Results from Neutrino Physics Experiments

David E. Jaffe

FPCP 2010
What I’m going to talk about

Preface:

▶ “...review the most relevant results from neutrino physics experiments...” since FPCP2009.

▶ From A. de Gouvêa’s FPCP2009 talk: “...a summary talk ... to a group of people more interested in quarks than neutrinos.”

Outline:

Quarks vs Neutrinos
Terrestrial Neutrinos
Solar Neutrinos
Extraterrestrial Neutrinos
Artificial Neutrinos
Global fit

Disclosure: I am a collaborator on MINOS, Daya Bay and LBNE.
Parallels of quarks and neutrinos

3 generations

\[ |\psi_i> = \sum_j V_{ij}^* |\psi_j> \]

Cabibbo-Kobayashi-Masakawa \( V_{ji} \)  
Pontecorvo-Maki-Nakagawa-Sakata

\[ \begin{align*}
13^\circ & \quad \theta_{12} & 34^\circ \\
2.3^\circ & \quad \theta_{23} & 43^\circ \\
0.2^\circ & \quad \theta_{13} & < 12^\circ \text{ (90\% CL)} \\
64.5^\circ & \quad \delta & [0, 360]^\circ
\end{align*} \]

\[ 3 \times 10^{-5} \quad J \leq 3500 \times 10^{-5} \]

CKMfitter (Oct09) ref. arXiv:1001.4524

Magnitude of CPV \( \propto \) Jarlskog invariant

\[ J \equiv \text{Im}(V_{ij} V_{kl} V_{kj}^* V_{il}^*) \]

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

where \( c_{ij} = \cos \theta_{ij}, \ s_{ij} = \sin \theta_{ij} \) for \( i < j = 1, 2, 3. \)

\(^1\) Jarlskog, PRL55(1985)1039
What we know about neutrino oscillations

\[
V_{ij} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha_1/2} & 0 & 0 \\
0 & e^{i\alpha_2/2} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[\theta_{23} \approx 45^\circ \]
Atmospheric \(\nu\)
Accelerator \(\nu\)

\[\theta_{13} < 12^\circ\]
Short-baseline Reactor \(\nu\)
Future accelerator \(\nu\)

\[\theta_{12} \approx 35^\circ\]
Solar \(\nu\)
Long-baseline Reactor \(\nu\)

Neutrinoless double beta decay

\[\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2 \quad \text{(solar)}\]

\[|\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{ eV}^2 \quad \text{(atmospheric)}\]

\(\nu_\mu\) disappearance in 2-\(\nu\) approximation:
\[P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)\]

\(L(\text{km}), E(\text{GeV}), \Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \text{ (eV}^2)\)
Topics and recent neutrino results not discussed

- Neutrinoless Double Beta Decay
- Neutrino mass measurement in $^3$H decay
- MiniBooNE: Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ NC single $\pi^0$ production cross section on mineral oil at $E_\nu \sim \mathcal{O}(1 \text{ GeV})$. PRD **81** (2010) 013005.
- MINOS: $\nu_\mu$ and $\bar{\nu}_\mu$ inclusive CC cross-sections. arXiv:0910.2201
Borexino: Observation of geo-neutrinos

- Located in LNGS, 3800 m.w.e. overburden
- 278 tons target of high-purity liquid scintillator (8.5m diam. inner vessel)
- 890 tons buffer (11.5m outer vessel, 13.7m SS shell)
- Target viewed by 2212 8” PMTs
- Water-filled external tank, viewed by 208 8” PMTs
- Exposure: 253 ton·year
Borexino: Detection of geo-neutrinos

- Geo-neutrinos are $\bar{\nu}_e$ produced by $\beta$ decays of $^{40}$K and nuclides in the $^{238}$U and $^{232}$Th chains.
- Provide a direct measure of abundance and distribution of radioactive elements in the Earth, and would permit an assessment of the radiogenic contribution of the Earth’s heat balance.
- $\bar{\nu}_e$ are detected via inverse beta decay $\bar{\nu}_e p \rightarrow e^+ n$.
  - Prompt $e^+$ energy $E_{\text{vis}} \approx E_{\nu} - 0.78$ MeV
  - Delayed $np \rightarrow d\gamma$ ($E_\gamma = 2.22$ MeV, $\tau \sim 256$ $\mu$s)

![Expected prompt spectrum (without energy resolution)](image)
Borexino: Geo-neutrino results

