# Thorium-Loaded Accelerator-Driven System Experiments in Kyoto University Research Reactor Institute

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  - **K**yoto **U**niversity **C**ritical **A**ssembly (KUCA)
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- $^{232}$Th plate irradiation experiments in **critical** state
  - Analyses of $^{232}$Th fission and capture reactions

- $^{232}$Th-loaded ADS experiments in **subcritical** state
  - Static analyses: $^{232}$Th capture reaction rates
  - Kinetic analyses: Subcriticality by varying
    - Core spectrum
    - External neutron source

- Summary

# Background and Purpose

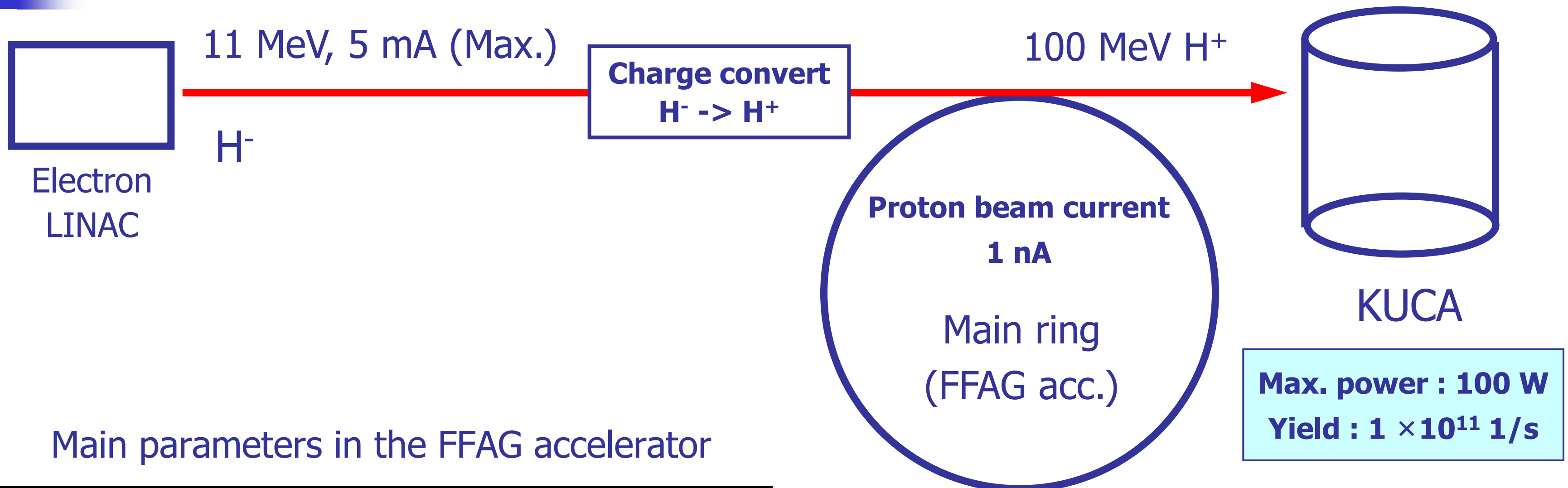
**Background**

- ➢ An original concept of ADS for producing energy and transmuting MA and LLFP
- ● **Energy amplifier system and Nuclear transmutation**
- ➢ $^{232}$Th conversion study in thorium fuel cycle
- ● Preliminary study on fission and capture reactions leading to **conversion ratio (Capture/ Fission)** in Critical state analyses
- ➢ $^{232}$Th-loaded ADS for the variation of
- ● Core spectrum: Fuel -> Thorium, HEU and NU
  Moderator -> Polyethylene, Graphite, Beryllium and Aluminum
- ● External source: 14 MeV neutrons vs. 100 MeV protons

**Purpose**

- ➢ Conduct $^{232}$Th conversion study preliminarily in critical state
- ➢ Investigate the neutronic characteristics of Th-ADS through the experiments and the accuracy of numerical (MCNPX) analyses

