Reactor Neutrinos

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Outline

- Nuclear Reactors
- Reactor Neutrinos
- Experimental detection
- The Daya Bay experiment

About me

- A physicist in the Electronic Detector Group (EDG), Physics Department, BNL
  - PhD at CalTech (2011)
    - KamLAND experiment (Japan)
  - Came to BNL as a postdoc then became a staff
    - Daya Bay experiment (China)
    - PROSPECT experiment (US)
- Love cats
World’s First Nuclear Reactor

Chicago Pile-1 (CP-1)

- Part of the Manhattan Project
- Designed and tested by a team of 49 scientists led by Enrico Fermi at U. Chicago
- Dec 2, 1942: first human-made self-sustaining nuclear chain reaction
  - Fuel: 40-ton Uranium Oxide and 6-ton Uranium Metal
  - Neutron moderator: 380-ton Graphite blocks
  - Control rods: Cadmium sheets
Fission and Energy Release

Key properties of fission
- Release substantial energy (mostly as kinetic energy of the fission fragments)
- Release excess neutrons: possibility of chain reaction.

Reactor design requirement
- Fission requires thermal neutron: needs “moderator” to slow down neutrons
  - Water, heavy water (D\textsubscript{2}O), Graphite, etc.
- Controllable fission: reactor engineering to make output neutron = 1 (critical condition)

1 gram U-235 fissioned = 8.6x10\textsuperscript{10} joules = 24,000 kwh
(Equivalent to lighting a small city for overnight)
24,000 kwh requires 3.2 tons of coal
12.6 bbls oil

Energy Density (energy / mass)
Energy Density of U-235 = 28,000 times energy density of coal
Core Heat Removal
- Coolant: Heat Transfer
- Safety Systems (Emergency)

Confinement of Radioactivity
- Electricity Production
- Spent fuel processing

Schematic of a Pressurized Water Reactor (PWR)

- Reactor Core Design
  - Core Power Distribution
  - Ability to shutdown plant
  - no fuel failure or melting
Full video with annotations: Breazeale Nuclear Reactor Start up, 500kW, 1MW, and Shut Down (ANNOTATED) - YouTube
North America hosts over 25% of the world's operating reactors.

49% of U.S. reactors are aged 40 years or older, by far the biggest share of aging reactors.

South America's 5 reactors are split between Brazil and Argentina, with 2 more under construction.

Germany pledged to close all nuclear power plants by 2022.

At 51 years, Switzerland's Beznau Unit 1 reactor is the oldest operating reactor in the world.

The United Arab Emirates completed construction of its first of four planned reactors in August 2020.

Once complete, India's under-construction reactors will almost double its nuclear energy production.

Africa only has two reactors, both in South Africa, though more are planned on the continent.

Dots with a white ring represent nuclear reactors built after 2010.

China hosts the most new reactors, with 45 of the world's 99 reactors less than 20 years old.

Japan shut down all reactors following the 2011 Fukushima disaster, but began restarting reactors in 2015.
Country Ranking in 2015

Total Electricity from nuclear

Percentage from nuclear
Nuclear Reactor as a Research Tool: Neutron Source

- Research reactors typically ~10 MW
- BNL’s past 3 reactors
  - BGRR, HFBR, BMRR

https://www.bnl.gov/about/history/reactors.php

HIGH-FLUX BEAM REACTOR
- Operated: 1965 to 1996
- Permanent shut in 1999
- Provided neutrons for research in material science, chemistry, biology, and physics.
- Scientists conducted experiments with external neutron beams delivered through ports placed around reactor core.
- Enriched uranium fueled the reactor. “Heavy” water — in which deuterium replaces the two hydrogen atoms — moderated fission and served as main coolant. Operated at 30, 40 or 60 megawatts.

Scientific advances
- Structure of cell’s “protein factory” — the 16-part ribosome — first discerned here.
- New uses of radioactive isotopes developed for treating illnesses such as cancer, heart disease and arthritis.
- Advanced understanding of life span and decays of isotopes such as zinc-80, which astrophysicists use to study supernovas.
- Magnet experiments led to Nobel Prize-winning theories of cooperative ordering in large collections of atoms.
- Scientists using the high-flux beam reactor determined structures of the 23 amino acids, which make up every protein in every cell in living things.