<table>
<thead>
<tr>
<th>Source</th>
<th>Bkg evts $(100 \text{ ton} \cdot \text{yr})^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9\text{Li} - ^8\text{He}$</td>
<td>$0.03 \pm 0.02$</td>
</tr>
<tr>
<td>Fast $n$'s (WT $\mu$s)</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Fast $n$'s (Rock $\mu$s)</td>
<td>$&lt; 0.04$</td>
</tr>
<tr>
<td>Untagged muons</td>
<td>$0.011 \pm 0.001$</td>
</tr>
<tr>
<td>Accid. coinc.</td>
<td>$0.080 \pm 0.001$</td>
</tr>
<tr>
<td>Time corr. bkgd</td>
<td>$&lt; 0.026$</td>
</tr>
<tr>
<td>$(\gamma, n)$</td>
<td>$&lt; 0.003$</td>
</tr>
<tr>
<td>Fission in PMTs</td>
<td>$0.0030 \pm 0.0003$</td>
</tr>
<tr>
<td>$(\alpha, n)$ in scintillator</td>
<td>$0.021 \pm 0.002$</td>
</tr>
<tr>
<td>$(\alpha, n)$ in the buffer</td>
<td>$&lt; 0.061$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.15 \pm 0.02$</td>
</tr>
</tbody>
</table>

$N_{\text{geo}} = 9.9^{+4.1}_{-3.4}$ ($N_{\text{geo}} > 0$ at 99.997% CL) and $N_{\text{reac}} = 10.7^{+4.3}_{-3.4}$ events

Consistent with Maximal Radiogenic Earth model: All terrestrial heat produced exclusively by radiogenic elements.
Neutrinos from the Sun

Bahcall–Serenelli 2005

Neutrino Spectrum ($\pm 1\sigma$)

Flux (cm$^{-2}$ s$^{-1}$)

Neutrino Energy in MeV

$^1\nu_p \rightarrow \nu_e \pm 1\%$

$^7\text{Be} \rightarrow \pm 10.5\%$

$^8\text{B} \rightarrow \pm 16\%$

$^7\text{Be} \rightarrow \pm 10.5\%$

$^8\text{B} \rightarrow \pm 16\%$

$^{13}\text{N} \rightarrow \pm 2\%$

$^{15}\text{O} \rightarrow \pm 2\%$

$^{17}\text{F} \rightarrow \pm 2\%$
**Borexino $^8$B flux measurement** (arXiv:0808.2868v3)

- Solar neutrinos are detected by $\nu e^- \rightarrow \nu e^-$ elastic scattering (ES) in Borexino's liquid scintillator. $\sigma_{ES}(\nu_e e) \approx 6.3 \sigma_{ES}(\nu_{\mu,\tau} e)$.
- A 3 MeV threshold limits background from radioactivity.
- Background is dominated by cosmogenic production of unstable isotopes from $^{12}$C. ($\sim 4300$ muons/day deposit energy in Borexino inner detector)
- Short-lived isotopes are suppressed by a $> 6.5$ s veto after a muon.
- Longer-lived isotopes ($^{10}$C, $^{11}$Be) are suppressed and subtracted.
- From 345.5 live days with a 100t fiducial mass, $75 \pm 13$ $^8$B solar $\nu$ candidates remain (Solar models: $86 \pm 10$ or $73 \pm 7$)
Solar Neutrinos

Sudbury Neutrino Observatory

arXiv:0910.2984

- Located in Creighton Mine, CA, 5890 m.w.e. overburden
- 1000 t D$_2$O in 12m diam., 5cm thick acrylic vessel
- 9456 20 cm PMTs mounted on 18m diameter steel frame in 8400 t H$_2$O
- Extensive calibration system
- Solar neutrino detection
  \[ \text{CC} \quad \nu_e + d \rightarrow p + p + e^- \]
  \[ \text{ES} \quad \nu_x + e^- \rightarrow \nu_x + e^- \]
  \[ \text{NC} \quad \nu_x + d \rightarrow p + n + \nu'_x \]
- Phase I: “D$_2$O” (resolved solar $\nu$ problem)
- Phase II: “Salt phase”, +2t NaCl

$^a$H.H.Chen, PRL 55 (1985) 1534
SNO: Low-Energy-Threshold Analysis (LETA)

Previous threshold $\sim 5$ MeV, LETA 3.5 MeV

CC $\nu_e + d \rightarrow p + p + e^-$

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

NC $\nu_x + d \rightarrow p + n + \nu'_x$ Phase I (nd)

NC $\nu_x + d \rightarrow p + n + \nu'_x$ Phase II (nCl)

$T_{\text{eff}} = \text{effective electron kinetic energy}$

$R^3 = \left( \frac{R_{\text{fit}}}{R_{\text{AV}}} \right)^3$

$\cos \theta_{\odot} = \text{direction wrt } \nu \text{ from Sun}$

$\beta_{14} = \text{‘isotropy’ (small } \beta_{14} = \text{ high isotropy)}$

LETA improvements:

1. A more sophisticated energy reconstruction narrowed the resolution by $\sim 6\%$, reducing the low-energy backgrounds by $\sim 60\%$.

