Design of the Daya Bay Antineutrino Detectors

Outline

1. Requirements
2. Overall Design
3. Mechanics
4. Liquid Scintillator (R. Hahn)
5. PMTs
6. Electronics
7. Calibration (B. McKeown)
8. Performance

Karsten Heeger
University of Wisconsin
Antineutrino Detector Requirements

• **High statistics** → large, homogeneous detectors

• **Clean inverse β-decay signature** with good background separation → Gd-loaded liquid scintillator (LS) (8 MeV/n-capture and 30 µs capture time with 0.1% Gd)

• ‘**Identical detectors**’ → precise, redundant relative measurements between the near and far detectors

• **Well determined fiducial mass** and hydrogen density → precise measurement of Gd-LS volume and mass (no need for vertex cut)

• **Low threshold** to detect e+ at rest → low single γ rate

• **Well-defined neutron detection efficiency** → γ-catcher, energy scale calibration, identical detectors

• **Good energy resolution** for energy scale, spectral distortion → high scintillation output, long L_{attn}, good photocathode coverage

• Enable **transport and swapping** in a reasonable tunnel size (~6m), manageable muon flux at the near site → moderate size (5m)
Antineutrino Detector Target Mass

Sensitivity after 3 years

Required target mass > 80 tons

\[ \Delta m^2 = 2.0 \times 10^{-3} \text{eV}^2 \]
\[ \sigma_{\text{sys}} = 0.2\% \]
\[ (B/S)_{\text{Near}} = 0.5\% \]
\[ (B/S)_{\text{Mid}} = 0.1\% \]
\[ (B/S)_{\text{Far}} = 0.1\% \]

\[ \text{80 tons} \]

4 x 20 tons at far site to achieve target mass
Multiple “Identical” Detectors

What is this experiment about …

- Relative measurement between detectors at different distances to cancel source (reactor) systematics
  → need “identical detectors” at near and far site

- Multiple modules at each site to obtain
  → enough target mass
  → systematic cross-checks

Detectors will never be “identical” but we can understand/measure/control

  → relative target mass & composition to < 0.2%
  → relative antineutrino detection efficiency to < 0.3%

…between pairs of detectors.
Detector Target

0.1% Gadolinium-Liquid Scintillator

- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time ($\tau \sim 28$ $\mu$s)
- Good light yield

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

<table>
<thead>
<tr>
<th></th>
<th>fraction by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.8535</td>
</tr>
<tr>
<td>H</td>
<td>0.1288</td>
</tr>
<tr>
<td>N</td>
<td>0.0003</td>
</tr>
<tr>
<td>O</td>
<td>0.0164</td>
</tr>
<tr>
<td>Gd</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

Gd capture | 86.7%
H capture  | 13.2%
C capture  | 10.08%

Most abundant isotopes:

- $^{155}$Gd $\Sigma_\gamma=7.93$ MeV $\sigma=61,400$ b
- $^{157}$Gd $\Sigma_\gamma=8.53$ MeV $\sigma=255,000$ b
Antineutrino Detector Design

Cylindrical 3-Zone Structure

I. Target: 0.1% Gd-loaded liquid scintillator, 1.6m
II. $\gamma$-catcher: liquid scintillator, 45cm
III. Buffer shielding: mineral oil, $\sim$45cm

Target Resolution

With 224 PMT’s on circumference and diffuse reflector on top and bottom:

$$\frac{\sigma}{E} \sim \frac{12.2\%}{\sqrt{E \text{(MeV)}}}, \quad \sigma_{\text{vertex}} = 13\text{cm}$$

$\gamma$ Catcher Efficiency

![Graph showing Gamma Catcher Efficiency at 6-MeV-Energy Cut]

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>$\gamma$ Catcher thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92%</td>
<td>20 t Gd-LS</td>
</tr>
<tr>
<td>95%</td>
<td>LS oil</td>
</tr>
<tr>
<td>90%</td>
<td>Mineral oil, ~45cm</td>
</tr>
</tbody>
</table>

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Karsten Heeger, Univ. Wisconsin  Daya Bay DOE Review, October
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III. Buffer shielding: mineral oil, ~45cm