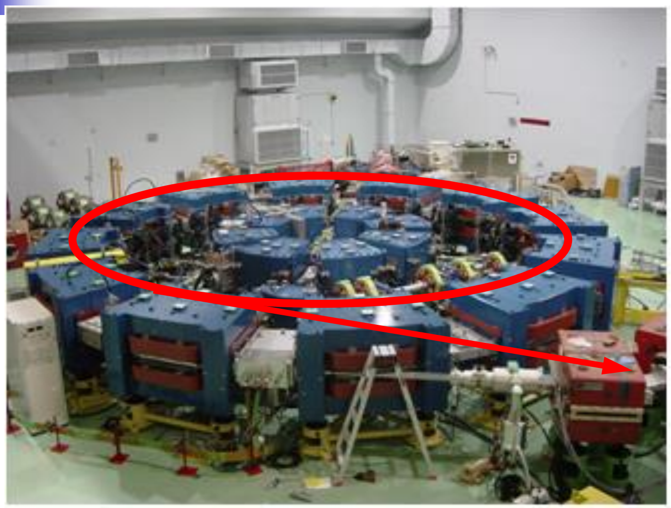
# ADS composition




Main parameters in the FFAG accelerator

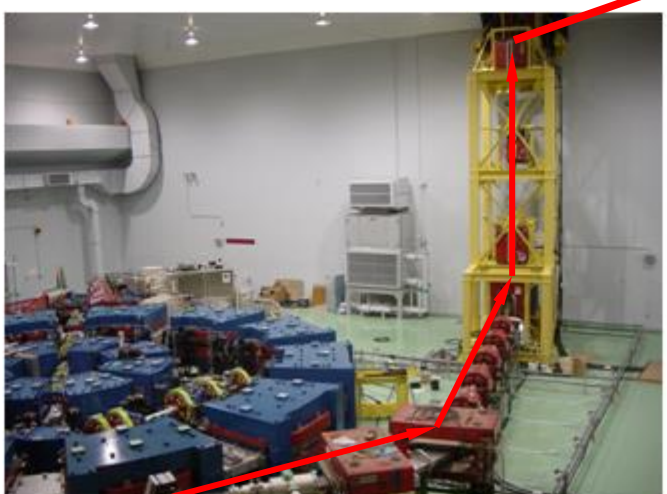
| | |
|---|---|
| # of sectors | 12 |
| Energy | 2.5 – 150 MeV |
| Repetition rate | 120 Hz |
| Average beam current | 1 nA |
| Rf frequency | 1.5 - 4.6 MHz |
| Field index | 7.5 |
| Closed orbit radius | 4.4 - 5.3 m |

# ADS composition in KUCA

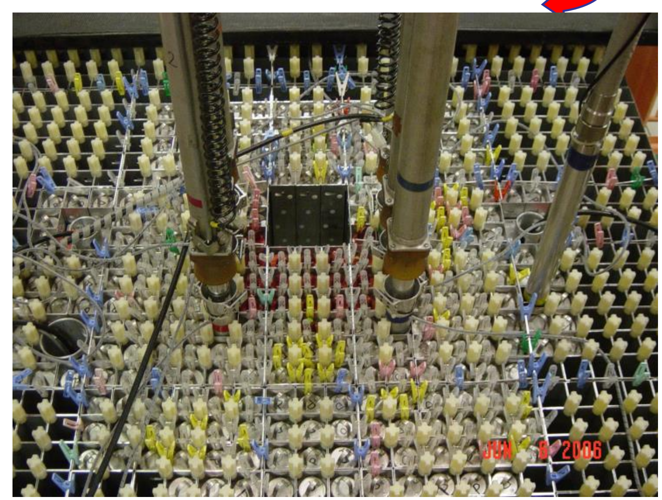


FFAG accelerator

KUCA A-core



100 MeV proton beam line



# Conversion of Thorium fuel cycle

- **Capture** reactions

$$^{232}\mathrm{Th} \xrightarrow{(n,\gamma)} {}^{233}\mathrm{Th} \xrightarrow[22.3\mathrm{m}]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[26.967\mathrm{d}]{\beta^-} {}^{233}\mathrm{U}$$

- **Fission** reactions

$$^{233}\mathrm{U}(n, f)$$

**General conversion concept**

**Capture / Fission**

However, as preliminary, attention should be paid to the following:

- **Capture** reactions (by thermal neutrons moderated from high-energy neutrons)

$$^{233}\mathrm{Pa} \xrightarrow[26.967\mathrm{d}]{\beta^-} {}^{233}\mathrm{U}$$

- **Fission** reactions (by high-energy neutrons from spallation neutrons)

