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Above-ground antineutrino detection for nuclear reactor monitoring

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ABSTRACT

Antineutrino monitoring of nuclear reactors has been demonstrated many times (Klimov et al., 1994 [1]; Bowden et al., 2009 [2]; Oguri et al., 2014 [3]), however the technique has not as of yet been developed into a useful capability for treaty verification purposes. The most notable drawback is the current requirement that detectors be deployed underground, with at least several meters-water-equivalent of shielding from cosmic radiation. In addition, the deployment of liquid-based detection media presents a challenge in reactor facilities. We are currently developing a detector system that has the potential to operate above ground and circumvent deployment problems associated with a liquid detection media: the system is composed of segments of plastic scintillator surrounded by ^{6}LiF/ZnS:Ag. ZnS:Ag is a radio-luminescent phosphor used to detect the neutron capture products of ^{6}Li. Because of its long decay time compared to standard plastic scintillators, pulse-shape discrimination can be used to distinguish positron and neutron interactions resulting from the inverse beta decay (IBD) of antineutrinos within the detector volume, reducing both accidental and correlated backgrounds. Segmentation further reduces backgrounds by identifying the positron's annihilation gammas, a signature that is absent for most correlated and uncorrelated backgrounds. This work explores different configurations in order to maximize the size of the detector segments without reducing the intrinsic neutron detection efficiency. We believe that this technology will ultimately be applicable to potential safeguards scenarios such as those recently described by Huber et al. (2014) [4,5].

1. Introduction

Antineutrino production in nuclear reactors is a direct result of the fission of uranium and plutonium atoms. The antineutrinos are produced by the beta decay of the neutron-rich fragments. On average, each fission produces approximately six antineutrinos: a typical nuclear power reactor will produce approximately 10^{22} antineutrinos per second. Monitoring of the antineutrino production rate provides a direct measurement of the number of atoms undergoing fission, and therefore the thermal power and operational status of the reactor. Additional information is contained in the energy spectrum of the antineutrinos. Specifically, antineutrinos arising from the ^{235}U decay chain will tend to be higher in energy than those from the ^{239}Pu decay chain. As the core evolves with the consumption of ^{235}U and the production of ^{239}Pu, the overall energy spectrum of antineutrinos will shift to lower energies. Although the interaction cross-section of antineutrinos is low, the copious amounts produced by a typical commercial reactor imply that a ~ 1 ton detector at 10–50 m standoff with a 10% antineutrino detection efficiency can expect on the order of hundreds of events per day (Klimov et al. [1]; Bowden et al. [2]). The type of detector obviously has a profound effect on both the backgrounds to the antineutrino signal and the detection efficiency.

1.1. Signal and backgrounds

Antineutrinos are typically detected through the inverse beta decay (IBD) interaction:

$$\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}. \quad (1)$$

The energy of the positron is linear with the antineutrino energy, $E_{e^+} = E_{\overline{\nu}_e} - (M_n - M_p)$ [6], and due to the IBD threshold and reactor antineutron spectrum, typically ranges from ~ 0 to 8 MeV. The positron subsequently annihilates with an electron, producing two 0.511 MeV gamma particles. In a scintillator-based detector, both the positron and annihilation gammas are detected simultaneously through ionization, with the gammas detected through the ionization of their Compton-scattered electrons. The neutron is frequently observed some time later, after thermalization and capture on a nucleus. The time between the detection of the positron and neutron, the neutron capture time, is governed by an exponential decay that depends on both the neutron capture cross-section and the concentration of the nucleus. In order to enhance the neutron

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detection efficiency, liquid scintillator is often doped with a capture agent such as gadolinium, which has a neutron capture cross-section ~ 5 orders of magnitude higher than hydrogen. The capture time for typical loading concentrations of gadolinium is reduced to $\sim 10\,\mu s$, compared to $\sim 200\,\mu s$ for captures on hydrogen in unloaded liquid scintillator. In either case, a very specific event signature arises: a prompt pulse with ~ 1–8 MeV of energy, coincident within the neutron capture time of a second pulse with energy of either 2.2 MeV (hydrogen) or ~ 8 MeV (gadolinium).

The dominant backgrounds to the antineutrino signal are from accidental coincidences within the neutron capture time window and correlated backgrounds from electromagnetic and hadronic showers initiated by cosmic muons within the detector or surrounding materials. For scintillator-based detectors, only one high-energy neutron from a cosmic shower can mimic an IBD event: a fast neutron recoil off of a proton can produce a prompt pulse with ~ 1–8 MeV, followed by a second pulse as that same neutron is captured. A single fast neutron can also undergo neutron spallation, resulting in two correlated neutron captures. In addition, as they propagate through the detection medium, cosmic rays can produce long-lived isotopes which eventually undergo (β,n) decay. Finally, within the large detector volumes required for a reasonable antineutrino detection rate (~ 1 ton), accidental coincidences between two high-energy gammas, or a high-energy gamma and a neutron, can be a large background.

The strategy presented here in mitigating these backgrounds is to take full advantage of the unique event signature of IBD by (1) uniquely identifying each interaction as gamma-like or neutron-like and (2) using detector segmentation in order to distinguish positrons from other more common charged particle interactions by the identification of annihilation gammas.

