Directional Analysis of Reactor Neutrino Detection

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Since the beginning of the nuclear age, mankind has implemented a variety of safeguards to provide information about what is occurring in a nuclear reactor. As the number of nuclear plants grows, it is in the world's best interest to have as many detectors and safeguards in place so information about a reactor is still available when some safeguards fail. A new type of detector which should be implemented is a neutrino detector. Neutrinos are extremely light neutral fundamental particles and there is one specific type of neutrino – electron antineutrinos – which are produced in fission reactors. A neutrino detector would operate by tracking the neutrinos' interactions with the crystal inside the detector. This project focused on modeling the energies of incoming neutrinos and their following interactions within the crystal. By implementing various rotations of a cubic crystalline structure, we were able to model a detector which could relay the direction of the neutrino source. Such a detector is beneficial for tracking where a fission reactor is, whether the exact location is known or not. The energies and number of incoming neutrinos also helps relay what is happening in the reactor core. In this project we study how the inherent anisotropy of crystals can be used to infer the direction of the incoming neutrino. Such detectors will allow for a safer and more controlled nuclear future.

I. INTRODUCTION

In the summer of 1957, the International Atomic Energy Agency (IAEA) was created by the United Nations in response to the fears of the nuclear arms race and threats nuclear technologies pose to mankind. One of the key mandates of the IAEA is to verify member states comply with the Non-Proliferation Treaty and other non-proliferation agreements. The IAEA upholds this mandate in a variety of measures, including observation by IAEA inspectors, the implementation of seals and tamper indicating devices, and other "objective measures," all of which are used to ensure the member state complies with its agreement with the agency [1]. While current safeguards do complete their respective responsibilities, they can be costly, and implementation and inspection can be time consuming.

A new form of detector which could lessen the amount of time and money put into safeguards while also remaining completely tamper proof is a neutrino detector. A neutrino detector utilizes the physical phenomenon of the production of electron-antineutrinos in fission reactors. Neutrinos are fundamental neutral particles which come in a variety of flavors. The neutrino is an extremely light particle and is the focus of many current day physics research projects. While there is still much to learn about the neutrino, it is a well-known fact that electron-antineutrinos are made during fission processes, allowing detectors to be tuned to that specific type of neutrino.

The electron-antineutrinos produced in the fission reaction carry information regarding what is happening inside the reactor core — including whether fuel is being added or removed, as well as the type of material being used in the core. These detectors would be specifically useful in times where the continuity of knowledge is interrupted, such as when the reactor is put offline. Even when it is offline electron-antineutrinos are still produced and the detector still can relay what is happening in the core. The neutrino detector would allow for information about the core to still be gathered when other safeguards have been interrupted.

II. CEVNS AND CRYSTAL DEFECTS

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) was initially proposed nearly half a century ago and is now the basis for many neutrino projects. CEvNS is the process in which a low energy neutrino coherently and elastically recoils off a nucleus, causing disruptions in the target material. CEvNS inherently works with the weak neutral force carrier, the Z-boson; an incoming neutrino scatters off a target material nucleus, exchanging a Z-boson, and continuing off leaving the nucleus to continue to interact with other surrounding nuclei [2] (Figure 1). In 2017 CEvNS was observed for the first time at Oak Ridge National Labroatory using a 14.6-kilogram CsI[Na] scintillator [3]. This discovery has led the way for the ability to use CEvNS reactions as a form of nuclear safegaurd.

Nuclear reactors continually produce electron-antineutrinos through the process of beta decay (Equation 1). A detector which is calibrated to electron-antineutrinos and uses CEvNS to observe the

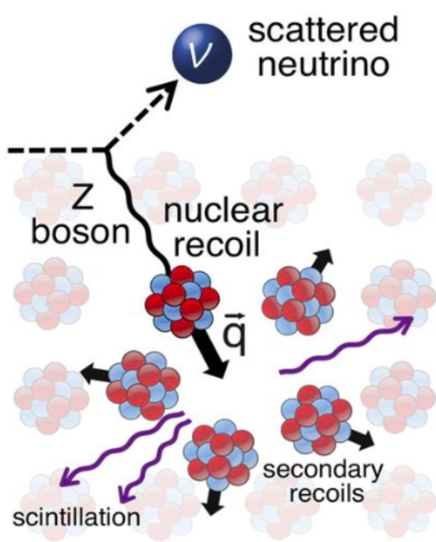

FIG. 1. Visual representation of a CEvNS reaction [3]

directionality of the incident neutrino can assist in determining the distance to the reactor (with the help of other measures), the power level of the reactor, as well as the fuel for the reactor [4]. A detector which is able to determine such factors would serve as a complement to the current safeguards in place by the IAEA.

