Experimental Benchmarks on Accelerator-Driven System at Kyoto University Critical Assembly

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**Background**

- An original concept of ADS for producing energy and transmuting MA and LLFP
  - Nuclear transmutation and Energy amplifier system
- Outline and Roadmap of ADS study
  - Focus on analyses of reaction rates and subcriticality
  - Deterministic methodology of ADS experiments
- ADS research activities in Japan
  - JAEA: TEF facilities in J-PARC
  - KURRI: ADS experiments with KUCA+FFAG (100 MeV protons) accelerator

**Purpose**

- Conduct feasibility study on ADS, relating energy amplifier and nuclear transmutation
- Investigate neutron characteristics of ADS through the experiments and the accuracy of numerical (MCNP) analyses
Roadmap of ADS for nuclear transmutation

- Actual ADS plant
  - 30 MW-beam, 800 MWth
  - MA nucl. trans. of 10 LWR plants

- MYRRHA in Belgium
  - ~2.4 MW-beam, 50~100 MWth
  - Demonstration of ADS tech.
  - Fuel irradiation

- TEF of J-PARC in Japan
  - Pb-Bi target exp.
  - Reactor physics exp. (MA in kg order)
  - R&D of basic and eng.

- R&D of
  - Reactor physics of MA fuel
  - Target materials

- Power
  - ADS tech. w/o MA fuel (Pb-Bi core, Accelerator, Operation experiences)

- Principle
  - Demonstration
  - Concept

- 2016
  - Reactor Physics Exps. at KUCA

- 2020
- 2025

- Future

- ① KUCA-FFAG: Reactor Physics Exp.

- ② ADS plant R&D of engineering feasibility
  - High-reliability of accelerator
  - Control of subcriticality
  - Removal system of heat decay

 EuCARD², CERN, Switzerland, 7-9 Feb. 2017

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# Experimental facilities in the world

Table: Specification of ADS facilities in the world

<table>
<thead>
<tr>
<th>Project or Facility</th>
<th>Country</th>
<th>Fuel</th>
<th>Reflector or Coolant</th>
<th>Spectrum</th>
<th>Accelerator (target)</th>
<th>Power</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUSE</td>
<td>France</td>
<td>MOX</td>
<td>Na</td>
<td>Fast</td>
<td>14 MeV – n</td>
<td>Zero</td>
<td>Finished</td>
</tr>
<tr>
<td>YALINA</td>
<td>Belarus</td>
<td>LEU</td>
<td>Solid metal</td>
<td>Fast &amp; Thermal</td>
<td>14 MeV – n</td>
<td>Zero</td>
<td>Finished</td>
</tr>
<tr>
<td>VENUS-F</td>
<td>Belgium</td>
<td>LEU (MOX)</td>
<td>Pb</td>
<td>Fast</td>
<td>14 MeV – n</td>
<td>Zero</td>
<td>Being</td>
</tr>
<tr>
<td>KUCA</td>
<td>Japan</td>
<td>HEU</td>
<td>Polyethylene (Gr, Pb &amp; Pb-Bi)</td>
<td>Thermal</td>
<td>14 MeV – n 100 MeV – p (W, Pb-Bi...)</td>
<td>Zero</td>
<td>Being</td>
</tr>
<tr>
<td>CLEAR-1</td>
<td>China</td>
<td>UO$_2$</td>
<td>Pb</td>
<td>Fast</td>
<td>14 MeV – n</td>
<td>Zero</td>
<td>Planned</td>
</tr>
<tr>
<td>TEF</td>
<td>Japan</td>
<td>LEU (Pu) + MA</td>
<td>Pb-Bi</td>
<td>Fast</td>
<td>400 MeV – p (Pb-Bi)</td>
<td>500 Wth</td>
<td>Planned</td>
</tr>
<tr>
<td>MYRRHA</td>
<td>Belgium</td>
<td>MOX + MA</td>
<td>Pb-Bi</td>
<td>Fast</td>
<td>600 MeV – p (Pb-Bi)</td>
<td>100 MWth</td>
<td>Planned</td>
</tr>
</tbody>
</table>
Main parameters in the FFAG accelerator:

- **# of sectors**: 12
- **Energy**: 100 MeV
- **Repetition rate**: 20 Hz
- **Average beam current**: 1 nA
- **Width**: 50 ns
- **Field index**: 7.5
- **Closed orbit radius**: 4.4 - 5.3 m

- **11 MeV, 5 mA (Max.)**
  - Electron LINAC
  - H⁻
  - Charge convert H⁻ -> H⁺

- **100 MeV H⁺**
  - Proton beam current 1 nA
  - Main ring (FFAG acc.)

**KUCA**

Max. power : 100 W
N Yield : $1 \times 10^9$ 1/s
ADS composition at KUCA

D + T target = 14 MeV neutrons

100 MeV protons + W target = Spallation neutrons

Beam line of D

Beam line of protons

KUCA core

Pulsed neutron generator

FFAG accelerator

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KUCA core (Solid-moderated core)

- KUCA core -
  A solid-moderated and reflected core

Fig. KUCA core

Fig. Image of KUCA core and fuel assembly loaded
235U-loaded ADS with 14 MeV neutrons

235U-loaded ADS experiments with 14 MeV neutrons (IAEA ADS CRP in 2007 to 2011)

- Subcriticality measurements
- Neutron spectrum (Activation foils)
- Reaction rates (M and k-source)

235\textsuperscript{U}-loaded ADS with 100 MeV protons

235\textsuperscript{U}-loaded ADS experiments with 100 MeV protons

(IAEA ADS CW from 2016 to 2019)

**235U-ADS: Source spectrum of target**

![Graph showing neutron spectrum](image)

- Very unique peak ranging between 85 and 100 MeV neutrons (for 100 MeV proton injection)

-> How about influences on neutron characteristics in the core?

**Fig. Neutron spectrum of injection of 100 MeV protons into heavy metal target**

- Spectrum of spallation neutrons (100 MeV proton injection)
  - W, W-Be and Pb-Bi targets
  - Almost same


![Graph showing comparison between neutron spectra](image)

**Fig. Comparison between neutron spectra of W and W-Be targets**
Static: Neutron multiplication

**Fig. Core configuration of $^{235}$U-PE core (100 MeV protons)**

Table Comparison between measured and calculated M values (Subcritical level: 2,657 pcm)

<table>
<thead>
<tr>
<th>Target</th>
<th>Calculation</th>
<th>Experiment</th>
<th>C/E value</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>1.73 ± 0.01</td>
<td>1.85 ± 0.02</td>
<td>0.93 ± 0.01</td>
</tr>
<tr>
<td>W-Be</td>
<td>2.29 ± 0.01</td>
<td>2.36 ± 0.03</td>
<td>0.97 ± 0.01</td>
</tr>
<tr>
<td>Pb-Bi</td>
<td>1.95 ± 0.01</td>
<td>1.94 ± 0.02</td>
<td>1.01 ± 0.01</td>
</tr>
</tbody>
</table>


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$^{232}$Th-loaded ADS Benchmarks

$^{232}$Th-loaded ADS experiments with 14 MeV neutrons or 100 MeV protons

(IAEA ADS CW from 2013 and 2014)

Exp. benchmarks on Th-loaded ADS

Fig. Proportionality of X secs. of $^{232}$Th and $^{115}$In in thermal neutron range

- **Measurement (Foil activation method)**

  - **Source:**
    - 14 MeV neutrons $\rightarrow ^{93}$Nb(n, 2n)$^{92m}$Nb (9 MeV threshold)
    - 100 MeV protons $\rightarrow ^{115}$In(n, n')$^{115m}$In (0.3 MeV threshold)
  - **Core:** In capture (~ Th capture; Proportionality) $\rightarrow ^{115}$In(n, $\gamma$)$^{116m}$In reactions

