Antineutrino detection based on ^6Li -doped pulse shape sensitive plastic scintillator and gadolinium-doped water

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The need for sensitive new reactor antineutrino detection methods is discussed. Two new methods are proposed, including a new technique suited for near field detectors unshielded from cosmic ray backgrounds and a new directional antineutrino detection technique suitable for long distance detectors.

Keywords: Reactor; Antineutrino.

1. Introduction

In recent years, reactor antineutrino detection has become relatively straightforward, so much so that it is now possible to make multiple detectors with equivalent efficiencies—to the 0.2% level.¹ However, two outstanding problems remain related to backgrounds. The first, and most common background, is caused by fast cosmic ray induced neutrons, which can produce antineutrino-like correlated signals in a scintillation detector from proton recoils followed by neutron capture. Such correlated signals cannot be

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distinguished from true antineutrinos in today's detectors. The second background concerns antineutrinos from other reactors. Since today's detectors are insensitive to antineutrino direction, it is impossible to determine if an antineutrino came from a reactor of interest or some other reactor. In this paper, we propose two methods directed at tackling each of these backgrounds.

2. Fast Neutron Backgrounds

Today, the best way to remove these backgrounds is to place the detector underground and surround it with thick layers of hydrogenous shielding. This method is very successful since the flux of fast neutrons dies off rapidly with depth. However, there are two scenarios where this solution cannot be applied. First, there is great interest in the possibility of neutrino oscillation over very short distance scales.²⁻⁴ Hints of this have been reported from a number of reactor antineutrino experiments in recent years,⁵⁻⁷ and it would be possible if there is at least a fourth so-called sterile flavor of the neutrino. Since the distance scales (5 to 10 m) required to test the sterile neutrino hypothesis preclude the placement of a detector more than a few feet underground, we need detectors that can identify the neutron induced backgrounds in the data. Second, there has been significant recent interest in using reactor antineutrino emission to directly monitor the fission processes inside a reactor for safeguard purposes.⁸ The reactor antineutrino flux is directly dependent on both the fission rate and fissile content of the core. However, according to the International Atomic Energy Agency (IAEA), widespread use of such technology probably awaits improvements that can enable the deployment of detectors above ground and without protection from cosmic rays. For these reasons, we are exploring some additional detection techniques to identify fast neutron backgrounds in the analysis. New materials under development now have the potential to add sensitivity to pulse shape discrimination (PSD), particle track length, and direction of a reactor antineutrino flux. If successful, the identification of false antineutrino signals

Fig. 1. The Double Chooz reactor antineutrino experiment (left). The figure shows the location of the two identical detectors used to study neutrino oscillations. The directional sensitivity of the Double Chooz far detector obtained from direction vectors drawn between the IBD induced positron and neutron capture (right).¹¹

caused by fast neutrons may enable above ground deployments with more limited shielding requirements.

Antineutrinos are generally detected via the inverse beta reaction on protons ($\bar{\nu}_e + p \rightarrow e^+ + n$).⁹ In principle, the antineutrino direction can be reconstructed kinematically from the position of the positron and direction of the neutron.¹⁰ Unfortunately until now, detectors have not been able to measure these parameters with sufficient accuracy. Figure 1 (above),¹¹ from the Double Chooz experiment, shows the best measurement of the direction of a reactor antineutrino flux reported so far. As shown, the directional uncertainty in Double Chooz is fairly large, requiring approximately 100 detected antineutrinos to narrow the angular uncertainty to $\pm 77^\circ$. The positron and neutron position uncertainties at Double Chooz are ~ 15 cm; about an order of magnitude too large.

Recently, a new class of plastic scintillator has been developed at Lawrence Livermore National Laboratory (LLNL),^{12,13} which can be used to discriminate between neutron and gamma-ray induced interactions based on the duration of scintillation light emission—a technique known as pulse shape discrimination (PSD). Until now, among scintillating materials sensitive to antineutrino induced inverse beta decay (IBD, both the positron and the neutron), PSD was only observable in liquid-organic scintillators. The new solid (and machinable) form makes fine-grained segmentation possible for the first time in antineutrino detection. The segmentation can be used to produce a design with excellent inherent position resolution and particle track length sensitivity, both of which are critical capabilities for identifying antineutrinos within a flux of fast neutrons.

The concept is outlined as follows. Rods of ^6Li -doped PSD plastic scintillator are arranged vertically in a square array as shown in Fig. 2. The fine-grained segmentation and position sensitive photomultiplier tube (PMT) readout can reveal the positions of the positron and neutron capture in the horizontal plane. In principle, the position resolution can be as small as the rod width (in this case, 0.5 cm). The positron would be detected as a prompt event with typical energy of a few MeV. High energy positrons can easily deposit energy over multiple contiguous rods. Two additional small energy deposits may also appear separately due to the annihilation gamma-rays. According to GEANT4 simulations, the neutron, with only ~ 10 keV of energy, would be captured on ^6Li 10–30 μs following thermalization, assuming concentrations of between 0.1–0.5%. While the positron reveals the approximate location of the IBD reaction, the neutron takes most of the momentum of the antineutrino. On average, a vector constructed from the positron to the neutron capture will point directly away from the reactor. Any number of modules can be combined into a single detector. In principle, an antineutrino now appears relatively distinct from a neutron-induced correlated background as shown in Table 1.

