The use of CEνNS to monitor spent nuclear fuel

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With a growing demand for a clean energy supply along with concerns over nuclear waste storage, it is imperative to be able to monitor highly radioactive waste in a safe and effective way. In this research the applicability of Coherent-Elastic Neutrino-Nucleus Scattering (CEνNS) to monitor the content of spent nuclear fuel (SNF) from dry storage casks is explored in comparison to Inverse Beta Decay (IBD). The electron antineutrino flux from SNF calculated in Brdar *et al.* is used to obtain event rates from both CEνNS and IBD events for a variety of isotopes such as ^{12}C, ^{40}Ar, ^{74}Ge, and ^{184}W. It is demonstrated that at low nuclear recoil energies CEνNS events can occur at magnitudes 2-3 times larger than IBD events for a given detector mass, owing to the N^2 dependence of the CEνNS cross section and the fact that CEνNS has no neutrino energy threshold. It is found that 10 kg argon and germanium detectors 3 meters from a fuel cask can detect over 100 events per year if a nuclear recoil threshold of 70 eV can be achieved. Irreducible backgrounds from cosmic ray neutrons are then considered, and it is demonstrated that with passive shielding of 2 m.w.e a S:N ratio of 10:1 is achievable. Finally, a maximum likelihood estimate is carried out to determine the 1 σ error on the measurement of fuel in the cask, to examine with what certainty the fuel content can be verified.

I. INTRODUCTION

The need to reduce reliance on natural gas and other environmentally damaging energy sources motivates more insight into effective energy forms. Included in these energy forms is nuclear energy, which while not as prominent as solar or other renewable energies, will play a large role in future energy considerations. To ensure both environmental safety and nuclear safety, future use must be complemented by the ability to monitor both reactors and highly radioactive reactor waste. The treatment of nuclear waste is a major concern among both professionals and the general public, and is a large component of the public's view of nuclear energy.

There are 83,000 tons of spent nuclear fuel in the United States alone, a number that will only increase in the coming years. Geological repositories have been proposed to store nuclear waste, but many are still years away. Ideally, there should be a way to remotely monitor spent nuclear fuel that is available for use in the near future. This motivation points in the direction of neutrino detectors, a commonly used technology that can ease concerns by monitoring a reactor's fuel content, operational status, and thermal power [1]. Much of the current detector monitoring efforts were spurred by the Treaty of Nuclear Non-Proliferation, signed in 1968 to ensure the non-proliferation of nuclear weapons, pursue nuclear disarmament, and ensure peaceful use of nuclear energy.

These neutrino detectors are a unique application of particle physics, and work well due to the unique nature of neutrinos produced by nuclear fuel. In a reactor, unstable parent nuclei such as ^{238}U or ^{239}Pu undergo beta decay and produce neutrinos. With large amounts of unstable nuclei, both active reactor fuel and spent nuclear fuel alike produce a large flux of low energy neutrinos. Neutrinos are electrically neutral subatomic particles with an incredibly small mass, and are created through weak interactions. They come in three flavors of electron neutrinos, muon neutrinos, and tau neutrinos, and oscillate between different flavors. As well, each flavor has a corresponding antineutrino. The neutrinos produced through the beta decay of reactor fuel are all electron antineutrinos, but will be referred to simply as neutrinos for the rest of the paper.

These neutrinos are unique in that they are able to pass through any shielding surrounding the nuclear fuel without attenuation, making them an ideal observable. The premise of neutrino detectors is that through measuring the amount of specific neutrino reactions induced by the reactor neutrinos, specific properties of the reactor can be found such as fuel content and operational status. This is done quite easily, as the event rate is correlated with the amount of fuel undergoing beta decay. While the applicability of monitoring active reactors has been demonstrated and is now a common use, a novel use is that of monitoring Spent Nuclear Fuel (SNF).

