Neutrino Oscillations
Dan Pershey (Florida State University) – Jul 18, 2024

Second school on neutrino and dark matter detection
South American Institute for Fundamental Research
Neutrino oscillations

Produced and detected in flavor basis but travel in mass basis
Interference of mass states $\rightarrow$ flavor transitions

Neutrino mixing encoded in PMNS matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}
= 
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23} \\
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{CP}} & 0 & c_{13} \\
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1 \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

Atmospheric  Reactor  Solar
### Parameters to measure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3 σ ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{12}$</td>
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<td>$</td>
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<tr>
<td>$\delta_{CP}$</td>
<td>157 – 349 deg</td>
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For today: cover historical experiments that determined five known parameters

*Solar, atmospheric, and reactor neutrinos*
Parameters to measure

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<th>2 mass splittings</th>
<th>CP violation</th>
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3 σ ranges

Tomorrow: efforts to answer remaining questions

Is CP conserved?

Is $\theta_{23}$ 45 deg? And if not, is it $> \text{or} < 45$ deg?

Is $\nu_2$ or $\nu_3$ the most massive state?
Two-flavor oscillations

\[ \frac{\Delta m^2_{32}}{\Delta m^2_{21}} \sim 30 \]

Oscillations at different length scales – they factor

\[ P_{\alpha \beta} = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E} \]

\[ P_{\alpha \alpha} = 1 - P_{\alpha \beta} \]

\[ \lambda/2 = \frac{2\pi E}{\Delta m^2} \]
Solar neutrinos
Solar neutrinos

Nuclear processes that fuel the sun also produce neutrinos – huge flux physicists can study.
Ray Davis searched for solar neutrinos via:
\[ \nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar} \quad E_\nu > 814 \text{ keV} \]
Built 620 ton tank of dry cleaning fluid (C$_2$Cl$_4$) and observed \( \approx 15 \) interactions / month for 30 yrs
A chemist’s neutrino experiment

Chemistry experiment discovered solar neutrinos

1: $\text{C}_2\text{Cl}_4$ pumped through system with eductors introducing bubbles of He into tank
2: Argon is a noble gas! Argon atoms that contact a He bubble get absorbed in gaseous state
3: Gaseous bubbles escape the tank entering a gaseous processing line. $\text{C}_2\text{Cl}_4$ vapor removed in -40 C condenser
4: Gas routed through liquid N$_2$ cooled charcoal trap. Argon freezes, He passes
5: Monthly, solute charcoal trap and heat, count $^{37}\text{Ar}$ decays in proportional counter
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D. Pershey

Neutrino oscillations
Discovering neutrinos – with a catch

The solar neutrino problem

1/3 the rate expected!
By 1980s, we understood the Davis experiment was right
- 99% of solar neutrinos from $p+p\rightarrow d+e^++\nu_e$
- Maybe, the lower-flux, higher-energy processes mis-modeled due to theory uncertainties in the sun. Measure pp!

Response: radiochemical experiment based on Ga
$\nu_e + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge}$
Threshold: 233 keV
Studied in GALLEX, SAGE
A decade of gallium data: the plot thickens

Gallium also sees a deficit! But it’s different from Davis. Energy dependence?
A decade of gallium data: the plot thickens

Gallium also sees a deficit! But it's different from Davis. Energy dependence?

Add $^{51}$Cr source
Monoenergetic 746 keV neutrinos emitted in electron capture.

Sage: Russia
Gallex: Gran Sasso

D. Pershey  Neutrino oscillations
First data from SuperKamiokande

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

Points to sun for background rejection

SK sensitive to neutrino-electron elastic scattering (ES) of $^8\text{B}$ neutrinos: $E_e > 6.5$ MeV
Also sees a deficit!

\[ E_e = 9.1 \text{MeV} \]
\[ \cos \theta_{\text{sun}} = 0.95 \]

Kamioka, Japan

SK, PRL 81, 1158 (1998)
The SNO experiment

Heavy water Cherenkov

- 1 kt of $d_2O$ held in 6-m radius acrylic vessel
- $d_2O$ is sunk into 8.5-m radius $H_2O$ tank providing shielding
- 9600 PMT’s monitor the Cherenkov light from both regions
- vertex reconstruction allows fiducialization
- calorimetric information of solar neutrinos in $d_2O$

Sudbury Ontario, Canad
SNO discovers neutrino oscillations

Multiple interaction channels!

