A Trial of Neutrino Detection from Joyo Fast Research Reactor

F.Suekane
Tohoku University
For KASKA group, made up of;
Tohoku Univ., Tokyo Inst. of Tech., Niigata Univ., Tokyo Metropolitan Univ., Tohoku Gakuin Univ., Kobe Univ., KEK, Hiroshima Inst. of Tech., and Miyagi Univ. of Education.
&
JAEA O-arai Research and Development Center.

ABSTRACT
Neutrino is an elementary particle which is generated by nuclear reactor. Because the number of neutrinos generated is proportional to the reactor operation power and that per unit operation power depends on the fuel components, the reactor neutrinos can, in principle, be used as an independent and real time monitor of the reactor operation and its fuel components. KASKA group is trying to detect neutrinos from Joyo research fast reactor by its prototype neutrino detector since 2006. This is the first attempt to detect neutrinos from fast reactor. For safeguards purposes, fast reactors are important objects for the monitoring due to its nature of plutonium breeder. Although the purpose of the test experiment is purely scientific oriented, many of the elements of this experiment have common issues to the neutrino detectors for safeguards and our experience should be useful for such activities. The status of the test experiment is described in these proceedings.

INTRODUCTION
Nuclear reactors generate a huge number of neutrinos through the beta decays of fission products. The neutrino interacts with matter so weakly that virtually all neutrinos generated in the reactor core come out through the thick iron and concrete shields without disturbances. Because the number of neutrinos generated is proportional to the fission rate in the reactor core and because the number of neutrinos generated per unit energy generation depends on the fuel components, the reactor neutrinos can, in principle, be used as an independent and real time monitor of the reactor operation. The main difficulty to use neutrinos as reactor monitor has been the difficulty of its detection. However, recent progress of neutrino detector technology in the field of elementary particle physics will improve the possibility to use neutrino in such applications. KASKA[1] is a planned experiment to measure a neutrino oscillation at the world's most powerful *Kas*hiwazaki-*Ka*riwa nuclear power station in Japan. KASKA group constructed a prototype neutrino detector to perform detector R&D. Since August 2006, it was set up at a distance of 25m from the Joyo fast research reactor core to try to detect reactor neutrinos. It is challenging to detect neutrino signals

under the harsh conditions, such as low reactor power and high background at the ground level. The prototype detector has capability to reduce backgrounds by delayed coincidence technology, various shields against backgrounds and cosmic-ray veto counters, energy and position correlations of the signals and neutron/γ pulse shape discrimination. We have taken net 40 days of reactor ON data and more of OFF data and analyzing the data now.

NEUTIRNOS and SAFEGUARDS

In an operating reactor core, uranium and plutonium perform huge number of fission reactions. The daughter nuclei produced in the fission reaction are generally neutron rich and perform several β-decays before becoming stable. One anti-neutrino ($\bar{\nu}$) is generated in each β-decay process.

$$^{Z}A \rightarrow ^{Z+1}A + e^{-} + \bar{\nu} \qquad \text{--- (1)}$$

A reactor with 3GW thermal energy produces about 6×10^{20} of $\bar{\nu}$ per second. The energy of $\bar{\nu}$ is equivalent to that of β-decays; that is a few MeV. Almost all the $\bar{\nu}$'s come out from the reactor because they interact with matter very weakly. Typically the $\bar{\nu}$ is detected by organic liquid scintillator by using the following inverse β-decay interaction.

$$\bar{\nu} + p \rightarrow e^{+} + n \qquad \text{--- (2)}$$

If $1m^3$ of organic scintillator is placed at a 25m distance from an operating $3GW_{th}$ reactor core, 2,000 such interactions take place per hour. Because the number of neutrinos generated is proportional to the operating power of reactor, the operation of reactor can be monitored by measuring the neutrino flux. Fig.-1 shows energy spectrum of reactor neutrino which performs the inverse beta decay reaction.

