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Neutron calibration sources in the Daya Bay experiment

J. Liu [b,a,*], R. Carr [a], D.A. Dwyer [a,d], W.Q. Gu [b], G.S. Li [b,*], R.D. McKeown [a,c], X. Qian [a,e], R.H.M. Tsang [a,f], F.F. Wu [a], C. Zhang [a,e]

[a] *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA, USA*
[b] *Department of Physics, Shanghai Jiao Tong University, Shanghai, China*
[c] *Department of Physics, College of William and Mary, Williamsburg, VA, USA*
[d] *Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[e] *Brookhaven National Laboratory, Upton, NY, USA*
[f] *Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA*

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ABSTRACT

We describe the design and construction of the low rate neutron calibration sources used in the Daya Bay Reactor Anti-neutrino Experiment. Such sources are free of correlated gamma-neutron emission, which is essential in minimizing induced background in the anti-neutrino detector. The design characteristics have been validated in the Daya Bay anti-neutrino detector.

1. Introduction

Neutron sources are important calibration sources with a wide range of applications. In modern reactor neutrino experiments such as Daya Bay [1], Double Chooze [2] and RENO [3], the electron anti-neutrinos are detected by liquid scintillator detectors via the inverse beta decay (IBD) reaction $\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$ with the time-correlated prompt positron signal ranging from 1 to 10 MeV, and the delayed neutron capture signal of ~ 8 MeV on the gadolinium dopant or 2.2 MeV on hydrogen. In the Daya Bay experiment, which is located in South China, the regular deployment of neutron sources allows a thorough characterization of the detector response to IBD neutrons, which contributes to the recent discovery of the neutrino mixing angle θ_{13} [4].

The automated calibration units (ACUs) of the Daya Bay anti-neutrino detectors (ADs) are detailed in [7]. Each AD is submerged in a water pool and is equipped with three ACUs on top. Neutrino interactions are rare, so minimizing potential background created by the neutron sources is a top consideration. In this paper, we discuss the design and construction of low rate ($\sim < 1\ Hz$) neutron sources that are free of correlated gamma emission. Although used in a specific experiment, such a source could also be potentially useful in other occasions where ultra low background is desired, or where one seeks a neutron source with no associated gamma rays.

2. Physical requirements to the neutron sources

As discussed in [4], the Daya Bay ADs are arranged in a 4-near and 4-far configuration to the nuclear reactor cores, with the near detectors sampling the reactor neutrino flux and far detectors detecting the $\overline{\nu_e}$ disappearance due to θ_{13}. The rates of the IBD in the near (far) detectors are approximately 700 (70)/day/AD [4]. For each AD module, three ACUs are instrumented, each of which is capable of deploying radioactive sources vertically into the detector. There is one neutron source in each ACU [1,7]. During normal neutrino data taking, the neutron sources are "parked" inside the ACUs right above the AD. Although these neutrons rarely leak directly into the neutrino target (gadolinium loaded liquid scintillator), they can get captured on surrounding materials, in particular, stainless steel, i.e. Fe, Mn, Cr, Ni, etc, and emit gamma rays ranging from 6 to 10 MeV. These high energy gamma rays, later referred to as SS-capture gammas, are difficult to shield, leading to two kinds of background due to accidental and correlated coincidences: (a) the

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* Corresponding authors.
E-mail addresses: jianglai.liu@sjtu.edu.cn (J. Liu), lgs1029@sjtu.edu.cn (G.S. Li).

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SS-capture gammas can be in random delayed coincidence with ambient gamma background, mimicking the IBD signals, and (b) if multiple neutrons are emitted per decay, or a neutron is emitted with a correlated gamma ray, or a neutron is producing gammas via inelastic scattering, they can form real correlated background to the IBDs. The signal to background ratio at the far site drives the requirements to the neutron sources:

- The accidental background to be less than 5% of the IBD signal at the far site. Such a background can be statistically subtracted;
- The correlated background to be less than 0.5% of the IBD signal at the far site, i.e. <0.35 per day. Such a background can be estimated via Monte Carlo (MC) simulation and benchmarked by special control data.

For a typical neutron source inside the ACU, a GEANT4 [8] simulation with realistic detector geometry predicts that the SS-capture gamma ray leaking into the detector satisfying the IBD delay energy cut is approximately 2×10^{-3} per neutron. Taking into account the $\sim$ 70 Hz singles rate [4] and 200 μs coincidence window, the first requirement translates into a limit of the neutron rate per source <1 Hz.

3. Design of the neutron source

3.1. Selection of neutron source

There are several types of commonly used compact neutron calibration sources, e.g. fission sources such as ^{252}Cf, (α,n) sources such as ^{241}Am–Be, and photo-neutron sources such as ^{124}Sb–Be . For the third type, photo-neutron cross-section is of the order millibarns, implying the need for a rather strong driving gamma source. Due to low background considerations, this option was rejected early on.