Neutral current (NC)
\(\nu_e + d \rightarrow \nu_e + n + p\)
doesn’t oscillate

Charged current (CC)
\(\nu_e + d \rightarrow e^- + p + p\)
Oscillates

Electron scatter (ES)
\(\nu_x + e \rightarrow \nu_x + e\)
Mostly oscillates

SNO, PRL 87 071301 (2001)
SNO discovers neutrino oscillations

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Mostly oscillates

NC flux from SNO consistent with solar models!
First consensus in 33 years

SNO, PRL 87 071301 (2001)
Analyzing the survival probability

\[ H = \frac{1}{2E} \left[ U \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2 \end{pmatrix} U^\dagger + \begin{pmatrix} \sqrt{8G_F} n_e E & 0 \\ 0 & 0 \end{pmatrix} \right] \]

with

\[ \Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2 \]

and

\[ \theta_{12} \approx 34^\circ \]
Analyzing the survival probability

\[ H = \frac{1}{2E} \begin{bmatrix} U & 0 \\ \Delta m^2 \end{bmatrix} U^\dagger + \begin{bmatrix} \sqrt{8}G_F n_e E & 0 \\ 0 & 0 \end{bmatrix} \]

Low-energy (E \ll \Delta m^2/\sqrt{8}G_F n_e):
Vacuum term dominates:

\[ P_{ee} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2 L}{4E} \]

\[ \langle P_{ee} \rangle = 1 - \frac{1}{2} \sin^2 2\theta_{12} \]

\[ 1 - \frac{1}{2} \sin^2 2\theta_{12} \approx 0.57 \]

\[ \theta_{12} \approx 34^\circ \]
Analyzing the survival probability

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Vacuum

Matter

Low-energy (E \ll \Delta m^2 / \sqrt{8G_F n_e}):
Vacuum term dominates:

\[ P_{ee} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2 L}{4E} \]
\[ \langle P_{ee} \rangle = 1 - \frac{1}{2} \sin^2 2\theta_{12} \]

High-energy (E \gg \Delta m^2 / \sqrt{8G_F n_e}):
Matter term dominates:

\[ |\nu_1\rangle_m = |\nu_2\rangle \]
\[ |\nu_2\rangle = \sin^2 \theta_{12} |\nu_e\rangle + \cos^2 \theta_{12} |\nu_\mu\rangle \]
\[ P_{ee} = \langle \nu_e | \nu_2 \rangle = \sin^2 \theta_{12} \]

But energy of ramp-on uncertain to order of magnitude

\[ 1 - \frac{1}{2} \sin^2 2\theta_{12} \approx 0.57 \]
\[ \sin^2 \theta_{12} \approx 0.31 \]
Estimating oscillation parameters

Taking Davis, Gallium, SK, and SNO data, a statistical log-likelihood fit can determine which oscillation parameters best fit solar data.

With earliest data, ok determination of the mixing angle.
Uncertainty in the mass splitting was nearly an order of magnitude.

Reactor measurement of $\Delta m^2$

- 1 kt of scintillator in balloon
- Buffer volume of mineral oil
- Outer water Cherenkov veto
- 1325 20” PMT’s

KamLAND PRL 101 221803 (2008)

Many reactors $<L> = 180$ km

KamLAND

D. Pershey

Neutrino oscillations
Reactor measurement of $\Delta m^2$

1 kt of scintillator in balloon
Buffer volume of mineral oil
Outer water Cherenkov veto
1325 20” PMT’s

