Neutrino Emissions from Plutonium-241 and Spent Nuclear Fuel

Patrick Huber[1] and Morgan Roadman[2]

[1]*Center for Neutrino Physics, Physics Department, Virginia Tech*

[2]*Concord University*

(Dated: July 23, 2024)

Abstract

This project examines the emissions of neutrinos from spent nuclear fuel and plutonium-241 specifically. By analyzing these signals, we aim to improve our understanding of the behavior of neutrinos in different storage environments for used nuclear material. The study evaluates the characteristics of these emissions, concentrating on detection and measurement, and the potential use of plutonium-241 in experimental applications.

I. INTRODUCTION

Nuclear energy has been harnessed as a carbon-neutral power source since the 1950s, utilizing the energy released from nuclear fission to generate electricity. This technology necessitates the management of spent nuclear fuel, a highly radioactive byproduct that requires specialized and long-term storage solutions.

A. Plutonium in Spent Nuclear Fuel

Radiation is not the only risk spent nuclear fuel poses. It also contains large amounts of plutonium, about 1% per weight, which could be used to make nuclear bombs. The amount of plutonium-239 required to make a bomb is about 4 kg whereas a single storage container full of spent nuclear fuel, roughly 5 tons, can contain 25-50 kg of that isotope, enough for 6-12 bombs.

Currently, only indirect means to track plutonium in spent nuclear fuel in storage exist, *e.g.* the overall gamma activity or neutron emission. Here, we investigate whether neutrino emissions from plutonium are detectable.

B. Neutrino Detection

Detection of neutrinos from spent nuclear fuel using inverse beta decay (IBD) has been considered[1]. However, only fission fragments, chiefly strontium-90, make neutrinos of sufficient energy for this reaction and hence provide only an indirect signature of plutonium inventories. We present here, for the first time, a study of the neutrino signals arising from the decay chains of the actinides themselves. Their neutrino emissions are all very low energy and hence cannot be detected via IBD.

Another method of neutrino detection is through coherent elastic neutrino-nucleus scattering (CEvNS), the process through which a neutrino scatters off an atomic nucleus. As long as a neutrino has some kinetic energy, it can interact with a nucleus and transfer a non-zero amount of energy, causing the nucleus to recoil. The first observation was reported in 2017 by the COHERENT collaboration, which confirmed a prediction made over 40 years earlier. Detection through CEvNS is ideal for neutrinos from actinides since, in principle, it has a zero energy threshold.

C. Neutrino Emissions

For the computation of the neutrino yield from the actinides, we perform a summation calculation using the methods of Ref. [1]. We follow the decay chains and include contributions from spontaneous fission. To illustrate the event rates obtainable for 1 kg of isotope with a 1 kg detector at 1 m in one year, we show these numbers for select actinides as a function of recoil detection threshold in Figure 1.

Isotope	0 eV	1 eV	10 eV	100 eV
U-235	4.280 E-7	3.343 E-9	4.453 E-10	2.463 E-15
U-238	3.437 E-7	1.609 E-7	4.015 E-9	4.834 E-12
Pu-239	4.019 E-10	1.479 E-11	1.045 E-11	1.864 E-12
Pu-241	0.0266	1.381 E-6	5.128 E-10	8.316 E-11

FIG. 1. Events per kg of isotope per kg of detector at a distance of 1 meter in one year.

D. Plutonium-241

As shown above, some of the actinide isotopes most present in spent nuclear fuel will have a non-zero number of neutrino events per year, at least for a low recoil detection threshold of 10 eV or less. Out of these isotopes, plutonium-241 is by far the most promising candidate. Also, in the context of the abuse of plutonium in spent fuel for weapons production, plutonium-241 is a direct tracer of the total plutonium content. That is, any extraction of plutonium by chemical means will extract all of its isotopes, including 241, at the same rate.

To gain a more comprehensive understanding of Pu-241 as a neutrino source, it is essential to investigate neutrino emissions across different fuel storage facilities. The amount of plutonium-241 in spent nuclear fuel depends on many factors, including time since fuel discharge, fuel burnup, and the type of reactor the fuel is coming from. The approximate amount of plutonium-241 present in spent nuclear fuel from pressurized water reactors (PWR) is .15% of the total isotopic composition, while the approximate amount from boiling water reactors (BWR) is .12% of the total[2]. A 1000 kg detector is used for the following calculations.

II. DRY CASK STORAGE AT BIG ROCK POINT

Big Rock Point Nuclear Power Plant was Michigan's first nuclear power plant, located near Charlevoix. It was a boiling water reactor that operated from 1962 to 1997, with decontamination being completed in 1999. The reactor vessel was removed and transported in 2003, and the fuel was transferred to the site's independent spent fuel storage installation (ISFSI) by March of that same year.