$$A_x^y \rightarrow \bar{\nu_e} + e^- + A_w^v \quad (1)$$

After the neutrino interacts with the nucleus, the recoiling nucleus will lose its kinetic energy in one of three ways: the release of phonons, ionization, and lattice defect creation [5]. A detector mapping CEvNS events can use color centers, optically active lattice defects, to trace how the recoil nucleus traveled in the crystal [5]. These color centers are created by the removal of the anion in an ionic crystal, therefore trapping an electron and acting as a potential well. This electron then can be excited and de-excited by visible light. The de-excitation releases a photon which is what the detector then able to measure [5].

The materials which fit the needs for a neutrino detector must be able to produce optical quality crystals, have color centers which are created solely by nuclear recoil, and have a low threshold damage energy[5] . The threshold displacement energy dictates the consequential damage that occurs in the crystal after the initial interaction with the neutrino [6]. The threshold damage energy is directionally dependent; it varies in response to the direction the incident neutrino. Due to this the probability of a CEvNS event occurring is susceptible to the original direction of the neutrino. The way in which the detector uses CEvNS events to determine the original direction of the neutrino is by mapping the sequential defects in the crystal. The recoil, however, is perpendicular to the initial direction, meaning if the recoil is measured it will simply be a plane. This plane is perpendicular to the initial direction of the neutrino, however there still lies an uncertainty of where on the plane the neutrino came from.

III. METHODS AND FINDINGS

We first calculate the event rates for CEvNS reactions. This was accomplished by integrating the differential cross-section equation, Equation 2, and selecting Silicon-28 as the target material [7]. In Equation 2, $\sigma_{\nu,l}$ refers to the cross section of CEvNS reactions, or the probability of a CEvNS reactions to occur. T is the energy of the recoil nucleus, G_F is the Fermi constant $(1.166 \cdot 10^-5GeV^2)$, E_ν is the energy of the incoming neutrino, and M_A refers to the mass of the target material nucleus. N is the number of neutrons in the target material's nucleus [7].

$$\frac{d\sigma_{\nu,l}}{dT} = \frac{G_F^2 M_A}{4\pi}(1 - \frac{M_A T}{2E_\nu^2})N \quad (2)$$

After calculating the event rates, they were then coupled with high and low efficiencies, corresponding to high and low threshold damage energies directions of the crystal respectively. Figure 2 shows the values of these efficiencies versus the incoming neutrino's energy. One can see only at low energies is there a visible difference between the high and low efficiency; this is the region we are concerned with.

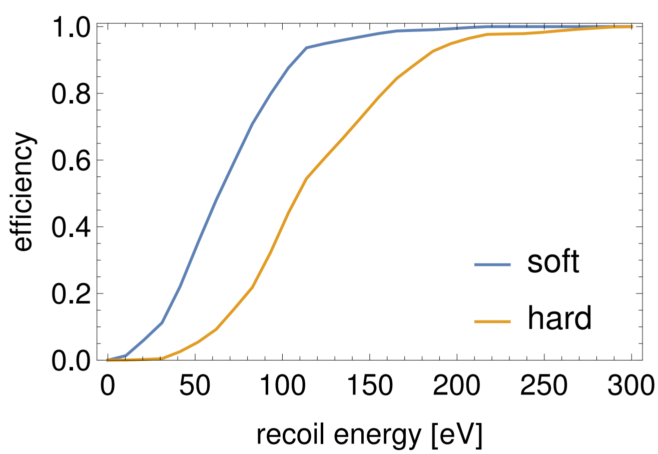

FIG. 2. Graph of efficiencies vs. recoil energy. Orange is the high efficiency, or "hard" direction, curve while and blue is the low efficiency, or "soft" direction, curve.

