Reactor Neutrinos I

Karsten M. Heeger
University of Wisconsin
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Alushta, Ukraine
Outline

• Lecture 1

– observation of the neutrino
– reactors as an antineutrino source
– prediction of the antineutrino flux from reactors
– detection of reactor antineutrinos
– oscillation searches with reactors
– observation of reactor antineutrino disappearance at KamLAND
– precision oscillation physics with reactor antineutrinos
Outline

• Lecture 2
  – precision oscillation physics: theta13 and beyond
  – the reactor anomaly
  – future reactor experiments
    • \( \theta_{12} \)
    • mass hierarchy
    • sterile neutrino searches
  – searches for new physics
    • magnetic moments
    • coherent scattering
    • NSI
  – experiments with antineutrino sources
  – applications of reactor antineutrinos: monitoring & communication
Neutrino Energies

Big-Bang neutrinos $\sim 0.0004 \text{ eV}$

Neutrinos from the Sun $< 20 \text{ MeV}$ depending of their origin.

Atmospheric neutrinos $\sim \text{GeV}$

Antineutrinos from nuclear reactors $< 10.0 \text{ MeV}$

Neutrinos from accelerators up to GeV ($10^9 \text{ eV}$)
What produces the largest neutrino flux on Earth?

The Sun, the Big Bang, or a nuclear reactor?
What produces the largest neutrino flux on Earth?

The Sun, the Big Bang, or a nuclear reactor?

Solar neutrinos: \(7 \times 10^{10}\)

Primordial neutrinos from the Big Bang: \(3 \times 10^{12}\)

Reactor neutrinos: \(1 \times 10^{10}\)

at a distance of 1 km
Discovery of the Antineutrino
History of the Neutrino

Pauli, 1930

\[ N \rightarrow N' + e^- \] some nuclei emit electrons!

Chadwick, 1914

Fermi, 1934

Fig. 5. Energy distribution curve of the beta-rays.
First Proposal For Direct Detection of Neutrino
Nuclear Reactors as a Neutrino Source

Reactors are intense and pure sources of $\bar{\nu}_e$


Good for systematic studies of neutrinos.
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.
1953: Project Poltergeist

Experiment at Hanford
Hanford Experiment

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

300 liters of liquid scintillator loaded with cadmium

Signal: delayed coincidence between positron and neutron capture on cadmium

High background (S/N ~ 1/20) made the experiment inconclusive

0.41 +/- 0.20 events/minute
1956: First Direct Detection of the Antineutrino

Clyde Cowan Jr.

Frederick Reines
A new design (1959)
tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs
target tanks (blue) were filled with water+cadmium chloride

inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
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
The Savannah River Detector

A new design (1959)

- tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs
- target tanks (blue) were filled with water+cadmium chloride

Inverse beta decay

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

- inverse beta decay would produce prompt and delayed signal in neighboring tanks
The Savannah River Detector

A new design (1959)

tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs
target tanks (blue) were filled with water+cadmium chloride

Shielding: 4 ft of soaked sawdust

shielding and background reduction is important
The Savannah River Detector

A new design (1959)

tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

target tanks (blue) were filled with water+cadmium chloride

Reines, Cowan, Phys Rev 113, (1959)273

first reactor $\bar{\nu}_e$ spectrum
1956: First Observation Observation of the Antineutrino

by April 1956, a reactor-dependent signal had been observed:
signal/reactor independent background ~ 3:1

in June 1956, they sent a telegram to Pauli

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[Image of telegraph sent to Pauli]
A Lesson from History

• A Science article reported that the observed cross section was within 5% of the $6.3 \times 10^{-44} \text{ cm}^2$ expected (although the predicted cross section has a 25% uncertainty).

