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RECENT EXPERIMENTAL RESULTS OF THE ACCELERATOR DRIVEN SYSTEM WITH A SUB-CRITICAL NUCLEAR REACTOR (ADS) PROGRAM

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Abstract

A series of studies on the accelerator driven system (ADS) has been carried out since 2009 at KURNS. In these studies, Kyoto University Critical Assembly (KUCA) has been used as sub-critical system connected with the proton beam line from FFAG accelerator facility (Fig. 1). A profile of accelerator facility and experimental results, including the first evidence of the transmutation of minor actinides at ADS, will be presented.

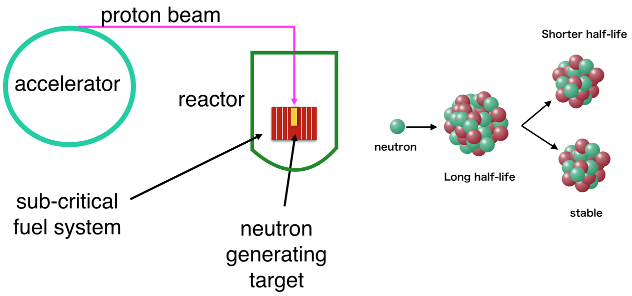

Figure 1: Concept of ADS.

INTRODUCTION

Disposal of spent fuel generated after light water reactor (LWR) operation is an urgent worldwide issue that must be addressed. For instance in Japan, approximately 17,000 tons of spent fuel is stored as of April 2014. Twenty tons of spent fuel is generated with operation of a 1 GWe class LWR for one year. If we assume that 15% of electricity demand in Japan (forecast for 2030) is to be covered by nuclear power, 20 units of this class of LWRs (20 GWe) will be required, and 400 tons of spent fuel will be generated annually. One ton of spent fuel contains 1 kg of minor actinides (MAs). That is, if a group of LWRs generating the electric power of 20 GWe is operated for one year, 400 kg of MA will be generated.

Some MAs have an extremely long half-life. For instance, ^{237}Np has over 2 million years. It takes about 10,000 years to reduce the potential toxicity of ingestion of high-level radioactive waste from spent fuel containing MAs to the same extent as natural uranium. This fact makes it difficult to dispose high-level radioactive waste. With accelerator driven system (ADS) described in this report, long-lived MAs in spent fuel can be converted into stable or short-lived nuclei, and the potential toxicity decay time can be reduced from 10,000 years to a few hundred years. Therefore, ADS research and development, which greatly contributes to the disposal of spent fuel, is extremely significant from this social background.

ACCELERATOR DRIVEN SYSTEM

An accelerator driven system is composed of a nuclear reactor facility and an accelerator facility. It sustains a nuclear fission chain reaction induced by spallation neutrons obtained by irradiation of a heavy metal target using a high energy proton beam from the accelerator. The nuclear reactor plays a role of neutron booster which amplifies the neutron flux from the target.

In resent years,the ADS is paid attention not only as an energy production facility but as a device which transmutes long-lived radioactive materials such as the minor actinide (MA) to other materials whose lifetimes are much shorter than the original ones [1]. In the nuclear fuel cycle, MAs can be processed in a fast breeder. But in terms of the stability of the reactor operation in a critical state, the fraction of the MAs in the fuel system is limited as a few percent. On the other hand, in the ADS, MA can be loaded up to some 30 % because the fuel system is operated in a sub-critical state, in which more stable chain reaction can be obtained.

EXPERIMENTAL FACILITY FOR ADS STUDIES AT KURNS

At the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS), basic experimental studies on the ADS have been started since 2009 using a research reactor Kyoto University Critical Assembly (KUCA) [2]. A fixed field alternating gradient (FFAG) synchrotron has been constructed to deliver high energy proton beams to the KUCA. In these studies, the KUCA is used as a sub-critical reactor and the FFAG accelerator is used as a proton driver.

KUCA

The research reactor KUCA has been designed for precise study on reactor physics. It is a thermal reactor. Its typical output power is on the order of 10 W even in a critical state. It consists of 3 cores: A-Core, B-Core and C-Core. Polyethylene is used as moderators and reflectors of neutrons in A-Core and B-Core while H_2O is used in C-Core. For the ADS experiments, A-Core is used in a sub-critical state.

