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Monitoring Akkuyu nuclear reactor using antineutrino flux measurement

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Abstract: We present a simulation-based study for monitoring Akkuyu nuclear power plant's activity using antineutrino flux originating from the reactor core. A gadolinium-doped water Cherenkov detector was designed and optimization studies were performed using the Geant4 simulation toolkit. It was found that the bottom (or top) face of the target should be instrumented by six 10-inch-diameter photomultiplier tubes with photon detection efficiency of about 35% and the optimum Gd concentration was found to be about 0.3%–0.5%. The first study on the design of a monitoring detector facility for Akkuyu nuclear power plant is discussed in this paper.

Key words: Nuclear reactor, neutrino, Cherenkov, detector, simulation

1. Introduction

The first nuclear power plant in Turkey will be constructed at Akkuyu, in Mersin Province. It is planned to start operating in 2023. Akkuyu nuclear power plant (NPP) will have 4 power units and each unit will have the capacity of 1.2 GW. Enriched uranium dioxides (^{235}U) will be used as fuel.

Since the thermal power produced in the fission process is directly related to emitted antineutrino flux, measuring the latter can provide quasi real-time information on the former. The relation between the neutrino event rate at the detector (N_ν) and reactor thermal power (P_{th}) can be expressed by $N_\nu = \gamma(1+k)P_{th}$, where γ is a constant that depends on the detector (target mass, detection efficiency, etc.) and k is the time dependent factor, which takes into account the time evolution of the fuel composition [1]. This property makes a compact antineutrino detector a powerful tool for monitoring a nuclear reactor.

Nuclear reactors are an intense source of antineutrinos. Each fission process releases around 200 MeV energy, 6 $\bar{\nu}_e$, and neutrons. Emitted antineutrino flux by a 1.2 GW nuclear reactor is about $2 \times 10^{20} \bar{\nu}_e/s$. Predicted emitted neutrino spectra for different nuclear fuels are shown in Figure 1. The spectra for ^{235}U, ^{239}Pu and ^{241}Pu isotopes were converted from ILL electron data [2] and the ^{233}U antineutrino spectra were taken from an ab initio calculation [3].

The neutrino interaction rate can be estimated approximately using [4]

$$R_\nu = \frac{N_f N_p \langle\sigma\rangle}{4\pi L^2}, \tag{1}$$

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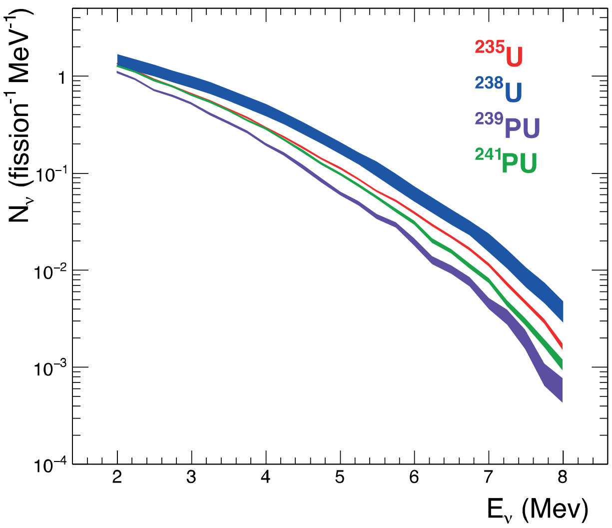

Figure 1. Predicted antineutrino spectra with their relative errors versus neutrino energy.

where N_p is the number of protons in the target medium, L is the distance between reactor core and detector, and N_f is the average fission rate given by the equation

$$N_f = 6.24 \times 10^{18} \left(\frac{P_{th}}{MW}\right)\left(\frac{MeV}{W_e}\right) s^{-1}, \tag{2}$$

where $W_e = 203.78$ MeV is average energy release per fission and $\sigma = 5.82 \times 10^{-43}\, cm^2$ is the average cross section. For a water target and 1.2 GW reactor thermal power, Eq. (1) can be rewritten as

$$R_\nu = 9.86 \times 10^5 \left(\frac{V}{m^3}\right)\left(\frac{m^2}{L^2}\right) events/day \tag{3}$$

Considering $L =$ 30 m and $V = 0.96\ m^3$, we expect around 1050 events in a day with a detector near Akkuyu NPP.

This figure can be compared to the rough estimation recommended in the IAEA Workshop on Antineutrino Detection for Safeguards Applications report [5], given as

$$\#events/day = 730 \times MW_{th} \times \frac{V}{L^2} \times \varepsilon, \tag{4}$$

where ε is the detection efficiency. At ε =1 the two formulae give very close answers: 1050 from the former and 934 from the latter.

