Neutron Calibration Sources In The Daya Bay Experiment

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Outline

- Introduction
  - Daya Bay
  - Common neutron sources
  - Why ^{241}Am-^{13}C as neutron source
- ^{241}Am-^{13}C
  - Design
  - Fabrication
  - Performance
- Calibration source induced neutron background at Daya Bay

Based on the work http://arxiv.org/abs/1504.07911, to be published in NIM A
J. Liu, R. Carr, D.A. Dwyer, W.Q. Gu, G.S. Li, R.D. McKeown, X. Qian, R.H.M. Tsang, F.F. Wu, C. Zhang

Daya Bay

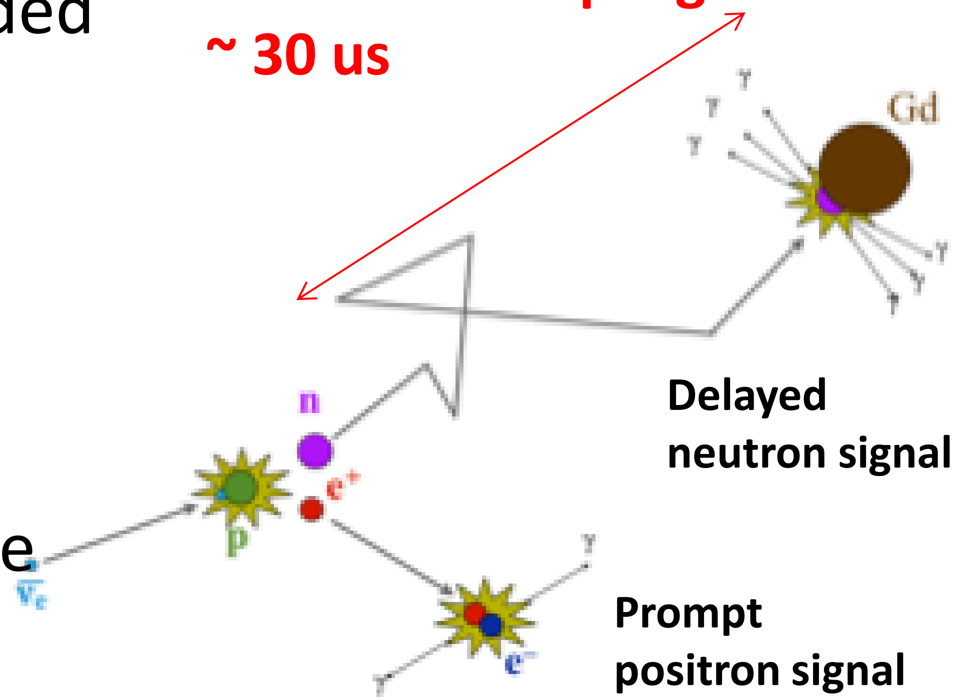
- Daya Bay is making a precision measurement for neutrino mixing angle θ_{13}
- Detector target is Gd loaded liquid scintillator
- Daya Bay measures antineutrino via IBD
- Prompt + delayed coincidence provides distinctive event signature

Inverse Beta Decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

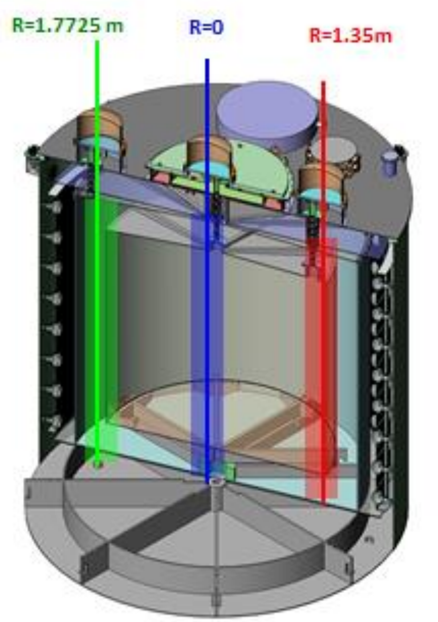
~ 8 MeV multiple gammas

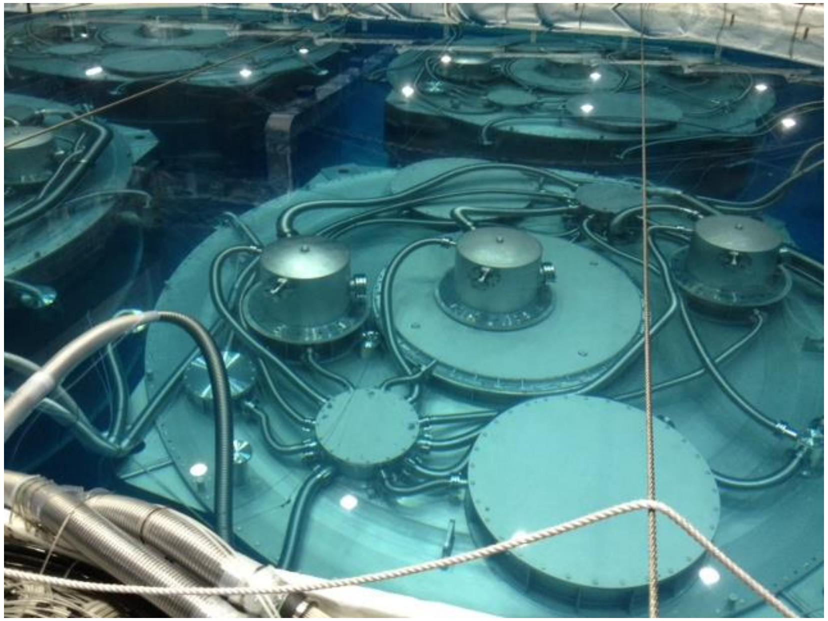
~ 30 us



Calibration System

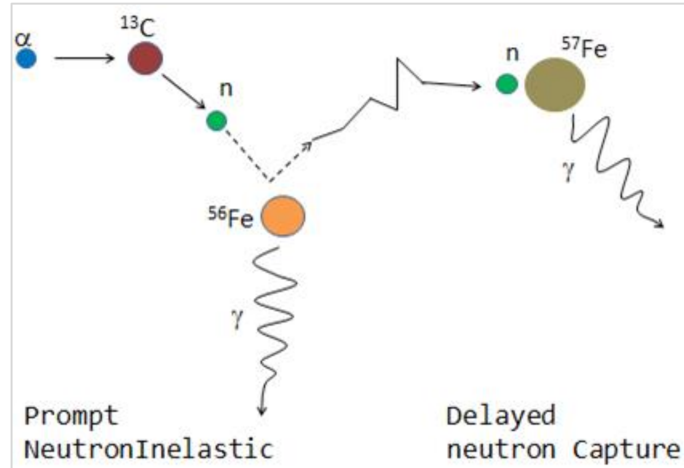
- Precision measurement requires detector to be very well calibrated with various sources regularly
- **Automated** calibration units (ACUs)
  - Allow weekly calibration of detector response
  - Sources stay on top of detector during regular data taking



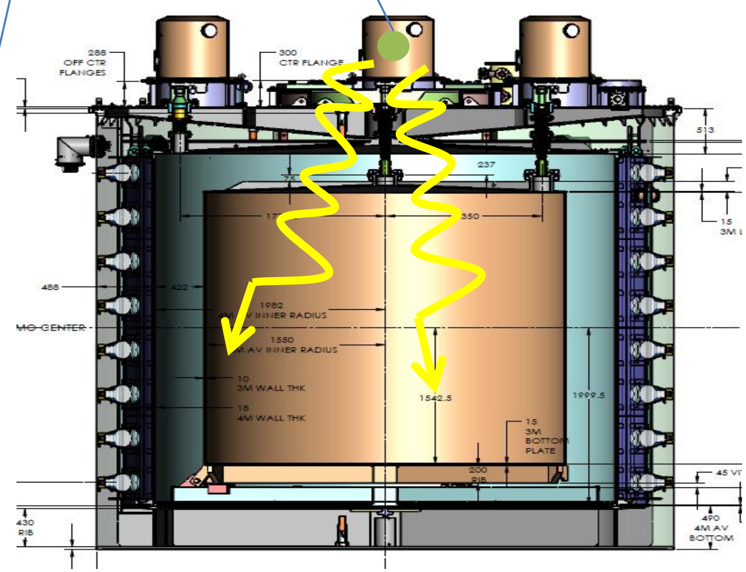


Potential Background

- Neutrons hardly leak into the detector, but n cap on SS (Fe, Mn, Cr, Ni) → high energy γ (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
  - γ, n correlated emission
  - Neutron inelastic scattering before capture