The A-Core accepts both 100-MeV proton beams from FFAG MAIN RING and 300-keV deuteron beams from a Cockcroft–Walton accelerator. The 100-MeV protons hitting heavy-metal targets such as W or Pb-Bi induce spallation neutrons, while the 300-keV deuterons hitting the Lithium

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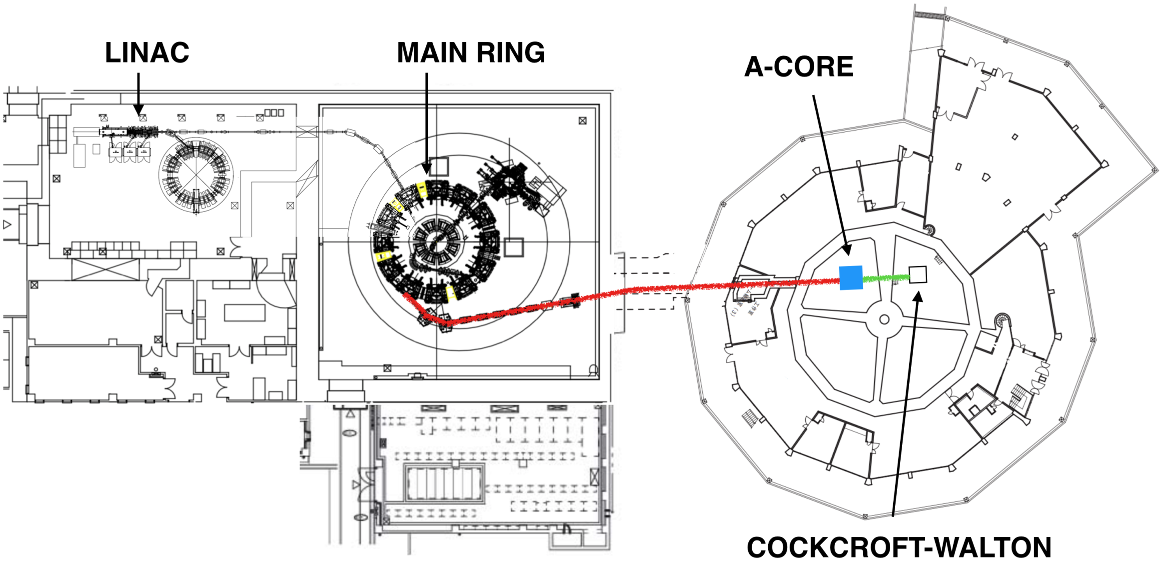

Figure 2: Layout of FFAG accelerator complex and KUCA.

target produce 14 MeV neutrons due to the D-T reaction. At the A-Core, two different types of accelerator driven neutron source can be used for the ADS study.

FFAG Accelerator Complex

The layout of the KURNS FFAG accelerator complex is shown in Figs. 2 and 3 [3]. The complex consists of an 11 MeV H$^-$ injector LINAC, an 11-MeV H$^-$ beam line, an FFAG synchrotron called MAIN RING and a 100-MeV proton beam line. Table 1 shows the basic parameters of the complex.

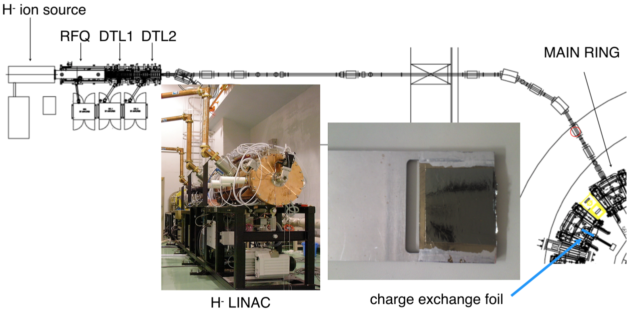

Figure 3: Detailed layout of FFAG accelerator complex.