The ISFSI at Big Rock Point consists of 7 overpacks containing 441 assemblies, and 1 overpack containing Greater-than-Class C (GTCC) waste. The overpacks rest on a 22.86 meter by 30.18 meter reinforced concrete pad with double perimeter fencing[3].

The storage at Big Rock Point contains a total of 57.9 metric tons of heavy metal (MTHM) from a BWR source[4], resulting in the site approximately holding 69.48 kg of plutonium-241.

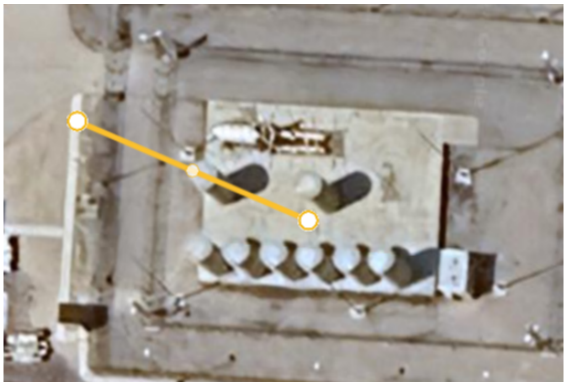

FIG. 2. Detector placed outside outer perimeter fence to center of storage.

Not accounting for any height difference between the detector and storage casks, there is a distance of 31.64 meters between the detector and the center of the storage on the concrete pad. The total amount of signals per year is 1.848 for 0 eV, 9.583 E-5 for 1 eV, 3.559 E-8 for 10 eV, and 5.772 E-9 for 100 eV.

III. WET STORAGE AT CLAB

The Clab is an interim waste repository for spent nuclear fuel from all Swedish nuclear power plants. The facility is located near the Oskarshamn Nuclear Power Plant, and it has been in operation since 1985. Buildings on the surface contain offices and control rooms, while the underground portion of the facility contains multiple water pools.

The underground portions consists of 8 sections of cooling pools, with each pool roughly able to hold a 14-by-14 grid of storage canisters. Each canister is approximately 5 meters tall, and .825 meters in length and width. These canisters are then covered by 3 to 8 meters of water[5].

The cooling pools at Clab contain a total of 6,600 MTHM. Of this amount, 4,700 MTHM are from BWR sources, 1,500 MTHM are from PWR sources, and the remainder is miscellaneous MTHM[6]. Plutonium-241 constitutes approximately 0.12% of the composition for BWR MTHM, 0.15% for PWR MTHM, and 0.135% for miscellaneous MTHM. Dividing the total amount equally among the 8 pool sections, each pool will contain 705 kg of plutonium-241 from BWR MTHM, 281.25 kg from PWR MTHM, and 67.5 kg from miscellaneous MTHM.

If a detector is suspended 1.77 meters (average human height) above the storage canisters, there is an approximate distance of 4.77 meters between the center of the detector and the center of the storage. The total amount of signals per year with that distance is 1233 for 0 eV, 0.06395 for 1 eV, 2.375 E-5 for 10 eV, and 3.851 E-6 for 100 eV.

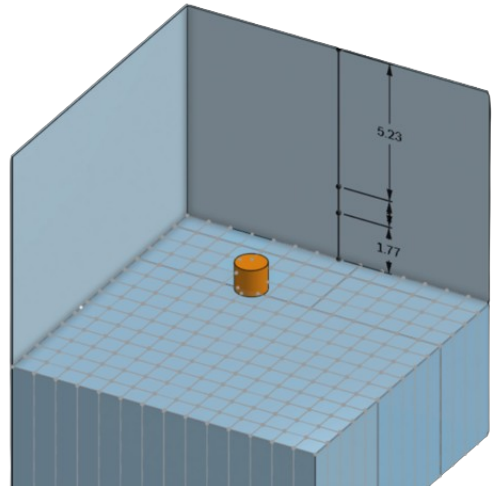

FIG. 3. Detector suspended above center of storage. Measurements are in meters.

IV. GEOLOGICAL REPOSITORY AT YUCCA MOUNTAIN

The Yucca Mountain Nuclear Waste Repository is a proposed spent nuclear fuel and radioactive waste geological storage facility located within Yucca Mountain. The purpose of the site was to comply with the Nuclear Waste Policy Act of 1982, which established a national program for the safe and permanent disposal of high-level waste. Construction began in the 1990s, but the project has faced many setbacks due to ongoing litigation, regional opposition, technical and safety concerns, and funding. No significant progress has been made on the project since 2009. As of today, there exists a five-mile exploratory tunnel with connected test facilities within the mountain for site characterization activities.

The proposed design of the Yucca Mountain Repository features a nuclear waste repository approximately 300 meters below the crest line of the mountain, with a level of water another 300 meters below the repository[7]. Ventilation shafts span from the storage to the crest line of the mountain, and two portals on the surface connect with access ramps that lead down into the repository. The South Portal and its access ramp are inline with an edge of the repository, and the North Portal and its access ramp are approximately 304.8 meters within the repository from the parallel edge. The repository itself is approximately 1207 meters long and 603.5 meters wide[8].

