Neutron Calibration Sources
In The Daya Bay Experiment

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Outline

• Introduction
  – Daya Bay
  – Common neutron sources
  – Why $^{241}\text{Am-}^{13}\text{C}$ as neutron source

$^{241}\text{Am-}^{13}\text{C}$
  – Design
  – Fabrication
  – Performance

• Calibration source induced neutron background at Daya Bay

Based on the work [http://arxiv.org/abs/1504.07911](http://arxiv.org/abs/1504.07911), to be published in NIM A

Daya Bay

Inverse Beta Decay (IBD)

- Daya Bay is making a precision measurement for neutrino mixing angle $\theta_{13}$
- Detector target is Gd loaded liquid scintillator
- Daya Bay measures antineutrino via IBD
- Prompt + delayed coincidence provides distinctive event signature

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

$n + {}^x\text{Gd} \rightarrow {}^{x+1}\text{Gd} + \gamma$

~ 8 MeV multiple gammas
~ 30 us
Calibration System

• Precision measurement requires detector to be very well calibrated with various sources regularly

• **Automated** calibration units (ACUs)
  – Allow *weekly* calibration of detector response
  – Sources *stay on top of detector* during regular data taking
**Potential Background**

- Neutrons hardly leak into the detector, but n cap on SS (Fe, Mn, Cr, Ni) → high energy $\gamma$ (6-10MeV) can travel into the detector
  - 1 Hz neutron source → 2e-3 Hz single neutron-like (>6MeV) signal in the detector

- **Accidental** background formed when another singles and such a neutron-like signal happens closely in time (<200us)
  - Less a issue since statistically subtractable with high precision

- **Correlated** background formed when both prompt and delayed from the same neutron
  - Multiple neutrons emitted
  - $\gamma$, n correlated emission
  - Neutron inelastic scattering before capture
Source Requirement

• Physics requirement
  – Accidental background at far site: B/S < 5%
    • Given 70Hz singles rate and 70/AD/day IBD at far site
    • Require neutron rate < ~1Hz \(\Rightarrow\) LOW RATE
  – Correlated background at far site: B/S < 0.5%
    (<0.35/AD/day) \(\Rightarrow\) GAMMA-LESS

• We need a low rate gamma-less neutron source
Source Considerations

• Fission source $^{252}$Cf
  – 3.7 neutrons/fission $\rightarrow$ corr. bkg. (2.6/AD/day @ 0.5Hz neutron)

• Photo-neutron source such as $^{124}$Sb-Be
  – Small photo-neutron cross section, need strong driving gamma source $\rightarrow$ high corr. bkg.

• $(\alpha, n)$ source
  – $^{241}$Am-$^9$Be
  – $^{241}$Am-$^7$Li
  – $^{241}$Am-$^{13}$C
AmBe

• Typical $(\alpha, n)$ sources suffer from correlated $\gamma, n$ emission

• Correlated $\gamma, n$ emission $\rightarrow$ corr. bkg. (1.3/AD/day @ 0.5Hz neutron)

• Too much correlated background!

\[
{^{241}\text{Am} \alpha : 5.5\text{MeV}}
\]
AmLi

- No correlated $\gamma$ below 5.5 MeV 😊
- But cross section cut off at 4.4 MeV $\rightarrow$ low n yield 😞
- No suitable stable Li salt 😞
  - LiF: large corr. $\gamma, n$ emission from $^{19}F$
  - LiCl: hydroscopic
• Small corr. $\gamma, n$ emission
• Ground states only for $E_\alpha < 5.11$ MeV!
  – Attenuate $\alpha$ below 5.11 MeV to remove $^{16}$O excited states
• AmC is a good candidate
Alpha Source

- One-sided $\alpha$ from NRD Inc.
  - 5 mm disk
  - 4.5 MeV
  - 28 uCi

- Customized energy by varying the thickness of electrodeposited gold coating
Alpha Measurement Setup