KamLAND PRL 101 221803 (2008)
Precision measurements: the Borexino experiment

Onion-like scintillator

– Inner 321-t volume with organic scintillator and wavelength shifter. 8.5 m
– Inner veto volume with dimethylphthalate, a charge quencher. 8.5 to 11 m
– Outer veto volume with similar chemical composition. 11 to 13.7 m
– Stainless steel tank with 2212 mounted PMT’s
– Surrounding water tank for additional passive shield
Flux measurements from Borexino

ES channel in scintillation detectors – must live with large, well-characterized background
Scintillator purification reduces $^{14}\text{C}/^{12}\text{C}$ ratio to $185\text{e}-18$

pp chain spectroscopy: leading measurements of pp / $^7\text{Be}$ / pep

CNO chain discovery
Nature 587 577-582 (2022)
New detections from XENONnT + PandaX-4T

Liquid xenon time projection chambers searching for WIMP dark matter at Gran Sasso with 3.9-4.1 t (XENONnT) and Jinping with 2.5 t (PandaX-4T)

2.7σ detection of CEvNS in 3.51 t-yrs (XENONnT) and 2.6σ in 2.29 t-yrs (PandaX-4T)

PandaX-4T arXiv:2407.10892

XENONnT IDM 2024
Future of solar neutrinos

One remaining flux to measure

The DUNE experiment

– Upcoming neutrino experiment studying long-baseline oscillations, BSM searches, and **astro neutrinos**
– 4 far detector (FD) modules are 17-kt LArTPC’s 1300 m below ground in the SURF laboratory
– First FD data expected in 2028
A new technology brings two critical strengths

Dominant channel: CC

Sub-cm tracking, reconstruction and background rejection
Sensitivity to CC makes DUNE ideal for studying oscillation probability as a function of energy.

Preliminary background estimates suggest a 5 MeV threshold – can dig deeper into upturn of survival probability plot.

Capozzi, Li, Zhu, Beacom, PRL 123 131803 (2019)
Atmospheric neutrinos
Atmospheric neutrinos

Atmospheric neutrinos produced when cosmic ray protons interact with nuclei in the upper atmosphere producing mesons. With solar neutrinos, atmospheric neutrinos definitively proved that neutrinos oscillate and have mass.
Atmospheric neutrinos

Atmospheric neutrinos produced when cosmic ray protons interact with nuclei in the upper atmosphere producing mesons. With solar neutrinos, atmospheric neutrinos definitively proved that neutrinos oscillate and have mass. — Arrive in detector from multiple baselines.
Atmospheric neutrinos produced when cosmic ray protons interact with nuclei in the upper atmosphere producing mesons. With solar neutrinos, atmospheric neutrinos definitively proved that neutrinos oscillate and have mass.

- Arrive in detector from multiple baselines
- 100s of MeV to multi-GeV

D. Pershey
Early history of atmospheric neutrinos

*Discovery: F. Reines in East Rand Mine, Johannesburg, South Africa, 1965*

+ Kolar Gold Field, India, 1965
Early history of atmospheric neutrinos

**Discovery:** F. Reines in East Rand Mine, Johannesburg, South Africa, 1965
+ Kolar Gold Field, India, 1965

1980s: dedicated study from proton decay experiments

Oscillations there, but need more convincing sample

- Kamiokande II
- Frejus
First data from Super-Kamiokande

535 days of SK data shows strong preference for disappearance of atmospheric $\nu_\mu$

Downward going (short baselines) agree well – sounds like oscillations

$\mu$: 766 MeV

$e$: 622 MeV

$0.4 < p < 1$ GeV

Downward

Upward

SK, PRL 81 1562 (1998)
First data from Super-Kamiokande

535 days of SK data shows strong preference for disappearance of atmospheric $\nu_\mu$

Downward going (short baselines) agree well – sounds like oscillations

Maximal $\nu_\mu/\nu_\tau$ mixing with a mass splitting $\Delta m^2_{32} \approx 2.4\times10^{-3} \text{ eV}^2$ (about 30x solar, 7.5x-5 eV$^2$)