• In 1959, following the discovery of parity violation in 1956, the theoretical cross section was increased by $\times 2$ to $(10 \pm 1.7) \times 10^{-44} \text{ cm}^2$

• In 1960, Reines and Cowan reported a reanalysis of the 1956 experiment and quoted $\sigma = (12^{+7}_{-4}) \times 10^{-44} \text{ cm}^2$

Ref:
THE DETECTION OF THE NEUTRINO, 1956

On August 27, 1956, at the Savannah River Plant (now Savannah River Site), Drs. Clyde L. Cowan, Jr. (1919-1974) and Frederick Reines (1918-1998) used P Reactor to detect the neutrino, a sub-atomic particle hypothesized in 1930 but unconfirmed until their experiment, one of the most significant in modern physics.

(Continued on other side)
Reactors as Antineutrino Source
Energy Release in Fission and Self-Fusion

- only nuclei with $40 < A < 95$ are stable against both fission and self-fusion
- $Q_{\text{fis}}$ calculated for symmetric fission

at $A=120$: 8.5 MeV

at $A=240$: 7.6 MeV

Fig: Basdevant et al.
Fission and Nuclear Deformation

variation of energy as a function of distortion

\[ E_A = \text{fission barrier} \]
$^{235}\text{U} \text{ Fission}$

distribution of fission fragments

$^{235}_{92}\text{U} + n \rightarrow X_1 + X_2 + 2n$

asymmetric fission into lighter

Together these have 98 p and 136 n while fission fragments $(X_1+X_2)$ have 92 p and 144 n

On average 6n have to beta-decay to 6p to reach stable matter $\rightarrow \nu_e$
Reactors as Antineutrino Sources

$\beta^-$ decay of neutron rich fission fragments

![Diagram showing $\beta^-$ decay of neutron rich fission fragments]

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy of fragments</td>
<td>165 ± 5</td>
</tr>
<tr>
<td>Energy of prompt photons</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Kinetic energy of neutrons</td>
<td>5 ± 0.5</td>
</tr>
<tr>
<td>Energy of $\beta$ decay electrons</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Energy of $\beta$ decay antineutrinos</td>
<td>10</td>
</tr>
<tr>
<td>Energy of $\gamma$ decay photons</td>
<td>6 ± 1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>200 ± 6</td>
</tr>
</tbody>
</table>

~ 200 MeV/fission and 6 $\bar{\nu}_e$/fission

3 GWth reactor produces $\sim 6 \times 10^{20}$ $\bar{\nu}_e$/sec

Energy per fission

Some energy taken away by neutrinos, neutrons etc

Pure source of $\bar{\nu}_e$
**Fission with thermal and fast neutrons**

Thermal $n + ^{235}\text{U}$ can lead to fission of $^{236}\text{U}$.

$n + ^{235}\text{U}$ has higher energy than lowest fissionable state.

Fission of $^{239}\text{U}$ requires addition of neutron with kinetic energy $T_n=6-4.8=1.2 \text{ MeV}$.

**some nuclei require thermal neutrons for fission, others require fast neutrons**

Nuclei which are used most easily as fuel (fission rapidly by thermal neutron capture): $^{233}\text{U}$, $^{235}\text{U}$, $^{239}\text{Pu}$.

Reactors which burn $^{239}\text{Pu}$ and which contains $^{238}\text{U}$ can produce more $\text{Pu}$ than it needs → breeder reactor.
Nuclear Reactors

Reactors are an extended neutrino source:
3-4m diameter, 4m high
Fuel Element for a PWR Reactor
Reactor Antineutrinos

Source

$\bar{\nu}_e$ from $\beta$-decays of n-rich fission products

pure $\bar{\nu}_e$ source

typical fuel composition

$^{235}\text{U} : ^{238}\text{U} : ^{239}\text{Pu} : ^{241}\text{Pu} = 0.570 : 0.078 : 0.0295 : 0.057$

$> 99.9\%$ of $\bar{\nu}_e$ are produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

$\sim 90\%$ of $\bar{\nu}_e$ are produced by fissions in $^{235}\text{U}$, $^{239}\text{Pu}$

Plutonium breeding over fuel cycle ($\sim 250$ kg) changes antineutrino rate (by 5-10\%) and spectrum
Build-Up of Fission Products & Burn-Up Corrections

- **Burn-up correction needed**
  - The percentage of the different primary isotopes change with time
  - Different fuel components yield different spectra

