CHANDLER: A Technology for Surface-level Reactor Neutrino Detection

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August 2020

NF Topical Groups:

☐ (NF1) Neutrino oscillations
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☐ (NF5) Neutrino properties
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Abstract:

CHANDLER is highly-segmented solid-plastic reactor neutrino detector, designed to work in the high-background surface-level environment near an active nuclear reactor. It could be used for a very sensitive short-baseline oscillation search, and for a variety of application including safeguards for nuclear non-proliferation and reactor monitoring.

Introduction

The CHANDLER detector technology is designed for the detection of reactor neutrinos in challenging environments. Its robust construction of commercially-available, all-solid components makes it an ideal detector for rapid deployment at existing nuclear sites. Its high segmentation and unique neutron tag are critical to rejecting backgrounds that would otherwise overwhelm the inverse beta decay (IBD) signal in above-ground locations, like those available at existing reactor sites. This technology was invented to conduct a definitive search for short-baseline neutrino oscillations, which are usually associated with a possible fourth, sterile neutrino, but advances in surface-level detector technology have stimulated new interest in a wide range of applications, including safeguards for nuclear non-proliferation and nuclear instrumentation.

Description of the Technology

The CHANDLER technology is based on alternating layers of wavelength-shifting plastic scintillator cubes and thin sheets of lithium-6 (^{6}Li) doped zinc sulfide (ZnS) scintillator. The cubes in each layer are optically connected in a Raghavan Optical Lattice (ROL), which uses total internal reflection to transport light along the cube rows and columns. This light is detected in PMTs at the ends of the rows and columns, and can be used to fix the position of an event to within the cube that lies at the intersection the active row and column. In the sheets, thermal neutrons capture on the ^{6}Li producing an alpha and a triton, which deposit their energy in the ZnS scintillator. Light from the ZnS goes into the plastic scintillator, where it is absorbed and re-transmitted. The resulting light is captured by total internal reflection in the ROL. ZnS is a relatively slow scintillator, which releases its light over a period that is 20 times longer than the plastic scintillator, and this fact is used to create a highly efficient and clean tag of thermal neutron captures.

In a CHANDLER detector, the signature of an IBD interaction is the correlation in both time and space of a primary positron and a delayed neutron capture. This is in contrast to large single-volume detectors like Daya Bay, Double Chooz and RENO, which do not use any spatial correlation information. Instead, these detectors use significant shielding, composed of hundreds of meters of earth cover and low-background materials, to stop cosmic rays and block external gammas, but this approach is just not practical for a mobile, surface-level detector. In addition to enabling spatial correlations, CHANDLER's high segmentation is used to tag the positron annihilation gammas, which further reduces backgrounds, particularly from cosmic fast neutrons.

The CHANDLER technology has been demonstrated with a four month deployment of the 80 kg MiniCHANDLER prototype detector at the North Anna Nuclear Power Plant in 2017 [1]. Figure 1 shows the observed IBD spectrum, which has a $5.5\,\sigma$ significance relative to the null hypothesis. With this successful observation, MiniCHANDLER became the first mobile neutrino detector; the first unshielded reactor neutrino detector; and one of the world's smallest neutrino detectors.

The Future of the CHANDLER Program

Due to the limited funding available to the R& D program, compromises were necessary to complete the MiniCHANDLER project. These included using old PMTs, which were coupled directly to the square cube faces. An upgrade is underway with new PMTs and compound parabolic light guides. This combination has been shown to improve the energy resolution by a factor of two. This is particularly powerful for the detection of the annihilation gammas. With the old optics, the Compton Edge of the 511 keV gammas formed a weak shoulder on the pedestal, but with the new optics this feature is cleanly separated. These changes should greatly improve the affirmative positron tag, helping us to achieve a signal to noise of better than one-to-one. When the upgrades

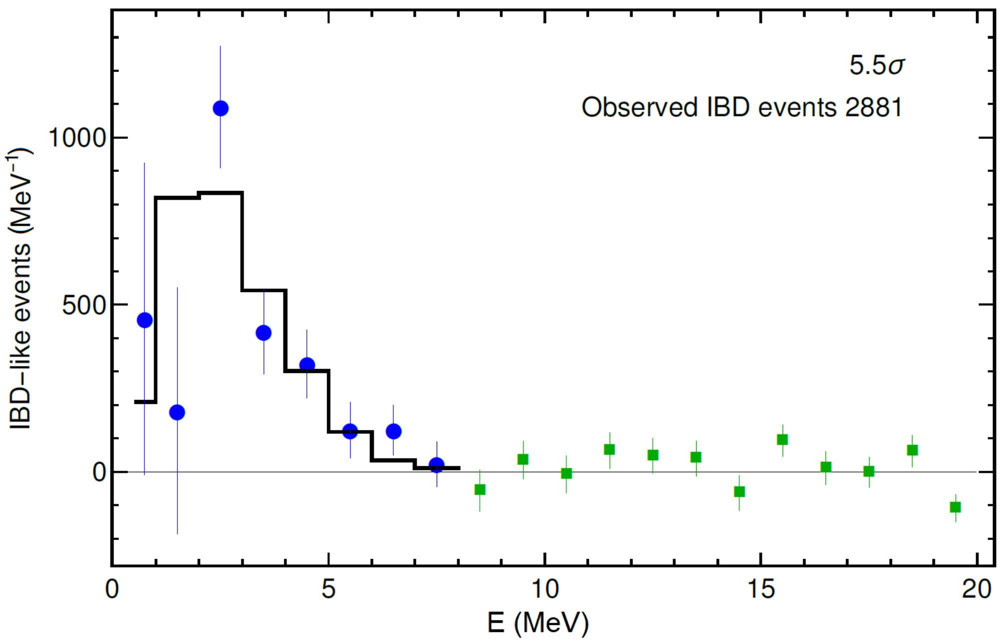

Fig. 1: The IBD positron spectrum observed by MiniCHANDLER during the North Anna Nuclear Power Plant deployment, fitted to the expected spectrum from Monte Carlo. For details of the analysis see ref. [1].

are complete the detector will be redeployment to North Anna, which will allow us to calculate the ultimate sensitivity of a full-scale detector.

Our goal is to build one or more ton-scale detectors, which we will use to measure the reactor neutrino flux at a variety of reactors, selected to maximize sensitivity to the different fissionable isotopes. These critical measurements are needed to better understand the utility of reactor neutrinos for applications such as tracking the production of weapons grade plutonium in the core, while at the same time they will address open questions in reactor flux modeling that are of active scientific interest. In addition, it is vital for this program to rule out or measure the short-baseline oscillations parameter space, since an unknown or poorly understood short baseline oscillation could lead to a misinterpretation of the fission isotope concentrations. For particle physics, the key takeaway is that any successful program in near-field reactor neutrino applications must necessarily resolve the sterile neutrino question. Therefore, particle physics programs should work with the National Nuclear Security Administration (NNSA), DOE Nuclear Energy and other agencies to ensure the ultimate success of this program.

References:

1 References

[1] Alireza Haghighat, Patrick Huber, Shengchao Li, Jonathan M. Link, Camillo Mariani, Jaewon Park, and Tulasi Subedi. Observation of Reactor Antineutrinos with a Rapidly-Deployable Surface-Level Detector. *Phys. Rev. Applied*, 13(3):034028, 2020. doi: 10.1103/PhysRevApplied.13.034028.