Cost to close: $64 million, with $32 million already spent. Stimulus money will pay about 90 percent of the remaining cost, which excludes taking it apart after 65 years.

NEWSDAY, MONDAY, MAY 4, 2009  www.newsday.com

MEDICAL RESEARCH REACTOR
- Operated: 1959 to 2000
- The smallest of the lab’s reactors, it was the first in the nation built just for medical research. Large objects were irradiated at one of the reactor’s four faces; holes in another face permitted irradiation of samples and production of short-lived radioisotopes. Neutron streams traveled from two remaining ports to treatment rooms for animal and clinical studies.
- Reactor operated at 3 megawatts but could generate 5 megawatts for short periods of time. Core was water cooled.

Scientific advances
- Boron neutron capture therapy, developed to treat a deadly form of brain cancer, was pioneered here.

Cost to close: Decommissioning plan and budget not yet developed.

Source: Brookhaven National Laboratory
Nuclear Reactor as (anti)Neutrino Source

- Pure $\bar{\nu}_e$ from beta decays of fission daughters
  - neutrino energy: $< 10$ MeV, peak ~ 4 MeV
- $2 \times 10^{20} \nu$ / sec / gigawatt
- free for physicists

Fission fractions in a typical power reactor

<table>
<thead>
<tr>
<th>Fission Product</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>55%</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>30%</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>10%</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>5%</td>
</tr>
</tbody>
</table>
Homework Problem 1

How many antineutrinos are produced per second for a typical 3-gigawatt (thermal) commercial reactor?

1. Each fission releases ~200 MeV energy. How many fissions are produced per second?

2. Each fission produce ~6 antineutrinos on average from the beta-decay chains. How many antineutrinos are produced per second?
Dear Radioactive Ladies and Gentlemen,

.......... 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. 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.......... 

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

“\(210_{83}^{83}\text{Bi} \rightarrow 210_{84}^{84}\text{Po} + e^- + \bar{\nu}_e\)
The Elusive Neutrinos

- An intensive neutrino source: a billion trillion (~$10^{21}$) $\nu$ per second
- A huge neutrino detector: tons to kilotons of target material
- A distinctive method to tell “neutrino interactions” from other backgrounds

Weak nuclear force

Neutrino detection requires:

- An intensive neutrino source: a billion trillion (~$10^{21}$) $\nu$ per second
- A huge neutrino detector: tons to kilotons of target material
- A distinctive method to tell “neutrino interactions” from other backgrounds
Neutrino Sources

- Sun
- Reactor
- Atmosphere
- Earth

Types of neutrinos:
- Solar neutrinos
- Supernova neutrinos
- Geological neutrinos
- Power plant neutrinos
- Atmospheric neutrinos
- AGN neutrinos
Neutrinos: First Detection

Frederick Reines and Clyde Cowan first detected (anti)neutrinos using the Savannah River nuclear reactor in South Carolina in 1956. (26 years after Pauli’s proposal)

“"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons""

Target: Water + CdCl₂   
Detector: Liquid Scintillator + PMTs
History of Reactor Neutrino Experiments

