The Use of Coherent-Elastic Neutrino-Nucleus Scattering to Monitor Spent Nuclear Fuel

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MOTIVATION

The motivation for this research comes from many corners of interest including environmental safety and nuclear non-proliferation safeguards. Neutrino-based detection approaches are a key instrument in monitoring active nuclear reactors to ensure adherence to nuclear safety treaties, with the ability to verify a reactor's operational status, fuel content, and thermal power. There are many operational detectors using signals from Inverse Beta Decay (IBD) as well as the recently-discovered Coherent-Elastic Neutrino-Nucleus Scattering (CEνNS). While the majority of running detectors focus on active reactors, this detector technology can be used to monitor the highly radioactive waste coming from the reactors, a favorable use while many geological repositories are years away. Specifically, this work aims to examine the effectiveness of using CEνNS to monitor the fuel content of Spent Nuclear Fuel (SNF) in dry storage casks. The results will inform what types of detectors to build, considering target detector isotopes, baselines, and resolvable nuclear recoil energies.

	CEνNS	**IBD**
Reaction	$\bar{\nu} + \chi \rightarrow \bar{\nu} + \chi$	$\overline{\nu_e} + p \rightarrow n + \mathrm{e}^+$
Cross Section	$\frac{d\sigma}{dT} = \frac{G_f^2}{4\pi} N_N^2 M_N (1 - \frac{M_N T}{2E_\nu^2})$	$\sigma = \frac{2\pi}{m_e^5 f^R \tau_n} E_e p_e$
Normalization	$N = tM \frac{N_A}{m} \frac{1}{4\pi L^2}$	$N = tMN_A \frac{2}{14} \frac{1}{4\pi L^2}$

CEνNS occurs when a neutrino of any flavor collides elastically with a nucleus, scattering it at very low recoil energies. IBD occurs when an electron antineutrino collides with a proton, producing a neutron and a positron. For IBD to occur, the neutrino must have an energy greater than 1.806 MeV, while CEνNS is a threshold-less reaction. The CEνNS cross section can be 3 magnitudes larger than that of IBD, with values of $10^{-40}\ cm^2$ compared to the $10^{-43}\ cm^2$. This is due to the dependence on N^2 in the CEνNS cross section, where N is the number of neutrons in the target detector mass. To compute the event rates, the cross sections and the flux from the spent nuclear fuel were multiplied and integrated over, and subsequently normalized with the according normalization factors.

FLUX FROM SPENT NUCLEAR FUEL

This analysis used the electron antineutrino flux from spent nuclear fuel as calculated in Brdar et al. The flux was calculated as a function of the neutrino energy and plotted for a variety of timescales since the discharge of the fuel. For this analysis timescales of 10-100 years were considered, as the age of the majority of SNF is within this range.