The LINAC consists of RFQ, DTL1 and DTL2. H$^-$ beams are injected into the MAIN RING through a charge stripping foil made of carbon, whose thickness is 20 µg/cm^2. In this injection scheme, no pulse device is used. Even orbit merging magnets are not necessary because the H$^-$ beams are merged inside the main magnet of the MAIN RING. Proton beams from the MAIN RING is delivered as extremely short bunch such as 100 ns. The instantaneous beam power is a few ten kW. Therefore, dynamic characteristics of ADS can be investigated with these beams. The beam specification from the MAIN RING is summarized in Table 1.

Table 1: Basic Parameters of KURRI FFAG Accelerator Complex

LINAC	
Energy	11 MeV
Peak current	< 5 µA
Pulse length	< 100 µs (uniform)
Repetition rate	< 200 Hz
MAIN RING	
Energy	11 - 100 or 150 MeV
Field index k	7.5
Magnetic field	1.6 T (max.)
Revolution frequency	1.6 - 4.3 MHz
Rf voltage	4 kV
Repetition rate	< 30 Hz

Although the repetition rate of the LINAC is 200 Hz, that of the MAIN RING is limited up to 30 Hz because of a low accelerating speed. If the accelerating cavity voltage can be increased, high df/dt can be realized. Therefore, a higher repetition rate at the MAIN RING can be obtained.

FIRST MINOR ACTINIDE TRANSMUTATION BY ADS AT KURNS

The experimental studies at KURNS have been carried out since 2009. Numbers of results have been obtained. These can be seen in the articles [4–8]. On 14th and 15th February 2019, the first nuclear transmutation of minor actinides by the ADS was successfully demonstrated [9] in a sub-critical core at KUCA, detecting following reactions:

- fission reaction of ^{237}Np and ^{241}Am,
- capture reaction of ^{237}Np.

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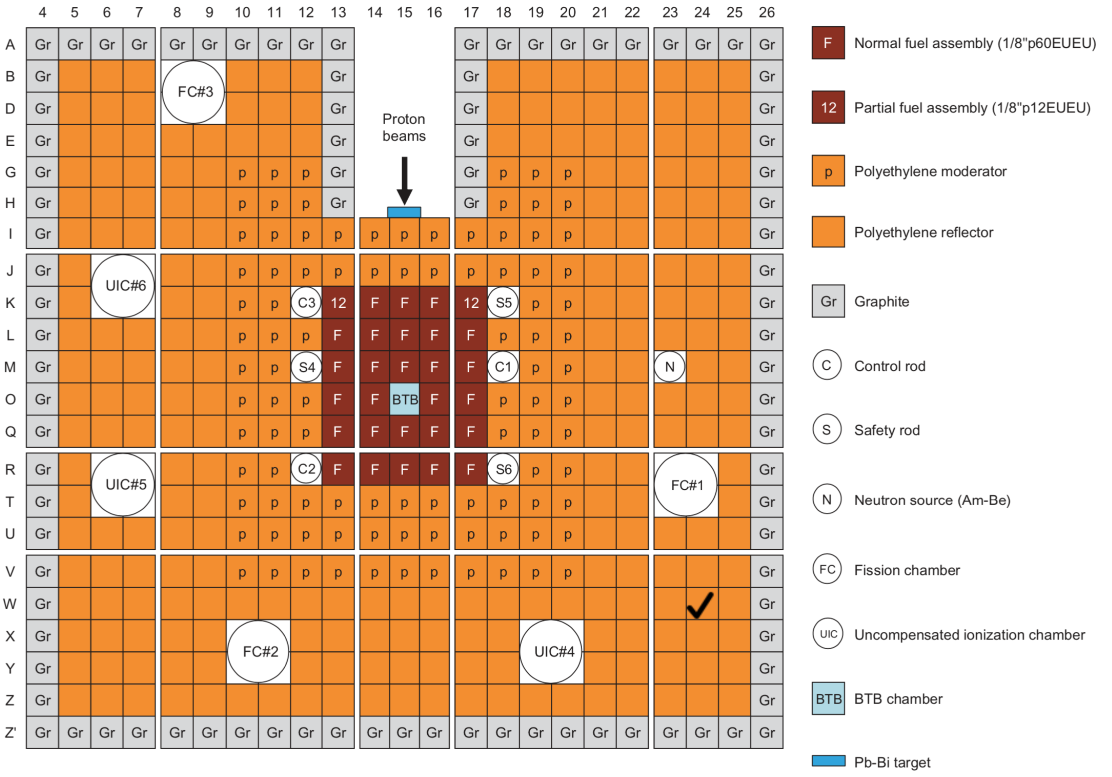

