2009 Neutrino Summer School

Neutrino History
accelerator, atmospheric, reactor and solar experiments
... and some lessons learned

Karsten M. Heeger
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• History of Neutrino Physics
  - how did we learn what we know today?
  - from saving energy conservation to discovering physics beyond the Standard Model

• Historical Lessons
  - how did we make the discoveries?

• Future Efforts
  - from discoveries to precision studies, picking the best tools at hand
  - where will neutrino physics go in the future?
  - neutrinos in particle/astrophysics?
A disclaimer

History of neutrino physics in ~1 hr?

I will be selective. Apologies to all experiments and results I cannot show.

I will draw heavily on my own personal experience (SNO, KamLAND, reactor neutrinos, 0νββ)
History of Neutrino Physics
Bohr: "At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations".
Pauli proposed that an undetectable particle shared the energy of beta decay with the emitted electron.
“I have done something very bad today by proposing a particle that cannot be detected; it is something that no theorist should ever do.”

- Wolfgang Pauli
Fermi’s Theory of Beta Decay

Enrico Fermi
Univ. of Chicago

Fermi’s Theory of beta decay based on Pauli’s Letter of Regrets

1933

Experiment: \[ M_n c^2 \neq E_p + E_e \]

Conjecture: \[ M_n c^2 = E_p + E_e + E_\nu \]

Consistency requires that \( E_\nu \) is not observable!

Fermi’s theory still stands (parity violation added in the 50s).
Fermi’s Idea for Measuring $m_\nu$

![Energy distribution curve of the beta-rays.](image)

**Fig. 5.** Energy distribution curve of the beta-rays.
Weak Interactions in the Standard Model

The weak gauge bosons $W^\pm$ act on left-handed doublets (charged-current interaction)

$\beta$-decay

Since $m_w=80.4$ GeV $>> m_p$ decay is governed by Fermi coupling $G_F$

Fermi coupling

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8m_W^2}$$

g_2 = W$ gauge coupling

Weinberg angle

$$\frac{e}{g_2} = \sin \theta_W = 0.48$$
Crossing Symmetry

**Basic Current-Current Interaction**

- **Lepton current** (electron/neutrino)
- **Nucleon current** (neutron/proton)

**Neutron Beta Decay**

- Initial state: $n$
- Final state: $p + e^- + \bar{\nu}$

**Electron Capture**

- Initial state: $e^- + p$
- Final state: $n + \nu$

**Inverse Beta Decay**

- Initial state: $\bar{\nu} + p$
- Final state: $n + e^+$
First Proposal For Direct Detection of Neutrino
First Antineutrino Detector

Reines and Cowan 1956

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
Enrico Fermi and the Neutrino

Enrico Fermi proposes "neutrino" as the name for Pauli's postulated particle.

He formulates a quantitative theory of weak particle interactions in which the neutrino plays an integral part.
Reines-Cowan Announcement

1956

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS.

FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO
Observation of the Free Antineutrino

1959 The Savannah River Detector - A new design

Second version of Reines’ experiment worked!

inverse beta decay
\( \bar{\nu}_e + p \rightarrow e^+ + n \)

positron annihilation

n capture
Reines-Cowan Experiment

coincidence event signature

event signal

electric noise

cosmic ray

cosmic ray

cosmic ray
Early Neutrino Oscillation Searches

New neutrino physics such as oscillations?
In 1960’s Pontecorvo contemplates $\nu - \bar{\nu}$ oscillation and suggests that if lepton number is not conserved $\nu_e$ could change into $\nu_\mu$.

**Early Reactor $\nu$ Experiments**

**Goesgen**
(3 baselines, 1 detector)

**Early Reactor $\nu$ Experiments 1956-2000**

<table>
<thead>
<tr>
<th>Distance to Reactor (m)</th>
<th>Nobs/Nexp</th>
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<tr>
<td>10^1</td>
<td></td>
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<td>10^2</td>
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<td>10^3</td>
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</tr>
<tr>
<td>10^4</td>
<td></td>
</tr>
<tr>
<td>10^5</td>
<td></td>
</tr>
</tbody>
</table>

- ILL
- Savannah River
- Bugey
- Rovno
- Goesgen
- Krasnoyarsk
- Palo Verde
- Chooz