- Discovery of $\nu$
- Solving solar $\nu$ problem on Earth
- Discovery of smallest oscillation angle $\theta_{13}$
- Currently hold the best precision of
  - $\Delta m^2_{21}$ (KamLAND)
  - $\theta_{13}$ (Daya Bay)
- Comparable precision to accelerator-based experiments
  - $|\Delta m^2_{32}|$ (Daya Bay)
A lot of recent short-baseline reactor experiments (2010 – now)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactor</th>
<th>Baseline (m)</th>
<th>Overburden (m.w.e)</th>
<th>Mass (ton)</th>
<th>Segmentation</th>
<th>Energy res. (@ 1 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEOS (South Korea)</td>
<td>LEU 2.8 GW</td>
<td>23.7</td>
<td>~20</td>
<td>1.0</td>
<td>none</td>
<td>5%</td>
</tr>
<tr>
<td>Nucifer (France)</td>
<td>HEU 70 MW</td>
<td>7.2</td>
<td>~12</td>
<td>0.6</td>
<td>none</td>
<td>10%</td>
</tr>
<tr>
<td>NEUTRINO4 (Russia)</td>
<td>HEU 100 MW</td>
<td>6 - 12</td>
<td>~10</td>
<td>0.3</td>
<td>2D</td>
<td></td>
</tr>
<tr>
<td>DANSS (Russia)</td>
<td>LEU 3.1 GW</td>
<td>10.7 - 12.7</td>
<td>~50</td>
<td>1.1</td>
<td>2D</td>
<td>17%</td>
</tr>
<tr>
<td>STÉLIO (France)</td>
<td>HEU 58 MW</td>
<td>9 - 11</td>
<td>~15</td>
<td>1.6</td>
<td>1D 25 cm</td>
<td>8%</td>
</tr>
<tr>
<td>PROSPECT (USA)</td>
<td>HEU 85 MW</td>
<td>7 - 12</td>
<td>&lt; 1</td>
<td>1.5</td>
<td>2D 15 cm</td>
<td>4.5%</td>
</tr>
<tr>
<td>SoLid (UK Fr Bel US)</td>
<td>HEU 70 MW</td>
<td>6 - 9</td>
<td>~10</td>
<td>1.6</td>
<td>3D 5cm</td>
<td>14%</td>
</tr>
<tr>
<td>CHANDLER (USA)</td>
<td>HEU 75 MW</td>
<td>5.5 - 10</td>
<td>~10</td>
<td>1.0</td>
<td>3D 5cm</td>
<td>6%</td>
</tr>
<tr>
<td>NuLAT (USA)</td>
<td>HEU 20 MW</td>
<td>4</td>
<td>few</td>
<td>1</td>
<td>3D 5cm</td>
<td>4%</td>
</tr>
</tbody>
</table>
Detecting Reactor Neutrinos

Inverse Beta Decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

20-ton Gd-loaded liquid scintillator

Daya Bay Reactor Neutrino Experiment
Inverse Beta Decay

- A distinctive coincidence signature
  - 6 orders of magnitude in background rejection

Daya Bay Data

![Events vs Energy (MeV)](chart)

- 10^{10}
- 10^{8}
- 10^{6}
- 10^{4}
- 1
- D - prompt
- E - prompt
- E - delayed
- D - delayed

Daya Bay Reactor Neutrino Experiment

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

- 20-ton Gd-loaded liquid scintillator
- ~20 μs
- \( \Sigma = 1.022 \text{ MeV} \)
- \( \Sigma = 8 \text{ MeV} \)
- \( \Sigma = 2.2 \text{ MeV} \)
Predict Reactor Antineutrino Flux (I)

- Summation (ab initio) method
  - Calculate each beta-decay spectrum using nuclear databases: fission yields, decay schemes, etc.
  - ~10% uncertainty

In total, >6000 tabulated decay branches.

Example: $^{96}$Y decay

Conversion Method

- Expose fission parents to thermal neutrons and measure total outgoing beta-decay electron energy spectra. (*Experiments done at ILL in the 1980s*).
- Predict corresponding anti-neutrino spectra with >30 virtual branches.
- Re-analyses in 2011 increased prediction by ~5%.
- More precise (~2.5%) but recent works indicate >5% uncertainty.
Antineutrino Signal Prediction

- Antineutrino flux predicted from reactor theory (with large uncertainties)
- IBD threshold: $E > 1.8$ MeV (why?)
  - only about 1/3 of the reactor antineutrinos can be detected
- Flux-weighted cross section $\sim 3 \times 10^{-43}$ cm$^2$
Event Rate

- Depending on the power of the reactors, size of the detectors, and the distance between them.

Daya Bay:
- 17 GW
- Distance: 500 m
- Event Rate: 800/day
- Size: 1.6 km
- Mass: 20 ton

KamLAND:
- 55 GW
- Distance: 180 km
- Event Rate: 0.5/day
- Size: 1000 km
- Mass: 1000 ton

Nuclear Bomb Test:
- 10 kt TNT-equivalent
Daya Bay’s antineutrino detector (AD) is a 20-ton liquid scintillator detector. The far ADs are placed at ~1.6 km away from reactors with a total power of ~17 GW. How many inverse beta decay (IBD) reactions are expected per day in each far AD?

