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A study of reactor neutrino monitoring at the experimental fast reactor JOYO

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ABSTRACT

We carried out a study of neutrino detection at the experimental fast reactor JOYO using a 0.76 tons gadolinium loaded liquid scintillator detector. The detector was set up on the ground level at 24.3 m from the JOYO reactor core of 140 MW thermal power. The measured neutrino event rate from reactor on–off comparison was $1.11 \pm 1.24(\text{stat.}) \pm 0.46(\text{syst.})$ events/day. Although the statistical significance of the measurement was not enough, backgrounds in such a compact detector at the ground level were studied in detail and MC simulations were found to describe the data well. A study for improvement of the detector for future such experiments is also shown.

1. Introduction

Reactor neutrinos have been playing an important role since its first discovery in 1956 [1] for the progress of elementary particle physics and to deepen our understanding of nature. Now the reactor neutrino detection techniques have become mature after a number of reactor neutrino experiments so far performed [2,3]. Research and development of compact reactor neutrino detectors utilizing the up-to-date technologies have become active recently [4] with an idea of using it as a monitor for Plutonium breeding in reactor cores [3,5] and as a very near detector to calibrate reactor neutrino flux for long baseline reactor neutrino oscillation experiments.

1.1. Reactor neutrinos

In operating reactors, ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu undergo a fission reaction after absorbing a neutron. The fission products are generally neutron-rich unstable nuclei and are subject to β-decays until they become stable nuclei. One $\overline{\nu}_e$ (anti-electron neutrino) is produced in each β-decay. The energy of the reactor neutrinos corresponds to β-decay energy of a few MeV. Approximately $6\overline{\nu}_e's$ are produced in a fission reaction along with ~ 200 MeV of energy release, resulting in $6 \times 10^{20}\overline{\nu}_e's$ production per second in a reactor with 3 GW_{th} power.

1.2. Non-destructive plutonium measurement

Main components of reactor neutrinos come from ^{235}U and ^{239}Pu fissions, and contributions of ^{238}U and ^{241}Pu are much smaller than those nuclei. Along with burn-up of the core, ^{235}U is consumed and ^{239}Pu is 'breeded' from ^{238}U through neutron absorption and β-decay. Because ^{239}Pu can be used for nuclear explosion, it is an important object of strict safeguard regulations. Therefore, it is important to monitor reactor operation and track the plutonium breeding. International Atomic Energy Agency (IAEA) watches reactors in the world with surveillance cameras, reviewing operation record, etc. Because it

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is impossible to hide the neutrinos, it could be a powerful tool to monitor the reactor operation, in addition to the traditional monitoring methods [6].

The reactor neutrino monitoring has a potential to non-destructively measure the plutonium amount in the core.

Table 1 shows the energy releases and expected number of emitted $\overline{\nu}_e$'s above 1.8 MeV per fission for major isotopes in nuclear reactors, and average ratio of fissions in the JOYO core. As shown in the Table 1, ^{235}U produces significantly more neutrinos than ^{239}Pu. Combining the neutrino flux and thermal power generation, there is a possibility to measure Plutonium amount in the core. This is simply depicted by the following equations assuming the fuel is made up only from ^{235}U and ^{239}Pu.

$$q_{235}F_{235}+q_{239}F_{239}=P_{th} \quad (1)$$

$$\nu_{235}F_{235}+\nu_{239}F_{239}=N_{\overline{\nu}_e} \quad (2)$$

where 235 and 239 represent ^{235}U and ^{239}Pu. F_x is the fission rate of the nucleus-x in the core, q_x is the energy release per fission. ν_x is the expected number of emitted $\overline{\nu}_e$'s per fission, $N_{\overline{\nu}_e}$ is the total emission rate of $\overline{\nu}_e$. A small contribution from ^{238}U and ^{241}Pu is ignored to simplify the calculation.

The fission rate of ^{239}Pu is calculated from those relations and the values of the parameters, and the ^{239}Pu amount in the core can be calculated from the fission rate.

1.3. Compact neutrino detectors

As R&D of compact neutrino detectors, an experimental program led by Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL) measured neutrino energy spectrum at a short distance from a ^{235}U-rich reactor with a thermal power of 3.4 GW$_{th}$, San Onofre Nuclear Generation Station (SONGS), and indicated feasibility of the neutrino monitoring [9]. On the other hand, further R&D studies of detector design and materials are still necessary to realize a compact detector operation above ground for practical use as a reactor monitor with the neutrino detection. Considering the neutrino interaction cross-section on proton target (inverse β-decay, $O(10^{-43})$ cm^2, see Section 3) and compact detector size, the detector must be set at a short distance (less than a few tens of meters) from the reactor core to accumulate enough statistics for monitoring. In addition, feasibility of the measurement at ground level is required for the monitor considering limited access to the reactor site, while the previous measurements of neutrinos were operated at underground to reduce cosmic-ray muon background. Therefore, the detector must be designed to be able to reduce external backgrounds, e.g. cosmic-ray muons and fast neutrons.

