Monitoring of spent nuclear fuel with antineutrino detectors

Vedran Brdar
PRISMA Cluster of Excellence & Mainz Institute for Theoretical Physics, Johannes Gutenberg University, Staudingerweg 7, 55099 Mainz, Germany
E-mail: vbrdar@uni-mainz.de

Abstract. We put forward the possibility of employing antineutrino detectors in order to control the amounts of spent nuclear fuel in repositories or, alternatively, to precisely localize the underground sources of nuclear material. For instance, we discuss the applicability in determining a possible leakage of stored nuclear material which would aid in preventing environmental problems. The long-term storage facilities are also addressed.

1. Introduction
A significant amount of nuclear waste has been produced in the 20th century. Moreover, having in mind many new reactors being built nowadays, the question of monitoring spent nuclear fuel is very relevant. We present the novel approach to monitor spent nuclear material by using antineutrino detectors. This concept is very closely related to the proposed monitoring of nuclear reactors [1, 2, 3, 4, 5, 6, 7], an idea which already found its application [8, 9]. Our benchmark scenarios are the Surry Nuclear Power Station (USA) as a representative case for a dry storage repository and Hanford site where the significant portion of USA’s nuclear material is stored in underground tanks. We also briefly address Yucca mountain which was proposed as a long-term nuclear waste storage facility.

2. Several examples for monitoring spent nuclear fuel
Spent nuclear fuel is transported to the storage facilities only after spending up to 10 years in specialized pools [10, 11]. On such timescales, there is only a few isotopes which contribute to the neutrino flux. The most important contribution arises from strontium-90, a radioactive element which undergoes a two stage decay. The spectrum of electron antineutrinos is shown in the left panel of fig. 1. We present the spectrum for several values of time measured with respect to the time after discharge from a reactor. The method for detecting electron antineutrinos is inverse beta decay [12] with an energy threshold $\sim$ 1.8 MeV. In this section, we present several benchmark scenarios for monitoring nuclear material [13].

2.1. Dry cask storage facilities
As a realistic example of a dry storage facility we consider Surry Nuclear Power Station with a layout shown in the right panel of fig. 1. The repository consists of both vertical and horizontal storage casks, each holding between 9 and 16 MTU (metric tons of uranium). We study one
particular scenario where the spent fuel content in two of the casks (labeled in red in fig. 1)) is only 50\% of what is expected.

The time after discharge from a reactor for all casks is assumed to be 10 years and the duration of the measurement is 1 year. The background events considered in our analysis are coming from a nearby nuclear reactor. Note that we ignore the backgrounds coming from the cosmic rays and the radioactive decays. Those are several orders of magnitude larger than the antineutrino signal and a new generation of antineutrino detectors is necessary for a successful suppression. In order to assess the sensitivity of a neutrino detector with respect to the particular case of a diversion that we study, we employ the following test statistics

\[ \chi^2 \equiv 2 \sum_i \left\{ F_i - M_i + (M_i + B_i) \log \left[ \frac{M_i + B_i}{F_i + B_i} \right] \right\}, \]  

(1)

where \( B_i \) is the number of background events in \( i \)-th bin (bin width equals 0.2 MeV), \( F_i \) and \( M_i \) are signal events assuming all casks full and 2 casks half full (with all others full), respectively. The 90\% CL curves indicating the range of detector positions viable for a discovery are shown in the right panel of fig. 1) for several values of exposure.

2.2. Hanford site
At the Hanford site, there is a constant environmental risk stemming from leaking tanks of nuclear waste [14, 15]. To test whether the leakage can be established with antineutrino detectors we find it necessary to employ directionally sensitive detectors which are still under discussion [16]. We focus on one particular tank farm at Hanford (T farm) that consists of 16 tanks containing up to 5 MTU each. Let us assume that a certain fraction of spent fuel in the most massive tank leaks and shifts by 20 meters in the vertical direction. We estimate that by placing a 20t detector 30 meters away from that tank, leakage of 55\% of the nuclear material can be established at 90\% CL. This statement, of course, becomes more optimistic for a larger fiducial mass of the detector. For instance, having an 80t detector leads to detection when only 25\% of the cask's content leaks. In Hanford, we assume the positions of the tanks to be very well known. We have also explored a related scenario where both positions and masses of the tanks are unknown. In this case, more than a single detector is necessary. We use a stochastic optimization method in order to project all the unknowns. For more details see Ref. [13].

2.3. Long-term storage facilities
Given the rapid increase of the total amount of nuclear waste that needs to be stored and monitored, a necessity for a long-term storage facility arises. One of the proposed repositories is at Yucca mountain (Nevada, USA). It was projected that this repository could hold up to 70000 MTU stored \( \sim 300 \) meters below the surface. Employing a kiloton detector at the surface, \( \mathcal{O}(10^4) \) events per year are expected (see Ref. [13]). However, our statistical analysis shows that a fairly large, unrealistic, leakage in the vast majority of the tanks would be necessary in order to have a discovery.

