PR9 Project Research of Accelerator-Driven System with Spallation Neutrons at Kyoto University Critical Assembly

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INTRODUCTION: At the Kyoto University Critical Assembly (KUCA), a series of the accelerator-driven system (ADS) experiments [1]-[5] had been carried out with the combined use of A core (solid-moderated and -reflected core) and the fixed-field alternating gradient (FFAG) accelerator. The Project research was composed of six research teams in domestic: Kindai University; Tohoku University; Japan Atomic Energy Agency (JAEA); University of Fukui, Nagoya University; Institute for Integrated Radiation and Nuclear Science, Kyoto University (former the Kyoto University Research Reactor Institute). In the Project research organized by the Institute for Integrated Radiation and Nuclear Science, Kyoto University, the ADS core was comprised of Uranium (U)-fueled and lead (Pb)-zoned core shown in Fig. 1, and 100 MeV protons generated by the FFAG accelerator was injected onto the lead-bismuth (Pb-Bi) target. For an injection of 100 MeV protons onto the Pb-Bi target, spallation neutrons were observed with a wide spectrum of high-energy neutrons, and were contributed to neutron multiplication of the U-Pb core. The objectives of the Project research were to examine experimentally neutron characteristics of the U-Pb core modeling actual ADS experimental facilities, and to investigate applicability of current measurement technologies and numerical methodologies to the ADS experiments with spallation neutrons at KUCA.

EXPERIMENTS: In the ADS experiments with spallation neutrons, main characteristic of proton beams by the FFAG accelerator were shown as follows: 100 MeV energy; 20 Hz frequency; 100 ns repetition rate; 30 to 70 pA intensity; 15 mm diameter beam spot. The research topics were revealed in each research team as follows:

- Subcriticality measurement by the Noise method (Kindai University)
- Measurement of reaction rate distribution (Tohoku University)
- Minor Actinide irradiation (JAEA)
- Measurement of neutron yield and neutron spectrum (University of Fukui)
- On-line monitoring of kinetic parameters (Nagoya University)
- Neutronics of U-Pb core in ADS (Kyoto University)

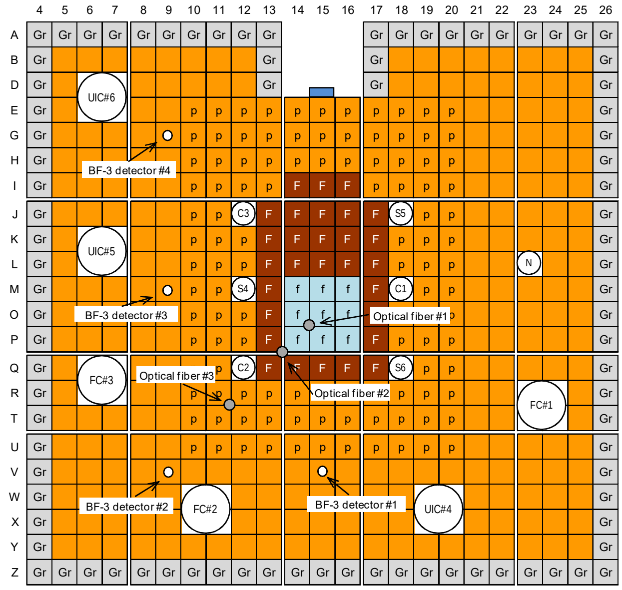

Fig. 1. Top view of U-Pb core configuration at KUCA

RESULTS: From the results of a series of ADS experiments, special attention was made to the following items: applicability of the Noise method to subcriticality measurement in ADS with spallation neutrons (Kindai); subcriticality dependency on reaction rate distributions (Tohoku); feasibility study on MA irradiation by spallation neutrons (JAEA); observation of high-energy neutron spectrum by spallation neutrons (Fukui); feasibility study on on-line monitoring of kinetic parameters by spallation neutrons (Nagoya); benchmarks on kinetic parameters in U-Pb core of ADS with spallation neutrons (Kyoto).

CONCLUSION: The Project research of ADS with spallation neutrons was successfully conducted with the combined use of U-Pb core and FFAG accelerator at KUCA. A series of static and kinetic ADS experiments revealed importantly applicability of current measurement methodologies to upcoming actual ADS facilities in the future.