Fig. Neutron spectrum in injection of **100 MeV protons**

Fig. Neutron spectrum in injection of **14 MeV neutrons**

Profile on $^{232}$Th capture reaction rates

(a) $^{232}$Th-loaded core with 14 MeV neutrons

(b) $^{232}$Th-loaded core with 100 MeV protons (W target)

Fig. Core configuration of $^{232}$Th-loaded core


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Kinetic parameters ($^{232}$Th-loaded ADS)

**Fig.** Time evolution of PNS method (14 MeV neutrons vs. 100 MeV protons with W target)

**Fig.** Noise data by Feynman-α method (14 MeV neutrons vs. 100 MeV protons with W target)

**Fig.** Comparison between a value by PNS and Feynman-α methods (14 MeV neutrons vs. 100 MeV protons with W target)

**Discussion issues**
- Detector position dependency
- Neutron spectrum (External Source)
- Subcriticality measurement methods

Solid Pb-Bi Study
(collaboration with KUCA and JAEA)

Uncertainties of Pb-Bi x-sec

Motivation
- Discrepancy between JENDL-3.3 and JENDL-4.0 of Pb-Bi x-sec. through numerical simulations of JAEA ADS model (Pb-Bi coolant model)

Experiments at KUCA (critical state)
- Sample worth (reactivity) of Pb plate in the critical state

Table Sample reactivity (C/E value) of Pb plates

<table>
<thead>
<tr>
<th>Reactivity (pcm)</th>
<th>JENDL-3.3</th>
<th>JENDL-4.0</th>
<th>ENDF/B-VII.0</th>
<th>JEFF-3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>94 ±7</td>
<td>1.63±0.13</td>
<td>1.13±0.10</td>
<td>0.79±0.08</td>
<td>0.89±0.09</td>
</tr>
<tr>
<td>110 ±6</td>
<td>1.53±0.10</td>
<td>1.07±0.08</td>
<td>0.85±0.07</td>
<td>0.97±0.07</td>
</tr>
<tr>
<td>145 ±6</td>
<td>1.65±0.08</td>
<td>1.12±0.06</td>
<td>0.94±0.05</td>
<td>1.00±0.05</td>
</tr>
<tr>
<td>156 ±7</td>
<td>1.76±0.08</td>
<td>1.13±0.06</td>
<td>0.94±0.05</td>
<td>0.98±0.05</td>
</tr>
</tbody>
</table>


Upcoming experiments (Successive investigation)
- Sample worth of Bi and Pb-Bi plates in the critical state
MA irradiation in ADS (on Oct. 2017)

Experimental settings
- $^{235}$U and Pb-Bi zoned core
- 100 MeV protons and Pb-Bi target
- Back-To-Back Type Fission Chamber (BTB fission chamber)
- MA sample ($^{237}$Np and $^{241}$Am)
  - $^{237}$Np: Capture and fission
  - $^{241}$Am: Fission
- Reference: $^{235}$U, $^{238}$U or $^{197}$Au

Fig. Core configuration of $^{235}$U and Pb-Bi zoned core

Fig. Neutron spectrum of core center in F' at 100 MeV proton injection onto Pb-Bi target
**Summary**

### Current status

- **ADS research project in Kyoto Univ. Research Reactor Institute**
  - Application of ADS with high-energy protons to nuclear transmutation and energy amplifier system

- **Current status on ADS in the world**
  - Outline and roadmap of ADS
  - Research activities in Japan (JAEA and KURRI)

- **At KUCA, $^{235}$U- and $^{232}$Th-loaded ADS experiments**
  - Feasibility study on ADS with $^{235}$U-loaded core and external sources
  - Preliminary study on $^{232}$Th fission and capture reaction rates

### Future plans

- Uncertainty analyses of Pb-Bi X-sec.
- MA irradiation at ADS with 100 MeV protons (Pb-Bi target)
- Analyses of $^{237}$Np and $^{241}$Am reaction rates
- Online monitoring of subcriticality by the PNS and Noise methods