Neutron interaction with SS



Source Requirement

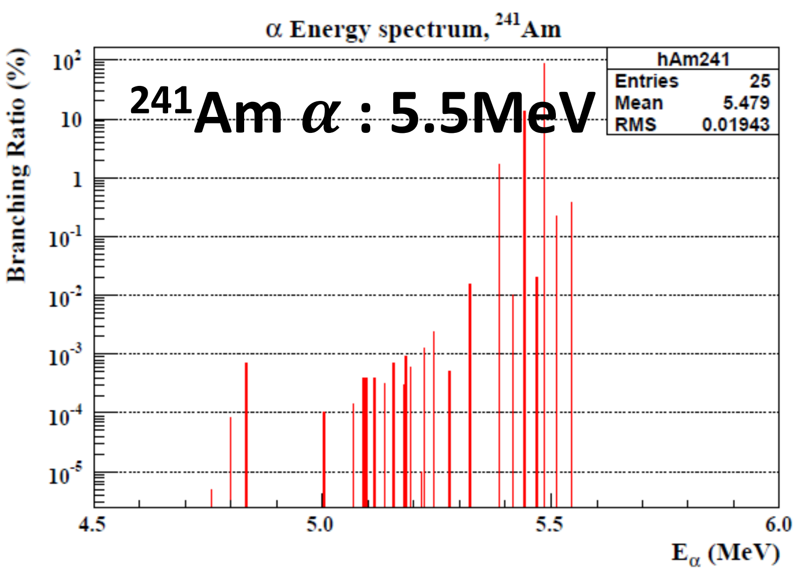
- Physics requirement
  - Accidental background at far site: B/S < 5%
    - Given 70Hz singles rate and 70/AD/day IBD at far site
    - Require neutron rate < ~1Hz → **LOW RATE**
  - Correlated background at far site: B/S < 0.5% (<0.35/AD/day) → **GAMMA-LESS**
- We need a low rate gamma-less neutron source

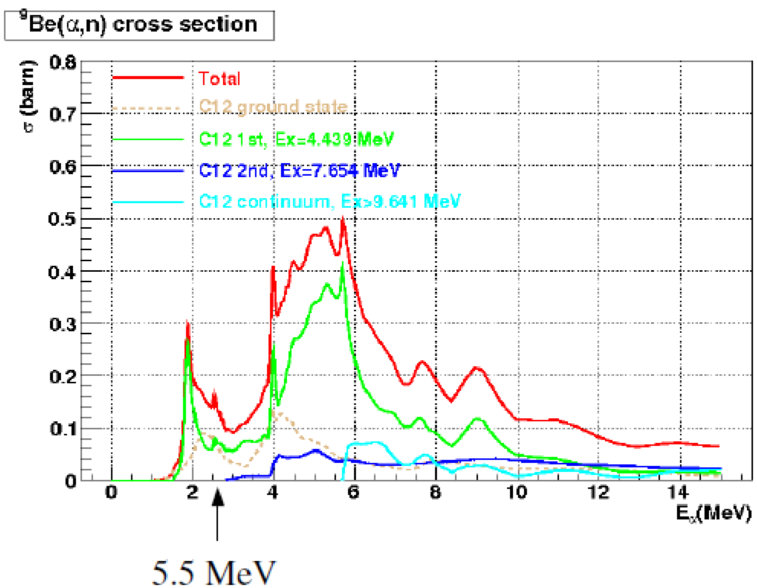
Source Considerations

- Fission source ^{252}Cf
  - 3.7 neutrons/fission→ 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 → high corr. bkg.
- (α, n) source
  - ^{241}Am-^{9}Be
  - ^{241}Am-^{7}Li
  - ^{241}Am-^{13}C

AmBe

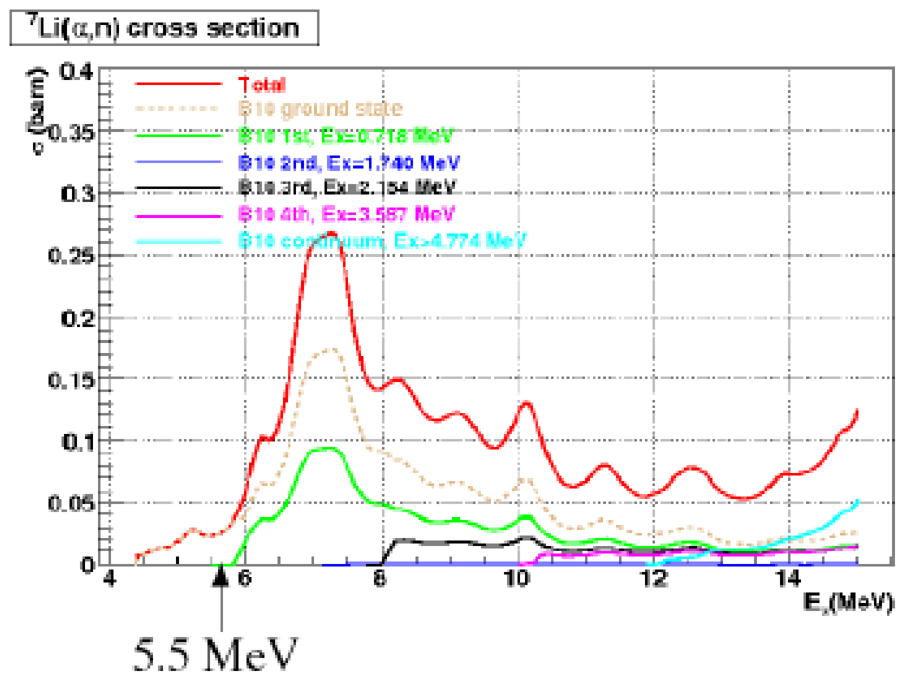
- Typical (α, n) sources suffer from correlated γ, n emission
- Correlated γ, n emission → corr. bkg. (1.3/AD/day @ 0.5Hz neutron)
- Too much correlated background!