3. Conclusion
We calculated the antineutrino flux from spent nuclear fuel and investigated the possibility of monitoring it with antineutrino detectors for several cases: dry cask storage facilities, facilities with underground radioactive sources (such as Hanford site), and long-term repositories. For the case of dry cask storage facilities, the current detector technology requires improvement toward suppressing backgrounds, whereas for the other considered scenarios detectors with angular sensitivity are necessary.
Figure 1. (a) The spectrum of electron antineutrinos from spent nuclear fuel shown for several times after discharge. (b) Layout of the dry storage facility at the Surry Nuclear Power station. The casks assumed to be half full in our study are labeled in red.

References
[1] L. A. Mikaelian, *Neutrino laboratory in the atomic plant*, in Proc. Int. Conference Neutrino-77, pp. 383–387, 1978.
[2] A. Bernstein, Y.-f. Wang, G. Gratta, and T. West, *Nuclear reactor safeguards and monitoring with antineutrino detectors*, J. Appl. Phys. 91 (2002) 4672, [nucl-ex/0108001].
[3] M. M. Nieto, A. C. Hayes, C. M. Teeter, W. B. Wilson, and W. D. Stanbro, *Detection of anti-neutrinos for nonproliferation*, nucl-th/0509018.
[4] P. Huber and T. Schwetz, *Precision spectroscopy with reactor anti-neutrinos*, Phys. Rev. D70 (2004) 053011, [hep-ph/0407026].
[5] A. Bernstein, G. Baldwin, B. Boyer, M. Goodman, J. Learned, J. Lund, D. Reyna, and R. Svoboda, *Nuclear security applications of antineutrino detectors: Current capabilities and future prospects*, Science & Global Security 18 (2010), no. 3 127–192. available from http://scienceandglobalsecurity.org/archive/sgs18bernstein.pdf.
[6] E. Christensen, P. Huber, and P. Jaffke, *Antineutrino reactor safeguards - a case study*, arXiv:1312.1959.
[7] E. Christensen, P. Huber, P. Jaffke and T. E. Shea, Phys. Rev. Lett. 113 (2014) no.4, 042503 doi:10.1103/PhysRevLett.113.042503 [arXiv:1403.7065 [physics.ins-det]].
[8] Y. Klimov, V. Kopeikin, L. Mikalyan, K. Ozerov, and V. Sinev, *Neutrino method remote measurement of reactor power and power output*, Atomic Energy 76 (1994) 123–127.
[9] N. Bowden, A. Bernstein, M. Allen, J. Brennan, M. Cunningham, et al., *Experimental results from an antineutrino detector for cooperative monitoring of nuclear reactors*, Nucl.Instrum.Meth. A572 (2007) 985–998, [physics/0612152].
[10] R. Alvarez, *Spent Nuclear Fuel Pools in the U.S.: Reducing the Deadly Risks of Storage*, tech. rep., Institute for Policy Studies, 2011. available from http://www.rational.org/radiation/NuclearExtinction/SspentNuclearFuelPoolsInUS.pdf.
[11] U. S. N. R. Commission, “Spent fuel storage in pools and dry casks: Key points and questions & answers.” http://www.nrc.gov/waste/spent-fuel-storage/faqsp.html.
[12] P. Vogel and J. F. Beacom, *The angular distribution of the neutron inverse beta decay, \( \bar{\nu}_e + p \rightarrow e^+ + n \)*, Phys. Rev. D60 (1999) 053003, [hep-ph/9903554].
[13] V. Brdar, P. Huber and J. Kopp, [hep-ph/1606.06309].
[14] M. Fuller, *Initial single-shell tank system performance assessment for the hanford site*, Tech. Rep. DOE/ORP-2005-01, Rev. 0, United States Nuclear Regulatory Commission, 2005. available from http://pbadupws.nrc.gov/docs/ML0622/ML062230233.html.
[15] M. L. Rockhold, D. H. Bacon, V. L. Freedman, M. J. Lindber, and R. Clayton, *Numerical modeling of \(^{90}\)Sr and \(^{137}\)Cs transport from a spill in the b-cell of the 324 building, hanford site 300 area*, Tech. Rep. PNNL-21214, Pacific Northwest National Laboratory, 2012.
[16] B. R. Safdi and B. Suerfu, *Directional Antineutrino Detection*, Phys. Rev. Lett. 114 (2015), no. 7 071802, [arXiv:1410.8530].

Neutrino2016  
IOP Conf. Series: Journal of Physics: Conf. Series 888 (2017) 012091  doi:10.1088/1742-6596/888/1/012091