1. The hydrogen mass fraction in the AD is ~12%. How many free protons (from hydrogen) are there in each AD?

2. How many reactor antineutrinos per cm$^2$ per second is expected at the AD? (this is referred as the “flux”)

3. The average IBD cross section is ~3x10$^{-43}$ cm$^2$, calculate event rate = flux * cross section * number of protons, assuming 100% detection efficiency. (remember that IBD can only detect 1/3 of all reactor antineutrinos)
Neutrino Oscillations with Reactors

A 4 MeV reactor neutrino

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{PMNS}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- Solar / Long baseline reactor
- Short baseline reactor / Long baseline accelerator
- Atmospheric / Long baseline accelerator
- Neutrinoless double beta decay
\[ P = 1 - \sin^2 2\theta_{13} \cdot \sin^2 (1.27|\Delta m_{ee}^2|eV^2) \cdot \frac{L(m)}{E(MeV)} \]

\[ \frac{N_{\text{far}}}{N_{\text{near}}} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \cdot \left( \frac{L_n}{L_f} \right)^2 \cdot \left( \frac{\varepsilon_f}{\varepsilon_n} \right) \cdot \left( \frac{P_{\text{survival}}(E, L_f)}{P_{\text{survival}}(E, L_n)} \right) \]
Δm^2 \sim 2.5 \times 10^{-3} \text{eV}^2

My postdoc work at BNL

Δm^2 \sim 7.5 \times 10^{-5} \text{eV}^2

Image credit: H. Murayama
Statistics

- powerful reactors ($17.4 \text{ GW}_{th}$) + large detectors (80 ton at Far site)

Systematics

- **Reactor**
  - Far/Near relative measurement

- **Detector**
  - multiple functionally identical detectors (4 Near + 4 Far)

- **Background**
  - deep underground (860 m.w.e at far site)
Double Chooz, France  
RENO Korea  
Daya Bay, China

Baseline Optimization

- Detector locations optimized to known parameter space of $|\Delta m^2_{ee}|$
- Far site maximizes term dependent on $\sin^2 2\theta_{13}$

Go strong, big and deep!

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Target [tons]</th>
<th>Depth [m.w.e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>16 (2 x 8)</td>
<td>300, 120 (far, near)</td>
</tr>
<tr>
<td>RENO</td>
<td>32 (2 x 16)</td>
<td>450, 120</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>160 (8 x 20)</td>
<td>860, 250</td>
</tr>
</tbody>
</table>

Large Signal  Low Background
Discovery of non-zero $\theta_{13}$ at 5.2 $\sigma$
- 2011/12/24 – 2012/2/17 (55 days)
- 6 detectors in operation first

In fact, in the first 5 days we already knew that $\theta_{13}$ is large from the data. In the homework I'll give you all the inputs to do a simplified analysis.

Homework Problem 3

- How to discover the smallest neutrino oscillation with 5 days of Daya Bay reactor neutrino data?
Reactor and Detector Location

<table>
<thead>
<tr>
<th>Reactor</th>
<th>D1</th>
<th>D2</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>x (m)</td>
<td>43.0</td>
<td>-44.6</td>
<td>856.0</td>
<td>792.3</td>
<td>1143.6</td>
<td>1076.5</td>
</tr>
<tr>
<td>y (m)</td>
<td>7.0</td>
<td>6.9</td>
<td>830.9</td>
<td>767.9</td>
<td>1206.1</td>
<td>1138.5</td>
</tr>
<tr>
<td>z (m)</td>
<td>12.0</td>
<td>12.0</td>
<td>12.0</td>
<td>12.0</td>
<td>12.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AD</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>x (m)</td>
<td>94.5</td>
<td>97.8</td>
<td>584.1</td>
<td>-254.3</td>
<td>-259.5</td>
<td>257.3</td>
</tr>
<tr>
<td>y (m)</td>
<td>350.2</td>
<td>345.2</td>
<td>1216.2</td>
<td>1892.6</td>
<td>1889.6</td>
<td>897.8</td>
</tr>
<tr>
<td>z (m)</td>
<td>20.0</td>
<td>20.0</td>
<td>16.6</td>
<td>15.4</td>
<td>15.4</td>
<td>15.4</td>
</tr>
</tbody>
</table>

- All reactor cores operated at approximately equal power for the 5 days
- L2 was powered off during the 5 days
Summary of event selection for the first 5 days