Buffer Oil Shielding

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Concentration</th>
<th>20 cm (Hz)</th>
<th>25 cm (Hz)</th>
<th>30 cm (Hz)</th>
<th>40 cm (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>40 ppb</td>
<td>2.2</td>
<td>1.6</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>40 ppb</td>
<td>1.0</td>
<td>0.7</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>25 ppb</td>
<td>4.5</td>
<td>3.2</td>
<td>2.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>7.7</td>
<td>5.5</td>
<td>3.9</td>
<td>2.2</td>
</tr>
</tbody>
</table>

A 45cm buffer provides ~20cm of shielding against PMT glass
Event Rates and Signal

Antineutrino Interaction Rate
(events/day per 20 ton module)

Daya Bay near site 960
Ling Ao near site 760
Far site 90

Distances (m)

Daya Bay near 363
Ling Ao near 481
Far site ~1800

Prompt Signal

Delayed Signal

Reconstructed positron spectrum

Energy spectrum. Neutron uniform in inner detector

Recon. Energy (MeV)
Event Distributions

Zone 1: Gd-LS target

Zone 2: LS $\gamma$-catcher

Contains energy of $\gamma$'s from neutron capture or positron annihilation

Neutron Production Vertex of Captured Events

Neutron Capture Position
Detector Performance

GEANT simulations

224 PMTs with 12% effective photocathode coverage

~100 photoelectron/MeV: 12.2%/√E(MeV)

Photoelectron yield vs. Radius,
(no mineral oil)

Energy resolution

Inner (1.6m) Outer (2.05m)

Resolution (%)

1 MeV deposit

Outer-15cm
Three-Zone Detectors

- 2-zones: simpler design/construction, some cost reduction but with increased risk to systematic effects (neutron e and $E_n$ spectrum)
- 3-zones: increased confidence in systematic uncertainties associated with detection efficiency and fiducial volume, but smaller volume

4 MeV cut can reduce the error by x2, but residual radioactivity in LS volume does not allow us to do so.

$n$ capture on Gd yields 8 MeV with 3-4 $\gamma$'s.
Background Studies

Rock Background
\( \gamma \) spectrum from Aberdeen:
same granite as Daya Bay

- Aberdeen spectra and rates measured
- Radioactivity of Daya Bay borehole samples measured
- Radon in boreholes measured

Energy Deposit from Fast Neutrons

Monte Carlo
## Event Rates per Detector Module

<table>
<thead>
<tr>
<th>Source</th>
<th>Units</th>
<th>DB</th>
<th>LA</th>
<th>far</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antineutrino Signal</strong></td>
<td>(day⁻¹)</td>
<td>930</td>
<td>760</td>
<td>90</td>
<td>signal</td>
</tr>
<tr>
<td><strong>Radioactive Backgrounds</strong></td>
<td>(Hz)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>e⁺-thresh.</td>
</tr>
<tr>
<td>Rock</td>
<td>(Hz)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>PMT glass</td>
<td>(Hz)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>other materials (steel)</td>
<td>(Hz)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Gd contamination</td>
<td>(Hz)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Muons</td>
<td>(Hz)</td>
<td>24</td>
<td>14</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Single neutron</td>
<td>(day⁻¹)</td>
<td>9000</td>
<td>6000</td>
<td>400</td>
<td>cal.</td>
</tr>
<tr>
<td>Tagged single neutron</td>
<td>(day⁻¹)</td>
<td>480</td>
<td>320</td>
<td>45</td>
<td>cal./bkg.</td>
</tr>
<tr>
<td>Tagged fast neutron</td>
<td>(day⁻¹)</td>
<td>20</td>
<td>13</td>
<td>2</td>
<td>Bkg est</td>
</tr>
<tr>
<td>β emitters (6-10 MeV)</td>
<td>(day⁻¹)</td>
<td>210</td>
<td>140</td>
<td>15</td>
<td>n-thresh.</td>
</tr>
<tr>
<td><strong>¹²B</strong></td>
<td>(day⁻¹)</td>
<td>400</td>
<td>270</td>
<td>28</td>
<td>cal.</td>
</tr>
<tr>
<td><strong>⁸He+⁹Li</strong></td>
<td>(day⁻¹)</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td>Bkg</td>
</tr>
</tbody>
</table>
## Detector Vessel Structure