Background estimations can be made with rather simple methods. Since the amount of solar neutrino flux on Earth is found to be about $7 \cdot 10^{10}$ particles/cm^2/s from the BP00 solar neutrino model [6], even assuming that all these neutrinos have sufficient energy for inverse beta decay (which is a huge overestimation) the expected total number of events is about 0.02 per day, negligible compared to the expected signal events. Since cosmic neutrino flux is even lower than solar flux, the background events from this source are not considered. For the actual measurement we propose a full experimentalist's approach: firstly, construct the detector before the nuclear reactor and collect background neutrino data. Secondly collect data while the nuclear reactor is running and finally compare the two, to estimate the thermal power of the reactor. We foresee that the total background levels (including those from detector issues) will be lower than the statistical uncertainty of daily measurements performed with our proposed detector.

2. Detector design

An antineutrino can be detected by charged-current antineutrino-proton scattering, also known as inverse beta decay (IBD): $\bar{\upsilon}_e + p \rightarrow e^+ + n$. The positron generates the prompt signal and subsequently the thermal neutron capture process will give a second delayed signal. This delayed coincidence of the two signals in the time window of 20–80 μs is commonly used as trigger for antineutrino detection.

For the monitoring of Akkuyu nuclear reactor, we propose a relatively cheap neutrino detector composed of compact and transportable units. Each unit is planned to be composed of a gadolinium (Gd)-doped water Cherenkov detector that can be used for antineutrino detection. A schematic view of such a unit is shown in Figure 2. Each detector unit should be divided into two physical regions. The inner region of the detector is planned to be of cubic form with dimensions 80 × 100 × 120 cm, containing about 1 t of Gd-doped water. Gd has the highest thermal neutron capture cross section, very suitable for such a detector. Therefore, the Gd-doped water will play the role of the target for the charged-current antineutrino-proton scattering. Several layers could cover the outer region of the detector unit. The first layer is made of about 3-cm-thick plastic scintillator panels to veto cosmic charged particles. The following layers are planned as passive shielding to suppress neutron and cosmic background. The design and material decision for passive shielding is under study. A large number of such units could be assembled and operated to increase the detection, thus monitoring efficiency of the overall system.

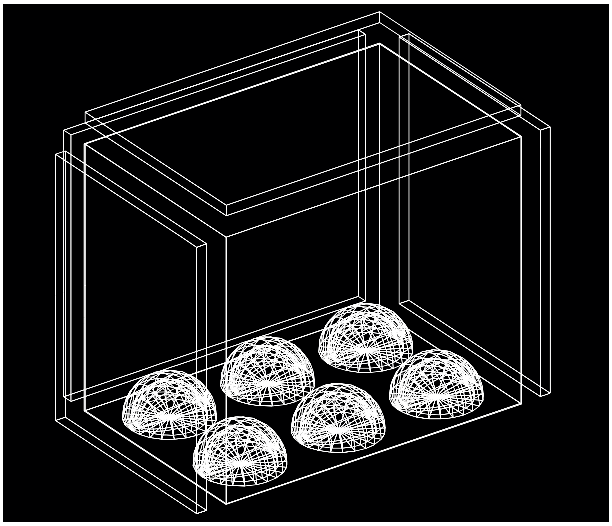

Figure 2. A monitoring unit proposed for Akkuyu nuclear power plant. The hemispheres represent the 10-inch photomultipliers; the rectangles stand for veto scintillators.

The bottom (or top) face of the target is instrumented by six 10-inch-diameter photomultiplier tubes (PMTs) [Hamamatsu Photonics K. K., http://www.hamamatsu.com]. The photon detection efficiency of this PMT positioning configuration is found to be about 35% using GEANT4 simulations [7]. Figure 3 shows photon acceptance efficiency, which is defined as the ratio between total number of photons hitting the surface of the PMTs to the total number of photons produced in target medium, for different PMT positioning configurations. Up to six PMTs are placed on the bottom (or top) face of the target and PMT positioning configurations are considered like the pips on a die. When the number of PMTs is greater than six, the PMTs are placed on both the bottom and top faces symmetrically.