II. NEUTRINO FLUX FROM SPENT NUCLEAR FUEL

Neutrino fluxes from SNF are less prominent than fluxes from active reactors, and thus detection using SNF fluxes is more technologically challenging, specifically in the case of dry storage casks. Dry storage casks act as long-term storage for SNF, after the fuel has been cooled

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in spent fuel pools. At the point that SNF is transferred to dry storage casks, the radioactivity comes from long-lived fission products. Different fission products have varying half-lives, but after around a decade the majority of the radioactivity comes from strontium-90 with a half life of 30 years, which will then decay to yttrium-90. Thus after several years, the detectable signal from neutrinos is entirely resultant from strontium-90.

In 2017, Brdar *et al.* explored the applicability of using Inverse Beta Decay (IBD) to monitor the amount of SNF specifically in dry storage casks [2]. They calculated the neutrino flux from spent nuclear fuel as a function of time since the discharge from the reactor, which is displayed in Figure 1. The flux lines of 10 and 100 years show the signature from strontium-90 and yttrium-90.

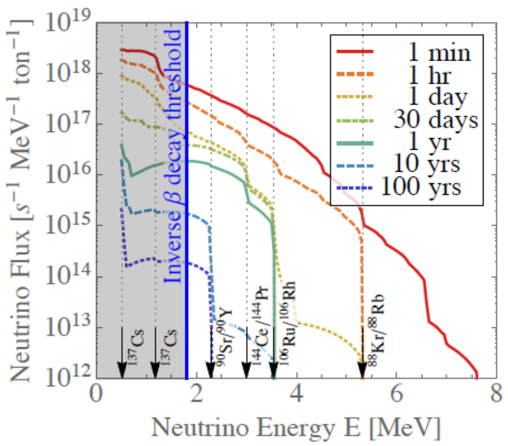

Figure 1. The spectrum of electron antineutrino flux emitted by spent nuclear fuel as a function of the time after discharge from the reactor.

These fluxes were then used to calculate how many IBD events resulting from this SNF flux could be observed for a variety of detector setups. With detector masses in the ton-scale range, it was demonstrated that such neutrino detectors could be useful to remotely detect any changes in the fuel content. Since this result, a signal from a new reaction called Coherent-Elastic Neutrino-Nucleus Scattering has been discovered by the COHERENT collaboration, and many new detectors including CONNIE, NUCLEUS, CONUS, RICOCHET, and MINER have been employed to look for CEνNS signals at active reactors [3, 4-8]. There are several advantages to a CEνNS detector compared to an IBD detector, including the potential for a much smaller, kilogram-scale detector. This research therefore focuses on examining the potential of employing a CEνNS detector to monitor spent nuclear fuel, and seeing how such a detector could improve upon an IBD detector.

III. CEVNS AND IBD REACTIONS

Inverse Beta Decay (IBD) occurs when an electron antineutrino collides with a proton, producing a neutron and a positron.

$$\bar{\nu_e} + p \rightarrow n + e^+ \tag{1}$$

The signal seen by an IBD detector arrives in two parts, first is a prompt flash of light from the positron after it undergoes matter-antimatter annihilation. After a slight delay the neutron will undergo neutron capture and produce another flash, and through timing and spatial localization the two signals can be detected. For the reaction to occur, the incident neutrino must have an energy ≥ 1.806 MeV.

The IBD cross section is dependent on the energy and momentum of the resulting positron, given as

$$\sigma_{IBD} = \frac{2\pi}{m_e^5 f^R \tau_n} E_e p_e \tag{2}$$

Where at zeroeth order,

$$E_e = E_\nu - M_n - M_p \tag{3}$$

and

$$p_e = \frac{1}{c}\sqrt{E_e^2 - m_e^2} \tag{4}$$

τ_n is the measured neutron lifetime and $f^R = 1.7152$ is the phase space factor [9]. The neutrino yield, n_{IBD}, from IBD reactions from the SNF flux, $\phi(E_\nu)$, is given in integral form as

$$n_{IBD} = \int_{1.806}^{4} \phi(E_\nu)\, \sigma_{IBD}(E_\nu)\, dE_\nu \tag{5}$$

In the case of SNF, the flux for fuel 10-100 years of age is effectively 0 past 4 MeV, thus the range 1.806-4 MeV is integrated over. The normalization factor for inverse beta decay is given as

$$N = tMN_A \frac{2}{14}\frac{1}{4\pi L^2} \tag{6}$$

based off of an operational IBD detector using CH2. Multiplying the normalization factor by the neutrino yield gives the amount of events seen by an IBD detector.