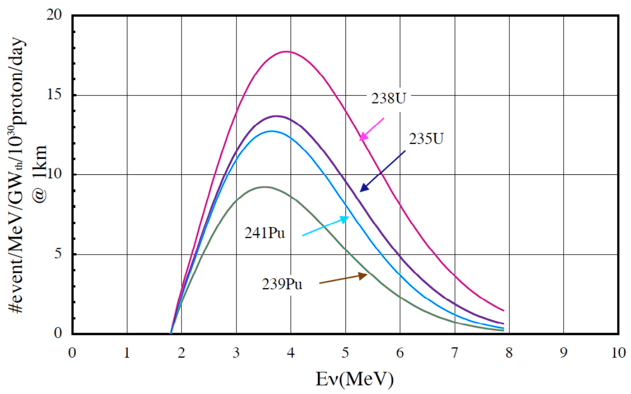


Fig.-1, Energy spectrum of reactor neutrino which performs the inverse beta decay reaction. Neutrino Spectra were taken from the references-[2].

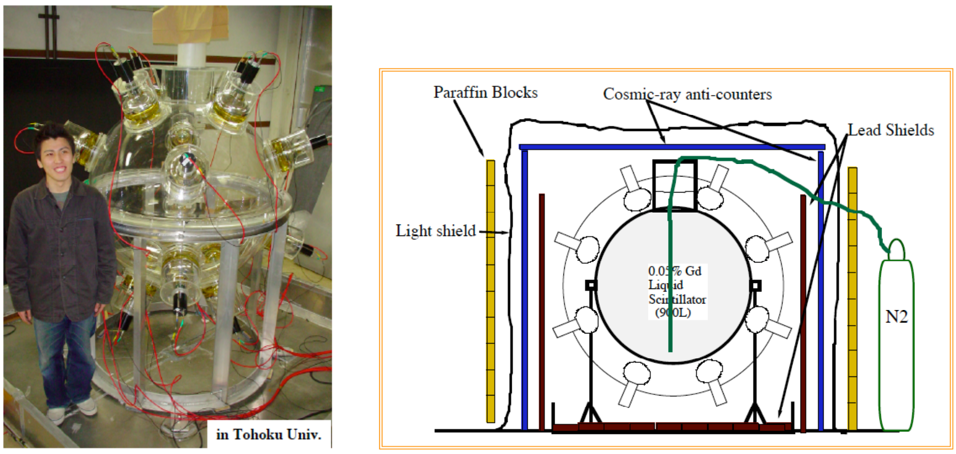
The number of neutrinos per fission energy depends on the fissile element. As shown in the Fig.-1, the difference amounts to 50% for ^{239}Pu and ^{235}U. This difference can be used to measure the ratio of plutonium and uranium in the core. To simplify the discussion, if small components of ^{241}Pu and ^{238}U are ignored, the ratio of fission rates of ^{239}Pu and ^{235}U can be obtained by the following equation.

$$\frac{n_{Pu}}{n_U} = \frac{1 - \nu_U r}{\nu_{Pu} r - 1}; \quad r = \frac{P_{th}}{qN_{\nu}} \qquad \text{--- (3)}$$

where, n_U and n_{Pu} are the fission rate of uranium and plutonium, q is energy release per fission (~200MeV), P_{th} is thermal operation power, N_ν is the number of neutrinos detected and $\nu_{\mathrm{U}}, \nu_{\mathrm{Pu}}$ are the number of neutrinos generated per U and Pu generations, respectively ($\nu_{\mathrm{U}}/\nu_{\mathrm{Pu}} \sim 1.5$). The number of neutrinos per thermal energy reduces along with the burn up of the reactor fuel. In recent years neutrino physicists are studying such neutrino applications and holding 'Applied Antineutrino Physics workshop' [3] every year since 2004 and discuss about this possibility. One experiment successfully has measured the burn up effect by neutrinos at San Onofre power station with relatively simple detector [4]. KASKA group is also trying to detect neutrinos from Joyo experimental fast reactor.