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PR9-1 Subcriticality Monitoring for a Reactor System Driven by Spallation Source

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INTRODUCTION: Feynman-α Method has been frequently employed to determine subcritical reactivity of nuclear reactor systems driven by Poisson source such as Am-Be neutron source. Recent theoretical studies indicated that a drive by Non-Poisson source such as spallation source enhanced the correlation amplitude Y_∞. The objectives of this study are to confirm experimentally the enhancement and to derive some characteristics of the spallation in a lead target from the enhancement.

EXPERIMENTS: A subcritical system was constructed on the A loading of the Kyoto University Critical Assembly. The system had a lead target, to which 100Mev proton beam was drawn to cause spallation reactions. The repetition period of the proton pulse beam was 50msec. Time-sequence counts data from five BF_3 proportional counters were acquired at several control rod patterns. For comparison, we also acquired time-sequence data under drives by Am-Be neutron source.

RESULTS: Figure 1 shows a gate-time dependence of Y obtained under a drive by Am-Be neutron source. The Y is a statistical indication of neutron-correlation amplitude and is defined as variance-to-mean ratio minus one of neutron counts registered within the gate. The correlation amplitude Y is small but the gate-time dependence can be observed just as expected.

Figure 2 shows a gate-time dependence of Y obtained under a drive by spallation source. Contrary to our expectation, the Y is unusually high and has an increasing tendency with longer gate time. This is because the proton beam intensity was much unstable throughout our experiments and consequently reactor power was largely fluctuated. In order to overcome this difficulty, the following formula was applied to the Feynman-α analysis under an unstable drive by spallation source.

$$Y(T) = Y_\infty\left[1-\left(1-e^{-\alpha T}\right)/\alpha T\right] + cT. \qquad (1)$$

The last term of the above equation was additionally introduced to consider a power drift with time scales of delayed neutrons [1]. The least-squares fit of the above equation was done to only the Y data at gate times of the integral multiple of pulse repetition period (50msec) [2]. Figure 3 shows a ratio of correlation amplitudes between spallation and Am-Be neutron source. We can observe a tendency of correlation amplitude enhanced by spallation source, however, the statistical error of the ratio is unacceptably large. The further advancement of data analysis is in progress.

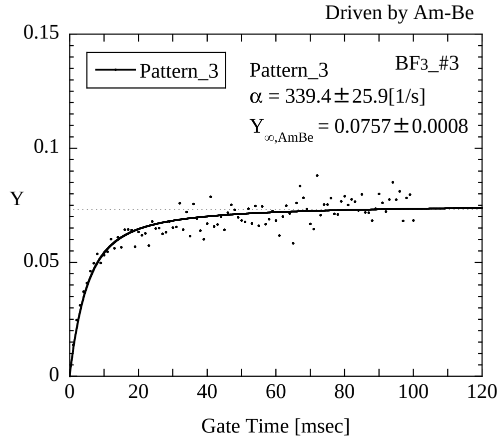

Fig.1. Y obtained in a subcritical system driven by Am-Be neutron source.

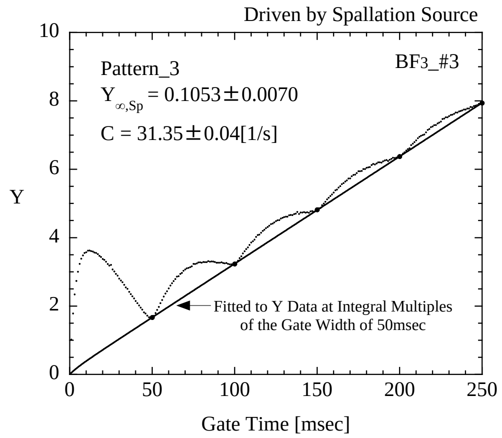

Fig.2. Y obtained in a subcritical system driven by unstable spallation neutron source.