<table>
<thead>
<tr>
<th></th>
<th>EH1 AD1</th>
<th>EH1 AD2</th>
<th>EH2 AD1</th>
<th>EH3 AD1</th>
<th>EH3 AD2</th>
<th>EH3 AD3</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBD Candidates</td>
<td>3278</td>
<td>3194</td>
<td>2193</td>
<td>338</td>
<td>350</td>
<td>348</td>
</tr>
<tr>
<td>DAQ Live Time</td>
<td>5.39</td>
<td>5.39</td>
<td>4.97</td>
<td>5.20</td>
<td>5.20</td>
<td>5.20</td>
</tr>
<tr>
<td>[days]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidentals</td>
<td>60.9</td>
<td>59.6</td>
<td>49.3</td>
<td>20.5</td>
<td>19.4</td>
<td>19.3</td>
</tr>
<tr>
<td>Li9</td>
<td>43</td>
<td>42</td>
<td>28</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Fast Neutron</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.8144</td>
<td>0.8120</td>
<td>0.8510</td>
<td>0.9515</td>
<td>0.9501</td>
<td>0.9508</td>
</tr>
</tbody>
</table>

- Calculate the signal rate per day after efficiency correction
  - EH1-AD1: \( \frac{3278 - 60.9 - 43 - 6}{0.8144 \times 5.39} = 721.7 \text{ events/day} \)

- Calculate the statistical error on the signal rate
  - EH1-AD1: \( \frac{\text{sqrt}(3278)}{0.8144 \times 5.39} = 13.0 \text{ events/day} \)
Background to IBD

- **Accidentals**: statistically calculate from uncorrelated singles
- **Li9 / He8**: measure time distribution of after-muon events
- **Fast neutron**: measure energy spectrum from AD/water/RPC tagged muon events

<table>
<thead>
<tr>
<th>Background</th>
<th>Near</th>
<th>Far</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>1.4%</td>
<td>2.3%</td>
<td>negligible</td>
</tr>
<tr>
<td>Li-9 / He-8</td>
<td>0.4%</td>
<td>0.4%</td>
<td>~30%</td>
</tr>
<tr>
<td>Fast neutron</td>
<td>0.1%</td>
<td>0.1%</td>
<td>~30%</td>
</tr>
</tbody>
</table>
How to discover the smallest neutrino oscillation with 5 days of Daya Bay reactor neutrino data?

1. Plot the measured antineutrino signal rate of each AD vs. the expected flux, assuming each AD has the same size, and each reactor has the same power.

2. Fit the data (what function to use?) with the near ADs and extrapolate to the far ADs. What do you see?

3. What is the “survival probability” in the far ADs relative to the near ADs? What is the statistical significance of this observation?

4. What is the size of $\theta_{13}$ using the oscillation formula?

\[
P = 1 - \sin^2 2\theta_{13} \cdot \sin^2 (1.27|\Delta m_{ee}^2|) \cdot \frac{L (m)}{E (MeV)}
\]

<table>
<thead>
<tr>
<th>$\Delta m^2$</th>
<th>$2.4 \times 10^{-3}$ (eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>$1.66 \times 10^3$ (m)</td>
</tr>
<tr>
<td>E</td>
<td>$3.5$ (MeV)</td>
</tr>
</tbody>
</table>
Data taking (12/24/2011 – 12/12/2020)
• 3275 days, 5.5M $\bar{\nu}_e$ events
largest reactor neutrino data sample in the world
Precision Oscillation

- Final results with the full data set
  - \[ \sin^2 2\theta_{13} = 0.0853 \pm 0.0024 \]
  - (2.8% precision)

  - Likely to be the best measurement in the foreseeable future
  - Critical input to the current and future long-baseline experiments (DUNE)
Go Closer: The **Precision Reactor Oscillation and Spectrum Experiment**

Search for “oscillation patterns” from eV-scale sterile neutrinos independent of reactor models at < 10 m
Reactor, Detector, Data

HFIR research reactor at ORNL
Power: 85 MW
Size: $\Phi=44$cm, $h=51$cm
Fuel: highly-enriched $^{235}$U ($^{235}$U fission fraction > 99%)

Detector near surface,
Segmented to 11 x 14 “cells”

$^6$Li-loaded liquid scintillator (4 ton) developed and produced at BNL

- > 50,000 antineutrinos from $^{235}$U fission collected
  (10 times more than the previous record from ILL in 1981)
- First surface-based detector to achieve S:B > 1 near a research reactor
No “Wiggles” Found

Energy spectra at different distances all agree with “no oscillation” prediction => No indication of “eV-scale” sterile neutrinos

“RAA” allowed region largely excluded (independent of reactor models)
Questions?