2. Better background rejection cuts

3. Better data quality cuts

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Results of SNO LETA (1)

Total $^8$B neutrino flux LETA results using the NC ($\nu_x d \rightarrow pn\nu_x$) reaction compared to previous results.

Assuming unitarity, the NC, CC and ES measurements can be combined to yield the most precise measurement of the solar $^8$B neutrino flux:

$$\Phi(^8\text{B}) = (5.046^{+0.159}_{-0.152}^{\text{stat}} + 0.107^{\text{syst}}) \times 10^6 / \text{cm}^2 / \text{s}$$
Results of SNO LETA (2)

Results of $3\nu$ fit to solar + KamLAND data. (Solar: SNO, Cl, SAGE, Gallex/GNO, Borexino, SK)

$$\theta_{12} = 34.06^{+1.16}_{-0.84}^\circ$$  \hspace{1cm}  $$\Delta m_{21}^2 = (7.59^{+0.20}_{-0.21}) \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{13} = (2.00^{+2.09}_{-1.63}) \times 10^{-2} \text{ or } < 0.057 \text{ at 95\% CL}$$
Extraterrestrial Neutrinos

Atmospheric neutrinos and Super-Kamiokande

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

\[ N(\nu_{\mu}) \approx 2N(\nu_{e}) \]

Super-Kamiokande:
cylinder with 39m diam., 41m h.
50kt ultra pure water
2700 mwe overburden
\( \sim 11000 \) 20” PMTs (\( \sim 40\% \) coverage)
Particle identification in SuperK

Super-Kamiokande
Run 4134 Event 367257
Date: 1994 July 19
Energy: 12.5 GeV p.m. (in-time)
Time: 3.9 ms
E.m. 317.8 cm
μ-like, μ = 368.8 m/sec

Super-Kamiokande
Run 4268 Event 789401
Date: 1994 July 8
Energy: 12.5 GeV p.m. (in-time)
Time: 0.0 ms
E.m. 458.0 cm
μ-like, μ = 422.0 m/sec

Muon

Electron

David E. Jaffe (BNL)
ν Results
25-29 May 2010
16 / 30
Atmos. $\nu$ osc. analysis with sub-leading effects (arXiv:1002.3471)

Change in $\nu_e$ flux as a function of neutrino zenith angle and energy assuming $\theta_{13} = 0$.

Change in $\nu_e$ flux as a function of neutrino zenith angle and energy for $\theta_{13}$ at 90%CL upper limit with $\Delta m^2_{23} = 0.0021$ eV$^2$, $\sin^2 \theta_{23} = 0.5$, normal hierarchy.
Sub-leading effects in atm. $\nu$ in SuperK: Results

Fit assuming $\theta_{13} = 0$:
$0.407 < \sin^2 \theta_{23} < 0.583$ (90%CL).
A $\sim 3$ GeV $\nu$ beam (93% $\nu_\mu$, 6% $\bar{\nu}_\mu$, 1% $\nu_e + \bar{\nu}_e$) sent from FNAL to Soudan. MINOS Near (100m depth) and Far (700m depth) Detectors are alternating layers of magnetized steel (2.54cm, 1.4 $X_0$) and scintillator strips (4.1cm wide).
Artificial Neutrinos

$\nu_\mu \rightarrow \nu_e$ with matter effect (Freund, hep-ph/0103300)

$$P(\nu_\mu \rightarrow \nu_e) \approx \frac{\sin^2 2\theta_{13} \sin 2\theta_{23} \sin^2 (A - 1)\Delta}{(A - 1)^2}$$
$$-8\alpha (J \sin \Delta - I \cos \Delta) \frac{\sin A\Delta \sin (1 - A)\Delta}{A(1 - A)}$$
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A\Delta}{A^2}$$

$$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31} \approx 0.03 \quad \Delta \equiv \Delta m^2_{31} L/4E$$
$$A = 2VE / \Delta m^2_{31} \approx (E_\nu/11 \text{GeV})$$ for earth’s crust
$$J \equiv \text{Im}(V_{ij} V_{kl} V^*_{kj} V^*_{il}) = \frac{1}{8} \sin \delta \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$
$$I \equiv \text{Re}(V_{ij} V_{kl} V^*_{kj} V^*_{il}) = \frac{1}{8} \cos \delta \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

$\nu_e$ appearance probability depends not only on $\theta_{13}$ but also on $\delta$ and the sign of $\Delta m^2_{31}$ (the mass hierarchy)
**MINOS $\nu_e$ appearance: Signal and background**

- **Signal:** $\nu_e A \rightarrow e^- X$
- **NC Background:** $\nu A \rightarrow \nu X$