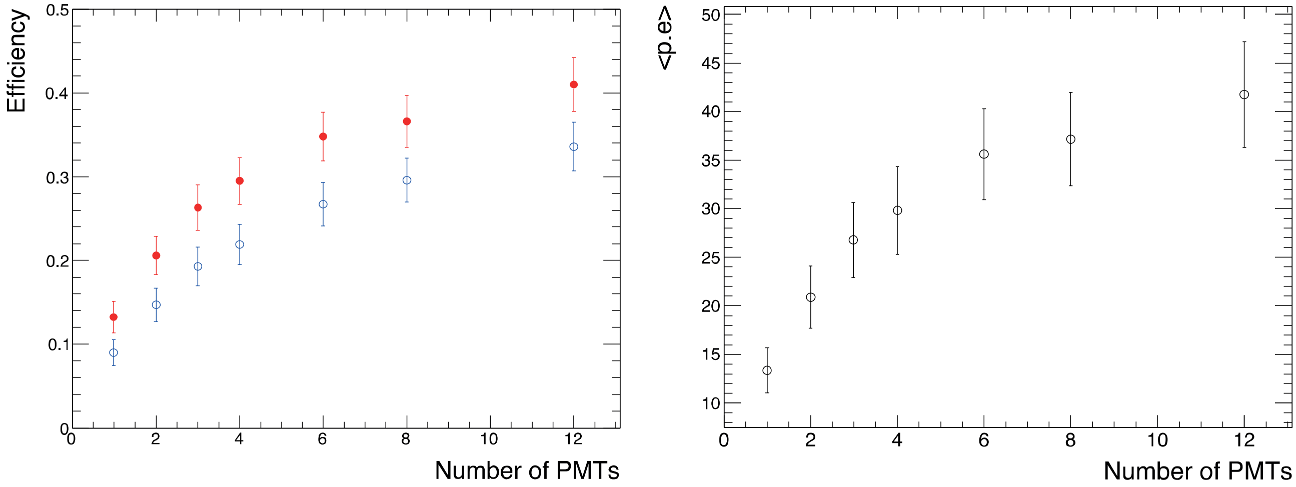

Figure 3. (Left) Photon acceptance efficiency for various PMT configurations. Open blue circles represent 8-inch-diameter PMTs, while the red solid circles are for PMTs with 10-inch-diameter. (Right) The average number of photoelectrons using the 10-inch PMTs as a function of the number of PMTs. 2 MeV positrons originating at the center of the detector have been simulated.

The Gd concentration in water directly affects the delayed second signal, which is caused by thermal neutron capture. This effect was studied using GEANT4 simulations. Figure 4 shows the time difference between the prompt and delayed signals for various Gd concentration values. The optimum Gd concentration was found to be about 0.3%–0.5%.

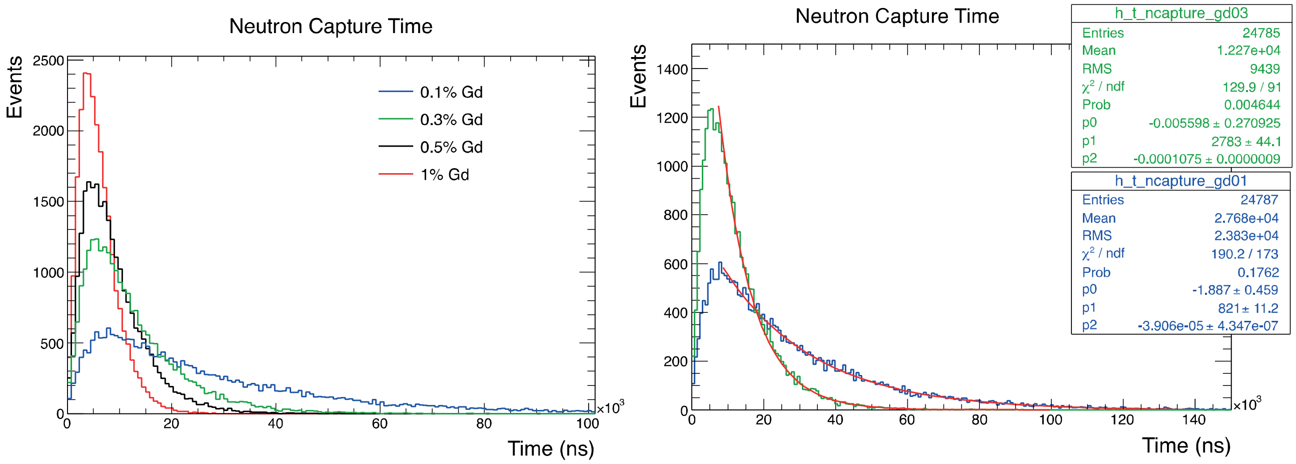

Figure 4. (Left) Time difference between prompt and delayed signals for different concentrations of Gd. (Right) The distributions of 0.1% and 0.3% Gd concentration are fitted to an exponential function.