- **Experiments receive information from reactor company who understand this very well**
  - Use information to calculate a time dependent rate of neutrinos vs energy

isotope uncertainties of 4-6% for most 0.1% for $^{238}$U, correlated

$\sim 5\%$ isotope uncertainty yields $\sim 0.5\%$ uncertainty in neutrino flux

Gram atomic weight per ton of fuel

Fig: Basdevant et al.
Reactor Refueling and Time Variation

$\bar{\nu}_e$ flux from reactor has time variation

3-6 week shutdown every 12-18 months

1/4-1/3 of fuel assemblies are replaced, remaining fuel repositioned

refueling at Palo Verde reactors and predicted antineutrino rate
Thermal Power → Fission → Antineutrinos

1. Power Measurement
most accurate measurement is secondary heat balance method offline, done weekly, uncertainty ~0.5-0.7%

2. Core Simulation
fission fraction of fuel isotopes are obtained by core simulation

3. Energy release per fission in MeV

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>James</th>
<th>Kopeikin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$U</td>
<td>201.7±0.6</td>
<td>201.92±0.46</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>205.0±0.9</td>
<td>205.52±0.96</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>210.0±0.9</td>
<td>209.99±0.60</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>212.4±1.0</td>
<td>213.60±0.65</td>
</tr>
</tbody>
</table>

4. Neutrino Spectra
Fission Products, $\beta$-spectra, $\bar{\nu}$

**Measurements**
- $\beta$-spectra resulting from fission of $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ have been experimentally measured
- use thin layer of fissile material in beam of thermal neutrons, e.g. Schreckenbach et al., Hahn et al.
- can be converted to $\bar{\nu}_e$ spectra

reference spectra from ILL over last 25 years

**Calculations**
$^{238}\text{U}$ beta spectra not available, fast neutrons required for fission
$\rightarrow$ determined from theory ($\pm 10\%$), contributes 7-10% of fissions in a PWR
Neutrino Flux Predictions

\[ \Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E) \]

- **Reactor data**
  - Thermal power, \( \delta P_{th} < 1\% \)

- **Reactor evolution codes**
  - Fraction of fissions from isotope \( k \), \( \delta \alpha_k = \text{few } \% \)

- **Nuclear databases**
  - \( E \) released per fissions of isotope \( k \), \( \delta E_k \approx 0.3\% \)

- \( S_k(E) = \sum \) all fission products
\[ S_{k}(E) \]

Sum of all fission products’ activities

\[ S_{k}(E) = \sum_{fp=1}^{N_{fp}} A_{fp}(T) \times S_{fp}(E) \]

Sum of all \( \beta \)-branches of each fission product

\[ S_{fp}(E) = \sum_{b=1}^{N_{b}} BR_{fp}^{b} \times S_{fp}^{b}(Z_{fp}, A_{fp}, E_{0fp}^{b}, E) \]

Theory of \( \beta \)-decay

\[ S_{fp}^{b} = \frac{K_{fp}^{b}}{\text{Norm.}} \times \mathcal{F}(Z_{fp}, A_{fp}, E) \times pE(E - E_{0fp}^{b})^2 \times \left( 1 + \delta_{fp}^{b}(Z_{fp}, A_{fp}, E) \right) \]

\[ \delta_{fp}^{b} = G_{v(QED)} + L_{0(coulomb \, size)} + C_{(weak \, size)} + S_{(screening)} + \delta_{WM(weak \, magnetism)} \]

Ref: Lhuillier
Neutrino Flux Predictions

- Fission fraction vs. burnup (5%)
  Burnup = Mega-watt days/ton uranium (From reactor company)

- Total uranium in core (0.4%)

- Reactor power vs. day (0.2%)

- Burnup vs. fortnight
  (From reactor company)

- Burnup vs. day

- Fission fractions vs. day

- Fission rate per day

- Fission rate per isotope per day

- Nonequilibrium corrections (O(1%))

- Beta to neutrino spectrum
  (3% calc or 1.4% meas (Bugey))

- Spent fuel (0.3%)
  (low-energy)
  (Not yet implemented)

- Neutrino spectrum vs. day
  (~few%)(uncertainties combine non-trivially)

Ref: Lewis
Goesgen Experiment (1986)

Comparison of Predicted Spectra to Observations

two curves are from fits to data and from predictions based on Schreckenbach et al.