Coherent-Elastic Neutrino-Nucleus Scattering (CEνNS) occurs when a neutrino of any flavor collides elastically with a nucleus of some material, producing a nuclear recoil signal [10].

$$\bar{\nu} + \chi \rightarrow \bar{\nu} + \chi \tag{7}$$

This reaction has a kinematic limit of the nuclear recoil energy, given by

$$T_{max} = \frac{E_\nu}{1 + \frac{M_N}{2E_\nu}} \tag{8}$$

The nuclear recoil is dependent on the incident neutrino energy, and thus occurs at relatively low energies. Due to this, CEνNS long evaded detection even though it was postulated in 1974 [10]. The first detection of CEνNS occurred in 2017 by Akimov *et al.* as a part of the COHERENT collaboration [3]. CEνNS has a variety of interesting applications aside from monitoring SNF, with the potential to probe beyond standard model (BSM) physics, as well as monitor reactor breeding blankets [11].

While these low nuclear recoil energies are technologically challenging to observe, CEνNS reactions offer several advantages over IBD reactions. In contrast to IBD, a CEνNS reaction can occur for any incident neutrino energy, thus a CEνNS detector would be able to probe the neutrino fluxes below the IBD threshold in Figure 1 which offers a great advantage. Additionally, the typical CEνNS cross section can improve upon the typical IBD cross section by up to 3 magnitudes. The relevant CEνNS cross section is given as

$$\frac{d\sigma_{CEV}}{dT} = \frac{G_f^2}{4\pi} N_N^2 M_N (1 - \frac{M_N\ T}{2E_\nu^2}) \tag{9}$$

where G_f is the Fermi constant, N_N is the target isotope's neutron number, M_N is the mass of a nucleus of the target isotope, E_ν is the incident neutrino energy and T is the nuclear recoil energy [12]. The neutrino yield n_{CEV} is given in integral form as

$$n_{CEV} = \int_0^4 \int_{T_{min}}^{T_{max}} \phi(E_\nu)\ \frac{d\sigma_{CEV}}{dT}(E_\nu)\ dT dE_\nu \tag{10}$$

As the cross section is doubly differential, it can be analytically integrated over the recoil energy from T_{min} to T_{max}, but T_{max} depends on the neutrino energy as given in Eq. 7 thus the integral over neutrino energy is done numerically. The numerical integral is evaluated from 0 to 4 MeV, as CEνNS has no energy threshold.

The normalization factor is given by

$$N = tM\frac{N_A}{m}\frac{1}{4\pi L^2} \tag{11}$$

where $t =$ detecting time in seconds, M is the mass of the detector in grams, L is the distance from the SNF to the detector, and $\frac{N_A}{m}$ is Avogadro's number divided by the atomic mass of the target material, giving the number of atoms in the detector material.

With the flux, cross section, and normalization, the event rates of both IBD and CEνNS can be found for a variety of detector setups.

IV. COMPARISON OF IBD AND CEνNS EVENT RATES

The first analysis of interest was to compare a potential CEνNS detector to an identical IBD detector, aside from target material. With this analysis, it could be observed whether CEνNS offered any advantage, and should such an advantage exist it could be quantified. The event rates of both CEνNS and IBD for a detecting time of one year were calculated for a given detector mass. A CEνNS detector could use any stable isotope, thus the target detector isotope for CEνNS was varied to observe how the cross sectional dependence on N^2 would affect event rates.

To illustrate this relationship, CEνNS event rates from isotopes ^{12}C and ^{184}W were calculated and the ratio of the CEνNS events seen to IBD events seen were plotted as a function of the time since the fuel discharge, also referred to as age of the fuel. Since both the normalization factors include the same scaling by detector mass and distance from detector, these parameters did not affect the ratio.