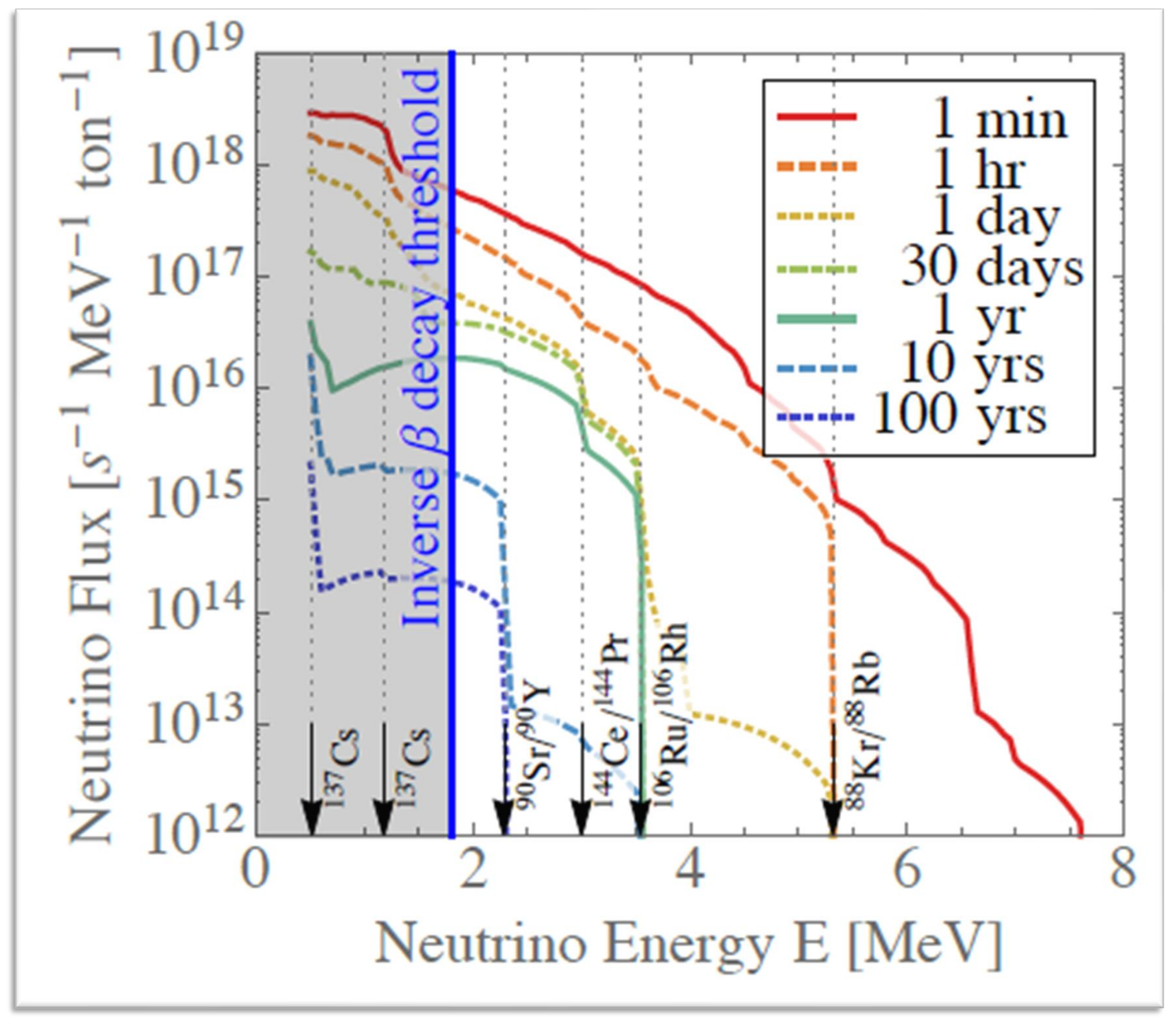
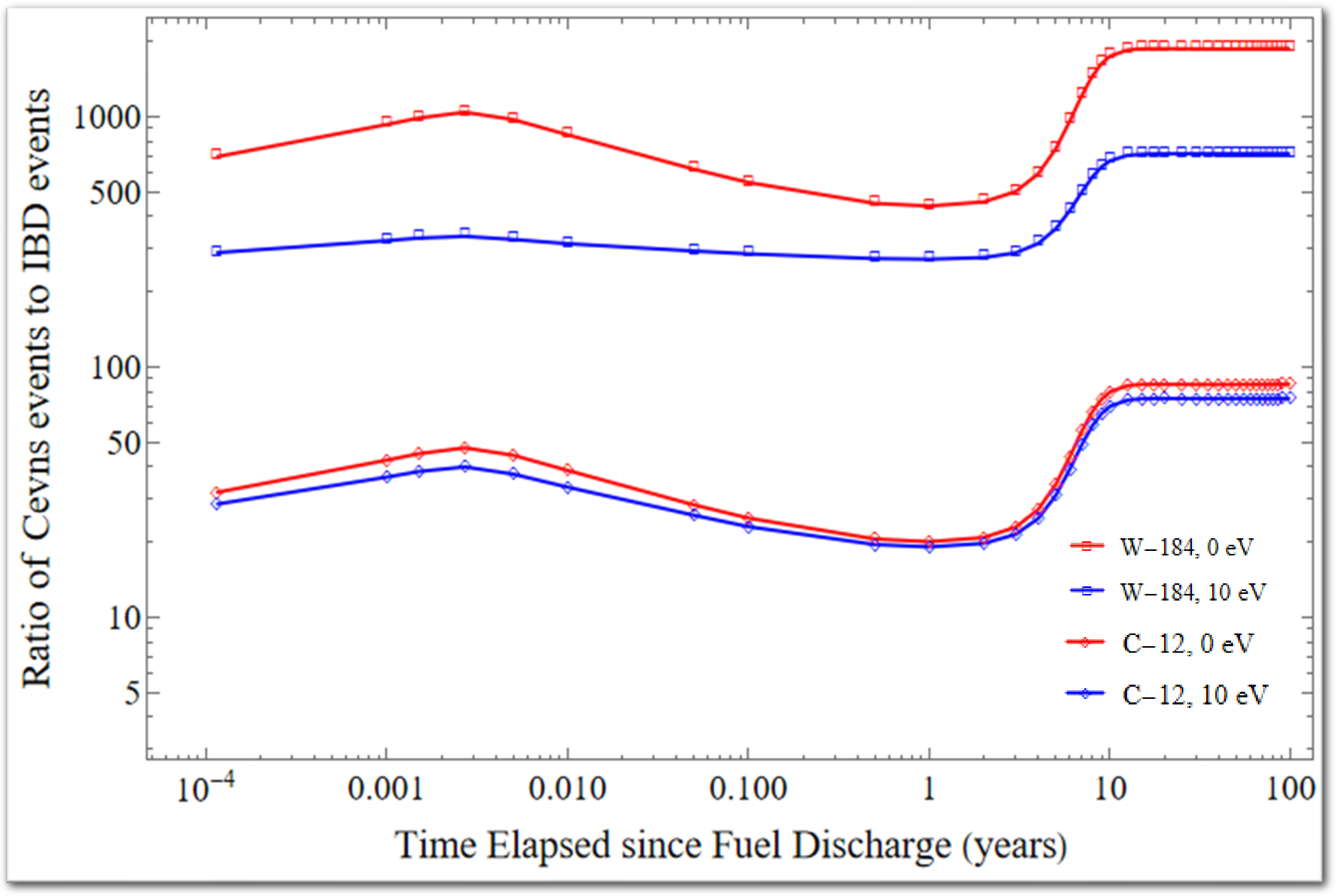