Karsten Heeger, Univ. of Wisconsin  
NUSS, July 10, 2009
Neutrino Oscillation Search with Reactor Antineutrinos

Oscillation Searches at Chooz + Palo Verde: $\bar{\nu}_e \rightarrow \bar{\nu}_x$

Distance: 1km

$\sim 3000$ events in 335 days

2.7% uncertainty

Absolute measurement with 1 detector
detector size: several tons

Karsten Heeger, Univ. of Wisconsin

NUSS, July 10, 2005
Discovery of Muon Neutrino

1962

\[ \overline{\nu}_\mu + p \rightarrow n + \mu^+ \]

\[ \nu_\mu + n \rightarrow p + \mu^- \]

Lederman, Schwartz, Steinberger

\[ 10^4 \nu_\mu \text{ and } \overline{\nu}_\mu \]

\( \mu \) produce nice tracks as they go through the chamber (29 events)

\( e \) produce showers as they cross Al (0 events)
Number of Active Neutrinos

Precision studies of Z-line shape, determine number of active light neutrinos

Each separate ($\nu_l)_L$ adds to total Z-width.

$$Z^0 \rightarrow q\bar{q}, l\bar{l}, \quad N_\nu = \left( \frac{\Gamma_{inv}}{\Gamma_\ell} \right) \left( \frac{\Gamma_\ell}{\Gamma_\nu} \right)_{SM}$$

From LEP, one finds:

$$N_\nu = 2.984 \pm 0.008$$

which argues strongly for only having 3 generations

Big bang nucleosynthesis gives a constraint on the effective number of light neutrinos at $T \sim 1$ MeV:

$$1.2 < N_\nu^{\text{eff}} < 3.3 \quad [99\% \text{ CL}]$$

Before $\nu_\tau$ was detected directly!
Search for tau Neutrino

Discovery of $\tau$ lepton at SLAC (Martin Pearl, 1975)
→ there should be a corresponding neutrino.

In 1989, indirect evidence for the existence of $\nu_\tau$ in measurement of Z-width
→ no one had directly observed the tau neutrino.

The tau neutrino interact and form a tau that has an 18% probability of decaying to
- a muon and two neutrinos (long event)
- an electron and two neutrinos (short event)

86% of all tau decays involve only 1 charged particle (a kink) which is the particle physicists are looking for in DONUT experiment.
Discovery of tau Neutrino

2000

An 800 GeV beam of protons from the TeVatron collides with a block of tungsten

$D_s \to \nu_\tau + \tau$
$\tau \to \nu_\tau + X$

Experimental Challenges:
- Very short lifetime of the $\tau$.
- $\nu_\tau$ is extremely non-interacting (detector must have a very fine resolution).

6,000,000 candidate events on tape
4 clean tau events

Detecting a $\tau$ Neutrino
A $\nu_\tau$ interacted with a nucleon in a steel layer, producing a $\tau$.

Long tau decay because it decays to one charged particle, the electron, and the decay vertex occurs several sheets downstream from the neutrino interaction vertex.
Neutral Current Discovery (1973)

Gargamelle bubble chamber at CERN showing how an invisible neutrino has jogged an electron

Major triumph for the Standard Model

Table 1

<table>
<thead>
<tr>
<th>No. of neutral-current candidates</th>
<th>$\nu$-exposure</th>
<th>$\bar{\nu}$-exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>No. of charged-current candidates</td>
<td>428</td>
<td>148</td>
</tr>
</tbody>
</table>
“Standard Model” Neutrino Physics

1914  Electron Spectrum in $\beta$ decay is continuous

1930  Pauli postulates that a new particle is emitted

1933  Fermi names the new particle neutrino and introduces four-fermion interaction

1956  Reines and Cowan discover the neutrino

1962  At least two neutrinos: $\nu_e \neq \nu_\mu$

1973  Discovery of neutral currents at CERN

1983  Discovery of the W and Z

1989  Measurement of Z width at CERN  $\rightarrow N_\nu=3$

2002  tau neutrino discovered.
Neutrinos in the Standard Model

Discovery of $\nu_\mu$ and $\nu_\tau$

Accelerator studies of $\nu$

The Standard Model

- 3$\nu$ flavors
- upper limits on $m_\nu$ from kinematic studies.
- massless $\nu$ (*ad hoc* assumption in Standard Model)
Particle Properties of the Neutrino