$^{232}\mathrm{Th}(n, f)$ (Threshold of 1 MeV neutrons)

# KUCA core (Solid-moderated core)

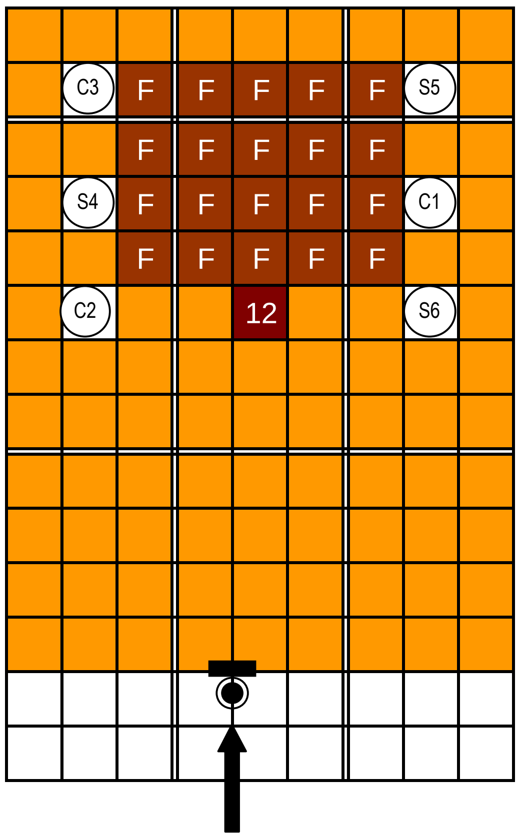



Fig. KUCA core

- KUCA core -

A solid-moderated and -reflected core

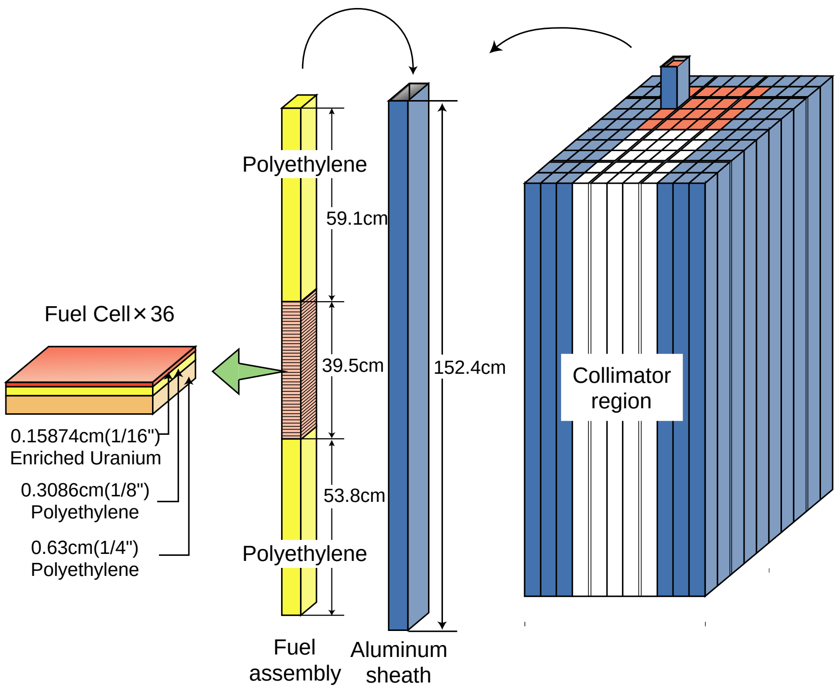



Fig. Image of KUCA core and fuel assembly loaded