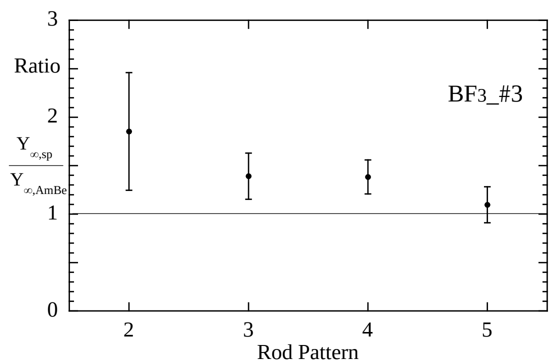

Fig.3. Ratio of correlation amplitudes between spallation and Am-Be neutron source.

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Basic Study of Beam Transient on Accelerator-Driven System with Spallation Neutron Source

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INTRODUCTION: An accelerator-driven system (ADS) is operated with the use of spallation neutrons generated by an accelerator beam. The core behavior is dependent on the beam condition, and some studies reported that the beam transient (transient by beam variation) has a possibility to cause core damage [1]. The experimental study of the beam transient on ADS has been planned to examine the change of core characteristics such as reaction rate distributions and neutron multiplication. FY 2017 was the first year of the ADS experiment with spallation neutron source, and the experiment was performed under the standard beam condition to understand the basic core characteristics.

EXPERIMENTS: The ADS experiment was carried out in the KUCA A core with spallation neutron source generated by the reaction of 100 MeV proton beam and Pb-Bi target. Fig. 1 shows the core configuration. The core is composed of PE (Polyethylene) moderated normal fuel assemblies "F" (1/8"p60EUEU), Pb-zoned fuel assemblies "f" which the PE plate was replaced with Pb plate in the central 40 fuel cells and PE moderators "p." All control and safety rods were withdrawn in the experiment, and four core patterns were configured by changing the number of normal fuel assembly in the row I and J. The subcriticality was ranged between 2487 and 5400 pcm. The 1 mm-diameter In wire was set along (B-P, 13-14) at the axial position of 700 mm from the bottom of core and the In foil was also attached near target to measure the reaction rate distribution by neutron activation analysis of ^{115}In(n, γ)^{116m}In and ^{115}In(n, n')^{115m}In.

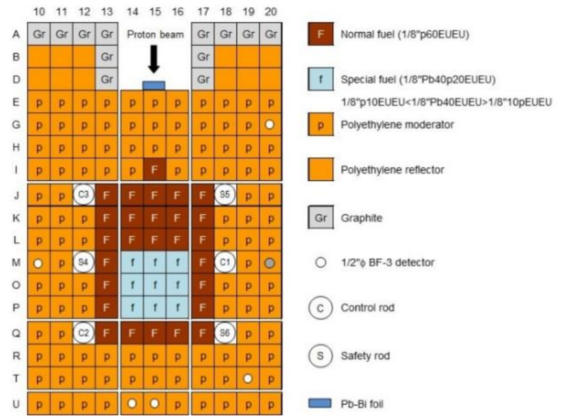

Fig. 1. Top view of the ^{235}U-fueled and Pb-zoned core

The measurement results were evaluated with the combined use of the PHITS, MVP and JENDL-4.0 library, and the subcritical multiplication factor k_s were calculated on the basis of a reaction rate distribution as follows:

$$k_s = \frac{F}{F+S} \quad (1)$$

where F is the total number of fission neutrons and S is that of source neutrons. The calculation method of F and S was referred to Refs. [2]-[4].

RESULTS: Fig. 2 shows the ^{115}In(n, γ)^{116m}In reaction rate distribution at the subcriticality of 2487 pcm as one example of the evaluation by the numerical calculations. Small differences were seen around the PE region but the calculated distribution was agreed well with the experimental one. The similar evaluation results were obtained in the other three core patterns, and a series of calculations were confirmed to reproduce the experiment results. The subcritical multiplication factor k_s was also calculated as presented in Table 1. The experiment results were larger than calculation ones in all cases but the differences were small as seen from the C/E values.
The basic core characteristics were successfully obtained on the standard beam condition in FY 2017, and on the basis of the obtained data, the experiment with different conditions such as beam and core configuration is planned.