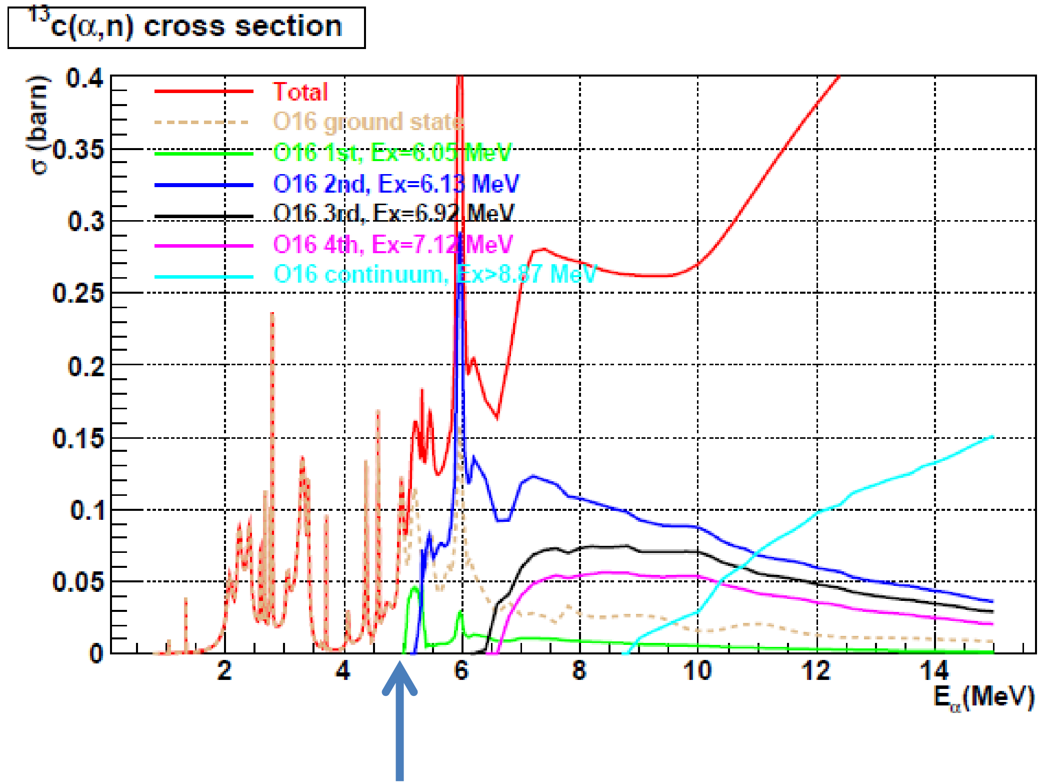
AmLi

- No correlated γ below 5.5 MeV ☺
- But cross section cut off at 4.4 MeV → low n yield ☹
- No suitable stable Li salt ☹
  - LiF: large corr. γ, n emission from ^{19}F
  - LiCl: hydroscopic



AmC

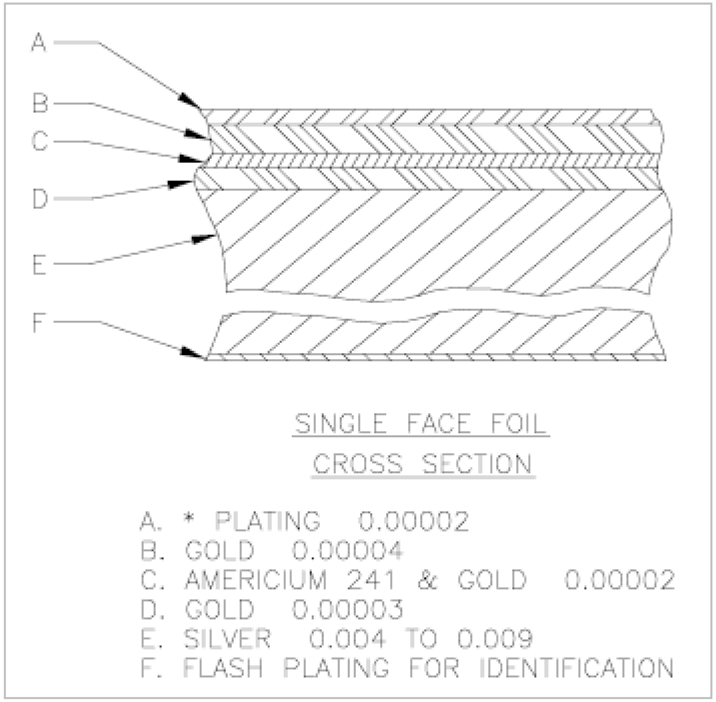
- Small corr. γ, n emission
- Ground states only for E_α<5.11 MeV!
  - Attenuate α below 5.11 MeV to remove ^{16}O excited states
- AmC is a good candidate



^{16}O excited state threshold

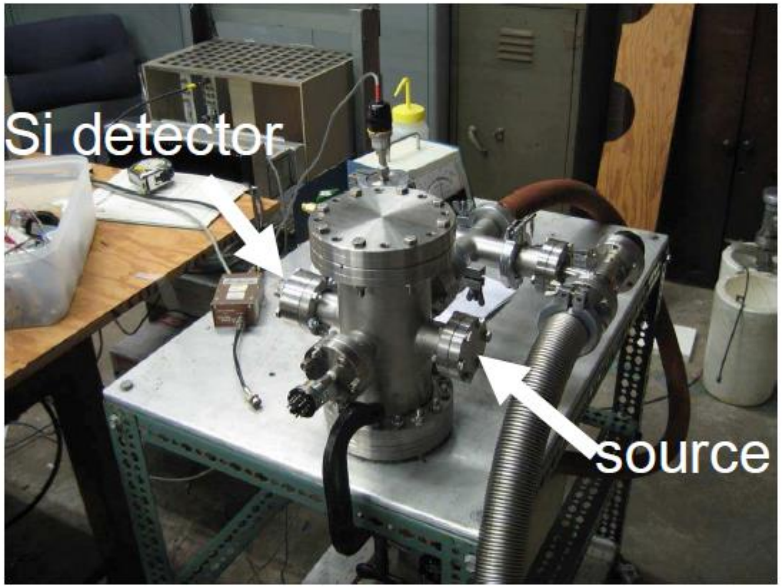
Alpha Source

- One-sided α from NRD Inc. with specs
  - 5 mm disk
  - 4.5 MeV
  - 28 uCi
- Customized energy by varying the thickness of electrodeposited gold coating



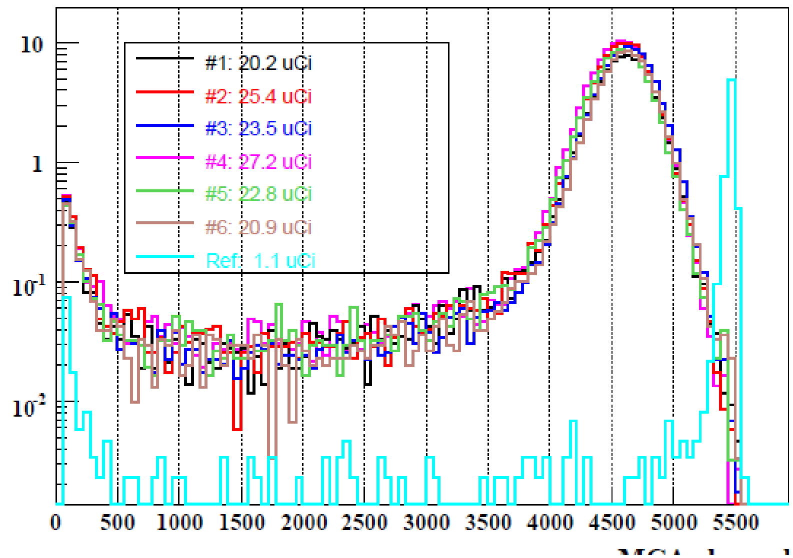
Alpha Measurement Setup

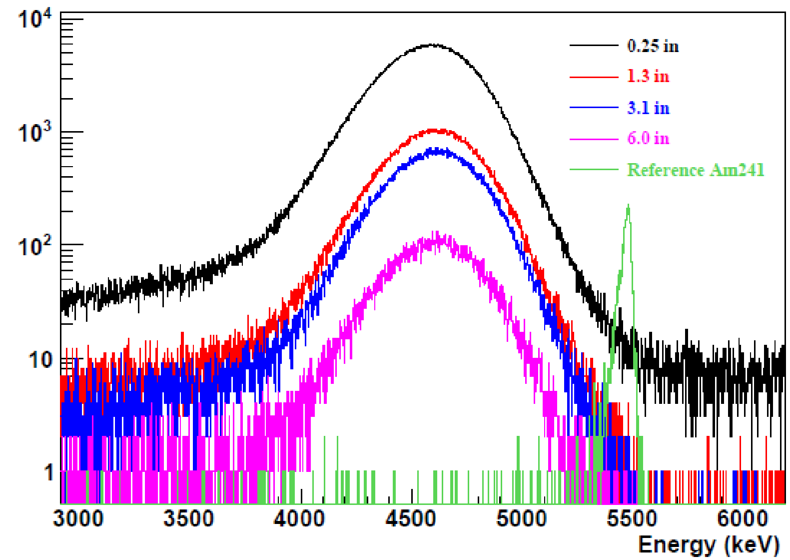
- A 0.75-inch in diameter Si detector measured NRD source at different distances in a vacuum chamber (<10mTorr)