KASKA PROTOTYPE DETECTOR and JOYO REACTOR

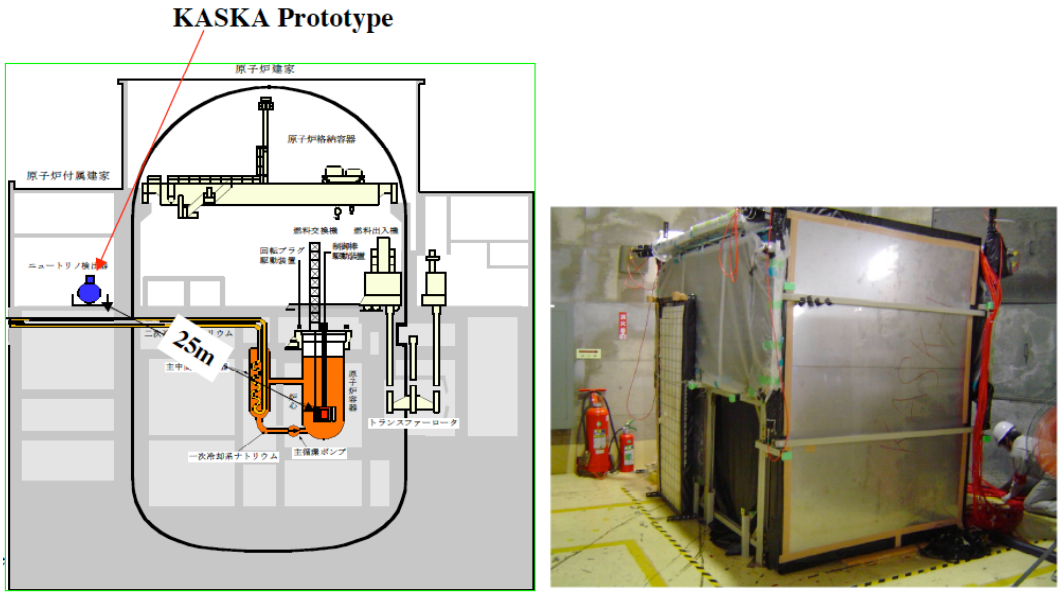
KASKA group constructed a prototype neutrino detector and studied its performances and backgrounds. The prototype, shown in the Fig.-2-(a), consists of an acrylic sphere of 120cm diameter. 900 liter of Gd doped liquid scintillator is contained in the acrylic sphere and sixteen 8 inch photo multipliers (PMT) view the scintillation lights. Energy and position reconstructions are possible through its charge and timing information.



(a) (b)

Fig.-2, (a) KASKA prototype detector. Liquid scintillator is not filled.
(b) Shields for background reduction.

After various studies were performed at Tohoku University, the prototype was moved to Joyo experimental reactor site in the summer of 2006 to try to actually detect reactor neutrinos. Joyo[5] is an experimental fast reactor operated by Japan Atomic Energy Association. At Joyo, the KASKA prototype is placed at a distance of 25m from the reactor core on the ground level in the reactor building as shown in Figs-3. In order to reduce the backgrounds of ambient γ-rays, neutrons and cosmic-rays, the prototype detector is surrounded by, 6mm thick lead vertical walls, 5cm thick lead bricks on the floor, paraffin walls made of boron loaded paraffin bricks, and large plastic scintillation counters to veto the cosmic-ray muons, as shown in the Fig.-2-(b). When there is a hit in at least one muon veto counter, 100μs of dead time is set to kill the cosmic-ray signal and to reduce associated neutron backgrounds. The liquid scintillator is continuously purged by nitrogen gas for neutron/γ pulse shape discrimination. Since the power of Joyo is small (140$\mathrm{MW_{th}}$) compared with reactors of commercial power plant, which typically produces 3,000MWth of energy, and the background condition is not good (originally the prototype was not designed to be used for this kind of experiment), we are aiming only to distinguish the reactor ON and OFF by neutrinos in this test experiment. A scientific interest is that the neutrinos from fast reactor (FR) have not been detected so far. Because fast reactor is plutonium rich, the main neutrino component comes from ^{239}Pu fissions. This is in contrast to the light water reactors (LWR) case in which main neutrino component comes from ^{235}U. If the energy spectrum of the fast reactor neutrinos are measured as precisely as LWR neutrinos in the future, it will be possible to determine neutrino spectrum of plutonium and uranium fissions separately by combining FR and LWR data. Those data will be very useful for future precise neutrino experiments and for safeguard purposes. For safeguards purposes, fast reactors are important objects for the monitoring due to its nature of plutonium breeder. This test experiment can be treated as the first trial to such challenge.