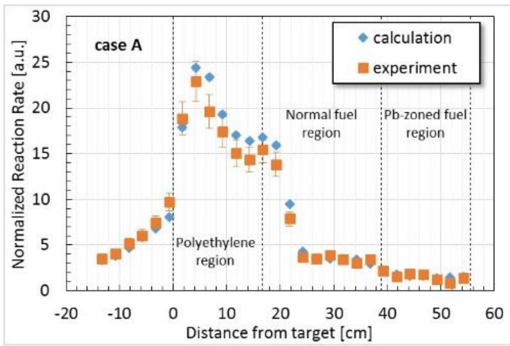

Fig. 2. Comparison of ^{115}In(n, γ)^{116m}In reaction rate distribution between measurement and calculation results at the subcriticality of 2487 pcm.

Table 1 Comparison of k_s between calculation and measurement values with different subcriticalities

subcriticality [pcm]	calculation	experiment	C/E
2487	0.660 ± 0.004	0.683 ± 0.050	0.97 ± 0.07
4016	0.486 ± 0.003	0.527 ± 0.036	0.92 ± 0.06
4924	0.422 ± 0.002	0.438 ± 0.029	0.96 ± 0.06
5400	0.385 ± 0.002	0.386 ± 0.025	1.00 ± 0.06

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PR9-3 Measurement of MA Reaction Rates Using Spallation Neutron Source

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INTRODUCTION: To transmute minor actinides (MAs) partitioned from the high level waste, the Japan Atomic Energy Agency (JAEA) has investigated neutronics of an accelerator-driven system (ADS): a lead-bismuth (Pb-Bi) eutectic cooled subcritical reactor with 800 MW thermal power. In the nuclear transmutation system such as ADS, the nuclear data validation of MA is required to reduce the uncertainty caused by the nuclear data of MA. To validate the nuclear data, many independent experimental data need to be mutually compared. An expansion of integral experimental data is the important issue since there is limited number of experimental data of MA. The Kyoto University Critical Assembly (KUCA) has a potential capability to perform the simulated experiment of ADS using a hybrid system of spallation neutron source and a subcritical core. This study aims to measure the reaction rates of neptunium-237 (^{237}Np) and americium-241 (^{241}Am) using the spallation neutron source in KUCA.

EXPERIMENTS: The MA irradiation experiments were conducted at A-core in KUCA with the fixed-field alternating gradient (FFAG) proton accelerator. Fission reaction rates were measured by using a back-to-back (BTB) fission chamber (diameter: 40mm, height: 42mm). The BTB fission chamber having two foils (mass: 10μg/nuclide) such as uranium-235 (^{235}U) and MA (^{237}Np or ^{241}Am), was installed just behind the Pb-Bi target as shown in Figure 1.

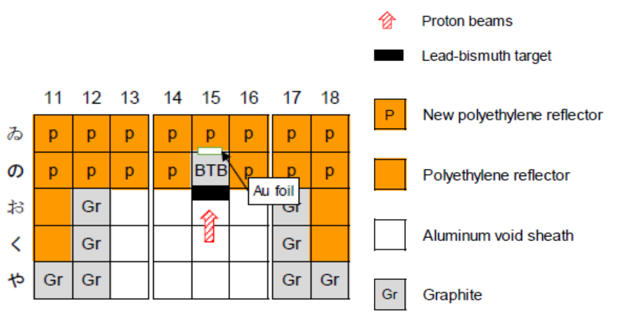

Figure 1. Loaded position of the BTB fission chamber and the Au foil in the A-core of the KUCA.

The pulsed-height distribution from the BTB fission chamber was acquired under the proton beam condition, such as 100 MeV energy, 20 Hz period, 100 ns beam width, and 47 pA current for 3 hours. Moreover, two gold (Au) foils (diameter: 3mm, thickness: 0.05mm) were attached at the rear of the BTB fission chamber as a reference of capture reaction rates of MA.