Interactions  weak
(and gravitational) only

Flavors  3 active flavors

Charge

Spin  s=1/2

Type

Dirac  \( \nu \neq \bar{\nu} \)

Majorana  \( \nu = \bar{\nu} \)

Mass

\( m_{\nu_e} < 2 \text{ eV} \) from tritium \( \beta \) decay

\( m_{\nu_\mu} < 170 \text{ keV} \) from \( \pi \) decay

\( m_{\nu_\tau} < 18 \text{ MeV} \) from \( \tau \) decay
Birth of Neutrino Astrophysics

1938  Bethe & Critchfield
\[ p + p \rightarrow ^2H + e^+ + \nu_e \]

1947  Pontecorvo, 1949 Alvarez
propose neutrino detection through
\[ ^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^- \]

1960’s  Ray Davis builds chlorine detector.
John Bahcall, generates first solar model calculations and \( \nu \) flux predictions.

“…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars…” (Bahcall, 1964)
Cl-Ar Solar Neutrino Experiment at Homestake

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]

1970 - 1994

Davis’ experiment only sensitive to \( \nu_e \)
What is the Solution?

Experimental Errors?
But all experiments show similar effect.

Astrophysics wrong?
Perhaps, but even with all fluxes as free parameters, cannot reproduce the data. $P_{\text{MSM}} < 1.7\%$ at 95% CL

New neutrino physics such as oscillations?
In 1968 Pontecorvo suggests that if lepton number is not conserved, $\nu_e$ could change into $\nu_\mu$.

Since the Cl-Ar detector was sensitive only to $\nu_e$, it would appear that the flux was low.
The Sudbury Neutrino Observatory
The Solar Neutrino Problem and Its Resolution

Too few $\nu_e$ observed from the Sun.

Even with all solar neutrino fluxes as free parameters, cannot reproduce the data. $P_{\text{SM}} < 1.7\%$ at 95% CL

KMH, Robertson PRL 77:3270 (1996)

2/3 of initial solar $\nu_e$ are observed at SNO to be $\nu_{\mu,\tau}$

Model-independent evidence for solar neutrino flavor change
Neutrino Oscillation

Neutrino States

<table>
<thead>
<tr>
<th>Mass States</th>
<th>Weak States</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>First</td>
</tr>
<tr>
<td>$\nu_1$</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>Second</td>
<td>Second</td>
</tr>
<tr>
<td>$\nu_2$</td>
<td>$\nu_\mu$</td>
</tr>
</tbody>
</table>

\[
|\nu_a\rangle = \cos \theta |\nu_1\rangle - \sin \theta |\nu_2\rangle \\
|\nu_b\rangle = \sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle \\
\]

\[
\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ 2\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}
\]

Time Evolution

\[
P_{i\rightarrow i} = \sin^2 2\theta \sin^2 \left( 1.27\Delta m^2 \frac{L}{E} \right)
\]

oscillation $\rightarrow$ energy and baseline-dependent effect

Pontecorvo, 1968
vacuum-matter transition in solar neutrino oscillation
Reactor Antineutrinos in Japan

Japanese Reactors

Kashiwazaki
Takahama
Ohi

55 reactors

Reactor Antineutrinos

$235U:238U:239Pu:241Pu = 0.570: 0.078: 0.0295: 0.057$

$\sim 200 \text{ MeV per fission}$

$\sim 6 \bar{\nu}_e \text{ per fission}$

$\sim 2 \times 10^{20} \bar{\nu}_e / \text{GW}_{\text{th}} \cdot \text{sec}$

reactor $\bar{\nu}$ flux $\sim 6 \times 10^6 / \text{cm}^2 / \text{sec}$
KamLAND Antineutrino Detector

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

through inverse $\beta$-decay

\[ E_{\bar{\nu}_e} \simeq E_p + E_n + 0.8 \text{MeV} \]

liquid scintillator target:
- proton rich \( > 10^{31} \) protons
- good light yield
KamLAND 2003:
First Direct Evidence for Reactor $\overline{\nu}_e$ Disappearance