The other parameter of interest was the nuclear recoil energy that a CEνNS detector would be able to resolve. Many running or in-progress CEνNS detectors are able to resolve nuclear recoil energies below 100 eV [4-8], thus a range of 0-100 eV was considered for the following analyses. For the ratio calculations shown in Figure 2, it was assumed that the CEνNS detector would be able to resolve either all nuclear recoil energies, or down to 10 eV. This is out of the range of feasibility of current detectors, but it displays effectively the maximum advantage that can be found by a CEνNS detector.

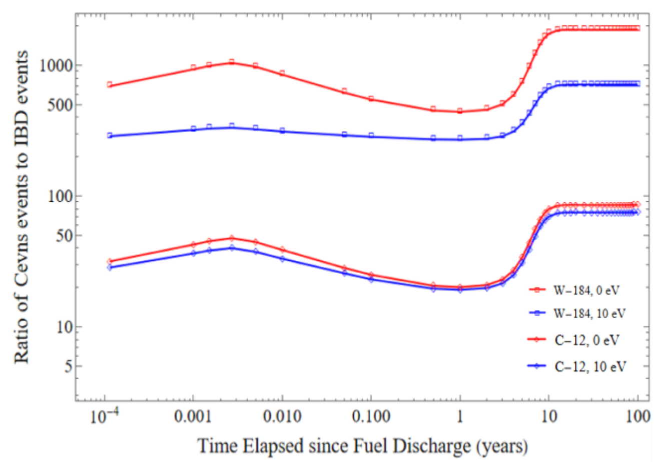

Figure 2. Event rate ratio between CEνNS and IBD for ^{184}W and ^{12}C at resolvable recoil energies of 0 and 10 eV plotted as a function of time elapsed since fuel discharge.

After an elapsed time of around 10 years, the event ratio becomes steady for all isotopes. Most spent fuel contained in dry storage casks is 10-70 years of age, thus this steady range is of most interest for this work. As displayed in Figure 2, a heavier isotope such as tungsten can reach a 2 to 3 magnitude improvement over IBD, while a lighter isotope such as carbon can reach a 1 to 2 magnitude improvement, a promising initial result.

Figure 2 also shows that while ^{184}W produces the highest ratio in the case that all nuclear energies are resolvable, an increase to 10 eV will cause the ratio to fall by over a half. In contrast, the ratio of ^{12}C stays comparably stable with an increase of 10 eV. This illustrates a trade-off between the N^2 dependence of the cross section with the maximum nuclear recoil energy T_{max}, which effectively scales as $\frac{1}{M}$ where M is the isotope mass. Higher mass isotopes have a larger cross section, but have much lower maximum recoil energies which act as a limiting factor.

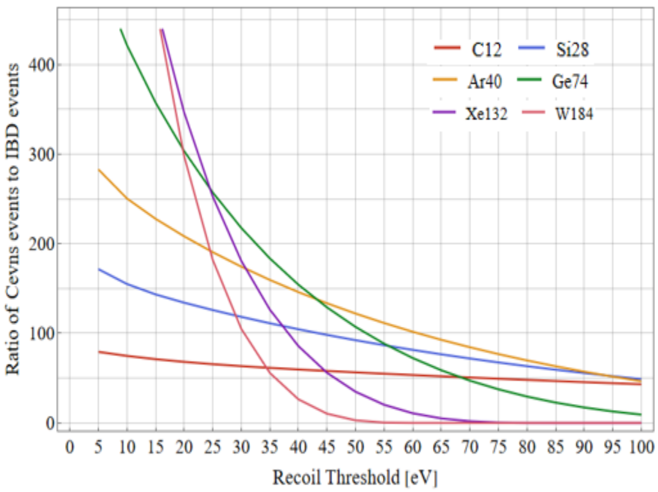

Figure 3. Ratio of CEνNS events to IBD events from SNF 10 years since discharge plotted for a variety of potential target isotopes given by color.

