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Experimental benchmarks on kinetic parameters in accelerator-driven system with 100 MeV protons at Kyoto University Critical Assembly

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ABSTRACT

Accelerator-driven system experiments with spallation neutrons (100 MeV protons and Pb-Bi target) are carried out in the ^{235}U-fueled and Pb-Bi-zoned core at the Kyoto University Critical Assembly, under a subcritical state ranging between 1160 and 11,556 pcm. In these experiments, measurement of the prompt neutron decay constant and the subcriticality is conducted by the pulsed neutron source (PNS) method and the Feynman-α method with the use of optical fiber detectors. The experimental results successfully validate the prompt neutron decay constant and the subcriticality through the deduction of kinetic parameters by both the PNS and the α-fitting methods. The detector position dependency, neutron spectrum and subcriticality measurement methods still remain, however, in these experiments. For onward studies, the experimental benchmarks obtained from these experiments are expected to be involved in the numerical verification of subcriticality on-line monitoring, in the analysis of subcriticality uncertainty and in the deterministic approach to kinetic parameters.

1. Introduction

The accelerator-driven system (ADS) is considered a practical technology for achieving nuclear transmutation of high-level radioactive wastes, including minor actinides and long-lived fission products produced by the light-water reactors. To resolve engineering challenges of nuclear transmutation by ADS, construction of ADS experimental facilities is scheduled in Japan and Belgium: the Transmutation Experimental Facility (TEF) (Tsujimoto et al., 2004) and the Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) (Abderrahim et al., 2007), respectively. In the two ADS facilities, liquid lead-bismuth (Pb-Bi) is expected to play an important role as the target material for generating spallation neutrons and as the coolant in fast neutron spectrum cores. Moreover, the neutron characteristics of Pb-Bi in ADS and its nuclear data uncertainty are supposed to have significant influence on the accuracy of nuclear design calculations. Among preliminary analyses of Pb-Bi neutronics, at the Kyoto University Critical Assembly (KUCA), Monte Carlo analyses (Pyeon et al., 2016) of Pb isotope cross sections have been conducted by Pb sample worth experiments, for evaluating the validation of Pb isotope cross-section data.

Feasibility studies (Lim et al., 2012; Pyeon et al., 2009, 2010, 2013) on ADS have been conducted experimentally in the uranium-235 (^{235}U)-fueled and polyethylene (solid) moderated core (A-core) at KUCA, with 100 MeV protons (tungsten or Pb-Bi target) generated from the fixed-field alternating gradient accelerator (FFAG accelerator) (Lagrange et al., 2013; Yamakawa et al., 2013). For further studies, experimental analyses on reactor physics parameters need to be carried out in the fast neutron spectrum core with Pb-Bi employed as the coolant material in actual ADS cores, as well as on the neutron characteristics (Pyeon et al., 2015) of the solid Pb-Bi target. The KUCA core is equipped to make locally a hard spectrum core region with the combined use of ^{235}U fuel, a polyethylene moderator and a Pb-Bi reflector for criticality, although the core is generally operated at zero power.

In previous ADS experiments with 14 MeV neutrons, subcriticality has been measured by the pulsed neutron source (PNS) method (Sjöstrand, 1956) and the Feynman-α method (Kitamura et al., 2000), at the MASURCA (Soule et al., 2004), the YALINA (Persson et al., 2008) and the VENUS-F (Uyttenhove et al., 2011, 2014) facilities. At KUCA, measurement of kinetic parameters is made in ADS experiments with spallation neutrons, from the

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viewpoint of current ADS research topics: detector position dependency, neutron spectrum and subcriticality measurement methods from the experimental aspect, and subcriticality on-line monitoring, analysis of subcriticality uncertainty and a deterministic approach to kinetic parameters from the numerical aspect. Especially, numerical approach of subcriticality is useful for deducing a certain value of subcriticality by the introduction of suitable correction factors with respect to measured results. In this study, the first attempt was made to examine experimentally the characteristics of kinetic parameters in ADS comprised of ^{235}U-fueled and Pb-Bi-zoned core, and spallation neutrons generated by an injection of 100 MeV protons onto the solid Pb-Bi target. Special attention was paid to the detector position dependency, the neutron spectrum and the subcriticality measurement methods on the kinetic parameters. For a series of the ADS experiments, the effective delayed neutron fraction and the neutron generation time were experimentally deduced with the combined use of subcriticality in dollar units and the prompt neutron decay constant by the PNS method.

The main purpose of this study was to examine experimentally the characteristics of kinetic parameters, under subcriticality ranging between 1160 and 11,556 pcm, in the ^{235}U-fueled and Pb-Bi-zoned core of ADS with spallation neutrons. The core configurations of the experimental settings are described in Sec. 2. The results of experiments are presented in Sec. 3 and the conclusions are summarized in Sec. 4.