Observed $\overline{\nu}_e$ 54 events
No-Oscillation 86.8 ± 5.6 events
Background 1 ± 1 events
Livetime: 162.1 ton-yr

reactor antineutrino experiment

suggested by solar neutrino experiments

mean, flux-weighted reactor distance ~ 180km

Reactor Neutrino Physics 1956-2003

Japan
KamLAND 2008: Precision Measurement of Oscillation

Prompt event energy spectrum for $\nu_e^-$

number of events
expected: $2179 \pm 89$ (syst)
observed: 1609
bkgd: $276 \pm 23.5$

significance of distortion: $>5\sigma$
best-fit $\chi^2$/ndf=21/16 (18% C.L.)

significance of disappearance (with 2.6 MeV threshold): $8.5\sigma$
no-osc $\chi^2$/ndf=63.9/17

Spectral Distortions: A unique signature of neutrino oscillation!
KamLAND 2008: Precision Measurement of Oscillation

L/E Dependence

\[ P_{ee} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

Solar neutrino problem solved! L/E figure demonstrates $\overline{\nu}$ oscillation.

1970-1995 first identified by Ray Davis (missing solar $\nu_e$)
2002-2008 SNO observes neutrino flavor change, finds evidence for neutrino mass
2003-2008 KamLAND demonstrates $\overline{\nu}$ oscillation, precision measurement of $\Delta m^2$
Neutrino Physics at Reactors

Next - Discovery and precision measurement of $\theta_{13}$

2008 - Precision measurement of $\Delta m_{12}^2$. Evidence for oscillation

2004 - Evidence for spectral distortion

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Atmospheric Neutrino Studies

Cosmic ray (proton)

Earth

\( E_{\nu} \sim 0.5 - 5 \text{ GeV} \)
\( L_{\text{down}} \sim 100 \text{ km} \)
\( L_{\text{up}} \sim 10,000 \text{ km} \)

\[ \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} = 2 \]

+2 muon neutrinos
+1 electron neutrino

\[ R' = \frac{(\mu/e)_{\text{DATA}}}{(\mu/e)_{\text{MC}}} \]

No osc.
Super-Kamiokande

Atmospheric Neutrino Studies

Inner detector
11146 20” PMTs
Outer detector
1885 8” PMTs

600MeV muon

500MeV electron
Atmospheric Neutrino Flavor Change

evidence for $\nu_\mu$ disappearance: zenith-angle dependence

$\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2 \neq 0 \rightarrow \text{at least } 1 \ m_\nu \neq 0$

Mixing angle is quite large ($\theta \sim 45^\circ$)
Precision Science with Accelerator \( \nu \) Minos

- 5.4 kton MINOS far detector
- 1 kton near detector

Monte Carlo
- Unoscillated
- Oscillated

NuMI beam line
Precision Science with Accelerator

5.4 kton MINOS far detector

Monte Carlo
Unoscillated
Oscillated

Events

Visible energy (GeV)

NuMI beam line

Linus
Fermilab
Lake Michigan
Lake Superior
Soudan
Duluth
MN
WI
MI
IA
IL
IN
MO

1.0 1.5 2.0 2.5 3.0 3.5 4.0

$\Delta m^2$ ($10^{-3} \text{eV}^2$)

sin$^2(2\theta)$

- MINOS best oscillation fit
- MINOS 90%
- MINOS 68%
- Super-K 90%
- Super-K L/E 90%
- MINOS 2006 90%
- K2K 90%
A Decade of Discovery: 1998 - 2008

**Super-K:**
atmospheric $\nu_\mu$ neutrino oscillation

**K2K:**
accelerator $\nu_\mu$ oscillation

**SNO:**
solar $\nu_e$ flavor transformation

**KamLAND:**
reactor $\bar{\nu}_e$ disappearance and oscillation
Experimental Indications for Neutrino Oscillations

**Atmospheric Neutrinos**

- **L**: 15 - 15,000 km
- **E**: 300 - 2000 MeV
- $\Delta m^2 = \sim 5 \times 10^{-5} \text{ eV}^2$
- $\text{Prob}_{\text{OSC}} = \sim 100\%$

