Non-Proliferation and Reactor Monitoring

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Abstract.
Neutrinos are the most elusive particles in the standard model particle physics and their oscillation phenomena is a key to understand the nature of the neutrinos. On the other hand, the neutrinos are second most abundant particles in the universe and the nuclear reactors are the intense source of artificial anti-neutrinos. We will overview the status of the projects trying to monitor or safeguard the nuclear reactors by detecting the reactor neutrinos.

1. Introduction
Reactor antineutrino detection can monitor two things; reactor power and fissile content of the reactors. Such monitoring may be useful for the IAEA’s reactor safeguards and non-proliferation since IAEA can’t directly measure fuel contents while fuel is loaded. Historically, the concept of reactor monitoring with neutrinos is originated by Mikaelian et al. from 1990’s in Russia [8]. The correlation of the antineutrino signal with the thermal power and the burn-up was demonstrated by the Bugey and Rovno experiments. Then in 2000’s, Bernstein et al. have installed and operated a prototype detector at the 3.46 GW thermal power San Onofre Nuclear Generating Station (SONGS) in Southern California. With the reactor neutrino anomaly in 2010s, dozens of proposals for short baseline neutrino experiments are proposed. Many of these experiments can work for reactor monitoring too. In future, a large, heavier than kton detector can be used to identify unknown reactor activity.

2. Reactor Neutrino Spectra
The theoretical models to calculate the flux and energy spectra of reactor neutrinos were continually developed by Davis, Vogel, Huber, Mueller et al., [1, 2, 5, 4], by combining the theories and experimental measurements from the beta decay of irradiated foils of four isotopes. The most recent model is the Huber+Mueller (H+M) model, which gave parameterization for the energy spectra in a 6th order polynomial form for each isotope.

Figure 1 shows a comparison of the neutrino flux of the four isotopes normalized per fission drawn with the H+M model. The reactor neutrinos were detected through the capture process by the protons, which produces a positron and a neutron. The cross-section of this process has been extensively studied by Vogel [2], and the uncertainty of the cross-section is known to be below 1%.

Figure 2 shows the number of neutrino absorption events with the proton target as a function of energy for the two different burn-up stages, initial and 500 days. The calculation is done for a 1 GW reactor for each isotope with the initial isotopic configuration for 4% enriched fuel. The $^{235}\text{U}$ isotope contributes most to the neutrino events. The y-axis shows a value for the total neutrino flux from 1 GW reactor multiplied by the total cross-section at the energy.
3. Experiments for reactor monitoring and safeguards
In the USA, an experiment at San Onofre Nuclear Generating Station (SONGS) tried to detect the reactor neutrinos to monitor the reactor thermal power and possibly the fuel composition. As in Figure 2, the neutrino spectra from the four different isotopes are slightly different, therefore in principle it is possible to measure the fractions of the isotopes by precisely measuring the energy spectra from the reactors. The SONGS experiment measured the total number of neutrinos as a function of elapsed time after the replacement of the fuels. It observed a reduction of approximately 10\% in the neutrino event rates in a period of about 500 days, even though the thermal power from the reactor was constant for that period [6, 7]. With the rate only, the amount of $^{239}$Pu being produced or removed from a reactor could be constrained to the 100 kg level [7]. If the new detectors at short baseline can measure the energy spectrum precisely, the sensitive amount of $^{239}$Pu will be reduced.

Figure 1. Number of neutrinos for each isotope in the nuclear reactor. The graphs are produced from the parameterization by Huber [5] and Mueller [4].

Figure 2. Number of events of the inverse beta decay of reactor neutrinos for each isotope. The y axis shows the total neutrino flux from a 1-GW reactor multiplied by the total cross section at the energy. The calculation is done with the initial (left) and 500 days of burn-up (right) isotopic configuration for 4\% enriched fuel.
In 2008, a workshop was held by the IAEA on antineutrino detection for safeguards applications. The workshop concluded that the antineutrino detectors have unique abilities to non-intrusively monitor reactor operational status, power and fissile content in real-time, from outside of the containment [6]. It also recommended IAEA to consider antineutrino detection and monitoring in its current R&D program for safeguarding bulk-process reactors. The optimized neutrino detector for reactor monitoring and safeguards should be in relatively compact size and preferably movable. Many proposals to achieve the goal have been made and prototype detectors have been tested as described in a later section.