Alpha Spectrum

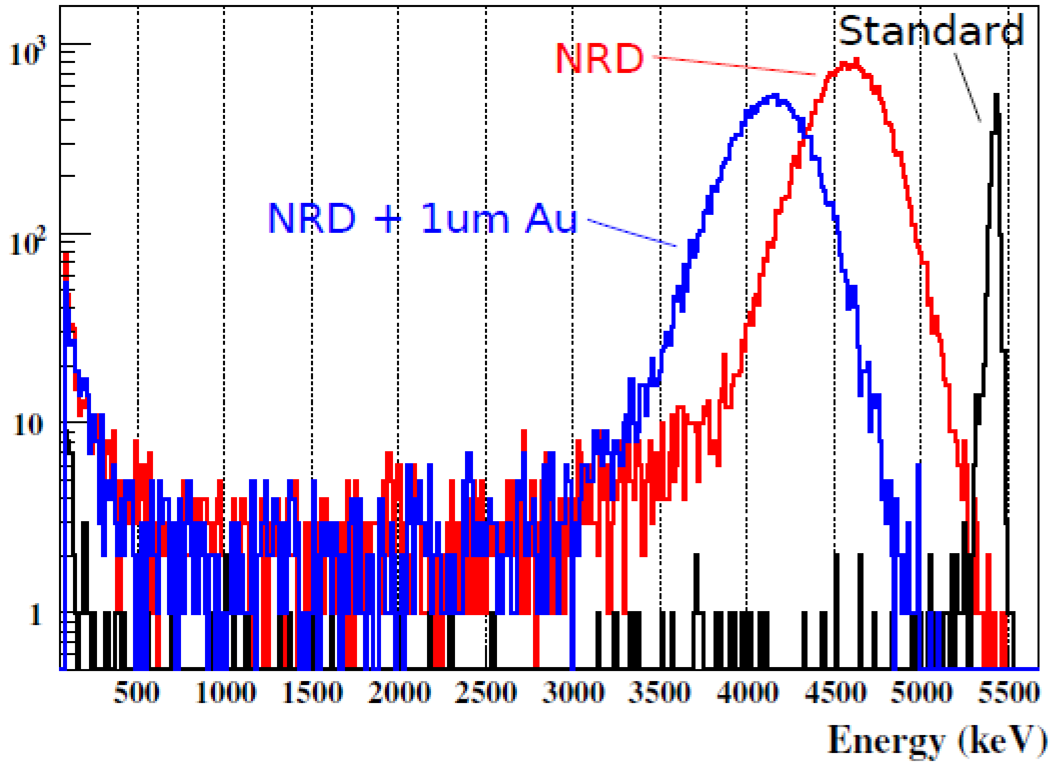
- All sources are consistent in spectrum and rate, measured rate is slightly lower than 28 uCi
- Though peaked at 4.6 MeV, board distribution extends up to 5.5 MeV, need extra attenuation
- Little spectrum shape dependence on distance to detector, indicating the gold plated surface is rough





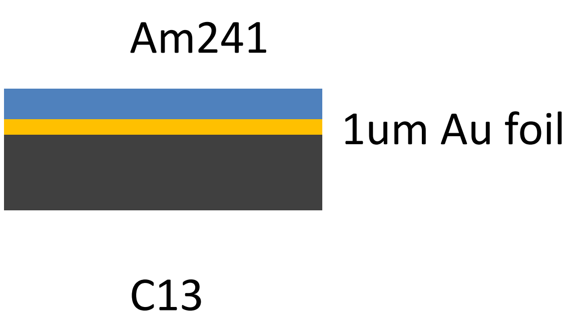
Further Attenuation

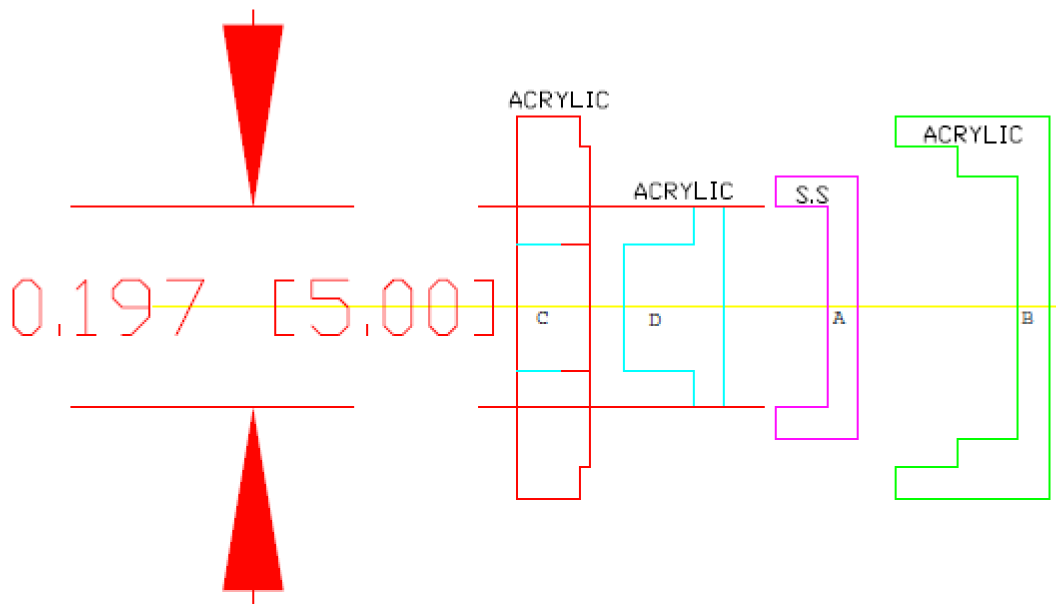
- Attach 1 um gold foil to alpha source
- Peak shifted by 0.5 MeV
- No events above 5.11 MeV out of 20000



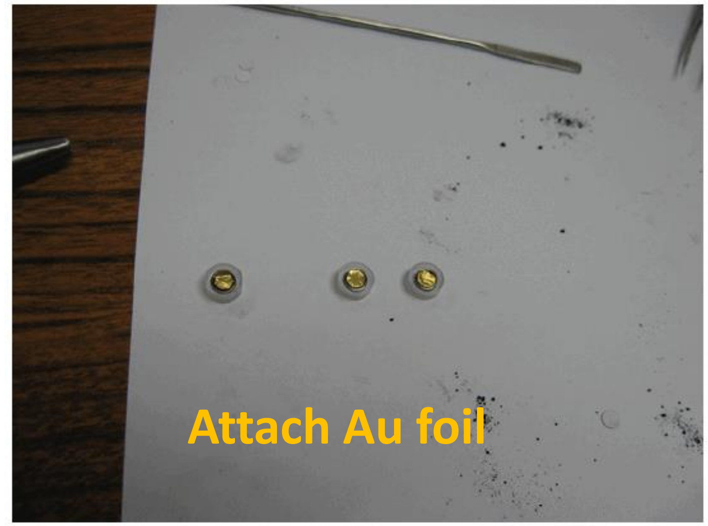
Mechanical Design

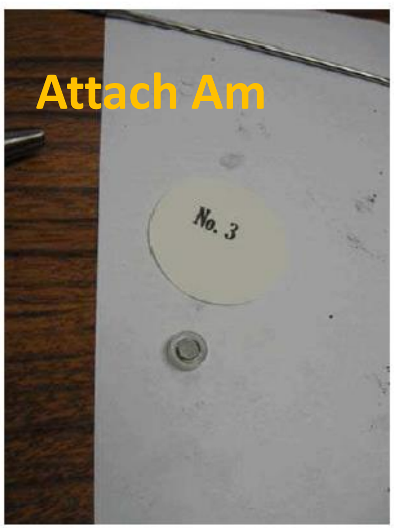
- Am, gold foil, C are sandwiched
- Ensure uniform and compact contact between alpha and C13
- Protect from alpha leakage, weld-on 3 cement