2. ADS experiments with 100 MeV protons

2.1. Experimental settings

At KUCA, A and B are polyethylene-moderated and -reflected cores, and C is a light water-moderated and -reflected one. The three cores are operated at a low mW power in the normal operating state, whereas the maximum power is 100 W. The ADS experiments were carried out in the A-core (Fig. 1) comprising a highly-enriched uranium (HEU) fuel, a polyethylene moderator and Pb-Bi reflector rods. The fuel assembly "F" (3/8″p36EU) is composed of 36 unit cells, and upper and lower polyethylene blocks are about 500 and 630 mm long, respectively, in an aluminum (Al) sheath 54 × 54 × 1524 mm, as shown in Fig. 2**(a)**. A special fuel assembly "f" (1/8″p15EUEU < 1/8″Pb-Bi30EUEU > 1/8″p15EUEU) shown in Fig. 2(b) is composed of a total of 60 unit cells: 30 unit cells with HEU plate 1/8″ (3.18 mm) thick and Pb-Bi plate 3.43 mm thick, and 30 unit cells with HEU plate 1/8″ thick and a polyethylene plate 1/8″ thick. As shown in Fig. 2(c), numeral "16" (3/8″p16EU) corresponds to the number of fuel plates in the partial fuel assembly used for reaching critical mass. The neutron spectra were numerically obtained by the MCNP calculations, when 100 MeV protons are injected onto the Pb-Bi target, as shown in Fig. 3 (a) and (b).

Subcriticality was attained by full insertion of control and safety rods, and the substitution of fuel assemblies for polyethylene ones, as shown in Table 1 and Fig. 4: an insertion (Cases 1, 2 and 3 ranged between 1160 and 2483 pcm in subcriticality) of control and safety rods, and the substitution (Cases 4, 5 and 6 ranged between 4812 and 11,556 pcm) of fuel assemblies for polyethylene moderators. In Cases 1, 2 and 3, the subcriticality was deduced experimentally with the combination of the worth of control (C1, C2 and C3) and safety (S4, S5 and S6) rods by the rod drop method and its calibration curve by the positive period method. Furthermore, in Cases 4, 5 and 6, the subcriticality was numerically obtained by the MCNP6.1 (Goorley et al., 2013) code with the JENDL-4.0 (Shibata et al., 2011) library, because the reactivities of control and safety rods were varied by the substitution of fuel assembly rods for polyethylene ones.

The Pb-Bi target was located inside the core at location (15, L) shown in Fig. 1 on the basis of the characteristics of the location of the target outside the core, as discussed in previous study (Lim et al., 2012). Note that the location of the original target is not easily moved to the center of the core, because control and safety rods are fixed in the core to function as the control driving system at KUCA. The Pb-Bi target was 50 mm in diameter and 18 mm thick. The main characteristics of proton beams were 100 MeV energy, 0.7 nA intensity, 40 mm beam spot, 20 Hz beam repetition, 100 ns beam width and 1.0×10^7 1/s neutron generation.

2.2. Measurements of kinetic parameters

During the injection of 100 MeV protons onto the Pb-Bi target located at (15, L) shown in Fig. 1, time evolution of prompt and delayed neutron behavior was examined by the optical fiber detectors (Yagi et al., 2013) set at three locations: Fiber #1 at (12-11, T-R) in Fig. 3(b) between the polyethylene moderator rods, Fiber #2 at (14-13, P-O) in Fig. 3(a) outside and Fiber #3 at (15-14, O-M) inside the ^{235}U-fueled and Pb-Bi-zoned core. The optical fiber was shaped with a mixture of lithium-6-enriched LiF and ZnS (Ag) scintillator pasted at its 1 mm diameter tip.

From the results of neutron signals shown in Fig. 5, prompt neutron decay constant α was deduced from the exponential function fitting of the PNS measurements in the region of prompt neutron behavior as follows:

$$N = C_{PNS} \cdot \exp(-\alpha t) + B_{PNS}, \tag{1}$$

where N indicates the counting rate of the neutron signal, and C_{PNS} and B_{PNS} the constant values obtained by the least-squares fitting. Additionally, subcriticality $\rho_\$$ in dollar units was deduced by the PNS method, on the basis of the following theoretical background: in the area ratio method (Sjöstrand, 1956), subcriticality $\rho_\$$ in dollar units was determined by the ratio of two prompt and delayed components in the decay of neutron density as follows:

$$\rho_\$ = \frac{\rho}{\beta_{eff}} = -\frac{A_p}{A_d}, \tag{2}$$

where ρ indicates the subcriticality in pcm units, β_{eff} the effective delayed neutron fraction, A_p the area of the decay curve by prompt neutrons and A_d the area of delayed neutrons. For reducing the spatial higher-mode components of neutron flux, the extrapolated area ratio method (Gozani, 1962) was introduced into the measurement of subcriticality as follows:

$$\rho_\$ = \frac{\rho}{\beta_{eff}} = -\exp(\alpha t_w)\frac{\int_{t_w}^{T} A_p(t)\,dt}{\int_0^T A_d(t)dt}, \tag{3}$$

where T indicates the measurement time, and t_w the waiting time for reducing the higher-mode components of neutron flux.

Another approach to the α value was attempted by the Feynman-α method (Kitamura et al., 2000) with the use of neutron noise data shown in Fig. 6. The α value was deduced from the least-squares fitting for the Y value with gate width t_g, on the basis of the theoretical background by taking delayed neutron effects into account (Kitamura et al., 2005), as follows:

$$Y = \frac{C_{Noise}}{\alpha^2}\left\{1 - \frac{1-\exp(-\alpha t_g)}{\alpha t_g}\right\} + \frac{B_{Noise}}{t_g}\sum_{n=1}^{\infty}\left\{\frac{1}{n^4\alpha^2 T_0^2 + 4\,n^6\pi^2}\sin^2\left(\frac{n\pi}{T_0}W\right)\sin^2\left(\frac{n\pi}{T_0}t_g\right)\right\}, \tag{4}$$

where C_{Noise} and B_{Noise} indicate the constant values obtained from the noise data, and W and T_0 the pulsed width as fitting parameter