Fig 1. The spectrum of electron antineutrinos emitted by spent nuclear fuel as a function of the time after discharge from the reactor.

CEνNS ADVANTAGE OVER IBD

A first step in the analysis was to quantify any advantage that CEνNS would have over IBD. The ratio of CEνNS events seen to IBD events seen for a given detector mass was calculated for a variety of isotopes. Assuming the detector was able to resolve either all recoil energies or down to 10 eV, heavier isotopes such as Tungsten were seen to have ratios with CEνNS events 2 to 3 magnitudes larger than IBD events. Smaller isotopes such as Carbon had an advantage of 1 to 2 magnitudes. This data showed that as the nuclear recoil limit increases, the ratio decreases quickly for heavier isotopes but slowly for lighter isotopes. This suggests that there is an ideal balance between the isotope and the resolvable nuclear recoil energy that produces the optimal ratio, and when this was investigated, argon and germanium were found to have the best ratios given the constraints and were thus chosen for further analysis.

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



EVENT RATES OF ARGON AND GERMANIUM

To examine the event rates from different detector setups, various parameters such as distance, mass, and resolvable nuclear recoil energy were varied. For argon and germanium, it was observed that under an energy of 45 eV, germanium saw an appreciably higher event rate, while above 45 eV argon dominated. For a 10 kg detector monitoring 10 tons of spent nuclear fuel, distances ranges of 3-5 meters saw event rates ranging from 50 to over 100 depending on the resolvable nuclear recoil energy. Figure 3 shows that at 3 m. from a fuel cask, if 50 eV is resolvable, fuel up to 40 years of age will produce over 100 detectable CEνNS events.

