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Status of PANDA and Japanese reactors

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Abstract. We are developing the Plastic Anti-Neutrino Detector Array (PANDA) to measure the reactor antineutrinos for the nuclear safeguard application. We completed construction of the PANDA100, which consists of 100 plastic scintillator modules, in August, 2016. After a study using background radiation in the laboratory at Kitasato University in Tokyo, we carried out a measurement of γ-ray bursts under the thunderclouds at Mt. Norikura in Gifu, Japan employing the PANDA100. As the results, we found three burst candidates in the data of 38 days. The original purpose of the PANDA project is to measure antineutrinos from a Japanese commercial reactor. We joined the Japanese reactor monitoring community arranged by University of Fukui group. In this community, we share the information about Japanese reactor activities and developement of a new monitoring tool. We are also preparing for a reactor monitoring with the PANDA100 when Japanese reactors resumed operation.

1. Introduction

The real-time monitoring of a nuclear reactor is an important issue because we must prevent diversion of fissile materials from civil nuclear fuel cycle facilities into weapons programs. International Atomic Energy Agency (IAEA) aims to establish procedures and technologies for the safeguard of nuclear reactor operation. For this purpose, they recommend the investigation of a reactor operation by the near-filed antineutrino monitoring. Because an antineutrino has high penetration power, we can perform the inspection at the outside of reactor buildings. Only reactors or accelerators can create antineutrino flux to be detected. By the measurement of rate and energy spectrum of antineutrinos, we can obtain the information of the isotopic content of the reactor fuel. From the above reasons, the detection of antineutrinos is a suitable tool for the reactor monitoring.

As a compact reactor monitoring tool, we proposed a segmented antineutrino detector, PANDA, which stands for Plastic Anti-Neutrino Detector Array [1–3]. To improve the safety characteristics, and make deployments and operations easier, its target volume was made of plastic scintillators. Fig. 1 (a) shows the structure of an individual PANDA module. It consists of

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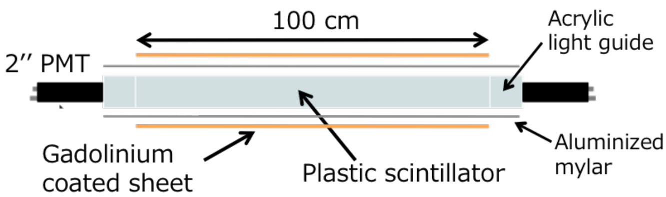
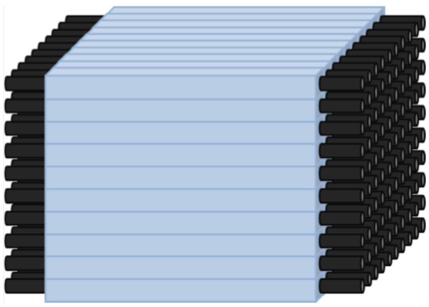
a $10 \times 10 \times 100\,\mathrm{cm}^3$ plastic scintillator bar of about 10 kg, aluminized Mylar films and gadolinium (Gd) coated Mylar films (4.9 mg of Gd per cm^2). Neutrons emitted from inverse-beta decay of protons are thermalized and captured at Gd. A total weight of one module is about 13 kg. Each plastic scintillator bar is connected to 2-inch Photo Multiplier Tubes (PMTs: Hamamatsu H6410) and acrylic light guides on both ends.

Charge from each PMT is asymmetrically divided into about 15% and 85%. The former of the original charge was sent to Charge(Q)-to-Digital Converters (QDCs: CAEN V792) and the latter is sent to leading edge discriminators (CAEN V895). A multiplicity logic, a gate generator and a time stamp recorder are integrated in a general purpose VME board (CAEN V1495) by programming the FPGA in it. Whenever the number of pairs of PMTs in the same module which flashed coincidentally is greater than or equal to two, a gate pulse of 400-ns duration is generated for the QDCs. We used the time information of the gate pulses provided by the time stamper logic to select neutrino events by the delayed-coincidence method offline.

We have completed to construct the PANDA100, which consists of 10×10 modules, in August 2016 (Fig.1(b)). The PANDA100 has target volume of $1,000$ kg. Thanks to the segmentation by 10×10, a muon-veto can be given by itself without any muon counter. It can be installed on a truck or a container, and placed outside of reactor buildings easily.