RESULTS: The distributions of pulsed height of ^{237}Np and ^{241}Am fission reactions were observed as shown in Figure 2. These distributions were significantly different from the ones generally observed in critical and pulsed neutron source (PNS) experiments. Therefore, they would contain not only signals of fission reactions but also noise due to detection of the ionizing signal of gas in the BTB fission chamber generated by the γ ray coming from the collision between 100MeV proton beams and the Pb-Bi target. On the other hand, the γ ray from ^{237}Np foil was measured for the capture reactions. After the irradiation, 213 counts were detected for 68 hours using the high-purity germanium detector. The capture reaction rate of ^{237}Np converted from the γ ray count was $(1.21\pm0.97)\times10^{7}$ #/cm^3/s. Moreover, the capture reaction rate of ^{197}Au was $(1.34\pm0.11)\times10^{8}$ #/cm^3/s. Here, the result of this experiment was compared with that of the critical experiment which was available to be measured the fission reaction rates of ^{237}Np and ^{241}Am using the same BTB fission chamber. The capture reaction rates of ^{237}Np and ^{197}Au were $(1.01\pm0.13)\times10^{8}$ #/cm^3/s and $(9.86\pm0.88)\times10^{7}$ #/cm^3/s in the critical experiment, respectively. Consequently, reducing the influence of the γ generated by the nuclear spallation reaction and extending the duration of the irradiation to 24 or more hours would be necessary for detecting signals of fission reactions under the spallation neutron source.

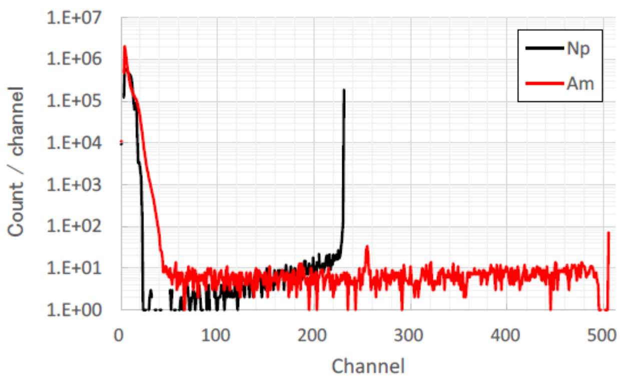

Figure 2. Signals from BTB fission chamber in the irradiation experiment using the nuclear spallation neutron source.

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PR9-4

Irradiation Experiments of ^{237}Np and ^{241}Am Capture and Fission Reactions in Critical Core

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INTRODUCTION: The underlying issue of the nuclear power generation is remained in the treatment of the high-level radioactive waste (HLW) contained in spent fuel. For treatment of HLW, the simple strategy had been proposed to manage spent fuels underground named as “once-through fuel cycle.” Once-through cycle has an advantage over the easiness of the treatment from unnecessary of chemical processing, however, poses the difficulty to maintain the structural soundness of management facility for over one million year to decay out the HLW, burdening the geological site. As an advanced proposal, the burden reduction to the geological site has attempted by loading minor actinides (^{237}Np and ^{241}Am), which are main cause of radiotoxicity in HLW, to nuclear power reactor (hard neutron spectrum) for transmutation after the chemical extraction from spent fuels.

In the reactor design analysis for the transmutation system such as the accelerator-driven system (ADS), the uncertainty induced by the nuclear data of ^{237}Np and ^{241}Am capture and fission reactions are estimated very large and as the dominant nuclide to the safety parameter [1]. To reduce the uncertainty by ^{237}Np and ^{241}Am fission (which is difficult reaction to measure the cross section in general) and capture reactions, an irradiation experiment is requisite as accumulation of integral experiments by loading their foils to the fast reactor with previous study [2-3] for acquiring important reaction rates.

In this study, special attention was paid for the fabrication of ^{237}Np and ^{241}Am foils from their solute and testing the validity by irradiation experiment with hard spectrum core at the Kyoto University Critical Assembly (KUCA).

EXPERIMENTAL SETTINGS: For the irradiation experiment, critical core was prepared and composed of lead-loaded fuel rod “f,” and polyethylene-moderated fuel rod “F” as shown in Fig.1. H/U value at irradiation spot was about 50, which is comparative hard spectrum in the KUCA-A core. Fabricated ^{237}Np and ^{241}Am foils were inserted into the back-to back (BTB) type double fission chamber separately. The advantage of BTB fission chamber is to enable the measurement of fission reaction by the objective foil (^{237}Np and ^{241}Am) and reference foil (^{235}U) in almost same position at the same time. Thus, measured result could be fission reaction rate ratio of the objective foil to the reference one. The foils were irradiated for about 1 hour under a thermal power of 3.5 W. After irradiation, ^{237}Np foil was extracted from the BTB fission chamber, and γ-ray was measured for ^{237}Np cap-ture reaction rates.