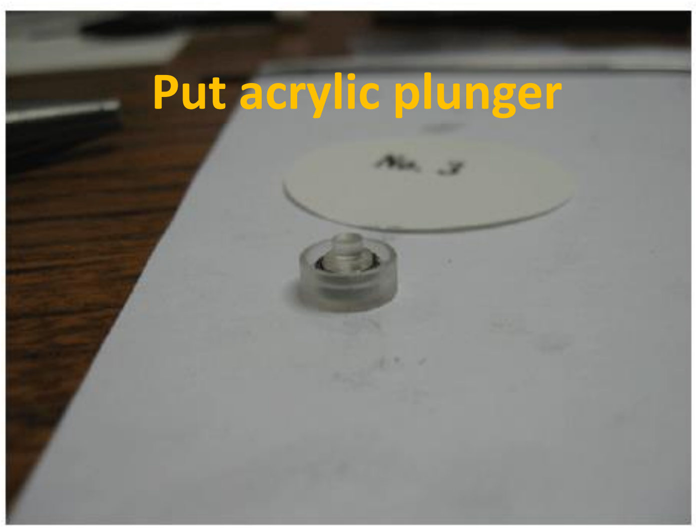




Fabrication







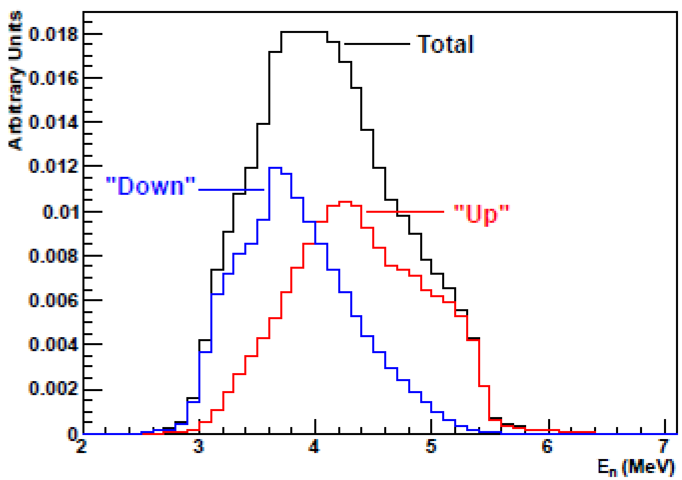
Simulation and Flux Prediction

- 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

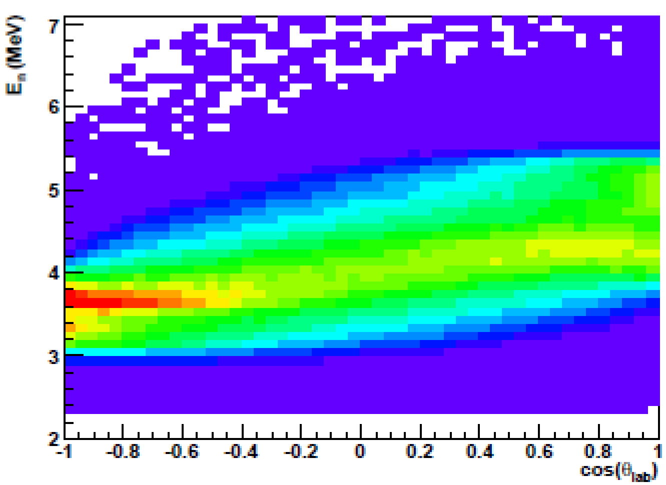
$$\text{weight}_i = \sigma(E_{\alpha,i}) \times d_i$$

$$R_n = R_\alpha \times \sum_i \text{weight}_i \times \frac{\rho_{^{13}C} \mathcal{N}_A}{13}$$