A ^{252}Cf source emits multiple neutrons per fission together with gammas. Typical (α,n) sources have correlated gamma neutron emission when the final state nucleus is in an excited state. As mentioned earlier, such sources would inevitably lead to correlated background in the AD, in addition to the accidental background. Just to set the scale, the predicted correlated background for ^{252}Cf and ^{241}Am–Be sources are 2.6/day and 1.3/day, respectively, assuming a 0.5 Hz neutron rate. There are also time-coincident 59.5 keV x-rays and 123 keV gammas from ^{241}Am, but their energies are too low to be detected by Daya Bay ADs.

The alphas from ^{241}Am are $\sim$5.5 MeV. To eliminate correlated gamma rays emission, ^{7}Li would be a good candidate target since such alpha energy can only produce ground state ^{10}B. However, the most common and chemically inert Li compound is LiF, and (α, n) on ^{19}F creates a significant amount of high energy gamma rays.

^{13}C is the final candidate. We note that ^{241}Am–^{13}C can produce neutrons with the final state ^{16}O either in the ground state, and the first or second excited state. The first excited state of ^{16}O decays into a e^+e^- pair, which will be stopped by the source enclosure and surrounding materials.[1] The second excited state of ^{16}O will emit a 6.13 MeV gamma ray, producing correlated background together with the neutron. However if the energy of α is attenuated to below 5.11 MeV, this correlated γ-neutron process can be eliminated entirely. Based on all considerations above, we selected ^{241}Am–^{13}C as the neutron source, further requiring that $E_\alpha<5.11$ MeV.

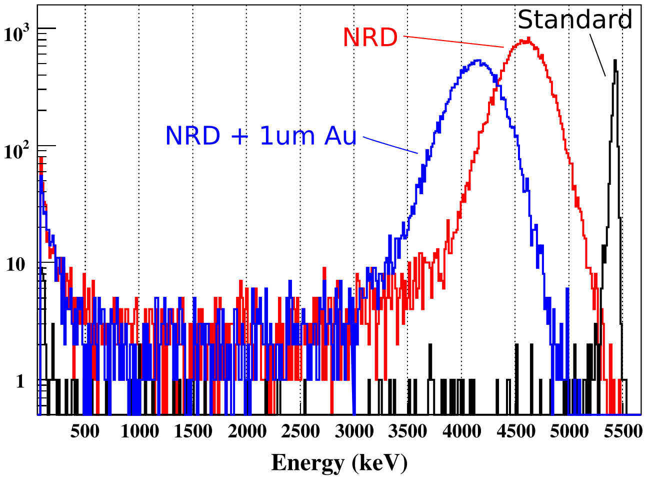

Fig. 1. Measured alpha spectra with (blue) and without (red) the 1 μm gold foil. The spectrum from a standard ^{241}Am α source (5.5 MeV) (black) is overlaid for reference. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

4. Physical design

4.1. ^{241}Am sources

^{241}Am discs from NRD Inc., 5-mm in diameter, were procured with 4.5 MeV alpha energy as a key specification (custom energy was achieved by varying the thickness of the electrodeposited gold coating). The activity of ^{241}Am is approximately 28 μCi, and is deposited on one side of the disc only. 28 μ Ci is the maximum activity the vendor offered to deposit for a 5-mm disc source, and the neutron emission rate using such alpha source was estimated to be around 1 Hz, which met our requirement. Measurements of the emitting alpha energy were performed at Caltech in a vacuum chamber with a Si detector. The raw energy spectrum from the ^{241}Am source is shown in Fig. 1. Also overlaid is the energy spectrum from a standard ^{241}Am source.[2] It was discovered that although the alpha energy for the NRD sources is peaked around 4.6 MeV, the distribution is rather broad, all the way up to 5.5 MeV. The same measurements were performed on multiple discs and the results were consistent. In order to further reduce the alpha energy, 1 μm thick gold foil was purchased from Alfa Aesar and attached to the front surface of a NRD source. The attenuated energy spectrum is overlaid in Fig. 1. Compared to that without the gold foil, the entire energy spectrum was shifted by about 0.5 MeV, as expected. Out of about 20,000 total alphas, no events were observed beyond 5.11 MeV threshold.

4.2. Expected neutron rate and energy spectrum

A GEANT4 program was developed to calculate the neutron rate from the source. To simulate the one-sided NRD source, the alphas were generated in random directions in the active hemisphere with energy sampled from the spectrum in Fig. 1 (the red histogram). The energy loss of the alphas in 1 μm gold and ^{13}C was simulated by GEANT4. GEANT4 tracks alphas until they are stopped. When an alpha enters ^{13}C, for each step i along the track, one computes a step weight (which gets summed at the end of the event)

$$\text{weight}_i=\sigma(E_{\alpha,i})\times d_i, \qquad (1)$$

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[1] The stopped e^+ would annihilate into two back-to-back 0.511 MeV gammas, which can hardly deposit enough energy in the AD to cross the trigger threshold.

[2] A typical alpha calibration source has a thin front window of 100 μg/cm^2, which attenuates the 5.5 MeV alpha energy only by about 22 keV.