Table 1 summarizes the specifications for the ongoing or future projects for reactor monitoring. Due to the high backgrounds from the cosmic neutrons, the reduction of the backgrounds is critical. High granularity and particle discrimination techniques in addition to larger overburden should be fully used to make the signal to background ratio larger. Currently, the signal to background ratios are reported as 0.25 for Nucifer [9], 0.2 for Vidarr, 0.25-0.3 for Neutrino-4 [10], about 20 for DANSS [11], and 23 for NEOS [12].

3.1. Nucifer
The Nucifer detector is deployed at 7.2 m away from the compact Osiris research reactor core (70 MW) operating at the Saclay research center. It is at a shallow depth equivalent to 12 m of water and under intense background radiation conditions. The detector volume is 850L of Gd loaded liquid scintillator with 16 8-inch PMTs at one end of the cylinder. Based on 145 (106) days of data with the reactor on (off), leading to the detection of an estimated 40760 $\bar{\nu}_e$, the mean number of detected antineutrinos is $281 \pm 7$ (stat) $\pm 18$ (sys) $\bar{\nu}_e$/day, in agreement with the prediction of $277 \pm 23 \bar{\nu}_e$/day. This is about 7% error and the sensitivity limit is reached for about 1.5 kg of $^{239}$Pu, a mass representing 10% of the total fissile mass, which can be identified with 95% confidence in the same data-taking period. [9].
3.2. Solid
The Solid detector will be located on-axis starting at 5.5 m distance from the core of the SCK-CEN BR2 reactor (60-100MW) in Mol, Belgium. The SoLid detector is a segmented detector (2.88t) divided in 10 modules (1.2m x 1.2m x 0.2m). Each module consists of 4 planes of 576 plastic scintillation PolyVinylToluene (PVT) cubes of 5\(\times\)5\(\times\)5cm\(^3\), each cube being covered with one layer highly sensitive to thermal neutrons (\(^6\)LiF:ZnS(Ag)) [13]. A prototype detector has been successfully run and a background rejection technique has been developed. In Phase I period (2017-2019), 1.6 ton fiducial mass will be installed at 5.7 m from the core.

3.3. NuLat
One promising design is the NuLat (short for Neutrino Lattice) detector [14]. It is composed of a 15\(\times\)15\(\times\)15 cubic array of 3375 individual cubes of \(^6\)Li-doped plastic scintillator, 6.4 cm on a side. These cubes are stacked and separated by about 0.3 mm air gap between them and there is no wrapping material for the cubes. The scintillation lights are propagated by the total internal reflection through the cubes along the three axis, and also scattered to off-axis direction. In this way, the event is localized in a cube without any energy loss in the wrapping materials. Two 511 keV gammas of the prompt signal will be measured by the neighboring cubes. All six surfaces of the array will be viewed by a 2-inch PMT, and then the total number of PMTs is 1350. The NuLat detector is ideal since there is no energy loss, there is no light loss in principle, and it has sufficient segmentation to reduce the backgrounds. The plastic scintillator also has a good PSD capability to further reduce the backgrounds from fast neutrons. The group should demonstrate that the energy resolution is better than 5% at 1MeV energy with a sufficiently big array, which requires fine machining. Though this configuration is optimized to reduce the background, the energy resolution will be worse than the homogeneous multi-layer Gd-LS target detector.

3.4. NEOS
NEOS (Neutrino Experiment for Oscillation at Short baseline) experiment is mainly for a light sterile neutrino search at a distance of 24 m from a commercial reactor core. The NEOS detector was installed in the tendon gallery of reactor unit 5 of the Hanbit Nuclear Power Complex in Korea, where the RENO experiment is running. The active core size of unit 5 is 3.1 m in diameter, 3.8 m in height. The tendon gallery is located 10 m below ground level and is directly under the wall of the containment building. The minimum overburden with the ground and building structures corresponds to twenty meter water equivalent. The NEOS detector consists of a neutrino target, mineral oil buffers, passive shieldings, and muon counters. The target is a stainless-steel tank with a 1008 liter filled with a 0.5% Gd- doped liquid scintillator. Each end of the target vessel is viewed by nineteen 8-inch photomultiplier tubes (PMTs) that are closely packed in mineral oil buffers. The target tank is enclosed by a 10 cm-thick borated polyethylene and lead layers.