### Dimensions

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Inner Acrylic</th>
<th>Outer Acrylic</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>3200</td>
<td>4100</td>
<td>5000</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>3200</td>
<td>4100</td>
<td>5000</td>
</tr>
<tr>
<td>Wall thickness (mm)</td>
<td>10</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Vessel Weight (ton)</td>
<td>0.6</td>
<td>1.4</td>
<td>20</td>
</tr>
<tr>
<td>Liquid Weight (ton)</td>
<td>~20</td>
<td>~20</td>
<td>~40</td>
</tr>
</tbody>
</table>

Liquid weights are for the 3 separate zones

Total detector mass
- empty: ~20 tons
- full: ~100 tons
Detector Steel Tank: Finite Element Analysis

Load condition: tank structure filled with liquids
Constraint condition: bottom annular surface was constrained

Max. stress: 108 MPa
Max. deformation: 2.8 mm

Stress (Unit: Pa)

Deformation (Unit: m)
Acrylic Vessels

- To contain and separate detector volumes
- Good optical properties and long-term stability
- Withstand mechanical stresses during transport and scintillator

AV transmittance
Detector Assembly

- *drawings from Robin here*
Photomultipliers

Default Configuration

- 224 8” PMTs in 7 rings of 32
- Low-radioactivity glass
- Two candidates
  - Hamamatsu R5912
  - Electron Tubes 9354KB

Under Investigation

- magnetic shielding
  (compensation coils? mu-metal shield?)
- reflectors
- PMTs on top/bottom
Front-End Electronics

Charge Specifications
Dynamic range: 0.025-500 p.e.
Noise: < 0.1 photoelectron (p.e.)
Shaping time: 300 ns
Sampling freq.: 40 MHz

Time Specifications
Resolution < 500 ns

Signal split two ways for ADC & TDC

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Electronics: Trigger

Primary Physics Triggers:
- $E_{\text{sum}}$: 0.7 MeV
- $E_{\text{mult}}$: 10 PMTs

Trigger rate per module:
- $\gamma < 50$ Hz
- $\mu = 24$ Hz (DB), 14 Hz (LA), 1 Hz (F)

Other triggers:
- LED
- Radioactive source
- Clock
- Minbias
- Muon system
Electronics (DAQ)

Primary Physics Triggers

1. Antineutrino Detector
   - $E_{\text{sum}}$: 0.7 MeV
   - $E_{\text{mult}}$: 10 PMTs

2. Muon System
   - Water Pool
   - Water Tracker
   - RPC

- Entire detector is readout on all physics triggers
- Each detector system at each site is readout independently (8 antineutrino streams and 9 muon streams). An event builder reassembles the streams
- Every $e^+$, $\gamma$, neutron or $\mu^+$ will independently trigger a readout
Moving the Detector

1. Installation and Deployment
   - down 10% grade when empty (20 t)
   - moving 100 t on 0.5% tunnel grade
   - lifting 100 t into water pool

2. Detector Swapping (optional)

Bridge crane option considered in one of the civil conceptual design reports
Detector Calibration & Monitoring

Goals

→ characterization of detector
  - target mass, geometry, etc.
  - optical response, efficiency
→ monitoring of detector components
  - acrylic vessels
  - Liquid scintillators
→ regular calibration
  → gains, PMT response, detector optics

For example:

determine energy scale to 1% at 6 MeV throughout detector volume

⇒ neutron detection efficiency known to 0.2%.