We constructed a 0.76-ton gadolinium loaded liquid scintillator detector as a prototype of KASKA detector [10] and we reused it to take part in such R&D efforts [11]. The detector was set up at 24.3 m from JOYO experimental reactor core which had a thermal energy of 140 MW [12]. Unique points of this experiment are: (1) the reactor power is much smaller compared with the ones so far used to measure the neutrinos, (2) the detector is located above ground, and (3) the reactor is a fast reactor, so that the neutrinos came mainly from Plutonium. The main goal of this experiment was to distinguish reactor-on and off by neutrinos under this unfavorable conditions. One of the possible safeguard applications is to monitor small reactors to prevent them from hidden operation to make plutonium. The points (1) and (2) of this experiment are useful to study such a possibility. As for (3), neutrinos from ^{235}U-rich light water reactors have been measured [13,14], while observation of neutrinos from ^{239}Pu-rich fast reactor has not been reported yet and this experiment could have been the first detection of the fast reactor neutrinos. If energy spectrum of fast reactor neutrinos is measured in the future, ν_{235} and ν_{239} can be determined separately by comparing the ^{239}Pu-rich neutrinos and ^{235}U-rich neutrinos. This experiment is a good practice to perform an experiment at a larger fast reactor in future to measure the Plutonium-rich neutrino spectrum.

Table 1
Number of $\overline{\nu}_e$ per fission with energy above 1.8 MeV [7] and energy release per fission for major isotopes in nuclear reactors [8].

Isotope	$\nu(>1.8$ MeV)	q (MeV)	Contribution at JOYO (%)
^{235}U	1.92 ± 0.02	201.7 ± 0.6	37.1
^{238}U	2.38 ± 0.02	205.0 ± 0.9	7.3
^{239}Pu	1.45 ± 0.02	210.0 ± 0.9	51.3
^{241}Pu	1.83 ± 0.02	212.4 ± 1.0	4.3

2. Experimental fast reactor JOYO

The experimental fast reactor JOYO, with a thermal power of 140 MW, is located in Japan Atomic Energy Agency (JAEA) Oarai Research and Development Center in Ibaraki prefecture, Japan. The JOYO reactor is a sodium-cooled fast reactor built as an experimental reactor to promote commercialization of fast breeder reactor development [12]. The reactor fuel is plutonium-uranium

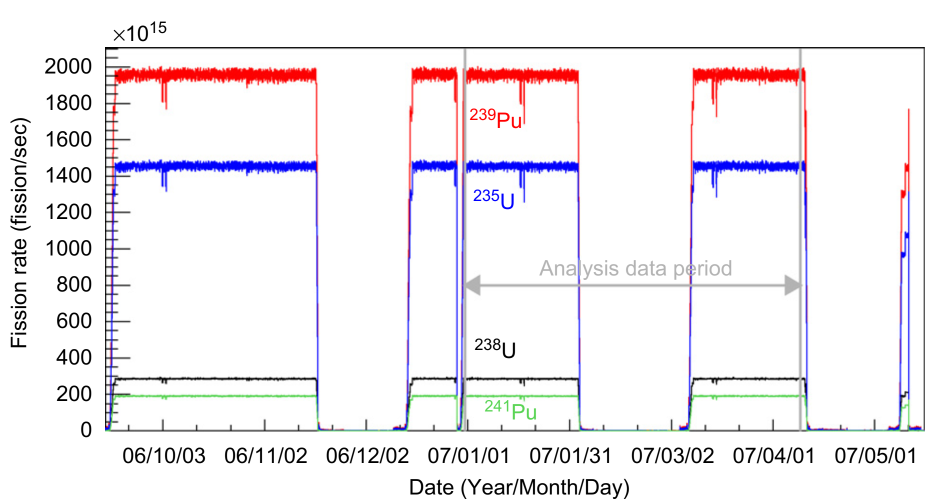

Fig. 1. Fission rate of each fissile element as a function of time from the 4th to 6th operational cycles of experimental fast reactor JOYO. Four lines correspond to ^{239}Pu, ^{235}U, ^{238}U and ^{241}Pu as indicated in the figure. A period used for data analysis is also shown.