This relationship is more clearly shown in Figure 3, with a variety of isotopes including potential target isotopes such as ^{12}C, ^{28}Si, and ^{74}Ge. While the larger mass isotopes such as ^{132}Xe and ^{184}W have high ratios at small recoil energies, they quickly fall and at energies over 80 eV no longer offer an advantage. Each isotope has an associated nuclear recoil energy at which the IBD events surpass the CEνNS events, detailed in Table 1. If a CEνNS detector is unable to resolve this energy, an IBD detector is favorable.

Isotope	C	Ne	Si	Ar	Ge	W
Min. Nuclear Recoil (eV)	648	420	314	236	144	76

Table I. Nuclear Recoil Energies (eV) at which the number CEνNS events is equal to the number of IBD events for a fixed discharge time of 10 years.

Out of the isotopes considered, argon and germanium were selected to have the best relationship between the advantage and the necessary nuclear recoil energy. Thus further analysis was conducted assuming target detector isotopes of either ^{40}Ar or ^{74}Ge.

V. EVENT RATES OF ARGON AND GERMANIUM DETECTORS

To examine the event rates from different detector setups, various parameters such as distance, mass, and resolvable nuclear recoil energy were varied. As the original neutrino flux used was measured per ton of SNF, the event rates were adjusted accordingly assuming a fuel content of 10 tons. Detector masses on the order of 10 kilograms were seen to have the optimal event rates. As well, distances of 3 to 5 meters from a dry storage cask were found to be ideal, as the event rate decreases as a function of $\frac{1}{L^2}$.

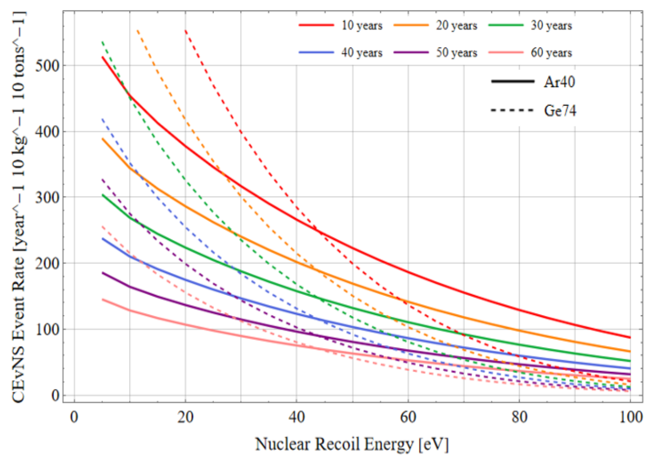

Figure 4. The event rate of CEνNS reactions for 10 kg ^{40}Ar (solid lines) and ^{74}Ge (dashed lines) detectors with a detecting time of one year at 3 meters from a 10 ton fuel cask of varying age, given by line colors.

Figure 4 displays the CEνNS events per year for a 10 kg detector 3 meters from a 10 ton fuel cask, calculated as a function of the resolvable nuclear recoil energy. The solid lines, representative of argon, have higher event rates than germanium above 43 eV for each respective fuel age. Under 43 eV, germanium had higher event rates, and the relative advantage increased with decreasing nuclear recoil energy values. The isotope used in the detector therefore will likely depend on what energy is resolvable, as well as how much material is available. For instance, a 100 kg detector would improve upon the event rates by a factor of 10 but should a 100 kg detector wish to be used, argon would be preferable as it is much less expensive than germanium.

Since most current CEνNS detectors can resolve energies in the sub-keV range, a benchmark energy of 50 eV is not unfathomable for a potential detector. For example, CONNIE has a threshold of 40 eV [4]. At 50 eV, argon has a slight advantage, with an event rate 1.1 times larger than germanium. Additionally, argon has a significantly larger advantage at higher nuclear recoil energies as is displayed in Figure 5.