Tools and Methods

• Load sensors, level sensors, thermometers, flow meters, mass flow meters
• LEDs
• Automated calibration with radioactive sources:
  –⁶⁸Ge (e⁺, 1.022 MeV), ⁶⁰Co (γ, 2.5 MeV), ²⁵²Cf (n-capture, 8 MeV)
  –3-4 locations (with full z travel)
• Data (¹²B, neutrons, Michel electrons)
Filling the Detector & Measuring the Target Mass

Three Liquids:  
I. Target: 0.1% Gd-loaded liquid scintillator  
II. γ-catcher: liquid scintillator  
III. Buffer shielding: mineral oil

Mass Measurements:  
mass + volume flow load sensors

Coriolis Mass Flow Meters  
Possible mass flow rates of 1g/hr - 8000kg/hr with 0.1% repeatability.

Flowmeters  
0.02% repeatability

Detectors are filled in pairs from common storage tanks
Detector Instrumentation

**Monitoring Goals:**
1. Mechanical stability during filling, transport, and movement
2. Liquid levels during filling
3. Detector geometry: acrylic vessel positions

- Laser reflection for in-situ measurement of:
  - attenuation length
  - acrylic vessel movement and position during transport

- Mass flow
- Volume flow
- Temperature
- Density

- Level sensors
- Tilt sensors
- Load sensors

Liquid Scintillator sampling

CCD camera
LED Calibration of the Antineutrino Detectors

**Calibration Goal: PMT gains**

Controls which LED(s) will be fired with what amplitude and at what time

Turn on the appropriate LED with the appropriate intensity, time and duration

Optical fiber bundle: each of equal length

Diffuser balls
Automated Source Calibration

Calibration Goal: energy scale, optical stability, uniformity, efficiency

Frequent automated calibration with vertically deployed radioactive sources

Example: Determination of attenuation length from 2 techniques:
- Neutron captures throughout volume relative to center (left)
- $^{60}$Co source in corner relative to center (right)

See talks by R. McKeown, J. Liu
Detector Prototype at IHEP

- 0.5 ton prototype
  (currently unloaded liquid scintillator)
- 45 8” EMI 9350 PMTs:
  14% effective photocathode coverage with top/bottom reflectors
- ~240 photoelectron/MeV
  9%/√E(MeV)

Energy Response/Linearity

Energy Resolution

\[
\chi^2 / \text{ndf} = 0.5883 / 1 \\
p_0 = -18.02 \pm 2.841 \\
p_1 = 273.5 \pm 2.765
\]

\[
\chi^2 / \text{ndf} = 28.22 / 1 \\
p_0 = 0.000627 \pm 0.00146 \\
p_1 = 0.08679 \pm 0.001967
\]
Prototype Performance

Testing the Energy Response: Comparison of data and Monte Carlo

- 0.5ton IHEP prototype
- L=1.0m, Φ=0.9m
R&D Tasks in the US

US groups involved in design and R&D of all critical detector elements

- Design and specification of acrylic vessels, support structures, and calibration interfaces.
- Identification and testing of PMTs.
- Design of HV and front-end electronics systems.
- Design of an integrated detector monitoring system and precision target mass measurements.
- Development of a safe transportation system for detector installation and swapping.
- Planning for assembly, testing and characterization of detector components and completed detectors.
- Simulations to support this effort.
Summary

• Conceptual design of the antineutrino detector is well advanced.

• Simulation of the detector response is well developed in a standardized software framework (g4dyb), including calibration and systematic studies.

• Detailed engineering of the vessels, supports and calibration system is underway.

• Detector prototype operational at IHEP. A second prototype to be built in Hong Kong. (Test bed for acrylic vessels, LS, PMTs, electronics, etc…)

• Design and R&D underway of PMTs, electronics, calibration systems and liquid scintillator.
Chooz Data

Reactor ON

\[d_+ \geq 30 \text{ cm}\]
\[d_n \geq 30 \text{ cm}\]
\[d_{e+n} \leq 100 \text{ cm}\]
\[2 \leq \Delta t \leq 100 \mu\text{s}\]

v candidate region

A

B

C

D

n-like Energy (MeV)

e\text{-like Energy (MeV)
Vertex Reconstruction

![Graph showing vertex reconstruction data with entries, mean, and RMS values.](image-url)
Antineutrino Detector

- I will discuss the overall detector design to minimize systematic uncertainties, including some discussion of electronics and calibrations

- Bob McKeown will show details of studies of the systematic uncertainties
Environmental conditions?