3 baselines with one detector

flux and energy spectrum agree to ~ 1-2%

reactors are a “well-calibrated” source of $\nu_e$
Bugey Experiment (1996)

Check $\bar{\nu}$ Spectrum Against Data

Measured $\bar{\nu}_e$ spectrum shape and normalization agreed with calculated predictions to ~10% and with converted electron spectra even better.

spectra derived from $\beta$-spectra: +/-1.4% agreement
Detection and Studies of Reactor Antineutrinos
Reactor Antineutrinos

Detection

inverse $\beta$-decay

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

observable rate and energy spectrum

only disappearance experiments possible

neutrinos with $E < 1.8$ MeV are not detected

only $\sim 1.5\bar{\nu}_e$/fission can be detected

$\bar{\nu}_e$ scattering

From Bemporad, Gratta and Vogel

calculated reactor spectrum
cross-section accurate to +/-0.2%

observed spectrum mean energy $\sim 3.6$ MeV

cross-section

calculated reactor spectrum

nu energy (MeV)

Events (kg/day/keV)

$\bar{\nu}_e N(SM)$

$\bar{\nu}_e N(SM)$

$1 \text{ c/kg/kev/d}$

$\bar{\nu}_e e(MM)$

$\bar{\nu}_e e(SM)$

recoil energy (keV)
Antineutrino Detection

inverse beta decay

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

\[ n + p \rightarrow D + \gamma \ (2.2 \text{ MeV}) \]

(delayed)

coincidence signature between prompt \( e^+ \) and delayed neutron capture on H, (or Cd, Gd)

\[ E_{\overline{\nu}_e} \approx E_{e^+} + E_n + (M_n - M_p) + m_{e^+} \]

including \( E \) from \( e^+ \) annihilation, \( E_{\text{prompt}} = E_{\overline{\nu}} - 0.8 \text{ MeV} \)

other detection mechanisms:

\[ \overline{\nu}_e + d \rightarrow e^+ + n + n \]

\[ \overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^- \]
Physics with Reactor $\bar{\nu}_e$

Discoveries and Precision Measurements of Neutrino Properties

Antineutrino Discovery

Reactor $\bar{\nu}_e$ Spectra

$\bar{\nu}_e$ Oscillations

Searches for New Physics

neutrino magnetic moment and coherent scattering searches

Reactor Monitoring and Application

fuel burnup and isotopic composition
Neutrino Oscillation Searches with Reactor Antineutrinos
Neutrino Oscillation

Neutrino flavor change occurs if neutrinos have mass and leptons mix

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

mixing matrix

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

mass eigenstates

Experiments study flavor conversion as a function of energy, distance and determine mixing angle and mass splitting

2-neutrino case, vacuum

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

$P(\bar{\nu}_e \rightarrow \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$
Oscillation Experiments with Reactors

Measure (non)-$1/r^2$ behavior of $\nu_e$ interaction rate

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

$L/E \rightarrow \Delta m^2$

amplitude of oscillation $\rightarrow \theta$

for 3 active $\nu$, two different oscillation length scales: $\Delta m^2_{12}, \Delta m^2_{23}$

$\Delta m^2_{12} \sim 7.6 \times 10^{-5} \text{ eV}^2$

$\Delta m^2_{23} \sim 2.4 \times 10^{-3} \text{ eV}^2$

$\Delta m^2_{23} \approx \Delta m^2_{13}$
Search for Neutrino Oscillations at Reactors

early experiments tried to probe “atmospheric neutrino anomaly”
early oscillation experiments didn’t know the length scales involved

At $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$,
$\sin^2 \theta_{13} < 0.15$
Neutrino Oscillation Search with Reactor Antineutrinos

Oscillation Searches at Chooz + Palo Verde:

\[ \overline{\nu}_e \rightarrow \overline{\nu}_x \]