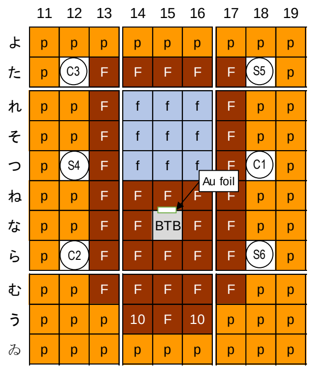

Fig. 1. Critical core for MA irradiation experiments.

RESULTS: The pulsed height of ^{235}U and ^{237}Np during the irradiation indicated double peak as shown in Fig. 2, implying that two fission fragment could be detected having different energy. Thus, the MA foils were considered successfully fabricated from their solvent. In case of ^{241}Am, the pulse height did not show distributed in 1 hour irradiation because the small number of ^{241}Am is permitted to insert into the KUCA-A core. However, both fission reaction rate ratios were obtained in both foils, and, ^{237}Np capture reaction rates were measured by γ-ray detection after the irradiation, as shown in Table 1.

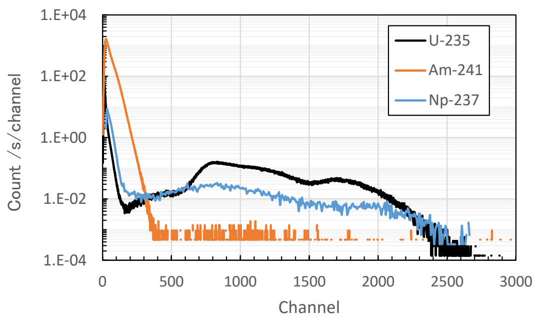

Fig. 2. Pulsed height from BTB fission chamber.

Table 1. Fission reaction rate ratio by ^{237}Np/^{235}U and ^{241}Am/^{235}U and ^{237}Np capture reaction rate.

Nuclide	Fission reaction rate ratio to ^{235}U	Capture reaction rate [1/cm^3/s]
^{237}Np	0.01381	$(4.26\pm0.11)\times10^8$
^{241}Am	0.03149	-

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29P9-4

Development of Real-time Subcriticality Monitor

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INTRODUCTION: The accelerator-driven subcritical (ADS) system has been developed for producing energy and for transmuting minor actinides and long-lived fission products [1-2]. The ADS system should be designed to be subcritical condition in any case and desirably monitored in real time. Real-time monitoring of subcriticality is important task for ensuring safety in ADS reactor operation. Iwamoto et al. already demonstrated real-time subcriticality monitoring for ADS system, in which they used only a pulsed neutron source (PNS) method [3]. However, to assure validity of the measured subcriticality, the subcriticality is desired to be determined by more than two methods. In this study, we attempt to measure the subcriticality in real time with the PNS method and a method based on reactor noise analysis simultaneously. As the subcriticality measurement algorithm based on reactor noise analysis, we applied the Rossi-α method.

EXPERIMENTS: Measurements of subcriticality were conducted in A-core of Kyoto University Critical Assembly (KUCA). As a pulsed neutron source, a Pb-Bi target bombarded with 100 MeV protons. The repetition rate of the pulsed proton beam was 20Hz. We applied a Tansparent RUbber SheeT type Eu: $LiCaAlF_6$ (TRUST Eu:LiCAF) scintillator as a neutron detector. The size of the TRUST Eu:LiCAF was 5x5x180 mm^3. The scintillation photons were detected with a photomultiplier tube (PMT) through a wavelength-shifting fiber (WLSF). The PMT signal was fed into a digital signal processor. In this processor, signal waveform was digitized and processed with a Field-Programmable Gate Array (FPGA). The information of pulse height, rise time and detection timing were extracted and transferred to an analysis computer. The analysis computer processed these data and calculated the subcriticality. The detector was placed at the polyethylene moderator region. The subcriticality was changed by inserting control and safety rods.

