Snowmass2021 - Letter of Interest
An Application of Pulse Shape Sensitive Plastic Scintillator - Segmented AntiNeutrino Directional Detector (SANDD)

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Recently, a new class of pulse shape sensitive plastic scintillators has been developed, which can be used to discriminate between neutron and gamma-ray interactions. A subset of these materials can be doped with ^{6}Li or ^{10}B to facilitate further identification of neutron captures. This new class of materials presents new opportunities for detector components that incorporate plastic scintillator. Until now, among scintillating materials sensitive to antineutrinos, this capability was only observable in liquid-organic scintillator. The new solid form makes self-supporting fine-grained segmentation on a large scale possible for the first time. While this capability may also be useful for science applications in nuclear or accelerator physics, we provide an example of a new detector prototype for antineutrino detection. We describe a concept that exploits this new material for better position resolution and particle ID sensitivity, to design a detector capable of determining the direction of an antineutrino flux, and reducing backgrounds caused by cosmogenic neutrons. Similar designs may improve the surface detection of antineutrinos, a capability that would be enormously beneficial to the neutrino oscillation field. Larger segmented detectors (e.g. ROADSTR [1]) may also be constructed from these new materials to enhance mobility for deployments at multiple reactors.

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Neutrino Frontier Topical Groups:	(NF02) Sterile neutrinos (NF07) Applications

Introduction

The recent development of pulse-shape-sensitive plastic scintillator has the potential to provide a powerful new tool for science applications that require high-fidelity position resolution combined with particle identification. The particular application highlighted here is reactor antineutrino detection via inverse beta decay (IBD). In this case a sub-genre of pulse-shape-discriminating (PSD) plastic doped with ^{6}Li enables neutron capture sensitivity in addition to fast neutron/gamma-ray discrimination. Here we provide a description of a new antineutrino detector design that attempts to exploit some of the new capabilities of these materials to increase sensitivity. We also provide a brief general synopsis of some other science applications enabled by these materials.

IBD detection and a description of IBD backgrounds

Reactor antineutrinos can be detected via inverse beta decay,

$$\overline{\nu}_e + p \rightarrow e^+ + n. \tag{1}$$

The detection medium must contain hydrogen in order to facilitate this inverse beta decay reaction. For reasons associated with light output and attenuation length, most successful experiments are based on liquid organic scintillator [2–7]. Most include a neutron capturing dopant such as Gd [5, 7] or ^{6}Li [3, 6] to maximize the neutron-capture efficiency and reduce the neutron diffusion time to capture.

Applications for PSD plastic scintillator

Antineutrino Directionality:

Directional antineutrino detection has only barely been measured. The neutron carries most of the momentum of the antineutrino, and so its initial direction carries it radially away from the reactor (on average) with respect to the positron. Double Chooz was sensitive to directionality by measuring the relative positions of the positron annihilation and neutron capture on gadolinium to reveal the direction of the incoming antineutrino [8]. The correlation was weak, however, producing a positron-neutron shift of only ∼1.5 cm on average. The uncertainties on the positron and neutron capture positions were almost an order of magnitude larger, which degraded the sensitivity. Large numbers of events were required to achieve sensitivity [8]. Gd capture produces a gamma-ray shower, which results in a poor determination of the position of the capture. ^{6}Li capture, however, produces a triton and an alpha with no gamma-rays emitted, which in principle can allow for better position resolution.

Antineutrino Background reduction:

More recently, the reactor antineutrino anomaly motivated the development of antineutrino detectors that can operate directly adjacent to a reactor core and aboveground, unprotected from cosmic-ray induced fast neutron background. Fast neutrons can produce IBD-like signals from proton recoils followed by neutron capture. Aboveground the flux of these fast neutrons from the local environment begins to overwhelm the IBD signal. Detectors must be able to identify and remove these false signals.

Recent detectors in this category include PROSPECT [6], STEREO [9], CHANDLER [10], NuLat [11, 12], SoLid [13] and PANDA [14]. The most sensitive of these detectors was PROSPECT. The key innovations of PROSPECT were ^{6}Li-doped PSD and segmentation, achieved using liquid scintillator. However, segmented liquid detectors are difficult to engineer, and the liquids available today, while much easier to handle than in the past, can still prove to be chemically aggressive and less than stable over time-scales of years. CHANDLER and NuLat were plastic and highly segmented. However, in the case of CHANDLER, an additional inhomogeneous inorganic neutron capturing scintillator was added, which was dead material for IBD interactions, while NuLat was before its time in the sense that a realization awaits a PSD plastic scintillator with excellent optical properties.

Advantages of plastic over liquid

PSD plastic scintillator with similar performance characteristics to liquid formulations [15, 16] enables the realization of a PROSPECT-like or NuLat-like experiment with a stable and scalable raw material, and the potential to easily segment as finely as desired with greatly reduced engineering difficulty. Plastic is self-supporting, which means that non-scintillating liquid containment materials that reduce efficiency and increase systematic uncertainties are no longer required. Large-volume pieces of new formulations of 0.1% ^{6}Li-doped plastic scintillator have been developed with attenuation lengths of $\sim$50 cm (for context, PROSPECT $\sim$85 cm at 0.077% ^{6}Li [17, 18]).

More generally, any particle detector concept that requires particle ID combined with high-fidelity position resolution, can be more easily implemented via a self supporting plastic material than liquid contained in a supporting vessel or container. This capability enables applications in accelerator detectors, experimental nuclear physics, or for homeland security.

Description of SANDD

SANDD is a prototype experiment designed to maximize sensitivity to reactor antineutrino directionality. Since the requirement for directionality is accurate position resolution on the positron and neutron capture, fine segmentation was sought via the use of PSD plastic and modern large-area silicon photomultiplier (SiPM) detectors, which are commercially available in segmented form. The aim was position resolution at the $\sim$1-cm level. The detector is 40-cm long and consists of 9 liters of PSD plastic scintillator doped with ^{6}Li at 0.1%. There is a 0.65 liter central module made up of a series of 0.5-cm x 0.5-cm cross-section segments read out by a pair of 8×8 SiPM arrays. This is surrounded by twelve 2.54-cm x 2.54-cm segments, and surrounded again by ten 2.54-cm x 5.1-cm segments. The larger segments are each read out by a pair of 1-inch PMTs. The central module achieves the position resolution goal of $\sim$ 1-cm. The outer segments achieve position resolutions approaching $\sim$ 1-inch. If shown to work at small scale, the plan is to leverage modern multi-channel ASIC-based electronics designed for PET-based medical imaging, which can read out 1000s of channels quickly via small chip-sets. This will allow easier scaling of the SANDD design to a larger sizes to increase efficiency.

At present, SANDD is awaiting the production of sufficient ^{6}Li-doped PSD plastic scintillator material for deployment. A few pieces have been produced to enable a characterization of the performance of each module type. Some discussion of these early results has been published [19, 20].

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