(a) Structure of the PANDA module



(b) Schematic view of the PANDA100

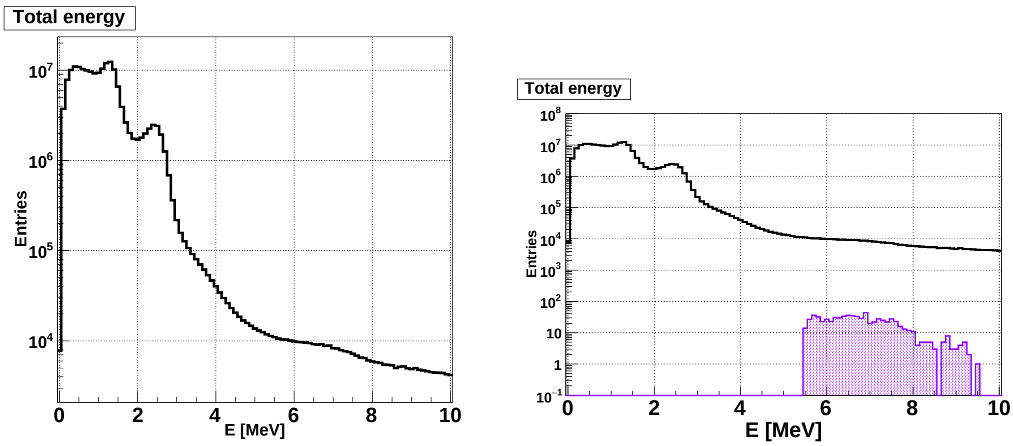
Figure 1. Conceptual design of the PANDA detector and module

The PANDA project was originally proposed by the team of the University of Tokyo. The development had been continued since 2006. So far, prototypes of the PANDA detector have been constructed and were used to demonstrate the capability of the reactor monitoring. Early prototypes have performed measurement close to the commercial reactors in Japan. The first prototype (PANDA16) mainly measured background events around the non-operated reactor, and the background rates measured in the reactor site were confirmed to be comparable to the rates in the site of the University of Tokyo [1]. The second prototype (PANDA36) detected the difference of antineutrino flux between the operated and no-operated reactor above ground [2]. Because any reactors were not operated in Japan for our use purpose, we couldn't use the third prototype (PANDA64) for the measurement of reactor activities. As an application to another field, the PANDA64 was employed to detect γ-ray bursts under thundercloud [3]. Since 2016, the PANDA project had been taken over to Kitasato University.

2. Background measurement

The major background source is environmental γ-rays and fast-neutrons. Especially, environmental neutrons are difficult to be distinguished from the neutron generated by the inverse-beta process of antineutrino. Therefore understanding the amount of environmental neutrons is important issue for us. In order to estimate such background events, we placed the PANDA100 in the Kitasato University laboratory, ground floor of four-floors building. We set the threshold value of each discriminator to be $-20\,\mathrm{mV}$ corresponding to the condition for the antineutrino measurement, and the module hit multiplicity was required two or more. Fig.2 show the typical energy spectra obtained by the PANDA100. In these results, the live time of measurements and average trigger rate were 0.38 days and 5.45 kHz, respectively. Fig.2 (a) is the total energy spectrum of single event without the delayed-coincidence method. The measured events were almost made from γ-rays by the environment isotopes (^{40}K (1.5 MeV) or ^{208}Tl (2.6 MeV)), and the event rate of the environmental γ-ray was 5.27 kHz. Cosmic-muon event rate was 0.09 kHz, which was estimated from the number of events which satisfied the condition where four or more modules hit and energies of over 15 MeV were deposited into each module.

Antineutrinos are detected as the delayed coincidence events. We estimated the accidental background rate for the antineutrino-like events by applying the delayed-coincidence cut to the background data. The selected accidental background events were shown as the filled histogram in Fig.2(b). The event select conditions are $5.5\,\mathrm{MeV} < E < 9.5\,\mathrm{MeV}$ for the energy window and $8\,\mu\mathrm{s} < \Delta t < 150\,\mu\mathrm{s}$ for the time coincidence window, where Δt is the time difference between a prompt-event and a delayed-event. The number of accidental background events was 727, and the event rate was about $1,913$ events/day. From the estimation by Monte Carlo simulations, the expected antineutrino event rate at the Ohi power plant[1] is to be around 147 events/day, where we assumed the thermal power was 3.4 GW and the distance from the reactor core was 48 m. Of course, we need further suppression of the accidental background rate with additional selection.



(a) Energy spectrum of single event

(b) Accidental background candidate events (filled histogram) with the single event spectrum (black solid line), which is same as (a)

Figure 2. Measured energy spectra with the PANDA100 in our laboratory.

3. γ-ray bursts detection

The PANDA detector can also be employed as the large target volume γ-ray detector. So far, application to measure γ-rays under the thunderclouds were proposed. Some results of such observations were referred in ref. [3].

The production model of γ-ray bursts under the thunderclouds was developed by Gurevich et al. [4,5]. Electric field in the thundercloud may accelerate seed electrons if the electric force is larger than the minimum stopping power of air. Such electrons are called “runaway electrons”.

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By generating knock-on electrons successively, the runaway electrons can cause an avalanche multiplication process called "relativistic runaway electron avalanche" (RREA). In the same time, Bremsstrahlung γ-rays are also produced by runaway electrons, therefore these γ-rays will be observed around the thunderclouds together with runaway electrons. We carried out the observation test of γ-ray burst using the PANDA100 at the Mt. Norikura, Gifu, Japan. This experiment was also the total system test for the PANDA100.