RESULTS: Figure 1 shows the time profile of neutron counts triggered by incident neutron pulses. In this time profile, the area ratio of prompt and delayed neutrons indicates the subcriticality. The subcriticality can also be estimated from the decay time of prompt neutrons. Figure 2 shows the signal pulse interval spectrum. Prompt neutrons produce an exponential decay component. This decay constant is also proportional to the subcriticality. Figure 3 shows the time trends of the measured neutron counts and measured subcriticality. Our system was confirmed to be able to determine the subcriticality with, at least, ten seconds time resolution.

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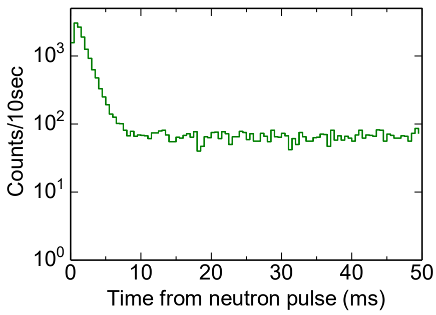

Fig. 1 Time profile of neutron counts triggered by incident neutron pulses.

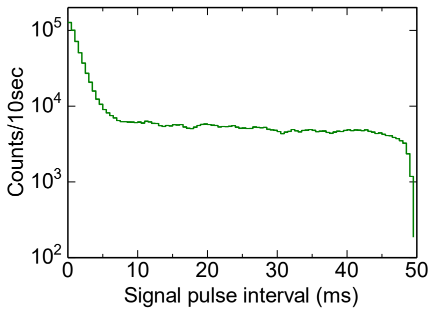

Fig. 2 Signal pulse interval spectrum of each detected signals.

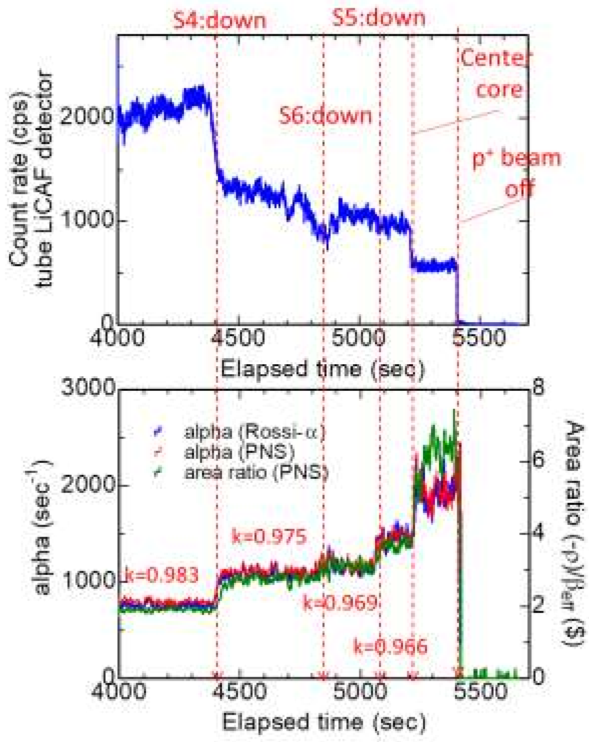

Fig. 3. Time trend of the measured neutron counts (top) and the measured subcriticality (bottom).

PR9-6 Neutronics of Accelerator-Driven System with Spallation Neutrons

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INTRODUCTION: The accelerator-driven system (ADS) has been proposed to reduce the amount of the minor actinides, generated from the daily operation of the commercial power plants, by the transmutation in the hard spectrum core at the subcritical states with the spallation neutrons by 1.5 GeV proton injection onto lead-bismuth (Pb-Bi) target [1]. To operate the ADS cores, the reactor design needs to make the analyses by the combination of the subcritical reactor and the external neutron source. Further, for the ADS as a new concept reactor, the subcriticality monitoring is also requisite to ensure the design accuracy and the safety of actual operation because the operation result is not existed.

In the subcriticality monitoring, measured subcriticality is converted from dollar units into pcm ones with the use of the kinetics parameter. However, the kinetics parameters are widely used by the estimation in eigenvalue calculations without the external neutron source, being questionable to apply the parameters to subcriticality measurements.