**Solar Neutrinos**

- **L**: $10^8$ km
- **E**: 0.3 to 3 MeV
- $\Delta m^2 = 3 \times 10^{-3} \text{ eV}^2$
- $\text{Prob}_{\text{OSC}} = \sim 100\%$

**LSND Experiment**

- **L**: 30m
- **E**: $\sim 40$ MeV
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\Delta m^2 = 0.3$ to 3 eV$^2$
- $\text{Prob}_{\text{OSC}} = 0.3\%$

---

800 MeV proton beam from LANSCE accelerator

Water target
Copper beamstop

LSND Detector

![Diagram of LSND Experiment](image)

Cosmic Rays
p, He, etc.

Air molecules

$\nu_\mu \sim 66\%$
$\nu_e \sim 33\%$

$\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_e$

$\nu_\mu \rightarrow \nu_x$

μ$^+$

μ−

e$^+$

ν$^+$

ν$^−$

ν$^+_e$

ν$^−_e$

ν$^+_e$

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LSND Experiment

800 MeV proton beam from LANSCE accelerator

Water target
Copper beamstop

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

Oscillations? \rightarrow \bar{\nu}_e

LSND took data from 1993-98
- 49,000 Coulombs of protons
- \( L = 30 \text{m} \) and \( 20 < E_\nu < 53 \text{ MeV} \)

Saw an excess of:
\[ 87.9 \pm 22.4 \pm 6.0 \text{ events.} \]

With an oscillation probability of
\[ (0.264 \pm 0.067 \pm 0.045)\%. \]

3.8 \( \sigma \) evidence for oscillation.
Other oscillations? Sterile Neutrinos?

\[ \nu_{\mu} \rightarrow \nu_e \] ?

\[ \nu_{\mu} \rightarrow \nu_\tau \]

\[ \nu_e \rightarrow \nu_{\mu, \tau} \]

Cannot be explained by 3 active neutrinos!
MiniBoone

- 1 GeV neutrinos (Booster)
- 800 ton oil Cerenkov
- operating since 2003
- $\nu_\mu \rightarrow \nu_e$ appearance

null hypothesis: 93% CL

$\nu_\mu \rightarrow \nu_e$ appearance only analysis is a limit on oscillation
Historical Lessons

- *how did we make the discoveries?*

#1 persistence
#2 data “anomalies”, the unforeseen
#3 theorists aren’t (always) right
#4 unique, model-independent measurements
#5 big steps vs incremental improvements
#6 and a little bit of luck ... in detecting a supernova
#1 persistence

Davis’ experiment only sensitive to $\nu_e$

1970-1995

Neutrino Flux

- Gallium
- Chlorine
- SuperK, SNO

Neutrino Energy (MeV)

Karsten Heeger, Univ. of Wisconsin

NUSS, July 10, 2009
#2 “anomalies”

Solar Neutrino Problem

Atmospheric Neutrino Anomaly

Low-Energy Excess in MiniBoone?
#3 theorists aren’t (always) right ...

quark mixing

V_{\text{CKM}} = \begin{bmatrix}
V_{\text{ud}} = 0.975 & V_{\text{us}} = 0.211 & V_{\text{ub}} = 0.005 \\
V_{\text{cd}} = 0.211 & V_{\text{cs}} = 0.974 & V_{\text{cb}} = 0.04 \\
V_{\text{td}} = 0.005 & V_{\text{ts}} = 0.041 & V_{\text{tb}} = 0.999
\end{bmatrix}

neutrino mixing

pre 2002

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

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

\[ = \begin{bmatrix}
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{bmatrix} \begin{bmatrix}
e^{i\alpha_1/2} & 0 & 0 \\
0 & e^{i\alpha_2/2} & 0 \\
0 & 0 & 1
\end{bmatrix}

Karsten Heeger, Univ. of Wisconsin

NUSS, July 10, 2009
#3 theorists aren’t (always) right ... 