After thermal neutron capture by Gd, a gamma cascade is emitted with average total energy of 8 MeV. Figure 5 (left) shows the total number of emitted photons after thermal neutron capture by Gd. The right panel of the same figure presents the total deposited energy in the target medium after the thermal neutron capture process. The peak around 2 MeV is produced by the thermal neutron capture from hydrogen. The peaks around 8 MeV and 8.5 MeV come from thermalization by ^{158}Gd and ^{156}Gd, respectively.

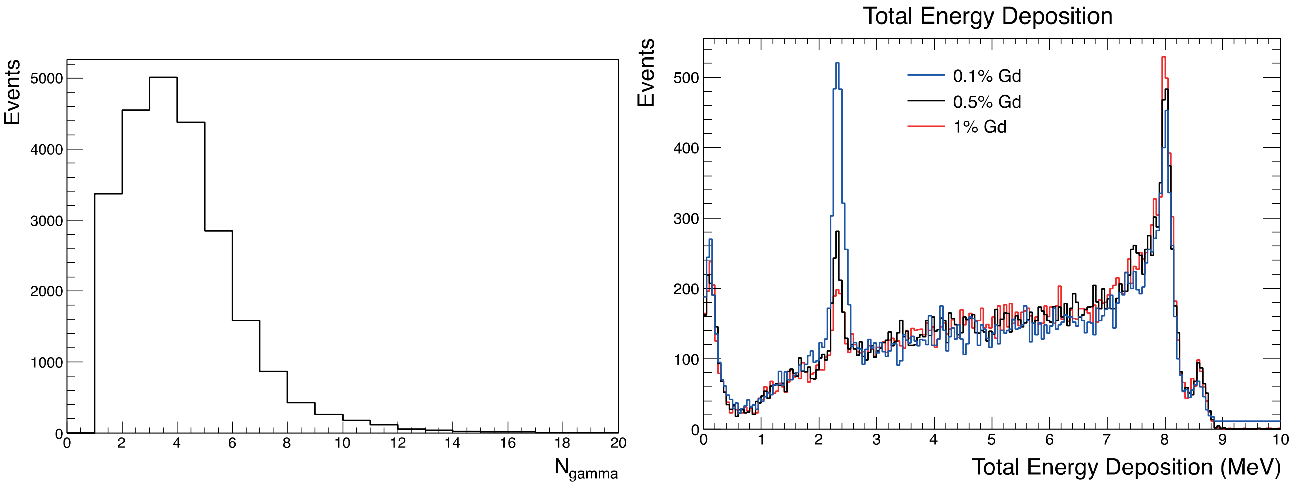

Figure 5. (Left) Total number of photons after thermal neutron capture. (Right) Total energy deposition in the medium with different Gd concentrations.

3. Readout and prototyping

The reading out of a module would require a charge analogue-to-digital counter (ADC) and a time-to-digital counter (TDC) with at least N channels, where N is the number of photomultiplier tubes, 6 for this case. Additionally the outer section's scintillators should also be readout in order to veto events originating from cosmic rays. For an 80 × 100 × 120 cm module, assuming scintillator blocks of 20 cm width and 100 and 120 cm height, an additional ADC load of 26 channels would be required. The digitizer cards and the readout computer can all be hosted in a 6U standard VMEbus crate. The single board computer would not need to run a real-time operating system; thus a Linux-based solution would be sufficient. The trigger logic can be initially set up using NIM modules, and later on can be upgraded to a faster timing and smaller footprint by using an FPGA. The data out of the VMEbus crate can be shipped off to another computer with a long-term storage device via a simple gigabit switched network.

A simple detector unit could be produced and tested with minimum effort in less than 2 years. The calibration of the detector can be easily achieved using a low energy electron or proton beam. A project has been submitted to TÜBİTAK for funding to produce a demonstration module.

4. Conclusions

In this paper, the first study on the design of a monitoring detector facility for Akkuyu NPP is outlined. Simulations with GEANT4 identified that 6 PMTs of 10-inch diameter active area would gather about 35% of photons produced in the detector. The same simulation study showed that the active volume of the detector itself could be made from 0.3%–0.5% Gd-doped water. The final design, construction, and commissioning of a monitoring unit is expected to take up to 2 years. Many such units could be combined to increase the event yield and thus the monitoring efficiency.

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