At the Kyoto University Critical Assembly (KUCA), to examine the validity of kinetics parameters obtained by the eigenvalue calculations for the subcriticality measurements, the ADS experiments were carried out with the use of two-zoned core, having very hard spectrum by Pb-loaded fuel inside, and spallation neutrons by 100 MeV proton injection onto the Pb-Bi target. In this study, the objective is placed on the examination of the validity of kinetics parameters through subcriticality measurements by the prompt decay neutron constant α in the ADS experiments in a wide range of subcriticality.

EXPERIMENTAL SETTINGS: The two-zoned core was constituted at KUCA-A core with the use of two different fuel rods (f: Pb-loaded fuel, F: polyethylene-moderated fuel in Fig.1), to attain hard spectrum modeling actual ADS core, and polyethylene reflector termed "p," as shown in Fig.1. For the subcritical measurements, four BF_3 and one LiCaF fiber detectors were placed around the core, and also three LiF fiber detectors between the gaps inside the core. 100 MeV protons were prepared by the fixed-field alternating gradient accelerator under the condition of pulsed frequency of 20 Hz, beam current of about 50 pA, and pulsed width of about 100 ns, and was injected onto the Pb-Bi target to supply pulsed spallation neutrons to the subcritical core. The α value was obtained by the fitting of pulsed neutron source (PNS) histogram in the PNS method. The subcriticality was varied by the fuel replacement for polyethylene reflector in 7 cases, ranging between subcriticality 500 and 7400 pcm.

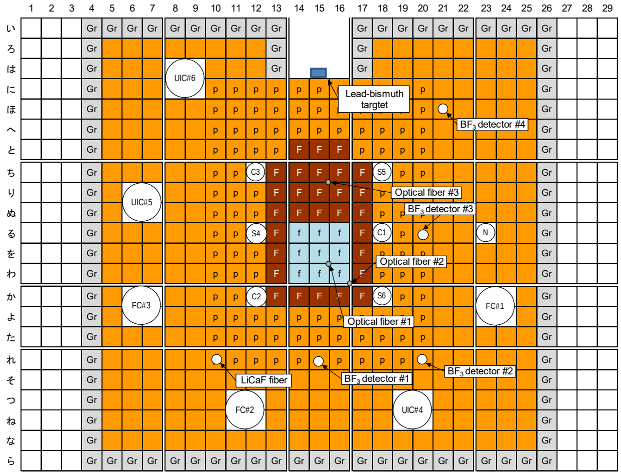

Fig. 1. Critical two-zoned core in KUCA (Case I).

RESULTS: The α values were quantified with the use of subcriticality, effective delayed neutron fraction and generation time by the eigenvalue calculations with MCNP6.1 for each subcriticality case. The results of measured α values by the detector placed on the different position around and inside the core indicated spatial effect especially in deep subcriticality at Cases V through VII. Further, in the comparison between the calculated and measured α values, the calculated α agreed with measured one in Cases I and II. However, calculated α value by the eigenvalue calculations showed a discrepancy with measured one, as the subcriticality became deeper in Cases III through VII, suggesting that the kinetics parameters were also differed by existing the external neutron source at a deep subcriticality, and kinetics parameters should be estimated in the fixed-source calculations.

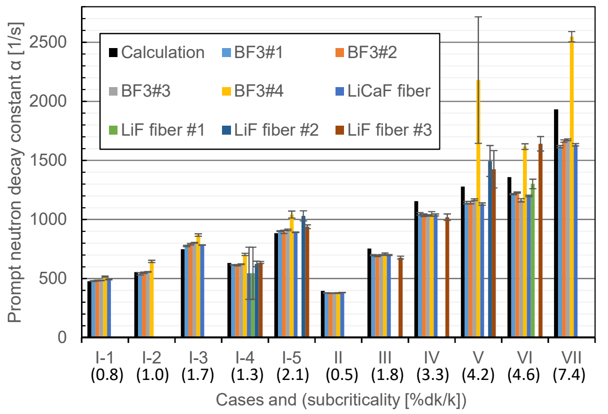

Fig. 2. Results of subcriticality with the use of prompt neutron decay constant α.

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