2948]
- RENO 416 Days [NuTel2013]
- T2K 11 Events [1304.0841]
- DC RRM Analysis [1305.2734]
- T2K 28 Events [EPS2013]
- Daya Bay 217 Days [NuFact2013]
Future Sensitivity

- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13} \ (|\Delta m^2_{ee}|)$
- Major systematics:
  - $\theta_{13}$: Relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds
- Precision of mass splitting measurement closing in on results from $\mu$ flavor sector
Neutrinos: Completing the Picture

- $\theta_{13}$ – the last mixing angle (reactor – now have it!!)
- Mass hierarchy ($\rightarrow$ accelerator, reactor?)
- CP violation – “leptogenesis” ($\rightarrow$ accelerator)
- Absolute mass scale ($\rightarrow$ Tritium b endpoint, cosmology...)
- Antineutrino=neutrino (Majorana $\rightarrow$ double b decay)?
Mass Hierarchy using Reactor Antineutrinos

- 60 km baseline
- E resolution ~DB/3

Learned et al. PRD78, 071302R, (2008)
Zhan et al. PRD78, 111103R (2008)
Zhan et al. PRD79, 073007 (2009)
Qian et al. PRD, 87, 033005 (2013)

Requires ~ 0.2% absolute energy scale
“JUNO” (~ 300 M$)

- 20 kT F.V. liquid scintillator detector at 55-60 km
- ~ 40 GW$_{th}$ power
- ~700 m underground
- < 3% resolution @ 1 MeV
- Sub 1% energy calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current</th>
<th>Daya Bay II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Dm^2_{12}$</td>
<td>3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$Dm^2_{23}$</td>
<td>5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>6%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>20%</td>
<td>N/A</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>14% $\rightarrow$ 4%</td>
<td>$\sim$ 15%</td>
</tr>
</tbody>
</table>

MH can be determined to $\Delta \chi^2 > 25$ in 6 years

From Y. F. Wang

Acrylic tank : F34.5m
Stainless Steel tank : F37.5m
\[ P(\nu_\mu \to \nu_e) = 4c_{13}^2s_{13}s_{23}^2 \sin^2 \Delta_{31} + 8c_{13}s_{13}s_{23}c_{23}s_{12}c_{12} \sin \Delta_3 \left[ \cos \Delta_{32} \cos \delta \sin \Delta_{32} \sin \delta \sin \Delta_{21} - 8c_{13}s_{13}s_{23}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} + 4c_{13}s_{13}^2 \left( c_{23}^2 + s_{23}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13} \cos \delta \right) \sin^2 \Delta_{21} \right] \]

-8c_{13}s_{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].

\( n_e \) Appearance

T2K - From Tokai To Kamioka

Mass hierarchy (+/-)

CP violation
Current US (Fermilab) Program

MINOS

\[ n_m \text{ disappearance:} \]

\[ Dm_{23}^2 = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2 \]

\[ n_m \rightarrow n_e \]
NOVA Sensitivity (2019)

- For Mass Hierarchy, 37% of $\delta$ range covered
- Slight improvement from combining with T2K

(R. Patterson, NuFACT 2012)
Far Detector : LAr TPC Detector

- 10 kt fiducial mass
- TPC design:
  - 3.7 m drift length
  - 5 mm wire spacing
  - three stereo views
LBNE Sensitivity

(Caveat: MH significance is not Gaussian statistics
Summary

• Many surprising discoveries in neutrino physics in the last decades

• We now have determined $\theta_{13}$! - large value facilitates future measurements

• Future experiments are being planned to study mass hierarchy, CP violation, supernova neutrinos ...

Perhaps the best is yet to come!
Stay Tuned!!