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

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**Background**

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

**Purpose**

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

- **Power**
  - 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.
- **Demonstration**
  - Actual ADS plant
    - 30 MW-beam, 800 MWth
    - MA nucl. trans. of 10 LWR plants
  - R&D of
    - Reactor physics of MA fuel
    - Target materials
- **Principle**
  - KUCA-FFAG: Reactor Physics Exp.
    - High-reliability of accelerator
    - Control of subcriticality
    - Removal system of heat decay

**Roadmap of ADS for nuclear transmutation**

- **2016**
  - Reactor Physics Exps. at KUCA
- **2020**
- **2025**
- **Future**

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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>UO₂</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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td># of sectors</td>
<td>12</td>
</tr>
<tr>
<td>Energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Average beam current</td>
<td>1 nA</td>
</tr>
<tr>
<td>Width</td>
<td>50 ns</td>
</tr>
<tr>
<td>Field index</td>
<td>7.5</td>
</tr>
<tr>
<td>Closed orbit radius</td>
<td>4.4 - 5.3 m</td>
</tr>
</tbody>
</table>
**ADS composition at KUCA**

- **Beam line of D**
  - D + T target = 14 MeV neutrons

- **KUCA core**
  - T target

- **Beam line of protons**
  - 100 MeV protons + W target = Spallation neutrons

- **Pulsed neutron generator**
  - FFAG accelerator

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

Plates/Blocks: HEU, NU, Th, PE, Pb, Pb-Bi, Gr, Be

EuCARD², CERN, Switzerland, 7-9 Feb. 2017
\(^{235}\text{U}\)-loaded ADS with 14 MeV neutrons

\(^{235}\text{U}\)-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)

$^{235}$U-loaded ADS with 100 MeV protons

$^{235}$U-loaded ADS experiments with 100 MeV protons

(IAEA ADS CW from 2016 to 2019)

Experiment Overview

Investigation of Effect of Target in ADS

Proton Beam  Target  Spallation Neutron

W  Pb-Bi  Be W


<table>
<thead>
<tr>
<th>Target</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>50.0</td>
<td>12.0</td>
</tr>
<tr>
<td>W-Be</td>
<td>50.0</td>
<td>12.0; Be: 10.0</td>
</tr>
<tr>
<td>Pb-Bi</td>
<td>50.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>
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EuCARD$^2$, CERN, Switzerland, 7-9 Feb. 2017

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

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


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

- How about influences on neutron characteristics in the core?

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

Fig. Core configuration of $^{235}\text{U}$-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 $\pm$ 0.01</td>
<td>1.85 $\pm$ 0.02</td>
<td>0.93 $\pm$ 0.01</td>
</tr>
<tr>
<td>W-Be</td>
<td>2.29 $\pm$ 0.01</td>
<td>2.36 $\pm$ 0.03</td>
<td>0.97 $\pm$ 0.01</td>
</tr>
<tr>
<td>Pb-Bi</td>
<td>1.95 $\pm$ 0.01</td>
<td>1.94 $\pm$ 0.02</td>
<td>1.01 $\pm$ 0.01</td>
</tr>
</tbody>
</table>


Fig. Measured reaction rate distribution (M and k-source study)
232Th-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


EuCARD$^2$, CERN, Switzerland, 7-9 Feb. 2017
Profile on $^{232}\text{Th}$ capture reaction rates

![Diagram of core configuration](image1.png)

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

![Diagram of core configuration](image2.png)

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


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![Comparison of neutron spectra](image3.png)

Fig. Comparison of neutron spectra

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

Fig. Measured $^{115}\text{In} (n, \gamma)^{116m}\text{In}$ reaction rates

(14 MeV neutrons vs. 100 MeV protons with W target)
Kinetic parameters ($^{232}$Th-loaded ADS)

Detector #1

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

Detector #1

**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)

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)


EuCARD², CERN, Switzerland, 7-9 Feb. 2017
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
Thank You for Your Attention