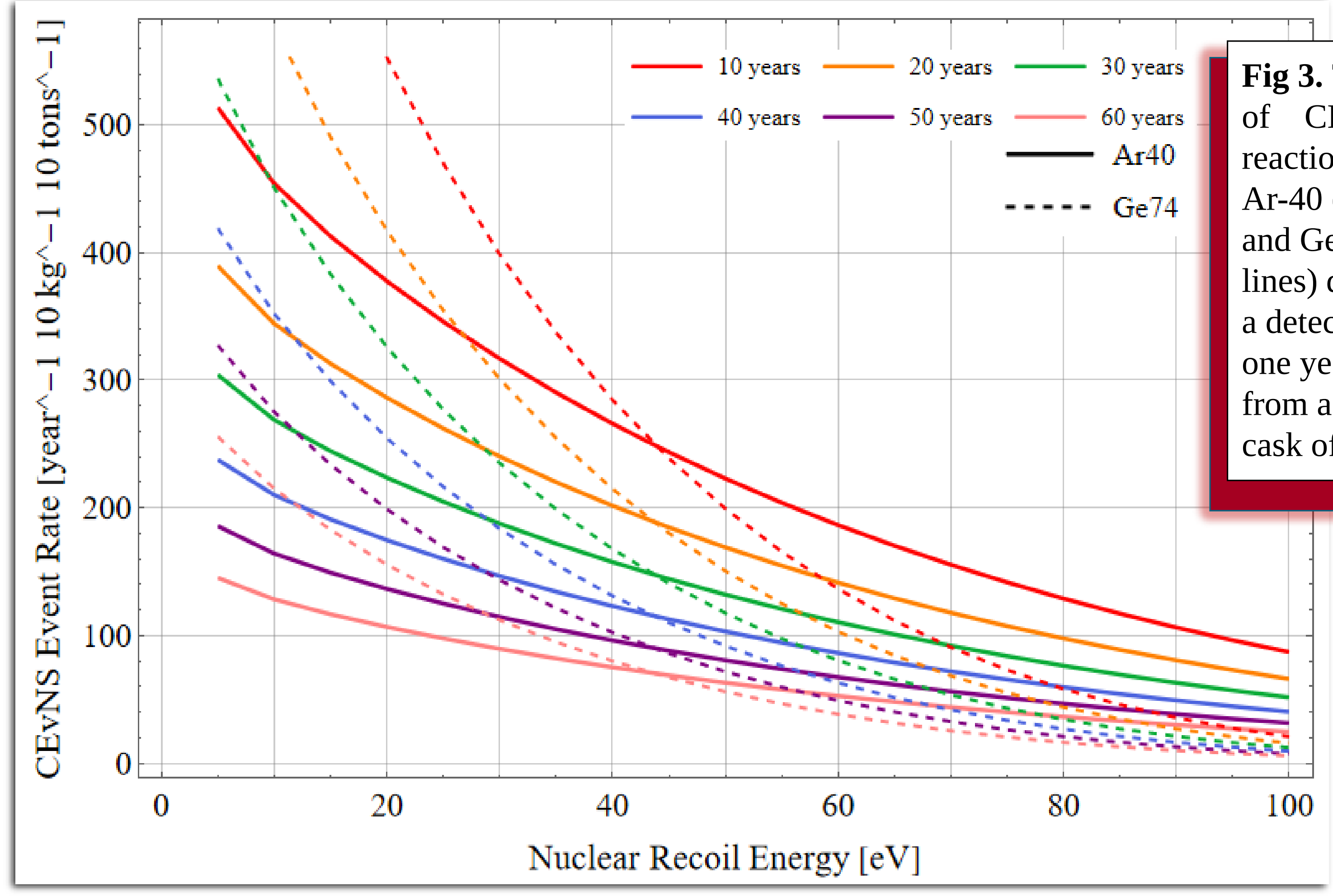


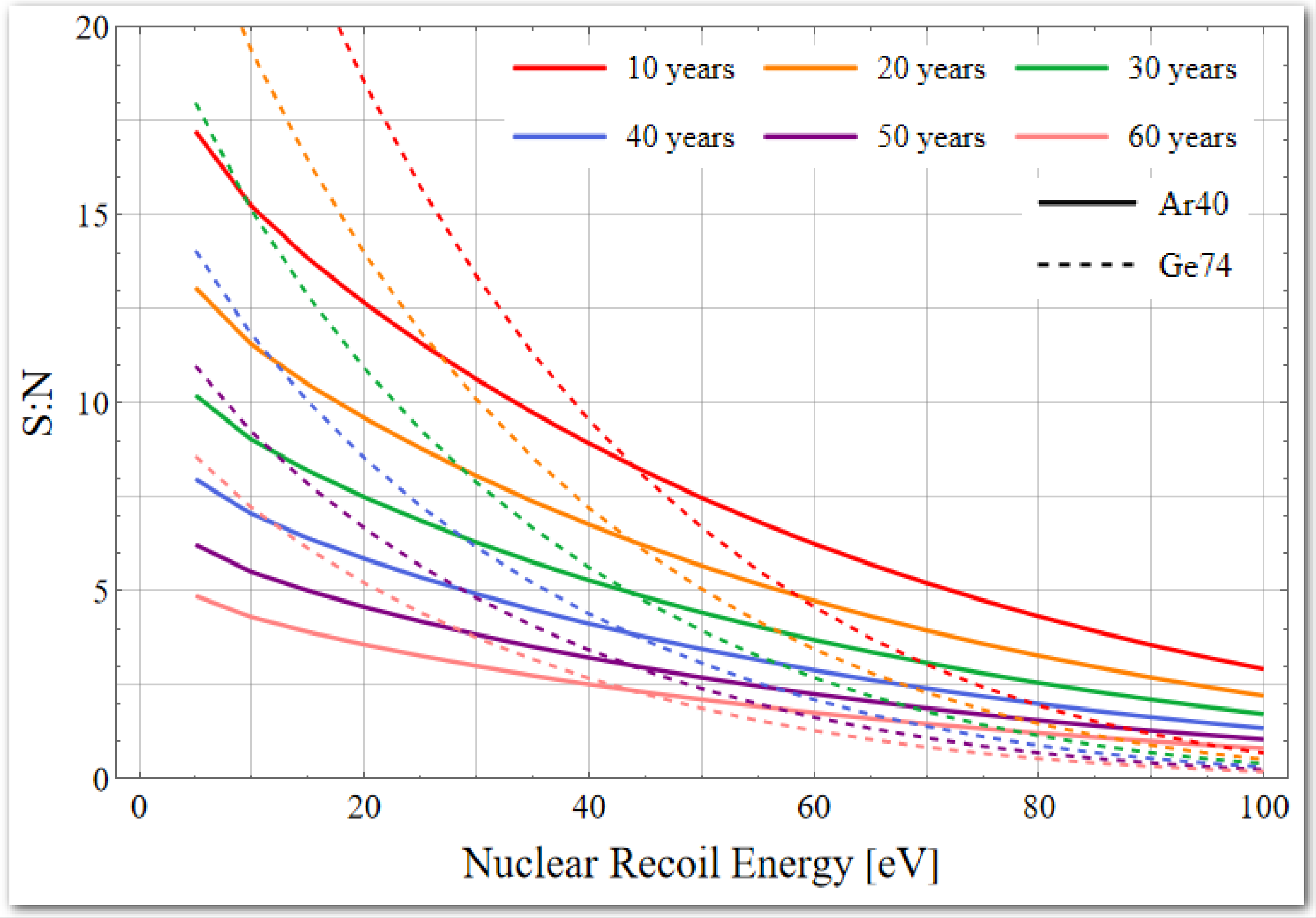
Fig 3. The event rate of CEνNS reactions for 10 kg Ar-40 (solid lines) and Ge-74 (dashed lines) detectors with a detecting time of one year at 3 meters from a 10 ton fuel cask of varying age.

50 eV is not unfathomable for current CEνNS detectors, and 10 kg is quite portable. The isotope used in the detector may 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 preferrable as it is much less expensive than germanium.

COSMIC RAY NEUTRON BACKGROUNDS

To continue the analysis, backgrounds were considered to estimate potential signal to noise ratios. Most background events can be shielded, except for cosmic ray neutrons which mimic a CEνNS signal. We considered the background from cosmic ray neutrons using magnitudes from Bergevin, et al., assuming a flat background shape. With 1 meter water equivalent (m.w.e) passive shielding and active shielding, the background is on the order of 10^1 per day per kg. With 2 m.w.e passive shielding, this becomes 10^{-1}, and the S:N ratio for a detector 3 m. can reach 10^1. This ratio is quite promising for future detectors should such a shield be employable.

Fig 4. The Signal to Noise Ratio for the CEνNS event rate from Figure 3 with backgrounds from cosmic ray neutrons, with passive shielding of 2 m.w.e employed.



MEASUREMENT OF FUEL CONTENT

As the main goal of potential detectors is to verify the fuel content in the cask, the next step was to carry out a maximum likelihood estimate to see how well the fuel content could be measured. We simulated an expected signal from CEνNS and neutron backgrounds with a true mass of 10 tons of fuel and found 1 σ errors of 11% and 6% for the measurements with backgrounds from 1 and 2 m.w.e shielding respectively, for a detector 3 meters away.

CONCLUSION

Through this work we have 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. 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. It is seen that with a 2 m.w.e passive shield, a detector can achieve a signal to noise ratio of 10 and greater. Further, we show the 1 σ errors on the measurement of the fuel in a dry storage cask, demonstrating the applicability to monitor the fuel content for any fuel unaccounted for. Future work will be done to refine what the optimal target isotope is, and to consider the applicability of these detector specifications.

ACKNOWLEDGEMENTS

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Fig 1. image credit to Brdar, V., Huber, P., Kopp, J., 2017. https://doi.org/10.1103/PhysRevApplied.8.054050