The detector operated for 46 days with the reactor off and 180 days with the reactor on, and the neutrino rates were 81 for reactor off and 1972 for reactor on period, which resulted in signal/background ratio 24. In Figure 3, the ratio spectra, data divided by the Huber-Mueller prediction is shown and 5MeV excess is clearly visible. Also the six month data shows the burn-up effect in the energy spectrum. Due to the large signal/background ratio, the sensitivity of Plutonium removel is 20 kg in a month data with a 90 % confidence.

4. Experiments for non-proliferation, remote sensing
There has been efforts to identify unknown nuclear activity remotely by neutrino detection. NUDAR (NeUtrino Direction and Ranging) points that measurement of the observed energy
Figure 3. The ratio between the NEOS data and prediction by H-M model. 5MeV excess is clearly seen for the first time in shot baseline reactor experiment.

spectrum can be employed to locate a neutrino source from even a single detector thanks to unique energy-dependent character of neutrino oscillations and can be improved still further by the use of multiple detectors [15, 16, 17].

The Water Cherenkov Monitor for Antineutrinos (WATCHMAN) is designed to satisfy a US Nonproliferation initiative and was proposed as a demonstration of remote reactor monitoring for future nonproliferation and cooperative monitoring agreements. The WATCHMAN baseline deployment is a kiloton scale gadolinium-doped water Cherenkov antineutrino detector deployed 10-20 km from a US or UK reactor. It is also a large-scale test-bed for study of Gd-H2O, water-based liquid scintillator, fast PMTs, and other technologies and methods useful for future particle astrophysics detectors [18].

5. Towards more precise reactor neutrino spectra
Since the energy resolution of the liquid scintillator is limited by the photoelectron statistics for most of the detectors constructed up to the present, we can improve the energy resolution by increasing the coverage of the PMT photocathodes. Indeed, the recently proposed JUNO experiment aims to measure the reactor neutrinos with an energy resolution of about 3% in standard deviation by increasing the number of PMTs to 18000 [19]. To measure the neutrino energy spectrum more precisely, a small detector located within a few tens of meters can obtain the spectra with similar or better energy resolution. The photoelectron statistics can be improved to more than 1000 photoelectrons per MeV, and we can make the energy resolution about 3%. The gamma catcher can be also adopted in the design. The attenuation length of 511 keV gammas is about 10 cm in the liquid scintillator, and the neutron capture length in liquid scintillator is about 9cm on average. Therefore the inverse beta decay events occurring at the Gamma Catcher can be misidentified as IBD events occurring at the target scintillator if the neutrons are captured by the Gadolinium isotopes in the target Gd-LS. We call these events spill-in. If the Gamma Catcher is not thick enough, these spill-in events will have some leakage of the two 511 keV gammas, and deteriorate the energy resolution of the whole IBD events. Therefore the thickness of the Gamma Catcher should be much larger than the attenuation length of 511 keV gammas.

The thickness of the Gamma Catcher could be 40 cm and the diameter of the target liquid scintillator can be 100 cm (450kg). The mineral oil layer is 40 cm thick and the PMTs are immersed in the mineral oil. For shielding, 10 cm lead will surround the liquids. Then the total size would be approximately 300 cm. To avoid the spill-in contribution, it could help to use the Boron loaded liquid scintillator (5% natural Boron) in the Gamma Catcher layer and mineral
oil layer. Then the neutrons from the IBD events occurring in the outer part of the Gamma Catcher will be mostly absorbed in $^{10}\text{B}$ and cannot satisfy the requirements for the delayed neutron capture signal. Therefore the spill-in events will not lose the 511 keV gammas and the energy resolution will be improved. The two 511 keV gammas of the IBD events occurring at the target will be detected, and the energy reconstruction of the prompt energy will be close to perfect with the 40 cm thick Gamma Catcher. Here one should be careful to make the scintillation efficiency of Gd-LS (Target) and Boron loaded LS (Gamma Catcher) the same for good energy resolution.

In this optimized reactor neutrino detector, PMTs will cover almost all of the surface area, and the coverage would be approximately 75% with 80 8-inch PMTs for the above configuration. Then we expect approximately 1500 photoelectrons per MeV with 2.5% energy resolution for 1 MeV signal, and this will greatly improve our current understanding on the neutrino spectrum from reactors.

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