Neutron Detector in the Aberdeen Tunnel Underground Laboratory

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Neutrino Physics

- Neutrinos have mass and can oscillate from one flavor to another
- The mass eigenstates are not the same as the flavor eigenstates (neutrino mixing)
- For three flavors, neutrino oscillations are completely described by six parameters: three mixing angles $\theta_{12}$, $\theta_{13}$, $\theta_{23}$, two independent mass-squared differences, $\Delta m^2_{21} = m_2^2 - m_1^2$, $\Delta m^2_{32} = m_3^2 - m_2^2$, and one CP phase angle $\delta_{CP}$.

Significance of $\theta_{13}$

- To date, neutrino oscillation is the only evidence of physics beyond the Standard Model
- Precision measurement of its value will allow design of future experiment for $\delta_{CP}$

The Daya Bay Experiment

- Reactor based experiment to measure $\theta_{13}$
  - Anti-electron neutrinos emitted from $\beta$-decay in nuclear reactors
  - 3 GW (thermal) reactor gives $6 \times 10^{20}$ anti-neutrinos per second
  - Mean energy $\sim 4$ MeV
- Disappearance experiment
  - Measure fluxes of anti-neutrinos at short baseline (near detectors at $\sim 400$ – $500$ m) and at long baseline (Far detectors at $\sim 1600$ – $2000$ m)
The Experimental Halls

- 2 anti-neutrino detectors at each of the 2 Near Halls and 4 detectors at Far Hall
- Experimental halls ready from late 2008
- Detectors start taking data from late 2009

Anti-Neutrino Detector

- Based on inverse beta-decay interaction
  \( \nu_e + p \rightarrow \beta^+ + n \)
  - Event is registered when the two 511 keV annihilation photons from \( \beta^+ \) is followed by the 8 MeV \( \gamma \) burst due to capture of neutron by Gd

- 3-zones design
  - Central Gd-doped liquid scintillator for capturing neutrons and to produce scintillations
  - Gamma capture containing normal LS for capturing \( \gamma \) that have escaped capture in the central zone
  - Outer mineral oil buffer for shielding against external neutrons; \( \gamma \) from rock; from PMTs and from stainless steel tank

Aberdeen Tunnel Laboratory
The Mountain Profile

The Cross Passage

The Laboratory

Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>N 22° 15' 41&quot;</td>
</tr>
<tr>
<td>Longitude</td>
<td>E 114° 10' 48&quot;</td>
</tr>
<tr>
<td>Altitude</td>
<td>~ 22 m above sea level</td>
</tr>
<tr>
<td>Minimum rock thickness over laboratory</td>
<td>~ 240 m</td>
</tr>
<tr>
<td>Average vertical muon energy</td>
<td>~ 60 GeV</td>
</tr>
<tr>
<td>Average intensity of muons</td>
<td>~ 2 x 10^{-5} cm^{-2} s^{-1} sr^{-1}</td>
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</tbody>
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The Objectives

• To study the muon flux, energy and angular distribution in an underground laboratory having an overburden of ~240 m of rock.
• To study precisely the production mechanism of neutrons originated from muons interacting inside gadolinium-doped liquid scintillators.
• Helps to predict and identify the muon-induced neutrons in the Daya Bay neutrino experiment.
• To train students in this field.

Neutrons in Underground

• Measured by a Bonner sphere neutron dosimeter
• Only knows the count-rates; has no information about the neutron energies
• Both high energy (hundreds of MeV) spallation neutrons and low energy neutrons (a few MeV) from $(\alpha,n)$ interactions were measured
Production of Neutrons in LS

- Single or multiple neutrons can be produced in the liquid scintillator by inelastic muon interactions
  - \( \mu^+ + ^{12}\text{C} \rightarrow \mu^+ + \pi^+ + ^{12}\text{B}^* \)
    - Then \( \pi^+ \rightarrow \mu^+ \rightarrow e^+ \)
    - and \( \text{B}^* \) will potentially emit nucleons
  - \( \pi^- + d \rightarrow n + n \)
    - \( d \) is a pseudo-deuteron in \(^{12}\text{C}\)

The System

- A muon tracker to track passage and direction of muons
  - 3 layers of crossed proportional counters and plastic scintillators to give x-y coordinates
  - Event is registered when coincidence occurs among the layers
- A neutron detector sandwiched between the muon tracker to detect neutrons produced by muons in the detector body
  - Event is registered when coincidence occurs among the muon tracker and the neutron detector

