Directional Analysis of Reactor Neutrino Detection

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Background

Nuclear security has been on the forefront of international concern since the mid-twentieth century. The International Atomic Energy Agency (IAEA) was created in 1957 by the United Nations to establish an international governing body to monitor nuclear sites around the world. The IAEA is tasked with implementing safeguards at nuclear sites to ensure the state is following the regulations set forth by the agency. These safeguards can be time consuming and costly. This project aims to explore the potential for a new type of safeguard which would be inexpensive and help with any losses in the continuity of knowledge about the reactor core.

Coherent elastic neutrino-nucleus scattering (CEvNS) reactions occur between an incoming neutrino and a nucleus of a target material. The neutrino and nucleus exchange a Z-boson and the nucleus scatters, creating a cascade of recoils off of the initial site of interaction, as shown in Figure 1. The nucleus will only be knocked out of its initial lattice cite if the incoming neutrino has an energy higher than the threshold damage energy of the material. The threshold damage energy is directionally dependent, meaning some directions of the crystal are easier to displace a nucleus than other directions.

Because reactors continually release electron-antineutrinos through beta decay, Figure 2, a CEvNS detector will have enough reactions to provide information on the reactor core. A CEvNS detector will use the tracks of lattice site vacancies to monitor color-centers, optically active lattice detects, which behave as a potential well for the electrons which get trapped there. Visible light will excite the electron and the de-excitation is what will emit a photon which the detector will then measure.

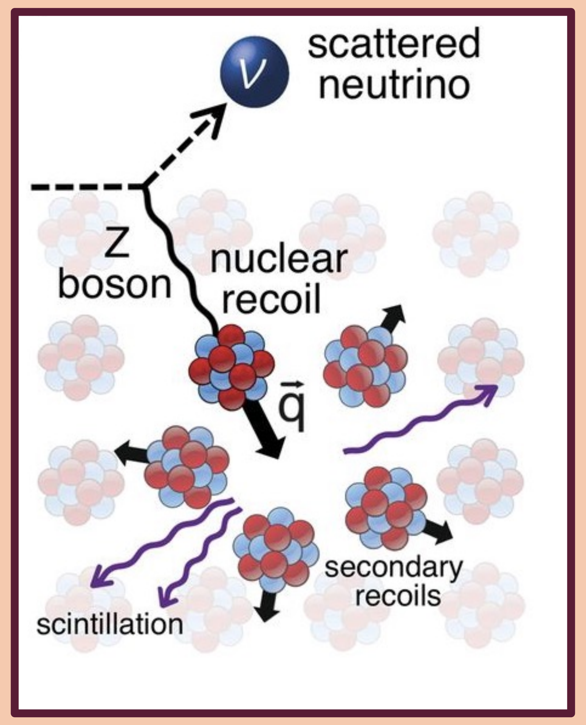

Figure 1: Visual representation of a CEvNS reaction.

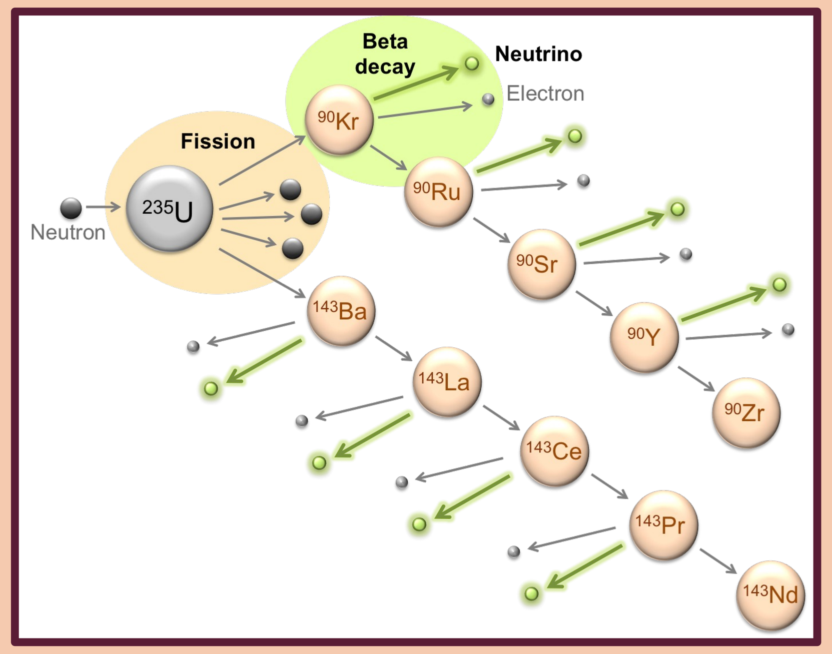

Figure 2: Visual representation of beta decay occurring inside a reactor core after a fission reaction takes place.

Methods

In order to simulate CEvNS reactions Equation 1 must be integrated. Equation 1 is the differential cross section of a CEvNS reaction, or the probability for a CEvNS reaction to occur.