# $^{232}$Th plate irradiation experiments

## Critical state

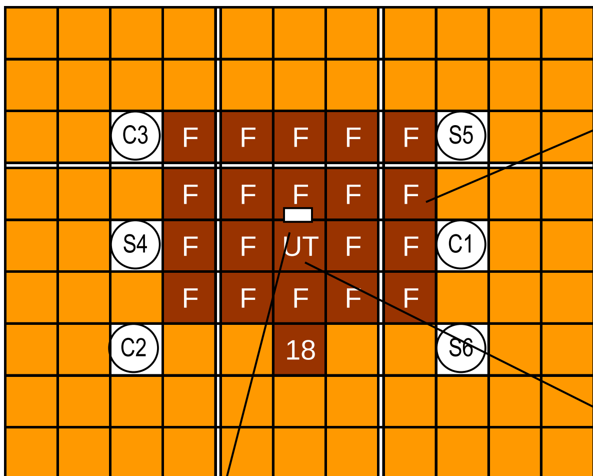
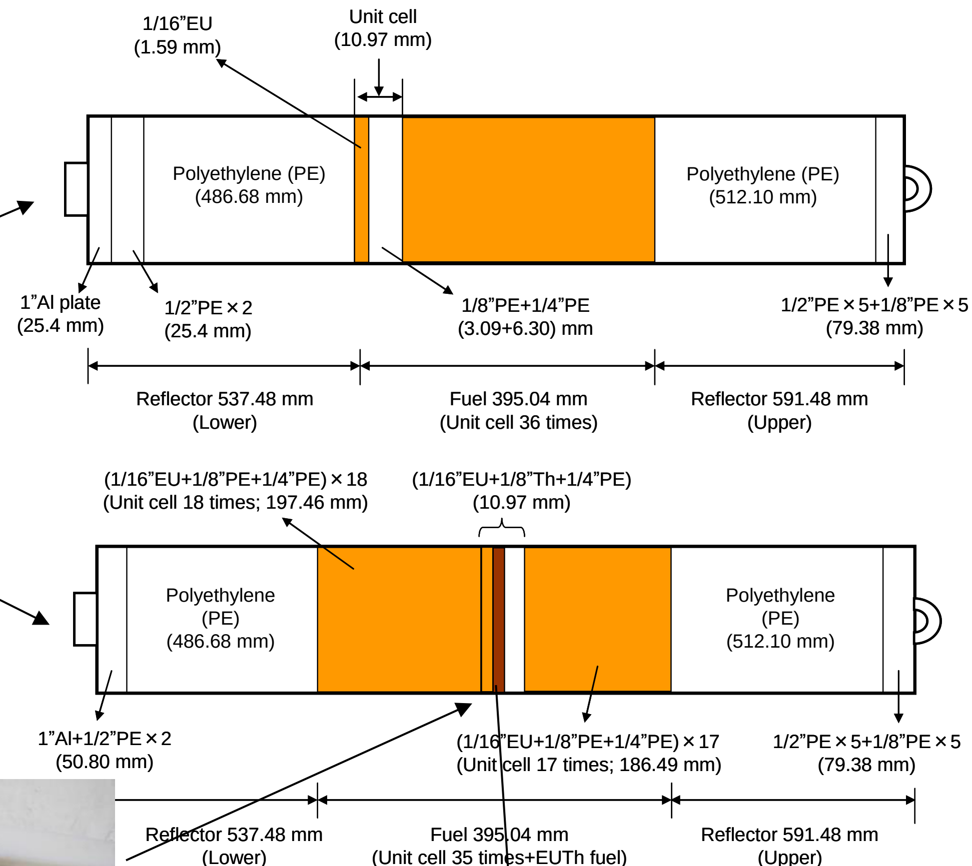
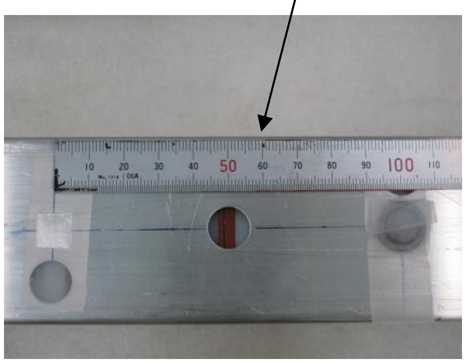
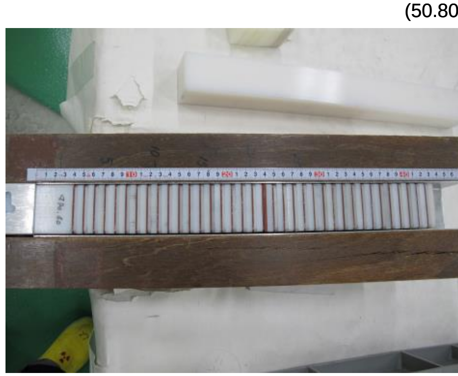



Fig. KUCA core
($^{232}$Th plate irradiation core)