The Neutron Detector

- 2-zone design because limited by space
  - Gd-doped LS (~0.7 ton)
    - Linear Alkyl Benzene (LAB)
    - PPO and bis-MSB as wavelength shifters
    - Contained in cylindrical acrylic vessel for light transmission
  - Mineral oil buffer (~1 ton)
    - Contained in rectangular stainless steel tank.
- Scintillations are detected by sixteen 8-inch Hamamatsu 1408 PMTs in stainless steel tank.
- Reflectors at top and bottom of steel tank to enhance light collection
Choice of Detector Configuration

Various detector configurations were studied

Uniformity of Light Collection

• Studied through simulation
• Recorded signal is higher when event occurs nearer to a PMT
• To maintain a fair uniformity, the PMT surfaces are kept at least 24 cm from the acrylic vessel

Energy Resolution

• 4 MeV and 8 MeV $\gamma$s are generated and the spread fit for Gaussian
• Energy resolution at 4 MeV = 9.7%
• Energy resolution at 8 MeV = 8.2 %
**Detection Efficiency**

- Energy deposition of $\gamma$ is almost always incomplete
- Efficiency is best at center of detector and decreases with increase in radial distance

**Concentration of Gd**

- Simulations of neutron capture by various Gd concentration in LS were done
- Capture time and track length depends on concentration of Gd
- For 0.1% Gd:
  - Mean capture time $\sim 10$ ns
  - Mean track length $\sim 20$ cm
- Neutron capture by H is also significant, but capture by C is negligible

**Neutron capture time (by Gd, H and C)**

**Neutron capture tracklength (by Gd, H and C)**
Effect of Ambient Gammas

- Gamma radiations are emitted from the rocks, the materials for making the detectors and detector frames.
- Genuine signals are those that have this sequence of event:
- A window of 100 ns will be opened to look for gammas exceeding 6 MeV as an indication of a neutron production.
- Gammas from all sources can arrive the detector coincidentally to produce fake event.
- Simulations were done which confirmed that coincident rate of gammas was very small even without any lead shielding around the detector.

Coincidence Rate of Gammas

- Shows up to 3-fold coincidence rate of gammas inside the detector with only 10 cm of mineral oil.
- An energy cut of 5.5 or 6 MeV will prevent all 2-fold coincidences.
- 3-fold coincidence rate above 6 MeV is about 0.86 per day or 1.7% of the 50 neutrons expected each day.

Calibration System

- Wheels containing stainless steel wire (for source) and optical fiber (for diffuser ball).
- Deployment box filled with nitrogen gas.
- 3 deployment ports for deploying radioactive source or light diffuser ball into the acrylic vessel.
- Deployment controlled by stepping motor controlled wheels when the port gate valve is opened.

Calibration with Radioactive Sources

- Gamma source: Co-60.
- Positron source: Ge-68.
- Neutron source: Am-Be & Pu-C.
  - Pu-C developed in CIAE.
  - Produce 6.13 MeV $\gamma$ and 4 MeV neutron.
  - $N(\gamma)/N(n) = 0.044$.

This image describes the calibration system of a detector with radioactive sources, highlighting the gamma and neutron production events and their coincidence rates. The system includes deployment boxes, overflow tanks, and controlled wheels for precise source placement. The radioactive sources used are Co-60, Ge-68, and Am-Be & Pu-C, each with specific energy outputs and interaction characteristics.
Pu-C

$^{13}\text{C}(\alpha,n)^{16}\text{O}$ cross section

LED Calibration System

- Diffuser ball
  - To act as an isotropic light source
  - 5 ns light pulses generated from a LED and connected to the diffuser ball by optical fiber
  - For setting $t_0$ of the DAQ system
  - For measurement of single photo-electron energy of PMTs

Overflow Tank

- Cater for thermal expansion of LS
- Maximum temperature rise may be up to 10 °C in the event of power breakdown leading to a volume increase of LS by 5.4L
- Average volume coefficient of thermal expansion
  - LS and mineral oil $\sim 7.7 \times 10^{-4}$/°C
  - acrylic $\sim 1.2 \times 10^{-4}$/°C
  - SS304 $\sim 5.2 \times 10^{-5}$/°C
- Pressure released by a balloon

The End

- The muon tracker has been completed
- The neutron detector is being fabricated and is expected to be finished after the summer
- Data taking will last for at least one year
- Hope to collect important experimental data for use in the Daya Bay Experiment