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Background evaluation for the neutron sources in the Daya Bay experiment

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ABSTRACT

We present an evaluation of the background induced by ^{241}Am–^{13}C neutron calibration sources in the Daya Bay reactor neutrino experiment. As a significant background for electron-antineutrino detection at 0.26 ± 0.12 per detector per day on average, it has been estimated by a Monte Carlo simulation that was benchmarked by a special calibration data set. This dedicated data set also provides the energy spectrum of the background.

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1. Introduction

Neutrons are common source of background for most of the underground experiments. They can be produced hadronically by cosmic rays, or by (α,n) and spontaneous fissions from environmental and internal primordial radionuclides such as ^{238}U [1]. For these experiments, neutrons have many different ways to produce background, for example, by elastic and inelastic scatterings, nuclear activations, or nuclear captures [2–6].

The underground Daya Bay neutrino experiment measures the neutrino oscillation driven by the mixing angle θ_{13} using the electron-antineutrinos from the Daya Bay nuclear power plant [7]. The electron-antineutrinos are detected by the gadolinium-doped liquid scintillator (GdLS) via the so-called inverse β-decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, producing a prompt positron signal and a delayed neutron capture signal on Gd with a total gamma energy of about 8 MeV. Cosmic-ray induced neutrons are obvious background as the prompt recoil and delayed capture signals can fake the IBDs. In addition, there is another unique and more important neutron background specific to the Daya Bay experiment arising from the neutron calibration sources positioned close to the detector. In this paper, we provide an experimental evaluation of this background combining the results from a special calibration run with a Monte Carlo (MC) simulation. The rest of this paper is organized as follows. The general description of this background and the two-component formalism is given in Section 2, followed by the evaluation of each component in Sections 3 and 4. A detailed discussion on the special calibration measurement will also be presented in Section 4. Finally, in Section 5, we conclude by summarizing the rate and energy spectrum of this background as well as their uncertainties.

2. The Daya Bay experiment and the neutron source background

In the Daya Bay experiment, eight identical antineutrino detectors (ADs) are positioned in three experimental halls (two near

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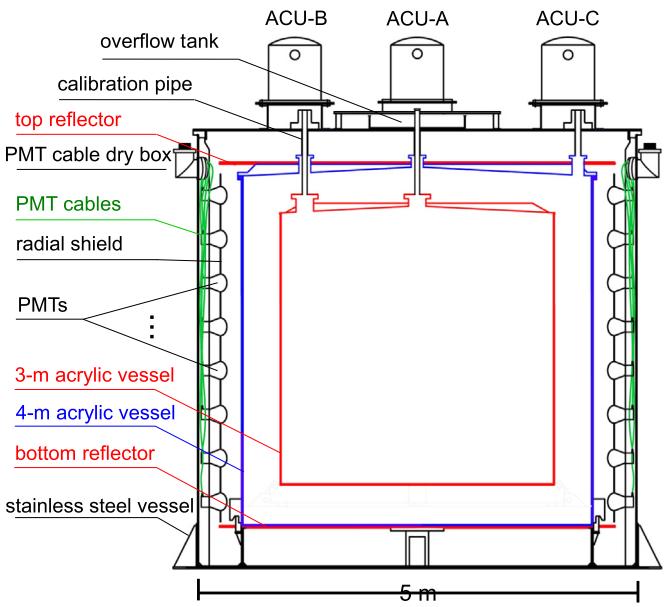

Fig. 1. Side view of an AD with the three automatic calibration units (ACU-A, ACU-B and ACU-C) on the lid. Most of the enclosures are made out of SS.

halls and one far hall) [8]. Two ADs are located in each near hall, and four ADs are positioned in the far hall near the θ_{13} oscillation maximum. The antineutrino detector is built with three concentric cylindrical vessels as shown in Fig. 1. Approximately twenty tons of GdLS reside in the inner acrylic vessel. The volume between the inner and outer acrylic vessels, known as the gamma catcher, is filled with un-doped liquid scintillator (LS) to improve the gamma detection efficiency. The volume between the outer acrylic vessel and the 24-ton stainless steel (SS, containing Fe: 70.8%, Cr: 18%, Ni: 8%, Mn: 2%, Si: 1%, C: 0.08% in mass fractions) tank is filled with mineral oil to shield the ambient radiation as well as that from the photomultipliers (PMTs) and the SS tank. The SS vessels are surrounded by two layers of water Čerenkov detectors and resistive plate chambers which serve as the muon veto.