Distance: 1km

Absolute measurement with 1 detector

detector size: several tons
Backgrounds for Reactor Experiments

• Backgrounds to the $e^+ - n$ coincidence signal

  **Uncorrelated Backgrounds**
  – ambient radioactivity
  – accidentals
  – cosmogenic neutrons

  **Correlated Backgrounds**
  – cosmic rays induce neutrons in the surrounding rock and buffer region of the detector
  – cosmogenic radioactive nuclei that emit delayed neutrons in the detector
    
    eg. $^8$He ($T_1/2 = 119$ ms)  
    $^9$Li ($T_1/2 = 178$ ms)

  ![Energy spectrum of backgrounds and signal](image)

  *from M. Shaevitz*
Chooz: Positron Spectrum

Reactor On/Off

- Positron Yields for Reactors I+II
- Fit to Spectrum
- Comparison to Expected Yield for No Oscillation
Chooz: Results

~3600 events in 335 days

~2.2 events/day/ton with 0.2-0.4 bkgd events/day/ton

2.7% uncertainty
Chooz: Degradation of Scintillator

\[ \lambda(t) = \frac{\lambda_0}{1 + \alpha t} \]

\[ \lambda_0 = (587 \pm 33) \text{ cm} \]

\[ \alpha = (4.2 \pm 0.4) \times 10^{-3} \text{ d}^{-1} \]

Attenuation degrades by \(\sim 0.4\%\) per day.
Reactor $\bar{\nu}_e$ Flux Measurements at Different Distances

Early Reactor $\nu$ Experiments

flux measurements at distances up to ~1km consistent with expectations
Reactor Antineutrinos in Japan

Japanese Reactors

- Kashiwazaki
- Takahama
- Ohi

55 reactors

Reactor Antineutrinos

\[ ^{235}\text{U} : ^{238}\text{U} : ^{239}\text{Pu} : ^{241}\text{Pu} = 0.570 : 0.078 : 0.0295 : 0.057 \]

\(~ 200\) MeV per fission

\(~ 6\) \(\bar{\nu}_e\) per fission

\(~ 2 \times 10^{20}\) \(\bar{\nu}_e/GW_{th}\)-sec

reactor \(\bar{\nu}\) flux \(~ 6 \times 10^6/cm^2/sec\)
KamLAND Antineutrino Detector

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

through inverse $\beta$-decay

liquid scintillator target:
- proton rich $> 10^{31}$ protons
- good light yield
Antineutrino Candidate Event

Prompt Signal
E = 3.20 MeV
\[ \Delta t = 111 \text{ ms} \]
\[ \Delta R = 34 \text{ cm} \]

Delayed Signal
E = 2.22 MeV
First Evidence for Reactor $\bar{\nu}_e$ Disappearance

KamLAND 2003

Japan

mean, flux-weighted reactor distance ~ 180km

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

Evidence of Spectral Distortion

KamLAND 2004

Observed $\overline{\nu}_e$ 258 events
No-Oscillation 365.2 ± 23.7 (syst.)
Background 17.8 ± 7.3 events
Livetime: 766.3 ton-yr

Spectral Distortions: A unique signature of neutrino oscillation!
Simple, rescaled reactor spectrum is excluded at 99.6% CL ($\chi^2=37.3/18$)

210Pb $\to$ 210Bi $\to$ 210Po $\to$ 206Pb
138d, $\alpha$ $\to$ 13C($\alpha$,n)16O ($\sim$10^{-7}) $\to$ 222Rn decay chain introduced in the LS during assembly

 fiducial volume syst.: 4.7%
total systematics = 6.5%
Measuring Neutrino Oscillation Parameters

solar neutrino problem

oscillation searches

atmospheric/beam neutrinos
\[ \theta_{23}, \Delta m^{2}_{23} \]
solar/reactor neutrinos
\[ \theta_{12}, \Delta m^{2}_{12} \]

1960-1990

1990-2000

2000 - Present
Measuring Neutrino Oscillation Parameters

Solar Neutrinos

Solar Neutrinos + KamLAND 2003 ($\bar{\nu}_e$ rate)