Overall, a 10 kg argon or germanium detector 3 meters

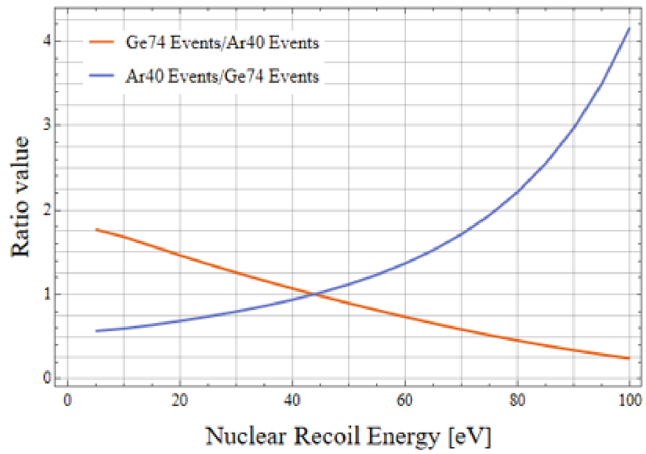

Figure 5. Relative event rates from identical ^{74}Ge and ^{40}Ar detectors, as a function of the nuclear recoil energy resolvable, given in eV.

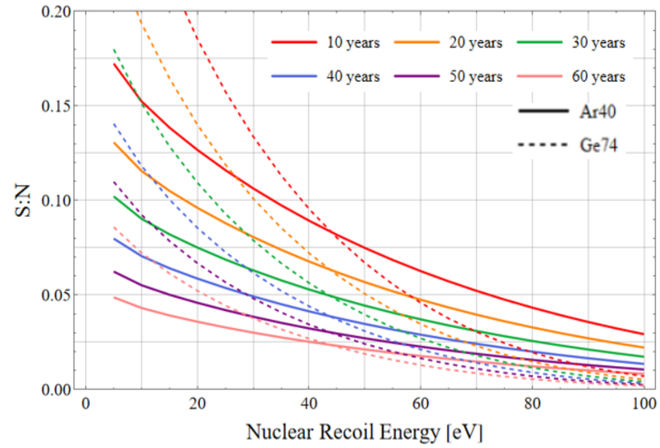

Figure 6. The Signal to Noise Ratio for the CEνNS event rate from a 10 kg detector 3 meters from the fuel cask with backgrounds from cosmic ray neutrons, with passive shielding of 1 m.w.e employed.

from a fuel cask can exceed 100 events per year regardless of isotope and resolvable energy, though older fuel requires lower resolvable energies. However, these are the raw CEνNS event rates, which do not capture the true signal seen by a detector. To better estimate the efficiency of a detector, backgrounds must be considered to estimate a potential detector's signal to noise ratio.

VI. APPLICABILITY WITH BACKGROUNDS CONSIDERED

The majority of backgrounds signals are easily shielded, but signals from cosmic ray neutrons cannot be neglected in the case of a CEνNS detector. A cosmic ray neutron, after collision with the detector isotope, will recoil at low energies, producing a signal almost identical to CEνNS. The most effective method to mitigate the background signals from cosmic ray neutrons is through a combination of passive and active shielding. Surface background levels of cosmic ray neutrons with energies ranging from 20-10,000 eV have been estimated to have magnitudes of 10^4 day^{-1}kg^{-1}, but 1 meter water equivalent (m.w.e) passive shielding brings the level down to 10^2. Active shielding improves the levels by another factor of 10, down to the order of 10^1 [13-15].

For the purposes of this research, the detector is assumed to be able to resolve nuclear recoil energies of 100 eV or less, thus only backgrounds events from neutrons with energies under 100 eV were considered. It was also assumed that the shape of the background signal was flat. With these considerations, the signal to noise ratio for the CEνNS events to the neutron background events was calculated.

With 1 meter water equivalent passive shielding and active shielding, signal to noise ratios of 1:10 can be found for a detector 3 m away, as shown in Figure 6. However, it is feasible to employ a passive shield of 2 meter water equivalence, effectively improving the signal to noise ratio by a factor of 100. For such a shield, the signal to noise ratio exceeds 10:1 for a variety of fuel ages and nuclear recoil energies, a promising result. A potential configuration of this shield could be that of the detector being placed 3 meters underground, with 2 m.w.e. shielding above it, and to have the dry storage cask placed over the detector. In future work the best detector and shielding configurations will be considered more thoroughly.