The PANDA100 detector was loaded on and transported by a 2 t truck, and was deployed at Norikura observatory of Institute for Cosmic Ray Research (ICRR) of The University of Tokyo. The place is about 2,770 m above the sea level. We continued the measurement for about one month (August 26th to October 2nd, 2016). Data taking of the detector was performed by remote control. In order to detect the incoming of thunderclouds, we also put a optical light sensor and a pair of electric field meters. The trigger condition for the γ-rays observation was that one or more modules were flushed. Average trigger rate at Norikura was about 5 kHz.

Although the analysis of data taken is still underwork, we found three apparent candidates of γ-ray bursts in September 8th, 17th and 20th, 2016, so far. The event rate around the burst candidate in September 8th, 2016 is shown in Fig.3. The upper and lower are the event rates for the energy range of 3 to 100 MeV and the electric field measured by us at the ground level, respectively. Two indication of the γ-ray bursts are seen in the figure. We continued observing γ-ray bursts with up to around 100 MeV. Such burst events had also been observed at the previous measurement with the PANDA64 detector [3]. We are continuing analysis of other two candidates, and also investigating more detail information such as incoming direction of the burst.

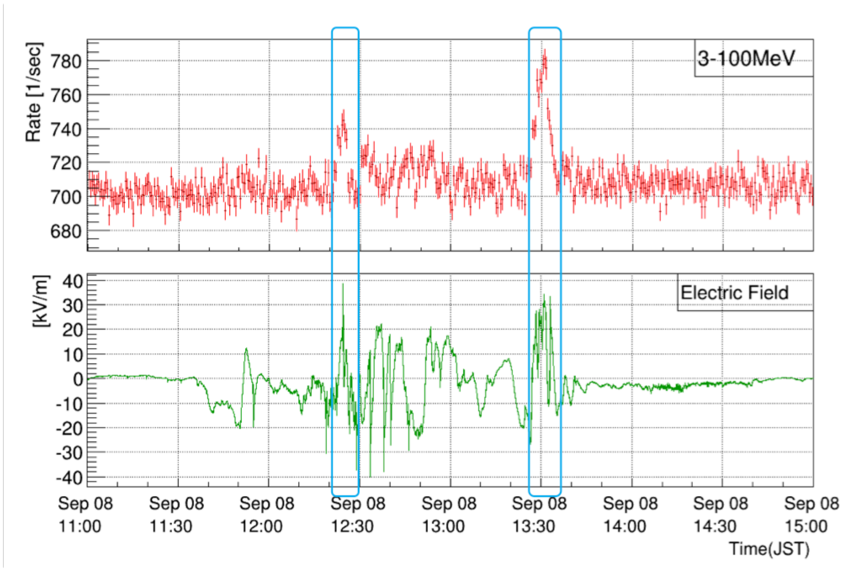

Figure 3. Event rate (upper panel) and measured electric field (lower panel) in the period of the burst candidate in September 8th, 2016. Two squares in the figure indicate the timing of γ-ray bursts observation.

4. Reactor monitoring community in Japan

After the Great East Japan Earthquake, regulations of nuclear rectors in Japan were renewed. Almost all reactors in Japan are shut down for inspection or decommissioning. Resume of operation is expected. However, the schedule is not clear. Japanese research reactor such as

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Monju (Fukui) and Joyo (Ibaraki), are also shut down by operational troubles. A use of them soon or near the future as a neutrino source facility is not clear.

When Japanese reactors resume operation, we are starting to build a synergistic relationship between Japanese physics researchers and electric companies having nuclear reactors. For the purpose, we have launched the community for research of the reactor monitoring centering at University of Fukui. There are several commercial reactors in Fukui Prefecture. University of Fukui has the research institute of nuclear engineering, one of the important center of fundamental research in nuclear energy in Japan. Kitasato university group, Tohoku University group and Nippon Dental University group are joined in the reactor monitoring community. We are sharing information and technologies related with a reactor monitoring.

5. Conclusion

We have been developing and constructing the portable antineutrino detector based on a plastic scintillator with gadolinium films, which is called the PANDA detector. In July 2016, construction of the PANDA100 having 100 plastic scintillator bars had completed at Kitasato University. The accidental background rate with the PANDA100 were evaluated in our laboratory. As the results, the background rate was $1,913$ events/day, therefore we must need improvement of analysis for decreasing the accidental background rate.

On the other hand, observation of γ-ray bursts under thunderclouds was also carried out at Mt. Norikura in 2016 summer. Although analysis is on-going, we found three candidates of the γ-ray burst.

We started to build a synergistic relationship between researchers of reactor monitoring and an electric company in Japan. For this purpose, the reactor monitoring community in Japan was arranged by University of Fukui group, and Kitasato University group and other institutes join in the community. We are sharing information about Japanese reactor status and technologies of antineutrino detection.

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