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

After integrating Equation 1, we paired the calculated event rates with efficiency values. These efficiency values correspond to the threshold damage energy of each direction of the crystal. Figure 3 shows the values of the efficiencies at each recoil energy. The orange markers represents the high efficiency values, and the blue markers represent the low. The key difference in the high and low values occur at low recoil energies, which is the region CEvNS reactions occur the most.

These high and low efficiency values were then paired with an initial neutrino direction of polar coordinates. This pair was then fed into a χ^2 function as shown in Equation 2.

$$\chi^2 = \sum_i \frac{(X_{0,i} - X_i)^2}{X_{0,i}} \qquad (2)$$

In Equation 2, X_0 represents the efficiency and event rate pair which were fed through the function with a given initial direction. X represents the efficiency and event rate pair which were given an arbitrary (x, y) initial direction. The function then fed to solve for X, and the confidence levels are shown by the χ^2 value.

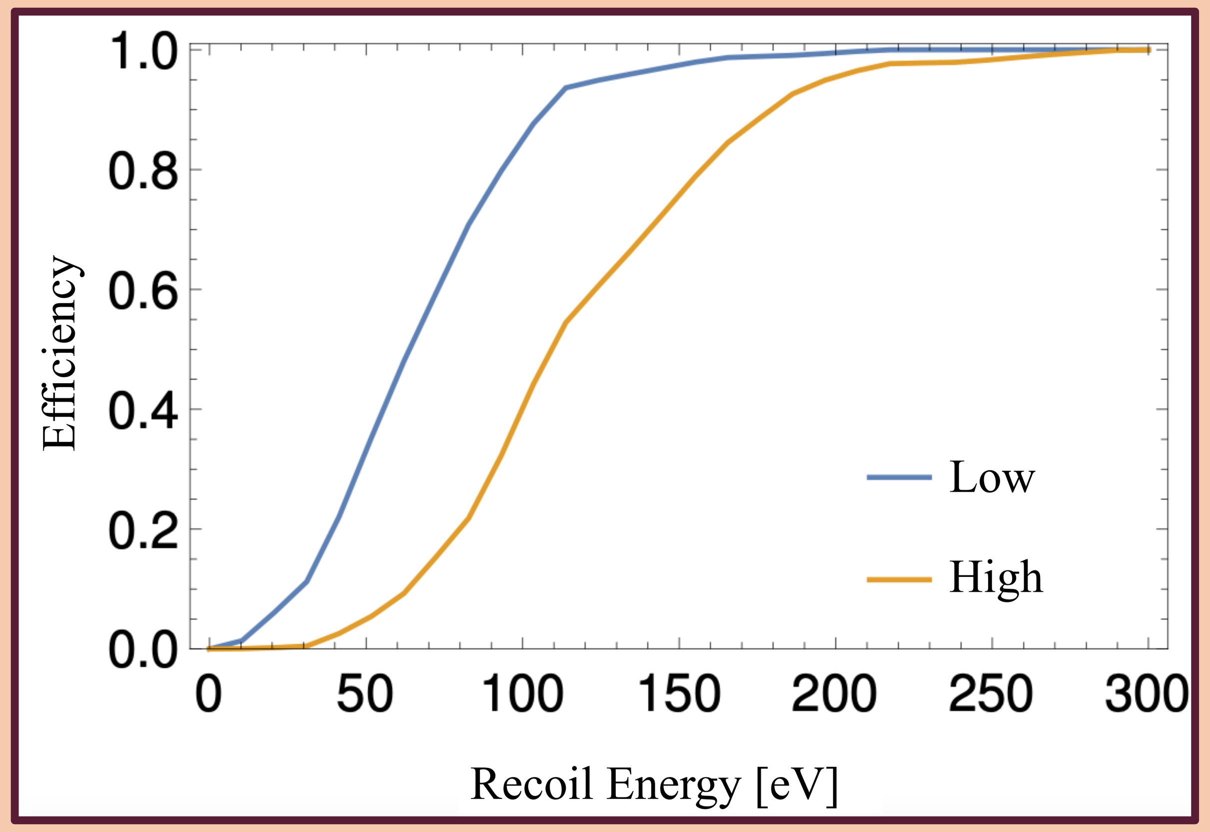

Figure 3: Recoil energy of the incoming neutrino (MeV) vs. Efficiency value. Orange is high efficiency and blue is low.

Results

The χ^2 values of 1, 4, and 9 were all plotted onto a spherical map projection, with the initial directions marked by the black dot. The directions were chosen by increments of 45º. We can see from Figure 4, there are bands marking the χ^2 values. This is due to the recoil being perpendicular to the initial direction of the neutrino.

In order to decrease these degeneracies, we can add the χ^2 functions of three different crystals together. This allows the high efficiency direction of the crystal to be in x, y, and z direction respectively in each crystal. This is what is shown in Figure 5. As one can see, using three crystals decreases the uncertainty substantially.