Oscillations disfavored at 6.7 $\sigma$

Modern best fit

SK, PRL 81 1562 (1998)
Possible uncertainties on event rates

\[ N_{\text{evt}}(E) = N_{\text{tar}} \times \phi(E) \times \sigma(E) \]

Flux and cross section more uncertain than in solar neutrino case!
Possible uncertainties on event rates – neutrino flux

\[ N_{\text{evt}}(E) = N_{\text{tar}} \times \varphi(E) \times \sigma(E) \]

- Mass balloon flew in 1991
- Time-of-flight + magnetic tracker for \( \nu + p \) reco
  \[ \rightarrow \] particle identification!
- Max altitude: 36 km
- Measures primary proton flux for input into atmospheric neutrino calculation

Bellotti et al., PRD 60 052002 (1999)
Possible uncertainties on event rates – neutrino flux

\[ N_{\text{evt}}(E) = N_{\text{tar}} \times \varphi(E) \times \sigma(E) \]

- Mass balloon flew in 1991
- Time-of-flight + magnetic tracker for $\nu + p$ reco
  → particle identification!
- Max altitude: 36 km
- Measures primary proton flux for input into atmospheric neutrino calculation

Data agrees with expectations!

Bellotti et al., *PRD* 60 052002 (1999)
Possible uncertainties on event rates – neutrino flux

\[ N_{\text{evt}}(E) = N_{\text{tar}} \times \varphi(E) \times \sigma(E) \]

Solution to flux uncertainties:
Data-driven model using primary data from balloons and meson production from HARP
EMPHATIC + SHINE experiments still using these methods for beam oscillations

HARP experiment at CERN studied meson production from p-nucleus collisions on multiple nuclei providing final-state kinematics


Barr, Robbins, Gaisser, Staney, PRD 74 094009 (2006)
Possible uncertainties on event rates – cross section

\[ N_{\text{evt}}(E) = N_{\text{tar}} \times \varphi(E) \times \sigma(E) \]

Bubble chamber data from 1980s
Effort to re-analyze in context of cross sections for atmospheric neutrinos

Uncertainty too small to explain oscillation effect

\[ N_{\text{evt}}(E) = N_{\text{tar}} \times \varphi(E) \times \sigma(E) \]

Lipari, Lusignoli, Sartogo, PRL 74 4384 (1995)
Final cross check: K2K

Want a laboratory test using a human-made neutrino source

– KEK: 12 GeV proton synchrotron produces a beam of $\nu_\mu$
– 1 km downstream: a 1-kt water Cherenkov near detector for uncertainties
– 250 km downstream: SK measures oscillated spectrum

Reactor antineutrinos
The Daya Bay experiment

Look for disappearance of reactor $\bar{\nu}_e$
Identical near/far detectors
Each 4 x 20 ton LS-Gd detectors
IBD with prompt-capture coincidence

20-t LS-Gd units

Water Cherenkov veto
First results – discovery of $\bar{\nu}_e$ disappearance

Predicted: 10675
Observed: 10416 (-2.5%)

> 95% pure IBD sample
Small, 2.5% effect, but observed at 5.2 $\sigma$
with first result
Near/Far ratio fits well to oscillation model
Implication: $\nu_\mu \rightarrow \nu_e$ common enough for
accelerator CP violation searches

Daya Bay, PRL 108 171803 (2012)
Summary

– Natural sources of neutrinos – solar and atmospheric – dominate the history of neutrino oscillation discoveries

– SNO / SK data definitively demonstrate oscillations with solar / atmospheric neutrinos which were both cross-checked by 2000-2005

– Reactor data measured last mixing angle $\theta_{12}$ in 2012
Aside
Gallium: solar neutrino problem 2 – electric boogaloo

Gallium calibration: lower event rate than expected, but not low enough to explain solar deficit
Maybe new physics?

BEST experiment released results in 2022 with much improved systematic uncertainties
> 5σ deficit
Could be sterile neutrino? Unknown uncertainty?
Back to solar neutrinos