**$^{232}$Th plate size: 2”×2” ×1/8”**

# Results of $^{232}$Th plate irradiation exp.

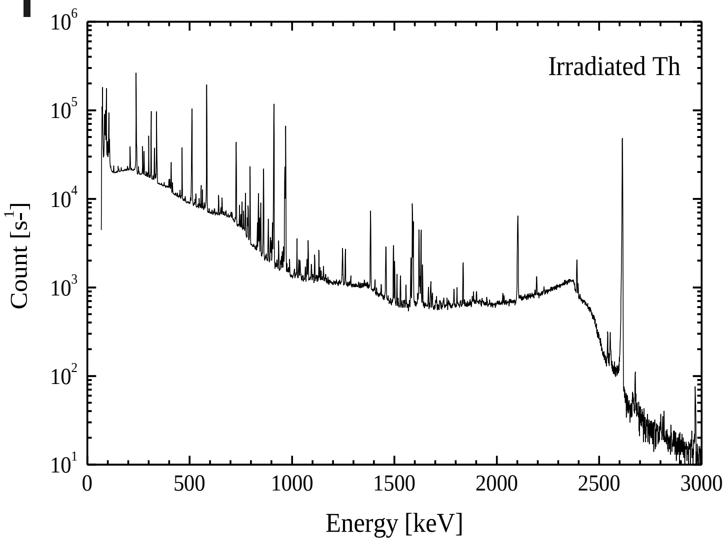



Fig. Measured γ-ray spectrum of irradiated $^{232}$Th plate

Table Neutron flux and Cd ratio

| | Measurement | Calculation | C / E |
|---|---|---|---|
| Thermal neutron flux (1/s/cm$^3$) | **(5.87±0.05)×10$^7$** | - | - |
| Cd ratio | 2.93±0.02 | 3.04±0.08 | **1.04±0.05** |

Table Measured reaction rates (RR) and C/E values

| Reaction | Nuclide | Measured RR (1/s/cm$^3$) | C / E |
|---|---|---|---|
| Capture | $^{233}$Pa | (5.82±0.04)×10$^6$ | **2.18±0.04** |
| Fission | $^{91}$Sr | (1.42±0.04)×10$^5$ | **1.39±0.05** |
| | $^{92}$Sr | (1.46±0.05)×10$^5$ | **1.36±0.06** |
| | $^{97}$Zr | (1.47±0.02)×10$^5$ | **1.35±0.03** |
| | $^{135}$I | (1.50±0.04)×10$^5$ | **1.32±0.04** |
| | $^{142}$La | (1.56±0.05)×10$^5$ | **1.27±0.05** |

**- Critical exp. (Confirmed)**

- Necessity of high-power operation in the core
- Accuracy of numerical analyses by MCNPX
- Discrepancy of $^{232}$Th fission and capture reaction rates between exp. and cal.
- Probability of subcritical experiments?