Three identical automated calibration units, ACU-A, B and C (Fig. 1), located on the lid of each AD, deploy LED, gamma, and neutron sources vertically into the AD on regular basis to calibrate the detector response [9]. The sources are parked inside the ACU during regular data taking. For the neutron source, traditional ^{252}Cf and ^{241}Am–^{9}Be sources have correlated multi-neutron and gamma-neutron emissions, respectively, which could lead to IBD-like background. Therefore, specially designed ^{241}Am–^{13}C (AmC) sources, each with ~0.7 neutron/s and free of correlated gamma-neutron emission, were used in Daya Bay [10]. We shall refer to these sources as the LAS (the low-activity sources) hereafter. According to a MC simulation with 10^8 neutrons, none of these neutrons diffuse into the GdLS region where they would produce both a prompt recoil signal and a delayed capture signal on Gd. However, being close to the AD all the time, a feeble but irreducible IBD-like background could still arise – the prompt γ produced by neutron inelastic scattering on the SS, followed by a high-energy gamma produced by the capture of the same neutron on the SS. Such background will be referred to as the correlated background hereafter.[1] To set the scale, each far site AD detects roughly 70 IBD reactions per day, and the neutron source background is about 0.2 events/day with an estimated uncertainty of 100% [7]. It was the most uncertain background in the Daya Bay far site ADs. Due to its low rate, it is impractical to directly measure the correlated background by temporarily removing the neutron sources. On the other hand, the single SS capture signals from these source neutrons with reconstructed energy between 6 and 12 MeV has a rate of ~230/day. They will be referred to as the "neutron-like" events hereafter, as they mimic the single-neutron capture signals on Gd. We define

$$R_{\text{corr.}} = R_{\text{neutron-like}} \times \xi = R_{\text{neutron-like}} \times \int_{E_{\min}}^{E_{\max}} f(E)dE \tag{1}$$

where $R_{\text{corr.}}$ and $R_{\text{neutron-like}}$ are, respectively, the rates of the correlated background and neutron-like events arising from the neutron sources, related by a ratio ξ. $f(E)$ is the differential form of ξ as a function of the prompt energy, and $E_{\min} = 0.7$ MeV and $E_{\max} = 12$ MeV define the prompt-energy cut for the true IBDs. Since $R_{\text{neutron-like}}$ can be directly measured and it is sensitive to the detector acceptance, Eq. (1) does not depend on the knowledge of absolute source rate and allows at least partial cancellation of the systematic effects due to inaccuracy in the MC. For ξ and $f(E)$, we performed direct measurements by deploying a high-activity (but otherwise nearly identically designed) neutron source (HAS) on top of the detector and benchmarked them with the MC.

3. Neutron-like events: data and MC comparison

The AmC background is studied with a Geant4-based [11] MC simulation (v4.9.2.p01) with detailed detector geometry. The neutron propagation and interaction is performed using the so-called High Precision neutron models [12], which is largely based on the ENDF library [13]. The so-called Low Energy electromagnetic processes are enabled for the gammas. Neutron sources with their enclosure geometry are placed in the ACUs with expected energy spectrum implemented in the particle generator. Realistic geometry of the detector, the ACU enclosure, as well as the main interior components inside the ACUs are implemented in the MC. Optical photons generated in the liquid scintillator are tracked all the way until they hit the surface of the PMTs. In addition, the readout simulation is implemented according to the PMT response and the electronics model to convert optical photons to the charge collected by the readout electronics. Based on the MC charge distribution on all PMTs, the vertex and energy are reconstructed with the same algorithm developed for data.

As mentioned earlier, the neutron-like events from the AmC sources are produced by capture gammas from the SS elements. In the data, we selected single neutron-like events that survive the muon veto from the AD and water Čerenkov detectors. Further details of muon veto will be provided in Section 4.2. The reconstructed vertical distribution of the neutron-like events in a typical AD is shown in Fig. 2, where a strong excess from the top is observed. Besides the AmC source, cosmogenic isotopes (e.g. ^{12}B) that miss the muon veto also contribute to this distribution. ^{12}B is the major muon-induced β-emitting isotope with a 29.1 ms mean lifetime. Due to the long lifetime, ^{12}B events easily escape the muon veto, and contribute to >50% of the non-AmC neutron-like events in all experimental halls. This type of events is expected to distribute uniformly in the GdLS and LS regions whereas the AmC induced background is expected to have the vertical distribution localized in the upper part of the AD. To confirm this, clean ^{12}B events are selected within a 100 ms window after a showering muon (see Section 4.2). The vertical distribution of ^{12}B is overlaid in Fig. 2. One observes good top-bottom symmetry with a difference less than 1.5% combining all ADs.

Based on the above, to extract the neutron-like events due to the AmC statistically, the difference between the top and bottom

[1] An alternative background caused by the random coincidence of two uncorrelated events, the so-called "accidental background", will be discussed in Section 4.2. It is not the main scope of this paper.

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