- **Other background:** $\nu_\mu$ CC with short $\mu$ track, intrinsic beam $\nu_e, \nu_\mu \rightarrow \nu_\tau$.
- Use artificial neural network (ANN) with 11 shower shape variables to discriminate signal and background.
- Utilize near detector to obtain a background sample and extrapolate to predict the far detector background.
MINOS $\nu_e$ appearance: Result ($7 \times 10^{20}$ POT, to be submitted to PRL)

<table>
<thead>
<tr>
<th>Component</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>36</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>6</td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>5</td>
</tr>
<tr>
<td>$\nu_\tau$ CC</td>
<td>2</td>
</tr>
<tr>
<td>Total Bkgd</td>
<td>49.1 ± 7.5</td>
</tr>
<tr>
<td>Observation</td>
<td>54</td>
</tr>
</tbody>
</table>
Global fit

- Uses Borexino, SNO LETA, SuperK and MINOS data shown in this talk.
- Also includes Chlorine, Gallex/GNO, SAGE radiochemical experiments, SuperK solar neutrino results and KamLAND.
- Includes uncertainties due to $\nu_e$ capture cross-section in gallium and in the solar model (low- and high-metallicity).
Global fit: Results

\[ \Delta m^2_{21} = (7.59^{+0.61}_{-0.69}) \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m^2_{31} = \begin{cases} 
(-2.36 \pm 0.37) \times 10^{-3} \text{ eV}^2 \\
(+2.46 \pm 0.37) \times 10^{-3} \text{ eV}^2 
\end{cases} \]
\[ \theta_{12} = (34.4^{+3.2}_{-2.9})^\circ \]
\[ \theta_{23} = (42.8^{+10.7}_{-7.3})^\circ \]
\[ \theta_{13} \leq 12.5^\circ \]
\[ \delta_{CP} \in [0, 360]^\circ \]

(Uncertainties, limits are at 3\(\sigma\))

Different contours correspond to 90\%, 95\%, 99\% and 3\(\sigma\) CL.

Full regions: High-metallicity solar model.

Void regions: Low-metallicity solar model.
Vague prognostications

1. 2-3 mixing is nearly maximal. $\theta_{23}$ might be 45°.
2. $\theta_{13}$ is small. It might be zero.
3. I predict the next two speakers will try to tell us when we will know
   3.1 $\theta_{13}$,
   3.2 the mass hierarchy,
   3.3 the mass of the neutrino,
   3.4 if CP is violated for leptons, and
   3.5 if neutrinos are their own anti-particles.

Thanks to Michael Sivertz and Brett Viren for comments on these slides.
Additional slides
Borexino $^7$Be flux measurement (PRL 101, 091302 (2008))

- Signature of monoenergetic 0.862 MeV $^7$Be neutrino is Compton-like edge of the recoil electrons at 665 keV
- Suppression of radioactive backgrounds requires outer 2/3 of scintillator to serve as an active shield yielding a 78.5t fiducial mass.
- $\alpha$ background from $^{210}$Po at $\sim$400 keV statistically subtracted using pulse-shape discrimination
Resolving the sign of $\Delta m_{21}^2$ with solar neutrinos

$$H = H_{\text{vac}} + H_{\text{matter}}(r) = \frac{\Delta m_{21}^2}{4E} \left[ \begin{array}{cc} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{array} \right] + \left[ \begin{array}{c} V(r) \\ 0 \end{array} \right]$$

$$V(0) \approx 0.75 \times 10^{-5} \text{ eV}^2/\text{MeV}$$

$$\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$$

David E. Jaffe (BNL)

$\nu$ results

25-29 May 2010
Energy reconstruction algorithm improved by inclusion of scattered and reflected Čerenkov light. Validated by extensive comparison of calibration data and simulated data. Calibration sources: Laser, $^{16}\text{N}$, $^8\text{Li}$, $^{252}\text{Cf}$, Am-Be, cosmogenic neutrons, etc.

Figure: Difference in $^{16}\text{N}$ data and MC energy scale vs. radius. (a) before and (b) after spatial energy correction.
$\chi^2 \text{ vs } \sin^2 \theta_{13}$

- Solar
- Before SAGE (09) SNO (09)
- Present (GS98 Fluxes)
- Present (AGSS09 Fluxes)
- Present (AGSS09)
  - with modified Ga cross section

- Solar + KamLAND
- ATM + CHOOZ and LBL (DS + APP)

- ATM + CHOOZ and LBL (DS + APP)
  - SK (+I + II + III) + CHOOZ
  - SK (+I) + CHOOZ
  - LBL (DS + APP)

- Global
  - ATM (+I + II + III) GS98
  - ATM (+I + II) GS98

- Global AGSS09
  - with modified Ga CS
  - and ATM (+I + II + III)

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$\nu$ results

25-29 May 2010