	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
A	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr				Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr
B	Gr				FC#3					Gr				Gr									Gr
D	Gr									Gr		Proton beams		Gr									Gr
E	Gr									Gr				Gr									Gr
G	Gr						p	p	p	Gr				Gr	p	p	p						Gr
H	Gr						p	p	p	Gr				Gr	p	p	p						Gr
I	Gr						p	p	p	p	p	p	p	p	p	p	p						Gr
J	Gr		UIC#6				p	p	p	p	p	p	p	p	p	p	p						Gr
K	Gr						p	p	C3	12	F	F	F	12	S5	p	p						Gr
L	Gr						p	p	p	F	F	F	F	F	p	p	p						Gr
M	Gr						p	p	S4	F	F	F	F	F	C1	p	p			N			Gr
O	Gr						p	p	p	F	F	BTB	F	F	p	p	p						Gr
Q	Gr						p	p	p	F	F	F	F	F	p	p	p						Gr
R	Gr		UIC#5				p	p	C2	F	F	F	F	F	S6	p	p			FC#1			Gr
T	Gr						p	p	p	p	p	p	p	p	p	p	p						Gr
U	Gr						p	p	p	p	p	p	p	p	p	p	p						Gr
V	Gr						p	p	p	p	p	p	p	p	p	p	p						Gr
W	Gr																				✓		Gr
X	Gr						FC#2									UIC#4							Gr
Y	Gr																						Gr
Z	Gr																						Gr
Z'	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr	Gr

F	Normal fuel assembly (1/8"p60EUEU)
12	Partial fuel assembly (1/8"p12EUEU)
p	Polyethylene moderator
🟧	Polyethylene reflector
Gr	Graphite
C	Control rod
S	Safety rod
N	Neutron source (Am-Be)
FC	Fission chamber
UIC	Uncompensated ionization chamber
BTB	BTB chamber
▬	Pb-Bi target

Figure 4: Configuration of sub-critical core (from the article [9]).

Core Configuration

A sub-critical core configuration for these experiments is shown in Fig. 4. The symbol “F” and “12” indicate the fuel assembly. The fuel used here was highly-enriched ^{235}U. A neutron production target made of solid state Pb-Bi was located at (15,H) on the core coordinate. The control and safety rods indicated by C1–C3 and S4–S6 were set in appropriate positions so that the sub-criticality was desired value.

The sample foils of ^{237}Np and ^{241}Am were installed in the special void element located at (15,O) with the reference ^{235}U foil and the back-to-back (BTB) fission chamber. The BTB chamber detects the signals of fission fragments due to the fission reaction in the sample foil and the reference one.

Proton Beams

A typical signal from the bunch monitor installed in the MAIN RING is shown in Fig. 5. The beam acceleration from 11 MeV to 100 MeV needs ~24.3 ms with the accelerating cavity voltage of 4 kV and synchronous phase of 30 deg. The repetition rate of the machine operation was 30 Hz. The characteristics of the proton beam for the experiments are summarized in Table 2.

There was a small amount of beam loss around 4 ms from the start of acceleration. It is attributed to the betatron resonance crossing. Except for this, no significant beam loss was observed after 4 ms from the start.