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

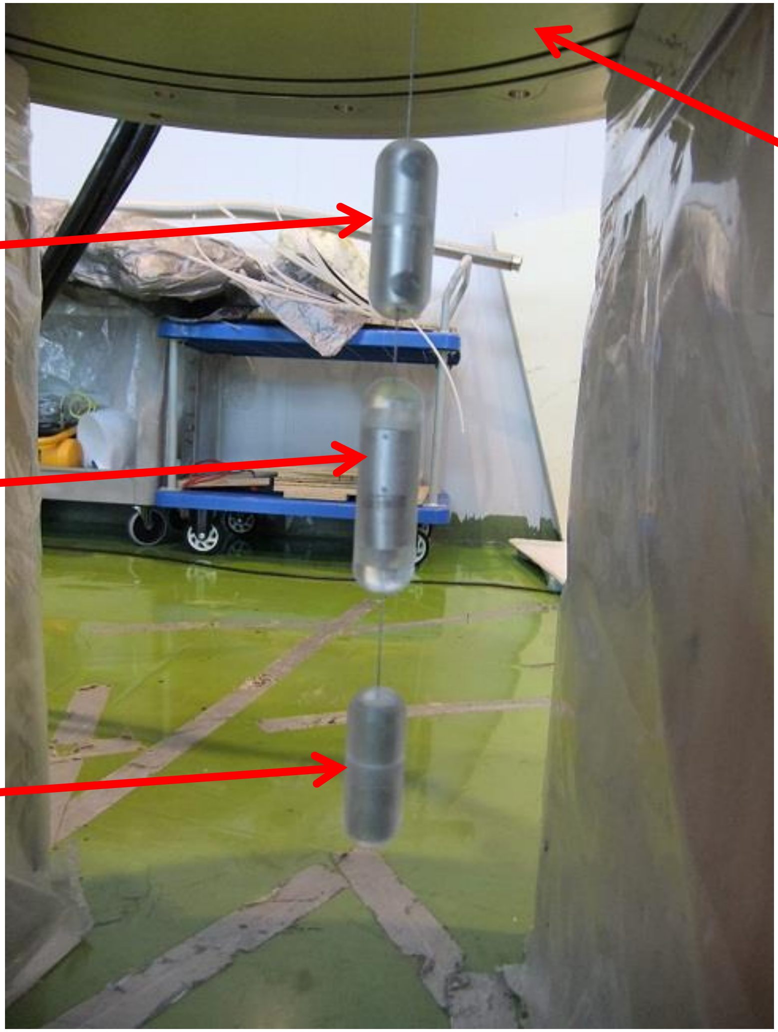


Neutron kinetic energy 3-5.5 MeV



(b) *Energy-angle correlation*

Installed In ACU



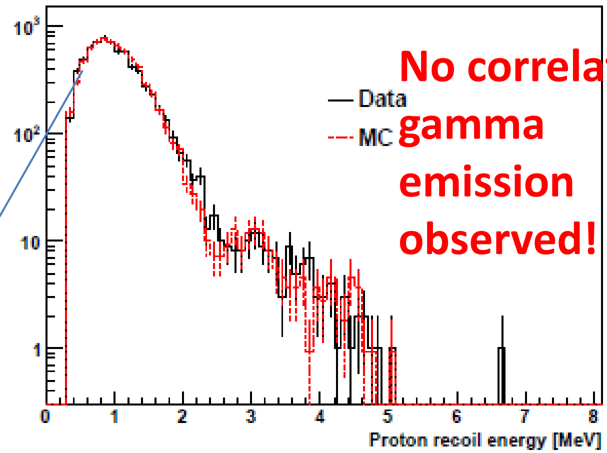
Top weight

Neutron source

bottom weight

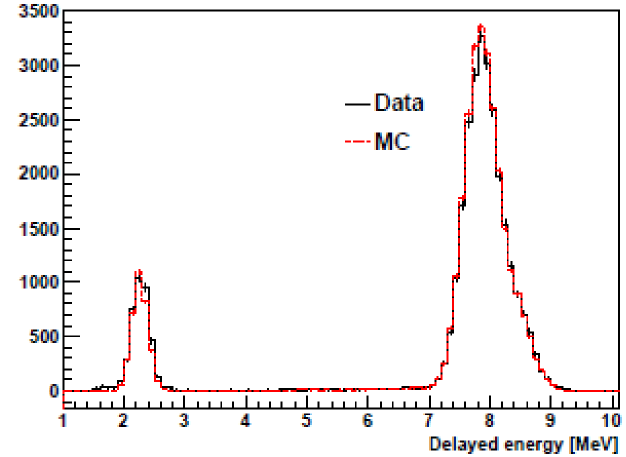
ACU

Performance at Daya Bay



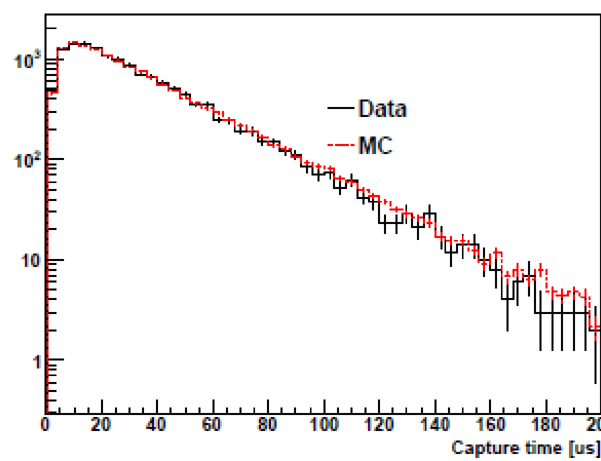
No correlated gamma emission observed!

(a) *Prompt energy spectrum*



(b) *Delayed energy spectrum*

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



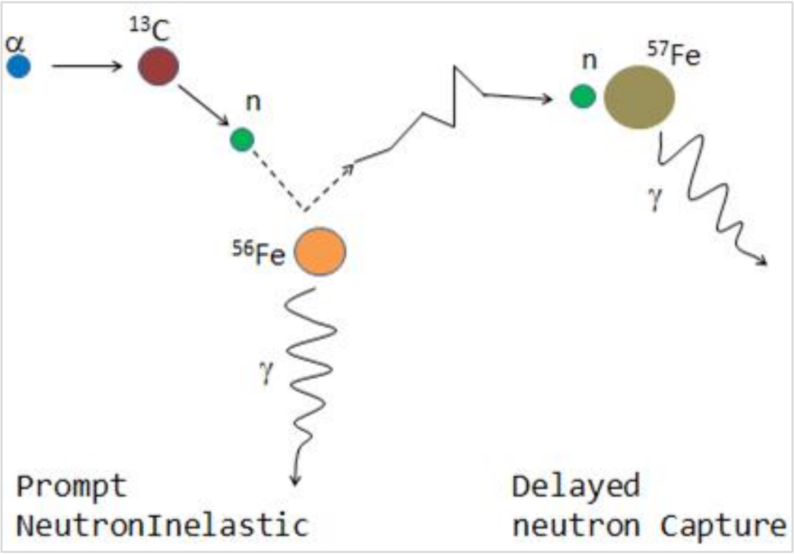
(c) *Prompt-delay time separation*

Very good data/MC agreement for all distributions!

Measured rate (0.75Hz) meets the design spec.

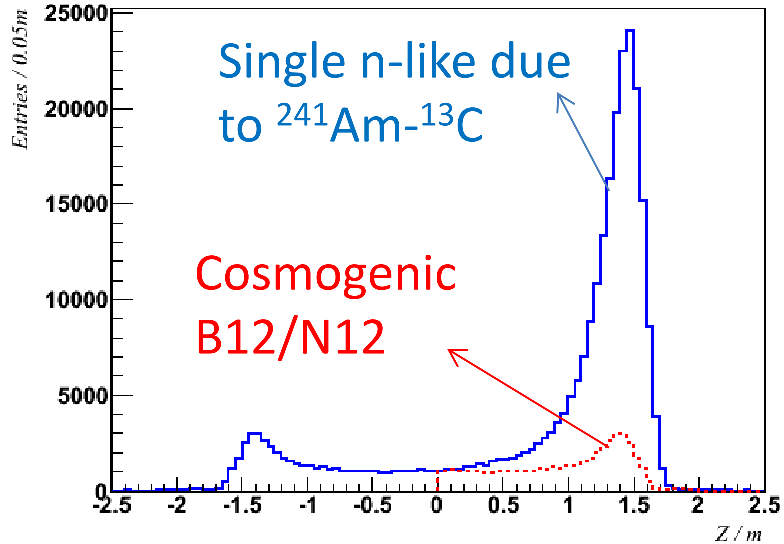
Residual Background

- 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”



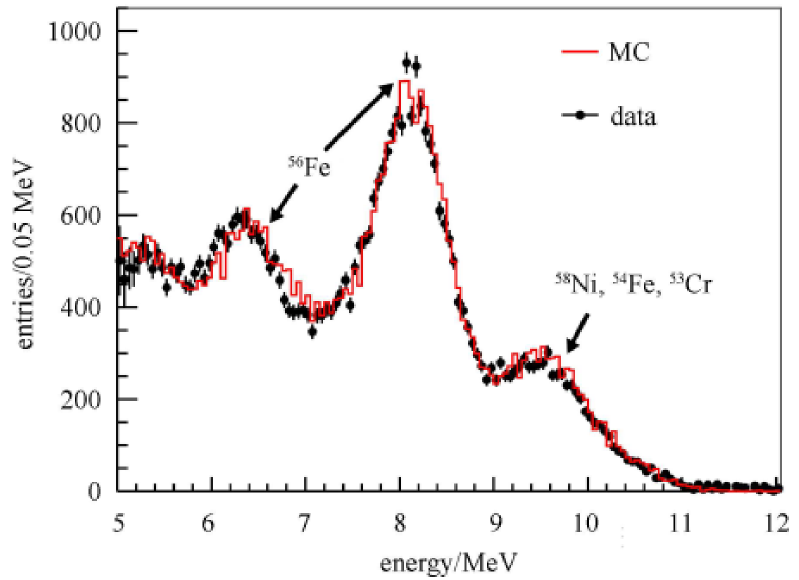
Single Neutrons Observed in Detector

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



bottom ← - - - - - - → top

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



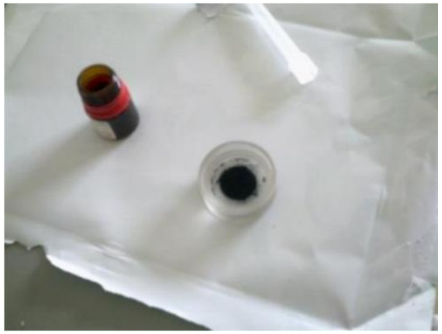
Correlated Background

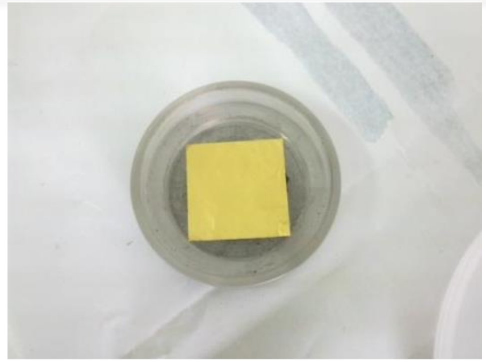
- Measure single neutron like (n-like) rate R_{single} from data
- Predict correlated rate R_{corr} using

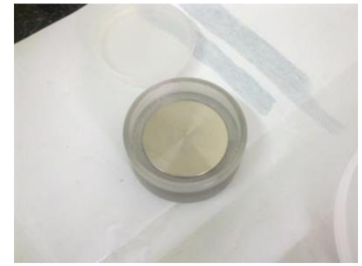
$$R_{corr} = Yield \cdot R_{single}$$

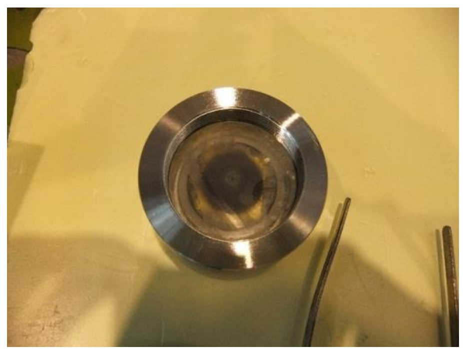
- Ratio of R_{corr} over R_{single} based on MC, constrained by benchmark measurement
  - A special "strong" AmC source was constructed to directly observe the correlated events