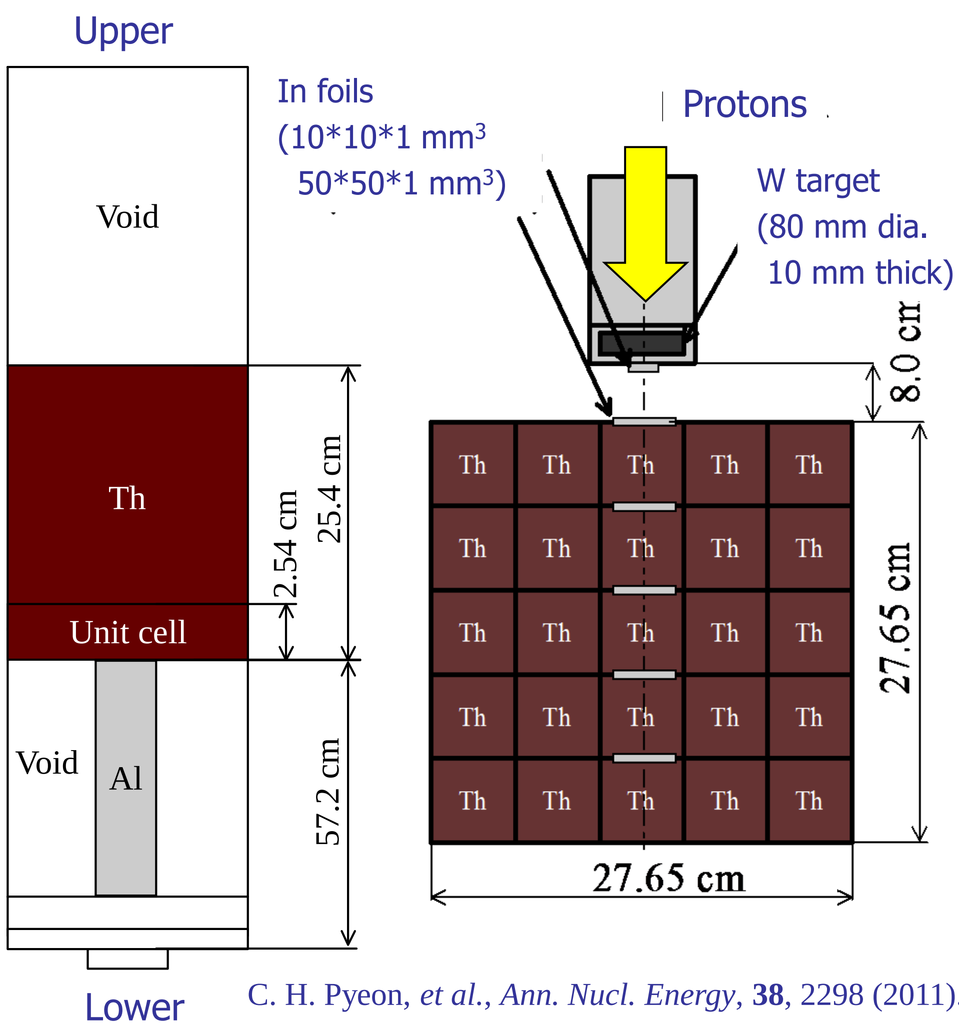
C. H. Pyeon, *et al.*, *Nucl. Sci. Eng.*, (2013). [in print]

# Experimental Benchmarks on the Th-Loaded ADS at KUCA

C. H. Pyeon, *et al.*, *Ann. Nucl. Energy*, **38**, 2298 (2011).

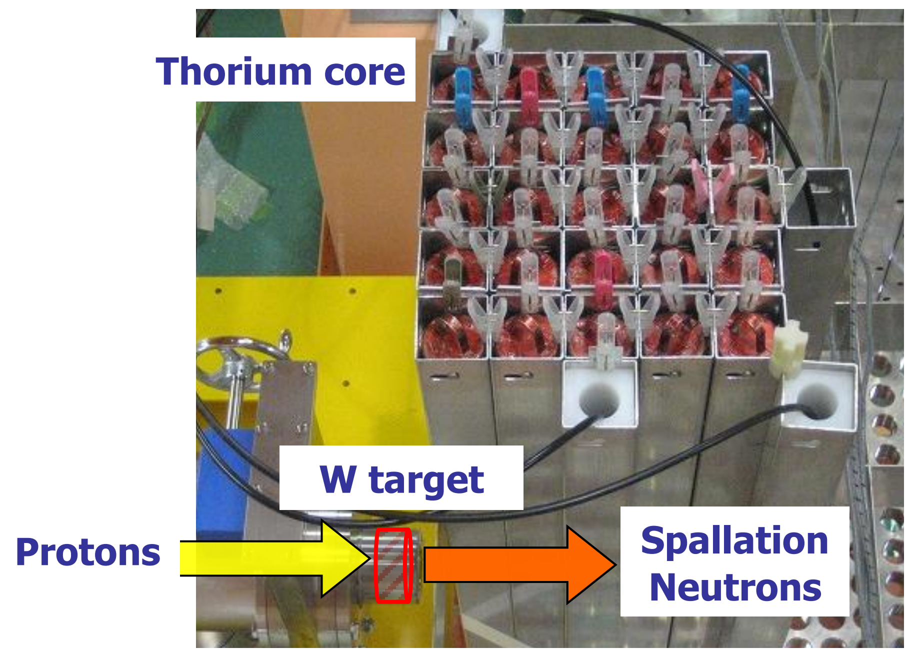
# Exp. Settings of $^{232}$Th-loaded ADS Exp.