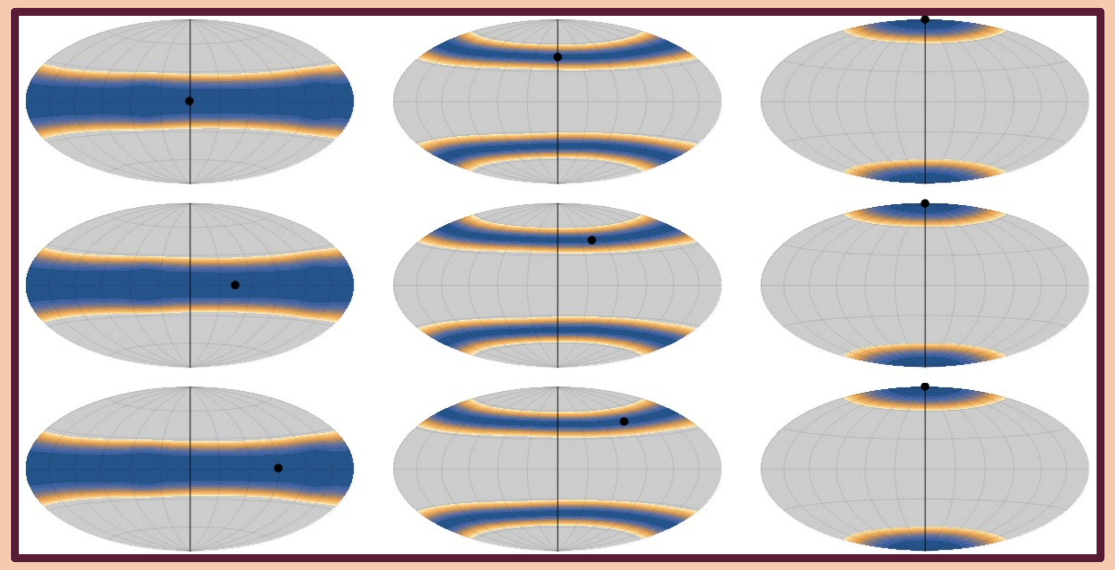

Figure 4: χ^2 values of 1, 4, and 9 of a single crystal shown with the initial direction (black dot)

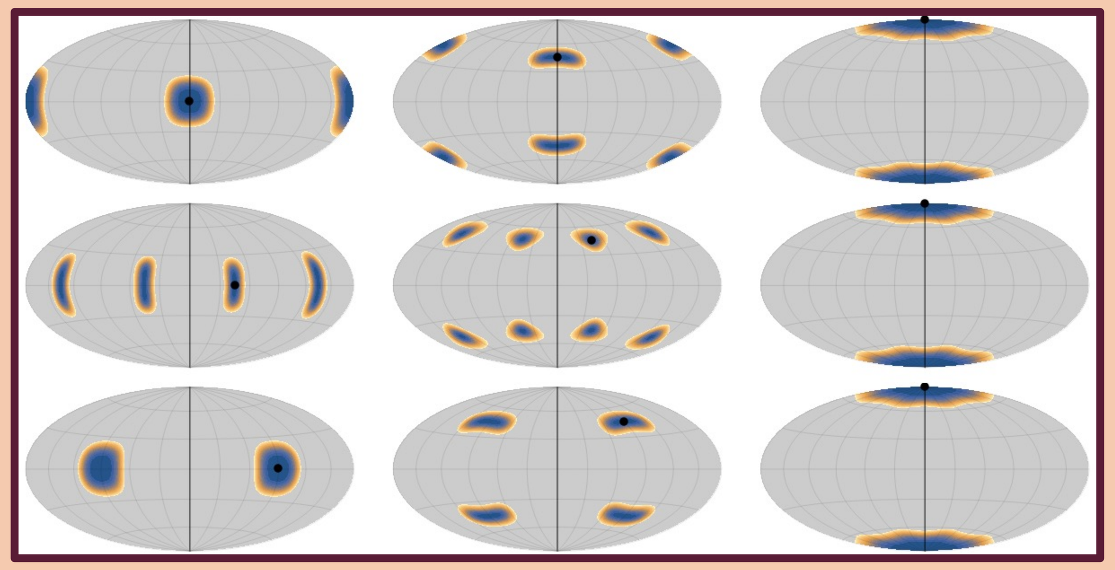

Figure 5: χ^2 values of 1, 4, and 9 of three crystals shown with the initial direction (black dot)

Conclusion

Through this project we found angular resolution is possible through CEvNS events and provides a new form of detector and safeguard for nuclear security. CEvNS events are difficult to mimic and stop, allowing the crystal detectors to be tamper proof. A CEvNS detector would provide extra knowledge about a reactor core and operate while other safeguards may fail, in the case of a power outage or in other instances where the continuity of knowledge about the reactor core is disturbed. The ability to determine directionality of incoming neutrinos can help with background suppression of other neutrino sources.

While the findings of this project helped to prove the possibility of angular resolution future projects should be conducted. These projects could include the ability for a CEvNS detector to differentiate between different neutrino sources, i.e. various reactor cores.

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Acknowledgements

C. Aldridge would like to thank Dr. C. Mariani and Ms. B. Wilkins for their help and support of the REU program at the Center for Neutrino Physics at Virginia Tech as well as her mentor P. Huber without whom this project would not be possible.