“Oscillation mixing angles must be small like the quark mixing angles”  
Wrong

“Atmospheric neutrino anomaly must be other physics or experimental problem because it needs such a large mixing angle”  
Wrong

“Natural scale for $\Delta m^2 \sim 10 - 100$ eV$^2$ since needed to explain dark matter”  
Wrong

“LSND result doesn’t fit in so must not be an oscillation signal”  
???
#4 unique, model-independent measurements

- Charged-Current (CC)
  \[ \nu_e + d \rightarrow e^- + p + p \]

- Neutral-Current (NC)
  \[ \nu_x + d \rightarrow \nu_x + n + p \]

- eliminate model-dependent assumptions and interpretation
- physics result independent of Monte Carlo
- any result from SNO would have been interesting: win-win situation!
And a slightly increased uncertainty on normalization of the scaled reactor spectrum without distortions from neutrino oscillation fitting the geo-neutrino contribution. The method incorporates Earth matter oscillations effects. The best fit is shown in Fig. 1. The joint confidence curve show the expectation accounting for the distances to the individual reactors, time-dependent flux variations and efficiencies. The p values obtained from a geological reference model are disfavored. The KamLAND data, together with the solar neutrino experiments, are plotted in Fig. 4 as a function of $L/E$. The spectrum indicates almost two cycles of the survival probability. Top panels: events in 100 months. Bottom panels: events in 20 months.

Karsten Heeger, Univ. of Wisconsin
NUSS, July 10, 2009
Supernova 1987A

Nobel Prize for the Detection of Cosmic Neutrinos

Kamiokande was ready to seize the opportunity.
Future Efforts

- from discoveries to precision studies, picking the best tools at hand

- what are the future directions of neutrino physics?

- neutrinos in particle/astrophysics
What we know...

Neutrino Mass Splitting

- KamLAND provides most precise value of $\Delta m_{12}^2$ (~2.8%)
What we know...

**Neutrino Mixing Angles**

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix} = \begin{pmatrix}
0.8 & 0.5 & U_{e3} \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]

**U_{MNSP} Matrix**

Maki, Nakagawa, Sakata, Pontecorvo

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha/2} & 0 \\
0 & 0 & e^{i\alpha/2+i\beta}
\end{pmatrix}
\]

atmospheric, K2K  \hspace{1cm} \text{reactor and accelerator}  \hspace{1cm} \text{SNO, solar SK, KamLAND}  \hspace{1cm} 0\nu\beta\beta

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

maximal?

\[\theta_{13} = ?\]

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

large, but not maximal!
Open Questions

\[ P(\nu_{\mu} \rightarrow \nu_e) - P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13} s_{23} c_{23} \]

\[
\sin \delta \sin \left( \frac{\Delta m_{12}^2}{4E} L \right) \sin \left( \frac{\Delta m_{13}^2}{4E} L \right) \sin \left( \frac{\Delta m_{23}^2}{4E} L \right)
\]

Questions

1. Is there a \( \mu-\tau \) symmetry in neutrino mixing?
2. Is there leptonic CPV?
3. What is mass hierarchy?
4. Do neutrinos have Majorana mass?
5. What is the absolute mass scale?
6. What is the role of neutrinos in the Universe?
Open Questions

The Tools

reactor & accelerator experiments

search for $0\nu\beta\beta$

$\beta$-decay experiments

astrophysics & cosmology

Questions

Is there $\mu-\tau$ symmetry in neutrino mixing?

Is there leptonic CPV?

What is mass hierarchy?

Do neutrinos have Majorana mass?

What is the absolute mass scale?

What is the role of neutrinos in the Universe?
Neutrino Sources

Neutrinos from the Big Bang
- ~330 neutrinos per cm$^3$
- 0.5 proton per cm$^3$

Supernova Neutrinos

Atmospheric Neutrinos

Geo Neutrinos

Accelerator & Reactor Neutrinos

High Energy Cosmic Neutrinos

Solar Neutrinos
Neutrino Energies

Big-Bang neutrinos $\sim 0.0004$ eV

Neutrinos from the Sun $< 20$ MeV depending on their origin.