• A 0.75-inch in diameter Si detector measured NRD source at different distances in a vacuum chamber (<10mTorr)
Alpha Spectrum

- All sources are consistent in spectrum and rate, measured rate is slightly lower than 28 uCi
- Though peaked at 4.6 MeV, board distribution extends up to 5.5 MeV, need extra attenuation
- Little spectrum shape dependence on distance to detector, indicating the gold plated surface is rough
Further Attenuation

- Attach 1 um gold foil to alpha source
- Peak shifted by 0.5 MeV
- No events above 5.11 MeV out of 20000
Mechanical Design

- Am, gold foil, C are sandwiched
- Ensure **uniform and compact contact** between alpha and C13
- Protect from alpha leakage, weld-on 3 cement
Fabrication

- Put $^{13}$C powder in SS cup
- Press $^{13}$C into a uniform disk
- Attach Au foil
- Attach Am
- Put acrylic plunger
- Press and seal with weldon-3
Simulation and Flux Prediction

- Use GEANT4 to track alpha in Au foil and $^{13}$C until it stops, calculate weight for each step in $^{13}$C and summed together

$$\text{weight}_i = \sigma(E_{\alpha,i}) \times d_i$$

$$R_n = R_{\alpha} \times \sum_i \text{weight}_i \times \frac{\rho_{13C} N_A}{13}$$

- Energy calculated by generating n at random direction w.r.t. alpha momentum using 2-body elastic kinematics
- Neutrons heading upwards have higher energy

Neutron kinetic energy 3-5.5 MeV

(b) Energy-angle correlation
Installed In ACU

Top weight

Neutron source

bottom weight

ACU
Performance at Daya Bay

No correlated gamma emission observed!

Neutron proton recoil energy peaked at ~1 MeV, scintillator quenching effect.

Very good data/MC agreement for all distributions!

Measured rate (0.75Hz) meets the design spec.
Residual Background

- Neutron background is important for DM experiment
- Kind of “similar” with DM experiment
  - Tiny background, can’t be measured, can only calculated indirectly
  - “Man-made” v.s. “Environmental”
Single Neutrons Observed in Detector

Z-distribution of single n-like events in physics data

Single n-like due to $^{241}$Am-$^{13}$C

Cosmogenic B12/N12

Single n-like events spectrum near the top of the ADs at the far site
Correlated Background

• Measure single neutron like (n-like) rate $R_{single}$ from data

• Predict correlated rate $R_{corr}$ using

\[
R_{corr} = \text{Yield} \cdot R_{single}
\]

• Ratio of $R_{corr}$ over $R_{single}$ based on MC, constrained by benchmark measurement
  – A special “strong” AmC source was constructed to directly observe the correlated events
Strong Neutron Source Fabrication and Installation
Benchmark Experiment

“Strong” AmC
A ~60Hz $^{241}$Am-$^{13}$C source (80 times stronger than regular ones) with the same design deployed during summer 2012

Single Neutron Spectrum from Strong AmC: Data vs MC

Strong AmC’s Prompt Spectrum: Data vs MC

Corr. bkg. prompt spectrum!
Background And Systematics

- Assigned 30% rate uncertainty from singles neutron rate variation
- Another 30% uncertainty for Yield based on benchmark experiment

Far site corr. bkg. requirement satisfied
- \( \sim 0.2 \pm 0.1 /\text{AD/day} \)

\[ f(E) = p_0 e^{-E/p_1} \]
\[ p_0 = 3.606 \times 10^{-3} \]
\[ p_1 = 0.783 \]

15% Shape uncertainty.
Summary

• A low rate & gamma-less neutron source was designed and fabricated for the Daya Bay experiment.
• Such source could be utilized in other experiments with low background requirement.
Backup
Measurement

- 4 NaI detectors (15*15*30cm)
- 3 muon paddles to reduce muon induced background
• More details in
Simulated Neutrons

Capture mainly on Fe, Cr, Ni, Mn

ACU enclosing structure and AD SS structures