Assuming a 5-degree incline, the two access ramps leading from the portal entrances at the mountain crest to a level storage area 300 meters below the crest would each measure approximately 3442 meters in length.

When evaluating the number of neutrino signals, it is assumed that the repository is able to hold 70,000 MTHM, and the amount of plutonium-241 is .14% of the total composition to account for differing years between discharge and fuel types present.

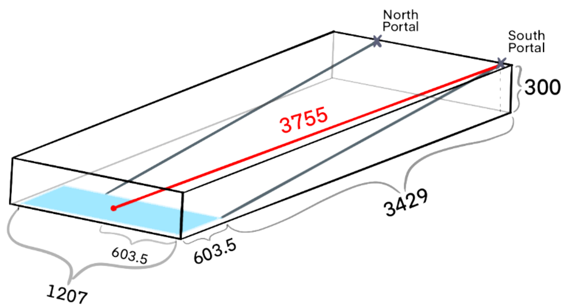

FIG. 4. South Portal detector to repository center. Measurements are in meters.

If a detector were placed at the South Portal entrance, there would be a distance of approximately 3755 meters between the detector and the center of the repository. This placement results in 0.1850 signals for 0 eV, 9.597 E-6 for 1 eV, 3.564 E-9 for 10 eV, and 5.780 E-10 for 100 eV.

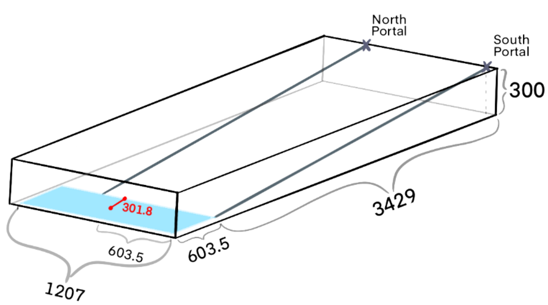

FIG. 5. Repository edge detector to repository center. Measurements are in meters.

If a detector were placed halfway along the repository wall closest to the access ramps, there would be a distance of approximately 301.8 meters between the detector and the center of the repository. This placement results in 28.64 neutrino signals for 0 eV, 0.001486 for 1 eV, 5.517 E-7 for 10 eV, and 8.948 E-8 for 100 eV.

V. REFLECTION

In conclusion, it is evident that a detector would need to be very close to the neutrino source, and it would need the lowest possible threshold of 1 eV or better to obtain ideal emissions. Only spent fuel ponds have enough inventory combined with a close enough standoff to yield usable rates. Ton-scale detectors would work with those caveats. Background radiation was not factored into these calculations, but spent fuel ponds, especially the underground Clab facility, likely provide reasonable shielding. Currently, no technology exists that can provide detectors of the required scale with the necessary very low recoil energy threshold. Once such a technology becomes available, more detailed studies of the backgrounds will be needed to assess feasibility as safeguards technology.

VI. ACKNOWLEDGEMENTS

We acknowledge support from the National Science Foundation, the Virginia Tech Physics Department and the Virginia Tech Center for Neutrino Physics. This work was made possible by the National Science Foundation under grant No. PHY-2149165. The work of PH was supported by the U.S. Department of Energy Office of Science under award number DE-SC0020262 and by the National Nuclear Security Administration Office of Defense Nuclear Nonproliferation R&D through the Consortium for Monitoring, Technology and Verification under award number DE-NA0003920.

[1] V. Brdar, P. Huber, and J. Kopp, Antineutrino monitoring of spent nuclear fuel, Phys. Rev. Applied **8**, 054050 (2017), arXiv:1606.06309 [hep-ph].

[2] B. K. Castle, S. A. Hoiland, R. A. Rankin, and J. W. Sterbentz, Plutonium discharge rates and spent nuclear fuel inventory ... (2012).

[3] P. Couture, Isfsi decommissioning funding plans (10 cfr 72.30) (2021).

[4] R. H. Jones, Dry storage cask inventory assessment (2016).

[5] SKB, Swedish nuclear fuel and waste management (2010).

[6] G. Rothwell, Spent nuclear fuel storage: What are the relationships between size and cost of the alternatives?, Energy Policy **150**, https://doi.org/10.1016/j.enpol.2020.112126 (2021).

[7] J. Birkholzer, S. Webb, N. Halecky, P. Peterson, and G. Bodvarsson, Evaluating the moisture conditions in the fractured rock at yucca mountain, Vadose Zone Journal - VADOSE ZONE J **5** (2006).

[8] C. Rivero and J. McManus, *Wanted: Secure Storage for Dangerous Waste* (1999).