Antineutrinos from nuclear reactors $< 10.0$ MeV

Atmospheric neutrinos $\sim$ GeV

Neutrinos from accelerators up to GeV ($10^9$ eV)
Reactor and Accelerator Experiments

**Reactor** ($\bar{\nu}_e$ disappearance)

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \right)$$

- Clean measurement of $\theta_{13}$
- No matter effects

**Accelerator** ($\nu_e$ appearance)

$$P(\nu_\mu \rightarrow \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$

$$+ 8 c_{13}^2 s_{13}^2 s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21}$$

$$- 8 c_{13}^2 s_{13}^2 s_{23}^2 s_{12} \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$+ 4 c_{13}^2 s_{12}^2 \left[ c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta \right] \sin^2 \Delta_{21}$$

$$- 8 c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2 s_{13}^2) \frac{aL}{4 E_\nu} \sin \Delta_{31} \left[ \cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right].$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of $\delta_{CP}$
Precision Measurement of Mixing with Reactor $\bar{\nu}$

Search for $\theta_{13}$ in new oscillation experiment with multiple detectors

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_{\nu}} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_{\nu}} \right)$$

Small-amplitude oscillation due to $\theta_{13}$ integrated over $E$

Large-amplitude oscillation due to $\theta_{12}$

~1-1.8 km

$> 0.4$ km

$\Delta m_{23}^2 \approx \Delta m_{23}^2$
Reactor and Accelerator Experiments

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$$- 8 c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2 s_{13}^2) \frac{a L}{4 E_{\nu}} \sin \Delta_{31} \left[ \cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right] .$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of $\delta_{\text{CP}}$
Accelerator Experiments (NOvA, T2K etc)

Long Baseline Accelerator Experiments

- $\nu_e$ appearance
- long baselines, off-axis
- matter effects
Future Neutrino Oscillation Experiments

Large Detectors and Long Baselines
- search for CP violation with neutrino beam
- $\nu$ mass hierarchy
- proton decay ($10^{34}$ yrs → $10^{35}$ yrs)
- astrophysics
- atm $\nu$, geo $\nu$

*R&D in US, Europe, and Japan*
Ultimate oscillation experiment by 2020?
India Neutrino Observatory (INO)

A Next-Generation Atmospheric Neutrino Experiment

Mass: 50 kTon
Size: 48 m (x) × 16m (y) × 12 m (z)

140 layers of 6 cm thick iron with 2.5 cm gap for active elements

magnetized iron calorimeter

Magnetic field ~ 1 Tesla along the y-direction

Karsten Heeger, Univ. of Wisconsin  
NUSS, July 10, 2009
Search for $0\nu\beta\beta$

The Next Frontier in Neutrino Physics

$2\nu$ mode: conventional 2$^{nd}$ order process in nuclear physics

$$\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$$

$0\nu$ mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \left( \langle m_{\beta\beta} \rangle \right)^2$$

G are phase space factors $G$

$0\nu \sim Q^5$
Neutrinos in the Universe

“neutrinos are the most abundant particles in the Universe besides photons”
Neutrinos and the Universe

very early universe | big bang nucleosynthesis | CMB | late time structure formation

large-scale structure

matter-antimatter ratio

CMB

large-scale structure
Future Cosmological Constraints on $\Sigma m_\nu$

Cosmology probes important aspects of particle physics:
- Neutrino mass
- Dark energy equation of state

Partial degeneracy between $m_\nu$, $\omega$
(neutrino mass states and dark energy equation)
→ cross-correlate CMB and LSS, weak lensing, BAO measurements

Planck + LSST-like lensing survey survey $\Rightarrow \sigma(\Sigma m_\nu) \leq 0.05$ eV
→ probes difference between normal and inverted hierarchy

Ref: astr-ph/0603019
Neutrinos and Supernovae

“without neutrinos dying stars would not explode”
Neutrinos and Supernovae

neutrino oscillation effects on supernova light-element synthesis

“neutrinos helped cook the light elements in the Universe”

Interdependencies/Redundancies of Experiments

Need all types of experiments & observations

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Some Concluding Thoughts

- Last 10 years have been the decade of discovery in neutrino physics. Neutrino physics has demonstrated physics beyond the Standard Model.

- Neutrino physics is transitioning from a discovery to a precision science. Reactor and accelerator experiments will play a critical role in precision studies (solar and atmospheric may help).

- A rich program of neutrino experiments is underway to understand neutrino properties.

- Neutrinos are important in many astrophysical processes, and astrophysics/cosmology may help us understand the particle nature of neutrinos.