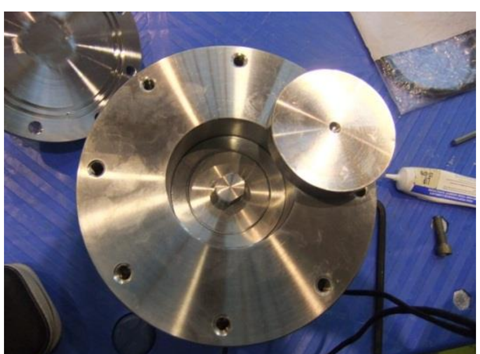
Strong Neutron Source Fabrication and Installation



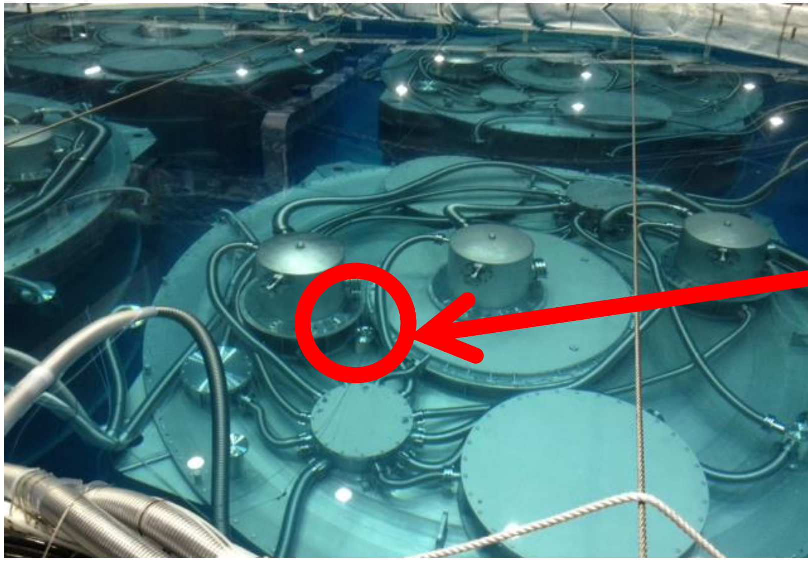








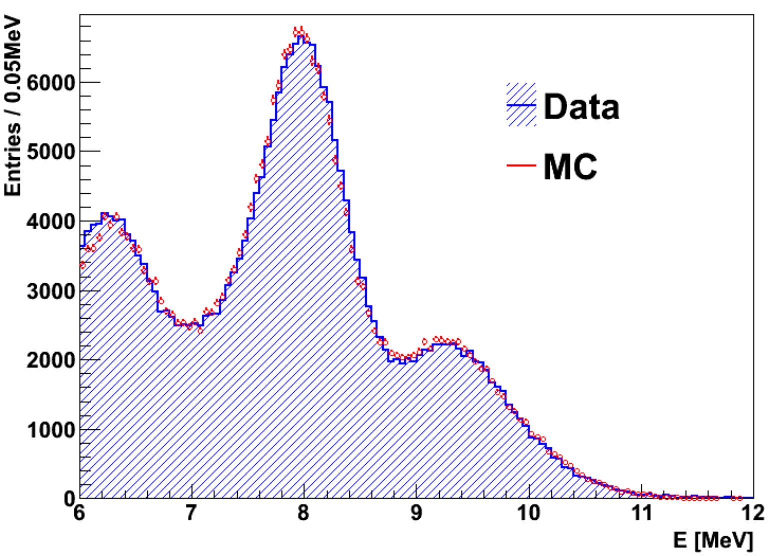
Benchmark Experiment



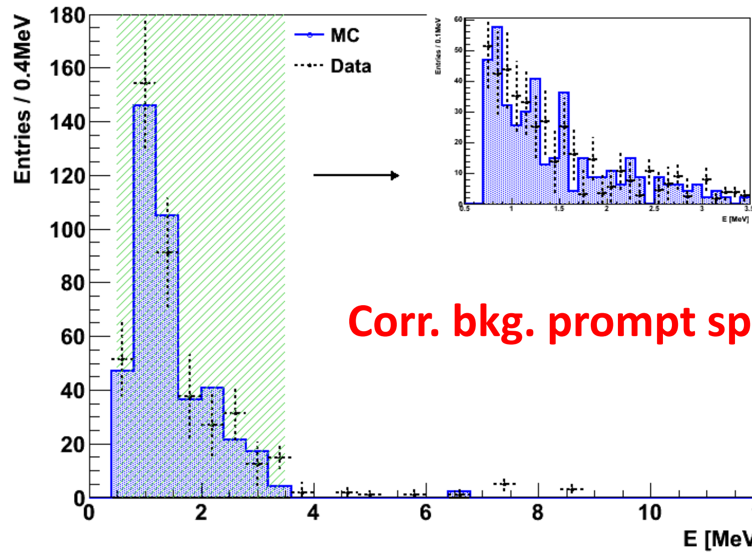
“Strong” AmC

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

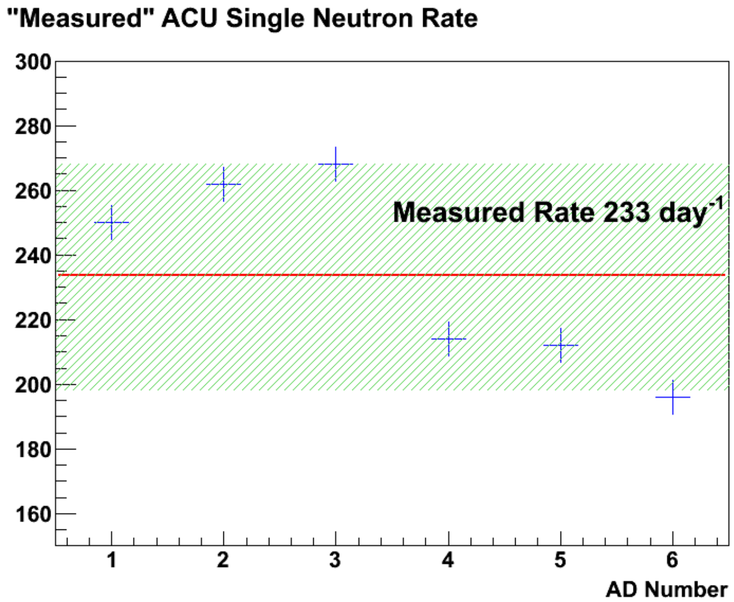
Single Neutron Spectrum from Strong AmC: Data vs MC

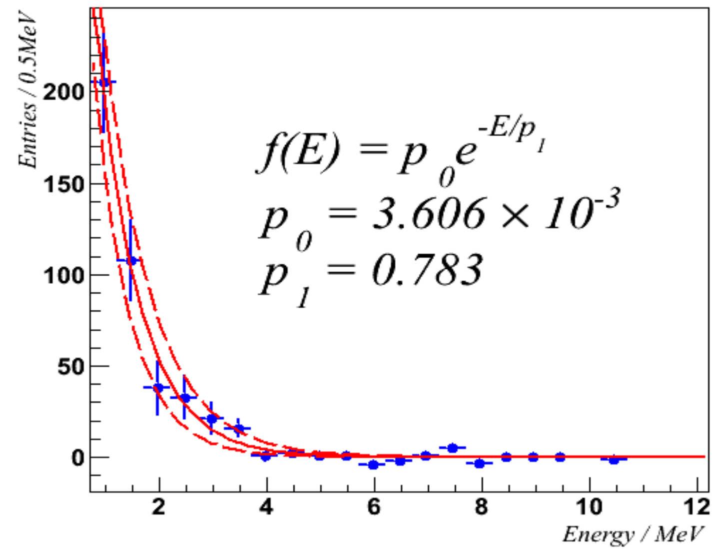


Strong AmC's Prompt Spectrum: Data vs MC



Background And Systematics





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

- 15% Shape uncertainty.