## Experimental settings




C. H. Pyeon, *et al.*, *Ann. Nucl. Energy*, **38**, 2298 (2011).

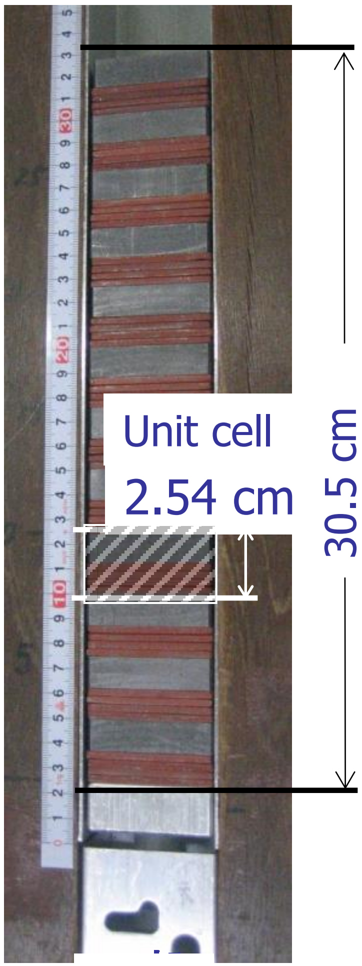
- Fuel size: 5 × 5
- Volume: 27.65 × 27.65 × 25.40 cm$^3$
- $k_{eff}$ = 0.03250 (ENDF/B-VII.0)
- $^{232}$Th(n, f ) threshold: 1.0 MeV
- $^{115}$In(n, n')$^{115m}$In threshold: 0.3 MeV
- Protons: 100 MeV, 50 mm dia., 30 pA



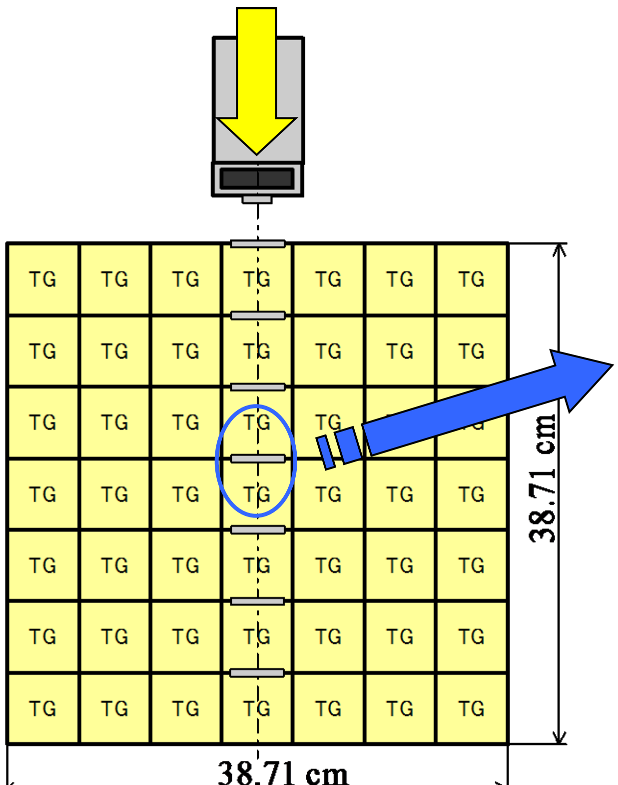
# $^{232}$Th-loaded ADS with Graphite

- Fuel size: 7 × 7
- Core volume: 38.71 x 38.71x 30.48 cm$^3$ (2.4 times than Th-core)
- $k_{eff}$ = 0.02399 (ENDF/B-VII.0)