In order to model a reactor neutrino interacting with a detector crystal, one must implement an initial direction from which the neutrino came. This was accomplished through a series of two functions. The first function translated the initial direction of the neutrino into

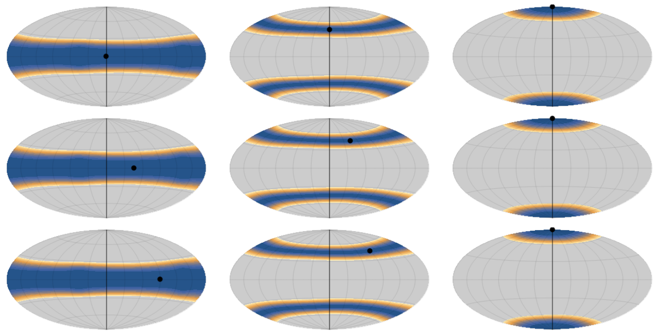

FIG. 3. CEvNS reactions in a single crystal placed 10m from a 3000 MW reactor operating for a year.

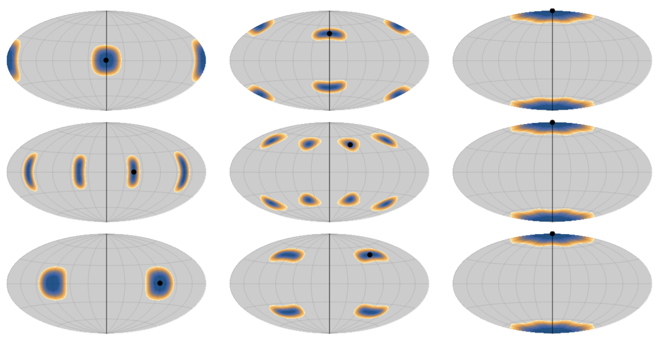

FIG. 4. CEvNS reaction through three perpendicular crystals placed 10m from a 3000 MW reactor operating for one year.

spherical coordinates. Then the second function focused on taking an average of the energy deposited along each direction, depending on the initial direction the neutrino came from. These results were then fed into a third function which combined the previously calculated efficiencies and event rates with the directionality components. Equation 3 shows the χ^2 function that was computed. X_0 represents the solution of the equation which combined the efficiencies and event rates with a predetermined direction and X represents the solution using an arbitrary (x, y) initial direction. The the results of the χ^2 are plotted in Figure 3.

$$\chi^2 = \sum \frac{(X_0 - X)^2}{X_0} \tag{3}$$

Figure 3 shows the results of the χ^2 function of a single crystal oriented with its high efficiency in the x direction and low efficiency in the y and z directions. The χ^2 values present on these graphs are 1, 4, and 9. As one can see there is a wide variety of orientations from which the neutrino could have come from as seen by the detector even though the true point of origin is marked by the black dot. This is due to the recoil being seen as a plane perpendicular to the initial direction of the neutrino. The plane has been projected onto a globe like graph in Figure 3, as one can see from the bands present.

These degeneracies can be minimized by the adding a series of crystals each with the high efficiency direction oriented in different directions. This is what is shown in Figure 4. Again, the χ^2 values present on the graphs of Figure 4 are 1, 4, and 9. In both Figure 3 and 4, each of the nine diagrams shows different initial directions of the incident neutrino, marked by the black dot, and the proceeding χ^2 values calculated. The difference between Figure 3 and Figure 4 is the addition of two crystals of the detector material rotated by 90º from the first crystal for Figure 4. From Figure 4, one can see the angular resolution achieved by using three crystals. A drawback of this method is there is no difference between a positive and negative direction along each of the high and low efficiency directions, which causes the multiple spots shown on each diagram in Figure 4.

IV. CONCLUSION

Through this project a potential detector for reactor produced neutrinos was explored. We found angular resolution is possible for CEvNS events, allowing a detector utilizing such event allows for an inexpensive measure for the IAEA to implement when placing security measures in locations of nuclear reactors. These CEvNS detectors are tamper-proof, the damage to the detector's crystals due to CEvNS events is difficult to mimic or stop, and provide a safe way for the IAEA to measure what is happening in the reactor core. Such detectors will be able provide information even when the continuity of knowledge is disturbed, such as when the reactor is shut down and other safeguards are halted. CEvNS events will continue to occur as long as fission reactions are occurring in the core and beta decay is takes place. Through understanding directionality, the implications of backgrounds from cosmogenic and reactor neutrons will be minimized. If a detector is placed near a reactor of a known location, then the CEvNS reactions must occur in the direction of the reactor, all other reactions are background. While the findings of this study provide evidence of angular resolution, further work should be placed to find in what manners can the detector differentiate between multiple sources of neutrino production.

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