Far site corr. bkg. requirement satisfied

- *~0.2+-0.1 /AD/day*

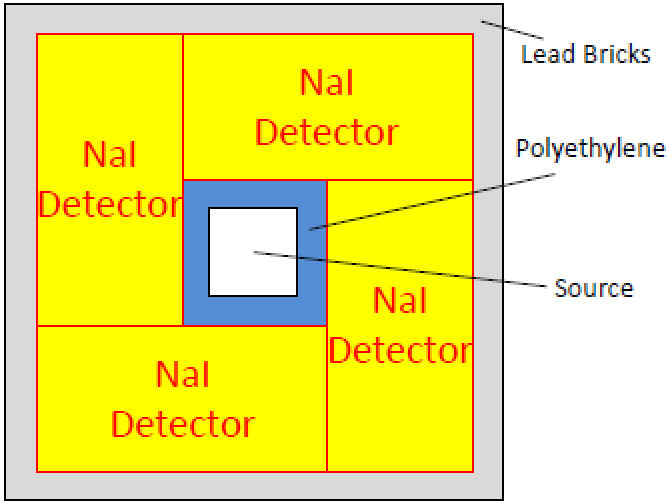
Summary

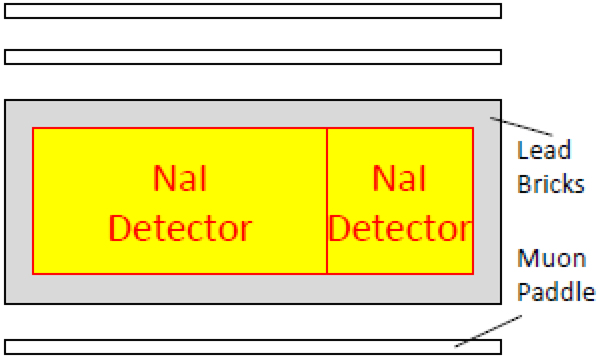
- A low rate & gamma-less neutron source was designed and fabricated for the Daya Bay experiment.
- Such source could be utilized in other experiments with low background requirement.

Backup

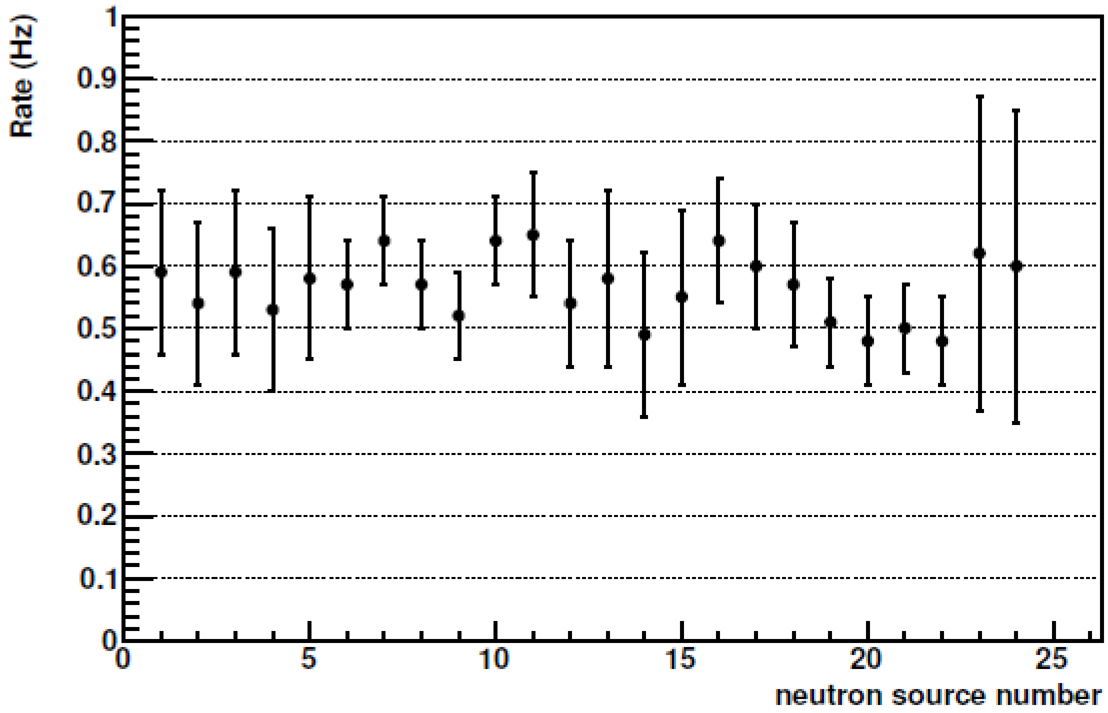
Measurement

- 4 NaI detectors (15*15*30cm)
- 3 muon paddles to reduce muon induced background



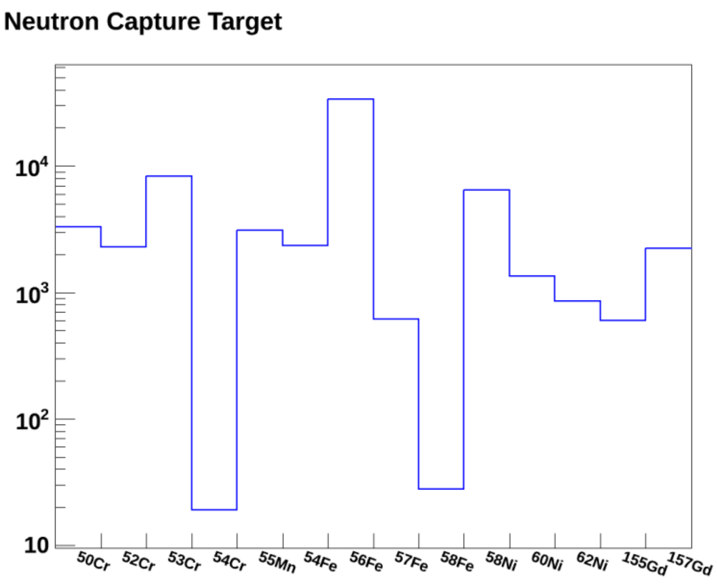


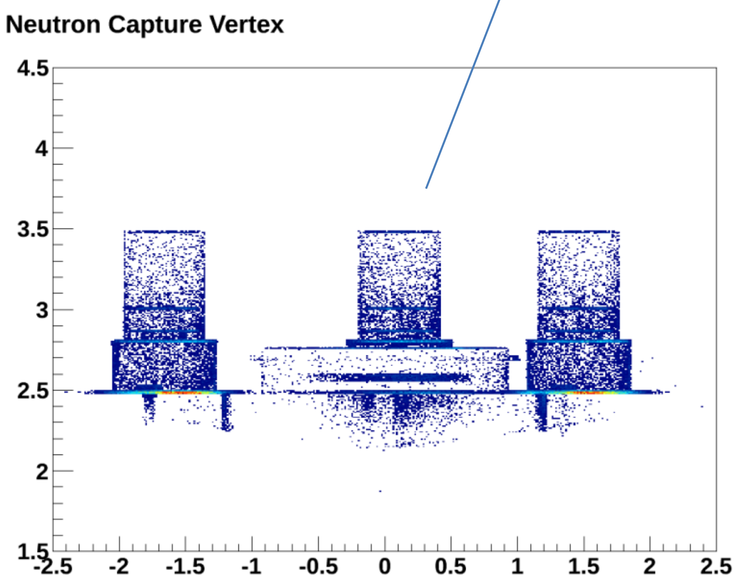
- More details in



Simulated Neutrons

ACU enclosing structure and AD SS structures





Capture mainly on Fe, Cr, Ni, Mn