Solar Neutrinos + KamLAND 2004 ($\bar{\nu}_e$ rate+spectrum)

Agreement between oscillation parameters for $\bar{\nu}$ and $\nu$

Beginning of precision neutrino physics
Precision Oscillation Physics with Reactor Neutrinos
Evidence of Spectral Distortion

KamLAND 2008

Prompt event energy spectrum for $\bar{\nu}_e$

- unbinned likelihood fit (rate+shape+time)
- 2-flavor oscillation analysis with w/Earth matter effects
- geo-neutrino U,Th amplitude is a free parameter

number of events
(expected)
(no-oscillation): $2179 \pm 89$ (syst)
(ground-state): $1709$
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Systematic Uncertainties and Backgrounds

### Systematic Uncertainties

<table>
<thead>
<tr>
<th>$\Delta m_{21}^2$</th>
<th>Detector-related (%)</th>
<th>Reactor-related (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale</td>
<td>1.9</td>
<td>$\bar{\nu}_e$-spectra [7]</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>1.8</td>
<td>$\bar{\nu}_e$-spectra</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>1.5</td>
<td>Reactor power</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.6</td>
<td>Fuel composition</td>
</tr>
<tr>
<td>Cross section</td>
<td>0.2</td>
<td>Long-lived nuclei</td>
</tr>
</tbody>
</table>

### Estimated Backgrounds

TABLE II: Estimated backgrounds after selection efficiencies.

<table>
<thead>
<tr>
<th>Background</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>80.5 ± 0.1</td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$</td>
<td>13.6 ± 1.0</td>
</tr>
<tr>
<td>Fast neutron &amp; Atmospheric $\nu$</td>
<td>&lt;9.0</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,n)^{16}\text{O}$ G.S.</td>
<td>157.2 ± 17.3</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,n)^{16}\text{O}$ $^{12}\text{C}(n,\gamma)^{12}\text{C}$ (4.4 MeV $\gamma$)</td>
<td>6.1 ± 0.7</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,n)^{16}\text{O}$ 1$^{\text{st}}$ exc. state (6.05 MeV $e^+e^-$)</td>
<td>15.2 ± 3.5</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,n)^{16}\text{O}$ 2$^{\text{nd}}$ exc. state (6.13 MeV $\gamma$)</td>
<td>3.5 ± 0.2</td>
</tr>
<tr>
<td>Total</td>
<td>276.1 ± 23.5</td>
</tr>
</tbody>
</table>

fiducial volume systematics reduced from 4.7% → 1.8%

total systematics: 4.1%

significantly reduced (number of events)
**4π Full-Volume Calibration**

**Design Concept**

Vertex distribution of $^{60}$Co/$^{68}$Ge composite source in $4\pi$ calibration runs.

**Calibration Data**

Vertex distribution of $^{60}$Co/$^{68}$Ge composite source in $4\pi$ calibration runs.

Fig. 17. The colors correspond to the level of detected activity. The source activity traces the outline of the calibration system, thus providing confirmation of the system location. The outer dotted line represents the balloon boundary. The inner dot-dashed line is the safety-zone. Plots like these were used during the deployment to confirm the location of the system before moving to the next position. The progression from left to right illustrates the sequence in which the pole was swept through a single azimuthal slice of the detector.

Fig. 18. An Instrumentation Unit equilibrium with the surrounding LS. In order to achieve better performance more care would need to be taken with the temperature compensation of the pressure sensor and the heat conductivity between the thermometer and the pressure sensor. The accelerometer data was also analyzed and found to be good to $10^{-6}$.$\degree$. In order to achieve better performance with the accelerometers more care would need to be taken with the mounting and calibration of these devices.

The temperature data from the units was very successful. The temperature gradient in KamLAND is an issue in several part of the analysis as temperature may affect the optical properties of the liquid scintillator. Data from the IU's taken during the off-axis deployments provided a detailed measurement of the temperature gradient in LS volume. This data has become very important recently as understanding the stability of this temperature gradient is critical to the success of the low-background phase purification effort.

Fig. 19. The Temperature Distribution in KamLAND.