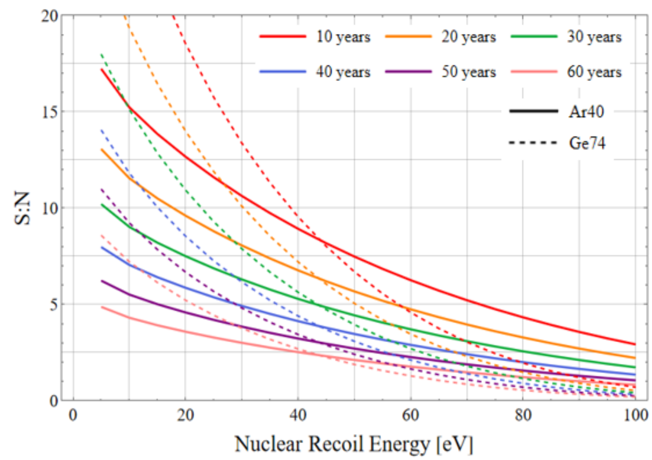

Figure 7. The Signal to Noise Ratio for the CEνNS event rate from a 10 kg detector 3 meters from the fuel cask with backgrounds from cosmic ray neutrons, with passive shielding of 2 m.w.e employed.

VII. VERIFICATION OF FUEL MEASUREMENT

The ultimate goal of this detector is to remotely verify the fuel content in a dry storage cask, to account for any otherwise undetectable losses in fuel. To do this, the detector must be able to accurately measure the true amount of fuel in such a cask. To explore how well a potential detector with the aforementioned ideal parameters could measure the true fuel content, a maximum likelihood estimate was carried out assuming a true mass of 10 tons. 1 and 2 sigma errors were found for both argon and germanium detectors, with varying levels of background shielding, as displayed in Tables II and III.

Shielding	1σ (%)	2σ (%)
1 m.w.e.	29.8	59
2 m.w.e.	6.9	13.8

Table II. Argon

Shielding	1σ (%)	2σ (%)
1 m.w.e	22.6	45
2 m.w.e	6.4	12.8

Table III. Germanium

Table IV. Sigma errors on the measurement of fuel in a dry storage cask for a 10 kg detector 3 meters from the cask, with varying background shielding levels.

Shielding levels of 2 m.w.e. greatly reduced the sigma errors of the fuel measurement, bringing the 1 σ errors down to 6.9% for ^{40}Ar and 6.4% for ^{74}Ge. Germanium has slightly better error values, preliminarily indicating that it may be better at measuring the true fuel content. Future work will be done to investigate these errors more thoroughly.

VIII. SUMMARY & OUTLOOK

Through this work a first analysis of the potential of a CEνNS detector to monitor spent nuclear fuel has been presented. It has been demonstrated that in the case of spent nuclear fuel, a CEνNS detector can greatly improve upon the event rate seen by an identical IBD detector. In this work a relationship between the selected target isotope, resolvable nuclear recoil energy and the resulting CEνNS event rate was also illustrated. Future work will look more deeply into this relationship, examining a larger variety of potential detector isotopes to gain more insight into the ideal isotope depending on feasible resolvable nuclear recoil energies. It was demonstrated that over 100 events per year could feasibly be seen by a kg-scale detector, which is significantly smaller than typical ton-scale IBD detectors. As expected, the CEνNS event rate decreased as the time since the fuel discharge increased, thus older fuel requires slightly lower nuclear recoil energies to reach event rates on the scale of 10^2. It is seen that with a 2 m.w.e passive shield, a detector can achieve a signal to noise ratio of 10 or greater. Further, the 1 σ and 2 σ errors on the measurement of the fuel in a dry storage cask were shown, demonstrating the applicability to monitor the fuel content for any fuel unaccounted for. Future work will continue this MLE analysis for a variety of detector masses and isotopes to offer a more whole picture of a detector's ability to verify the fuel content in a dry storage cask. As well, the feasibility of construction and design of a CEνNS detector with the most preferable parameters demonstrated in this research will be considered. Overall a CEνNS detector is a promising tool to monitor spent nuclear fuel and with further work more applications may be considered.

ACKNOWLEDGEMENTS

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