Our group is currently constructing a 64-channel module in order to characterize its performance. Our aim is to deploy a multiple module detector at a reactor in early 2019 in order to test the effectiveness of these techniques.

Fig. 2. A schematic view of a single antineutrino detector module comprising an 8 x 8 array of ^6Li -doped PSD plastic scintillator rods. In this configuration, two 64-channel position sensitive PMTs readout both ends of the module. An antineutrino IBD interaction is shown, including the final state positron and a hypothetical neutron track.

Table 1. Summary of detectable differences between antineutrino and fast neutron induced events in ^6Li -doped PSD plastic scintillator.

	Antineutrinos		Fast Neutrons	
	Prompt	Delayed	Prompt	Delayed
Multiple Contiguous rods	Yes	No	No	No
Non-contiguous	Yes	No	No	No
Annihilation gamma-rays	No	Yes	Yes	Yes
Direction vector points away from reactor	Yes		No	

3. Antineutrino Directionality

The KamLAND detector proved the feasibility of detecting antineutrinos over distance scales of up to ~ 100 km.¹⁴ However, depending on the location, it will not always be certain which reactor was the source over such distances. In the safeguards context, the ability to determine the direction of an antineutrino flux might be crucial in excluding the possibility of an undeclared reactor in a region where other reactors are operating. We now propose a way to determine the direction of an antineutrino flux.

Until now, the reactor antineutrino detection medium of choice has been the organic scintillator. However, IBD is also detectable with a water Cherenkov detector doped with a neutron capturing agent such as gadolinium.^{15,16} This medium has the advantage of scalability—meaning that detectors can be made very large before cost and/or the optical attenuation become problematic. Another advantage of water Cherenkov over scintillation is that in addition to IBD sensitivity, it is sensitive to charged particle direction. The electron elastic scattering reaction $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ imparts much of the momentum of the antineutrino to the scattered electron. This method is analogous to the neutrino–electron scattering reaction used by the Super-K detector to detect solar

neutrinos; however in the case of antineutrinos, the cross sections and energy are slightly smaller.

A schematic of the kiloton-scale WATER Cherenkov Monitor for ANTineutrinos (WATCHMAN) detector is shown in Fig. 3. Recently we published an investigation of the likely directional sensitivity of the WATCHMAN detector deployment at the Fairport mine in Ohio to the 3.7 GWth (gigawatt thermal) Perry reactor situated 13 km away.¹⁶ Included in this work was a thorough analysis of the expected background levels that would impact such a measurement. Unlike IBD, electron scattering events appear as a singular energy deposit, making them more difficult to identify than IBD events. The most significant backgrounds were those from the detector walls and PMTs—cosmic ray initiated radionuclides, radon dissolved in the water, solar neutrinos, and reactor IBD events where one of the positron or neutron was not observed. Figure 4 shows the detected photoelectron spectra for all the identified backgrounds and the reactor signal.

As shown in Fig. 4, radon is the most dangerous background. Radon can enter the water either by the mine air, or the decay of trace amounts of ^{238}U in the water itself.

Fig. 3. The proposed gadolinium doped water Cherenkov WATCHMAN detector.

Fig. 4. The antineutrino–electron elastic scattering signal (ES signal) and backgrounds expected at WATCHMAN for a deployment at the Fairport mine in Ohio—13 km from the Perry reactor during one year.

While ^{222}Rn alpha decay is not directly observable in a Cherenkov detector, the ^{214}Bi daughter beta decay can result in a detectable signal. The radon levels in the detector are very difficult to predict since they will depend on location specific variables that are unknowable at this stage, such as the concentration of uranium in the surrounding rock, the air flow in the mine, and the degree to which effort and funding are applied to the task during the design phase. For our analysis, we assumed dissolved radon levels the same as the Sudbury Neutrino Observatory (SNO) detector. Figure 5 shows the statistical sensitivity to reactor directionality that can be expected as a function of depth and dissolved radon level over 5 years. Our work shows that radon levels would need to be at least ~ 100 times lower than at SNO to achieve any degree of sensitivity. At fairly ambitious factors of 10^4 , it is possible to achieve significant directional sensitivity. WATCHMAN will include an R&D component dedicated to minimizing the dissolved uranium and radon concentrations of water.

Fig. 5. The directional sensitivity of the WATCHMAN detector to the Perry reactor over a 5-year data run as a function of depth and water-dissolved radon level. Three radon levels are shown: (a) $1 \times \text{SNO}$, (b) $10^{-2} \times \text{SNO}$, and (c) $10^{-4} \times \text{SNO}$.

4. Conclusion

Innovative new ways to improve reactor antineutrino detector sensitivity may be found by employing new detector materials. New PSD sensitive organic plastic scintillators seem to be ideally suited to deployment scenarios requiring a small detector placed as close to the reactor as possible. The main challenge is that the new scintillators are still under development, and their optical properties at present make it difficult to readout large volumes. By contrast, water Cherenkov offers a detector medium that can be scaled to very large volumes. Particle directions can be reconstructed by the resulting directional Cherenkov emission cone, as shown by Super-K in the solar neutrino context. Reactor antineutrino detection by the same technique is more challenging because the antineutrino-electron cross sections are lower and the reactor antineutrinos have less energy. While most of the likely backgrounds are manageable with today's technology, radon presents a significant challenge. Factors of 10^2 to 10^4 in improvements in radon concentrations over today's best technology are required in order to make such detectors feasible.

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