2.2. Offline Position Determination

Knowledge of the geometry of the pole and its suspension system can be used to determine the source position to an accuracy of several centimeters. The center of gravity for an idealized nylon segment pole suspended from two weightless cables is first calculated. One then uses the cable lengths together with the distance between the attachment points to calculate the shape and orientation of the pole-cable triangle. The source-end position is then specified by the pole angle and the distance along the pole as measured from the center of gravity which lies 11 cm.

Calibration Data: 4π Full-Volume Calibration

- $^{60}$Co sources along pole
- $^{60}$Co/$^{68}$Ge source at end
Oscillation Parameters

Rate-Shape-Time Analysis

KamLAND only
\[ \tan^2 \theta = 0.56 \pm 0.14 \]
\[ \Delta m^2 = 7.58 \pm 0.21 \times 10^{-5} \text{eV}^2 \]

KamLAND+solar
(combined under assumption of CPT invariance)
\[ \tan^2 \theta = 0.47 \pm 0.06 \]
\[ \Delta m^2 = 7.59 \pm 0.21 \times 10^{-5} \text{eV}^2 \]
KamLAND L/E Dependence

Solar neutrino problem solved!
1970-1995 first identified by Ray Davis (missing solar $\nu_e$)
2002-2007 SNO observes neutrino flavor change, finds evidence for neutrino mass
2003-2008 KamLAND demonstrates $\nu$ oscillation, precision measurement of $\theta$, $\Delta m^2$
Pathway Towards Discovery

baseline: 1 km
size: 5 ton

180 km
1000 ton

- Take big steps
- Don’t always trust “theoretical” guidance
- A little bit of luck
1968  Ray Davis detects 1/3 of expected solar neutrinos.  
(Nobel prize in 2002)

1998  SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002  SNO finds evidence for solar $\nu_e$ flavor change.

2003  KamLAND discovers disappearance of reactor $\bar{\nu}_e$
55 years of liquid scintillator detectors
A story of varying baselines...

1956 - First observation of (anti)neutrinos

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

1995 - Nobel Prize to Fred Reines at UC Irvine

2003 - First observation of reactor antineutrino disappearance

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

Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Measurement of Fundamental Parameters

Mass Splittings

KamLAND has measured $\Delta m_{12}^2$ to $\sim2.8\%$
Neutrino Oscillation

Mixing Angles

\[ U = \begin{pmatrix}
  U_{e1} & U_{e2} & U_{e3} \\
  U_{\mu1} & U_{\mu2} & U_{\mu3} \\
  U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
  0.8 & 0.5 & U_{e3} \\
  0.4 & 0.6 & 0.7 \\
  0.4 & 0.6 & 0.7
\end{pmatrix} \]

\[ U_{\text{MNSP Matrix}} \]

Maki, Nakagawa, Sakata, Pontecorvo

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

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

atmospheric, K2K
reactor and accelerator
SNO, solar SK, KamLAND
\( 0\nu\beta\beta \)

Schwetz et al
updated as of 2010
Neutrino Oscillation - Before 2011

Mixing Angles

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
0.8 & 0.5 & U_{e3} \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]

\(U_{\text{MNSP}}\) 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

reactor and accelerator

SNO, solar SK, KamLAND

0\(\nu\beta\beta\)

\[
sin^2 \theta_{23} = 0.50^{+0.07}_{-0.06}
\]

\[
sin^2 \theta_{13}
\]

small? zero?

maximal?

\[
sin^2 \theta_{12} = 0.318^{+0.019}_{-0.016}
\]

large, but not maximal!
Neutrino Oscillation - Before 2011

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

reactor and accelerator

SNO, solar SK, KamLAND

0νββ
Tell me $0_{13}!$

Sheldon Lee Glashow

14 May 2003

「教えてください、$0_{13}$を！」
シェルトン・リー・グラショウ
2003年5月14日

グラショウ氏は物理学特別講演のため夫人と共に来日し、吉本高志東北大学総長と会見後、ニュートリノ科学研究センターを訪問され、ニュートリノ研究の新たな成果を称賛して記された。