Table 2: Proton Beam Characteristics

Energy	100 MeV
Intensity	0.5 nA - 1 nA
Pulse width	100 ns
Repetition rate	30 Hz
Beam size at Pb-Bi target	40 mm in diameter

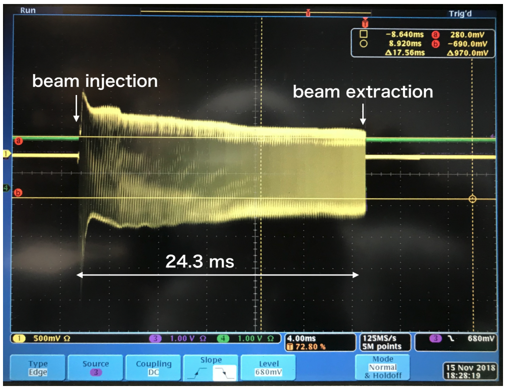

Figure 5: Typical signal from bunch monitor.

RESULTS

For the fission reaction, the pulse height distributions from BTB fission chamber for ^{237}Np and ^{241}Am were obtained as shown in Fig 6. The fission reactions in both the ^{237}Np and the ^{235}U foils were clearly observed over entire region of pulse height. For the case of ^{241}Am, signals lower than

480 ch are attributed to α-ray induced by ^{241}Am. In the higher pulse height region, although the fraction is small, signals from fission reaction can be observed.

Also for the capture reaction, γ-ray emission was detected by germanium detector after the irradiation. Obtained γ-ray spectrum is shown in Fig. 7.

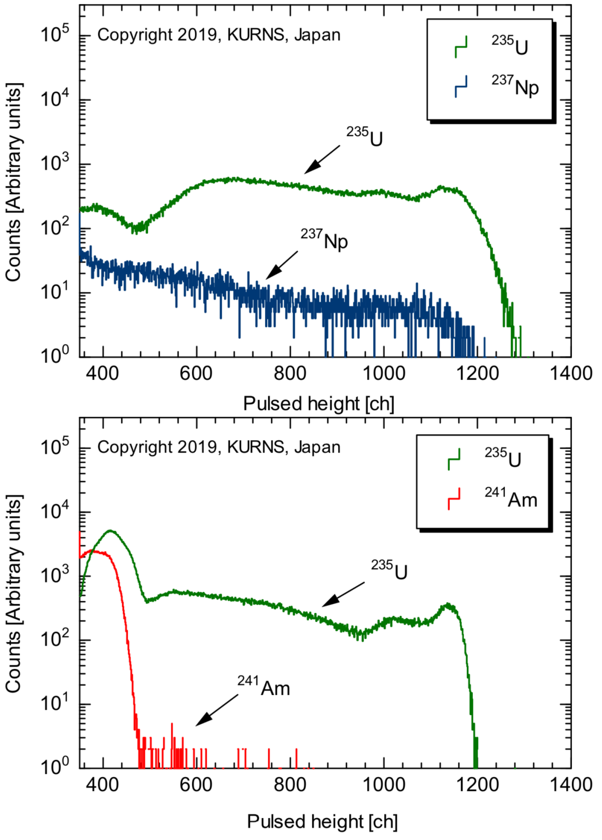

Figure 6: Pulse height distribution from BTB fission chamber for ^{237}Np and ^{241}Am.

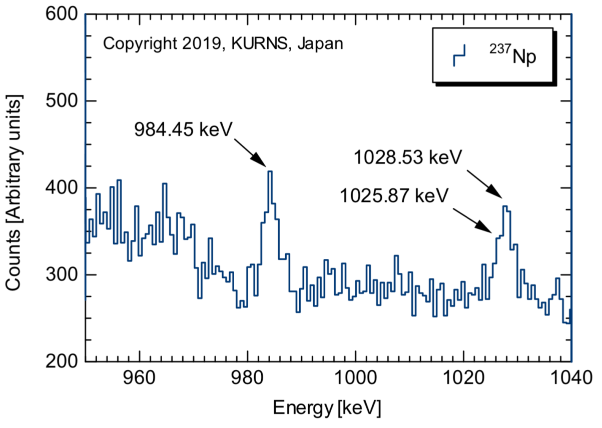

Figure 7: Measured γ-ray spectrum of capture reaction of ^{237}Np.

CONCLUSION

The world's first experiments for transmutation of minor actinide (^{237}Np and ^{241}Am) in accelerator driven system have been accomplished at the Institute for Integrated Radiation and Nuclear Science, Kyoto University.

ACKNOWLEDGMENTS

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