(a) (b)

Fig.-3, (a) Joyo reactor and location of then KASKA prototype.
(b) A view of the prototype detector at Joyo. The acylic shpere is behind the shields and cosmic-ray anti counters.

KASKA prototype uses gadolinium(Gd) loaded liquid scintillator. The neutrons produced in the inverse β-decay reaction shown by the equation-(2) is absorbed by the Gd in the liquid scintillator and the excited Gd emits cascade γ's whose total energy is 8MeV.

$$n + Gd \rightarrow Gd^{*} \rightarrow Gd + \gamma' s \qquad \sum E_{\gamma} = 8MeV \qquad \text{--- (4)}$$

This reaction takes place 30 μs after the positron signal in average. By taking the 'delayed coincidence' of the positron signal and the neutron signal, the backgrounds are severely suppressed. The positron signal is called 'prompt signal' and the neutron signal is called 'delayed signal' based on the timing correspondence. About net 40 days of reactor ON data were taken between December 2006 and June 2007 and more reactor OFF data have been taken so far. After coincidence timing cut ($2<\Delta t<50\mu s$), delayed energy cut ($7.5<E_d<9.5$MeV) and fiducial volume cut by using a charge valance information (normalized standard deviation of the 16 PMT charges outputs <1.0 for prompt signal and <0.75 for delayed signal) on the 20 days of reactor ON and OFF data, the energy distributions of the prompt signal are obtained as shown in Fig.-4.

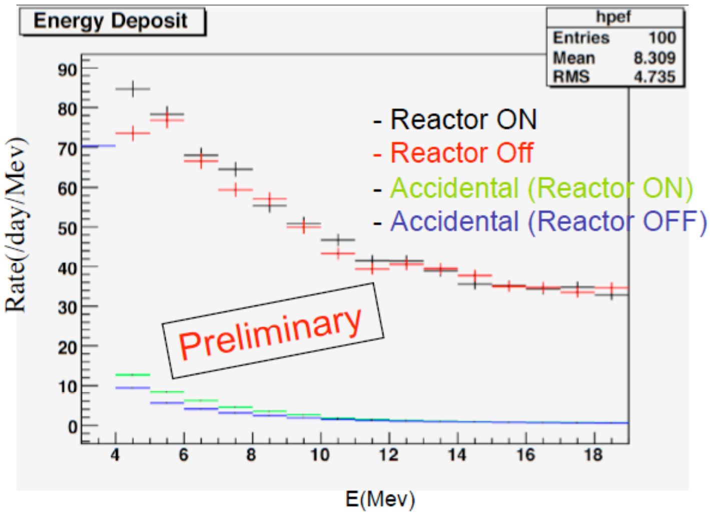


Fig.-4, Energy spectra of the data taken during reactor-ON and OFF.

The accidental backgrounds are calculated by using single rates within delayed energy cut range and coincidence timing window. After subtracting reactor OFF data from ON data, 7 ± 4/day of events remained. The number of reactor neutrino is expected to be 1~2 events/day by a Monta Carlo simulation. The error is still too large to extract any conclusive results. The dominant source of the error comes from the correlated backgrounds from fast neutrons which are produced by cosmic-rays. There will be possible improvements of signal to noise ratio by using pulse shape neutron/γ discrimination technique, cuts using the distance between prompt and delayed signal, improved fiducial cut, etc.

SUMMARY

The KASKA group is trying to detect neutrinos from Joyo experimental fast reactor by using KASKA prototype detector. So far we have not obtained conclusive result but there are possibilities to reduce the error by improving the background to signal ratio.

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