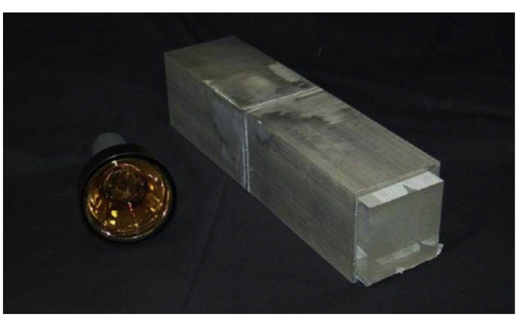

Fig. 1. The plastic scintillator bar in its aluminum housing, and a 5-in. ADIT photomultiplier tube before coupling to the end of the bar.

2. Detector description

Our basic detector unit is a plastic scintillator bar with a 5×5 in. cross-section. The bar is surrounded on four sides by ^{6}LiF/ZnS:Ag sheets approximately 0.45 mm thick. The cross-sectional area of the bar was chosen so that at least 50% of neutrons capture on ^{6}Li rather than the hydrogen in the bulk scintillator. The bar has a 5-in. ADIT photomultiplier tube, model number B133D01W, on each end. The plastic scintillator bar in its aluminum housing is shown in Fig. 1, before the photomultipliers were coupled to the bar.

An interaction is determined to be gamma-like or neutron-like by discriminating against the different pulse shapes which arise from the distinct scintillation decay times of the bulk scintillator and ZnS:Ag. Positrons interacting in the bulk scintillator will have a scintillation decay time on the order of 10 ns, however neutrons, which are detected through their ^{6}Li capture products (a triton and an alpha particle) scintillating in the ZnS:Ag, will have a scintillation decay time of ~ 200 ns. Fig. 2 shows two example pulses from gamma and neutron depositions. By using a standard pulse shape discrimination technique (PSD), significant separation between neutron and gamma interactions is achieved (see Fig. 3). This PSD virtually eliminates accidental coincidences from high-energy gammas, while accidental coincidences from a high-energy gamma and neutron are reduced by half simply by requiring that the gamma is detected before the neutron rather than the neutron before the gamma. Correlated backgrounds from two neutron captures are also eliminated to the degree by which the interactions are correctly identified as neutron-like.

Segmentation allows for topology cuts to be made on the positron candidate: the back-to-back annihilation gammas will often deposit their energy in neighboring segments, an event signature not typically shared by gammas or fast neutrons. Fig. 4 illustrates an antineutrino event in which both annihilation gammas interact in neighboring segments as well as a fast neutron that recoils off of protons in two neighboring segments. Although the degree to which proton recoils from fast neutrons spill into nearby segments is not well quantified, a large percentage of fast neutrons are expected to be rejected by topology cuts. Finally, topology cuts largely eliminate backgrounds caused by cosmic-ray induced long-lived radioisotopes, so long as they decay to (β^{-},n) rather than (β^{+},n). The most concerning of long-lived radioisotopes that are produced off of a carbon target are ^{9}Li and ^{8}He, neither of which have decay channels including a positron.

2.1. Test deployment at the San Onofre Nuclear Generating Station

A four-segment prototype detector using this technology was deployed at the San Onofre Nuclear Generating Station (SONGS)

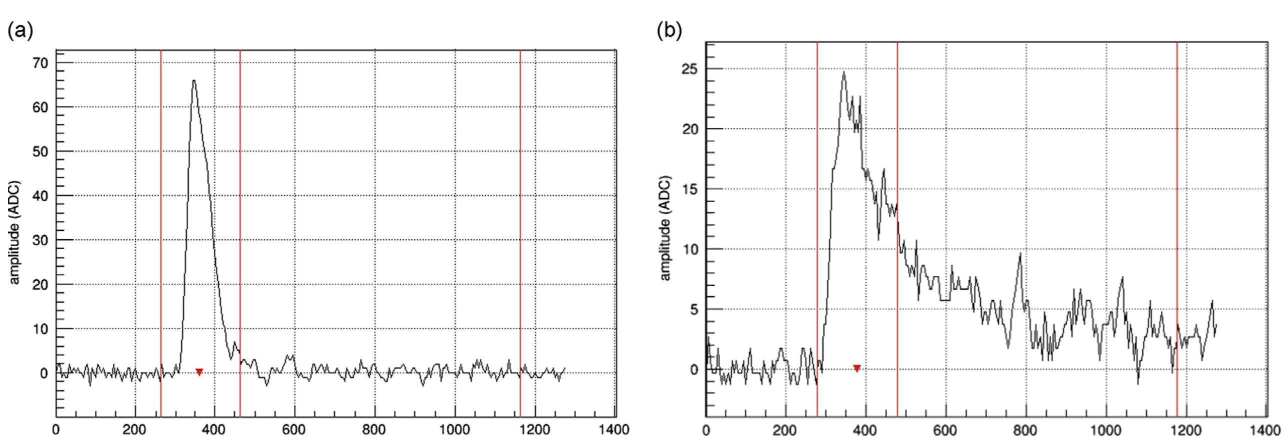

Fig. 2. (a) A gamma-like pulse trace with tail and total windows indicated by red bars and the pulse time indicated with a red triangle. (b) A neutron-like pulse trace. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)