Upper




Lower



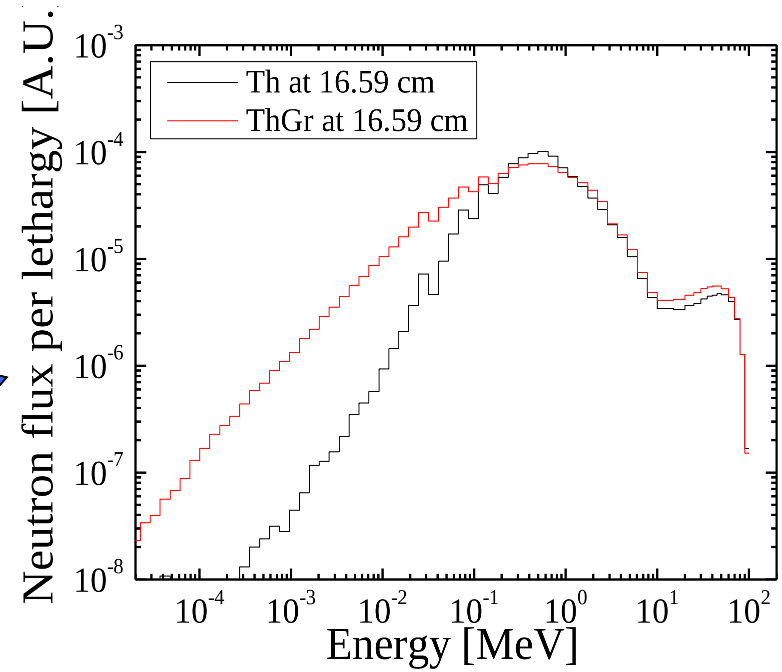




Fig. Neutron spectra of $^{232}$Th-loaded cores in ADS exp.

C. H. Pyeon, *et al.*, *Ann. Nucl. Energy*, **38**, 2298 (2011).

# Static Experiments in $^{232}$Th-loaded ADS

- $^{232}$Th fission reactions by Monte Carlo approach

$$RR_{total} = RR_{source} + RR_{fission}$$

**Solution**

- Convert Th fission reactions to capture reactions ("fission turnoff" option)

$$RR'_{total} = RR_{source} + RR_{capture}$$

- **Finally**,

$$RR_{fission} = RR_{total} - RR'_{total} + RR_{capture}$$

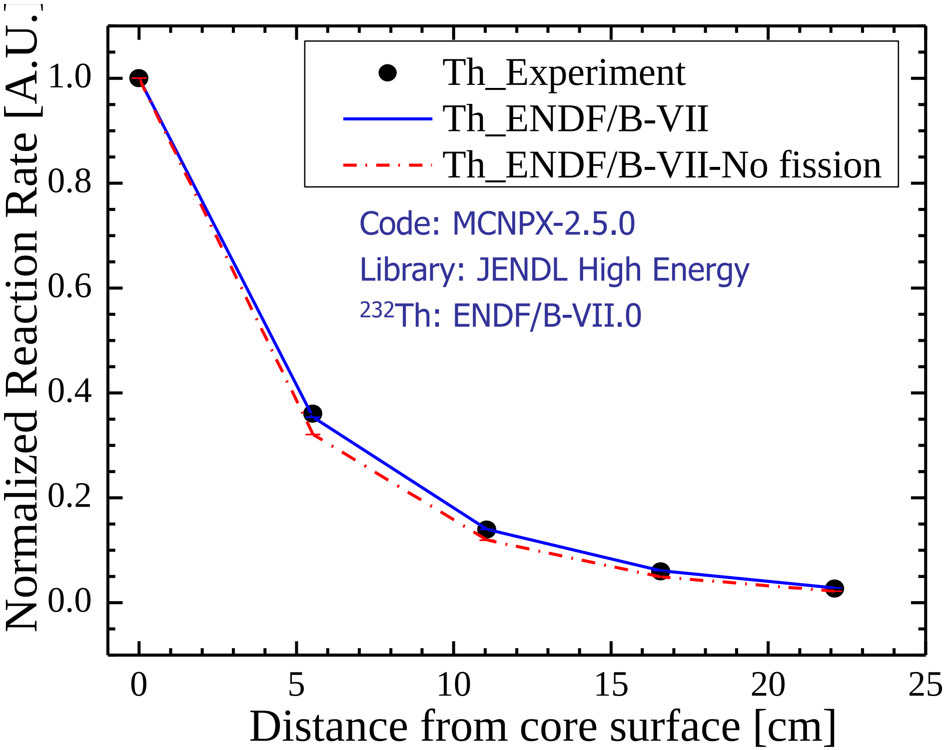



Fig. Comparison of measured and calculated reaction rates in $^{232}$Th-loaded core

**Confirmation of $^{232}$Th fission reactions generated by spallation neutrons (using "fission turnoff" option in MCNPX)**

# Comparative study on

- Neutron spectrum (core)
- Subcriticality (core)
- External neutron source (target)

C. H. Pyeon, *et al.*, *Nucl. Sci. Eng.*, (2013). [in print]

# X-sec. proportionality and Spectrum

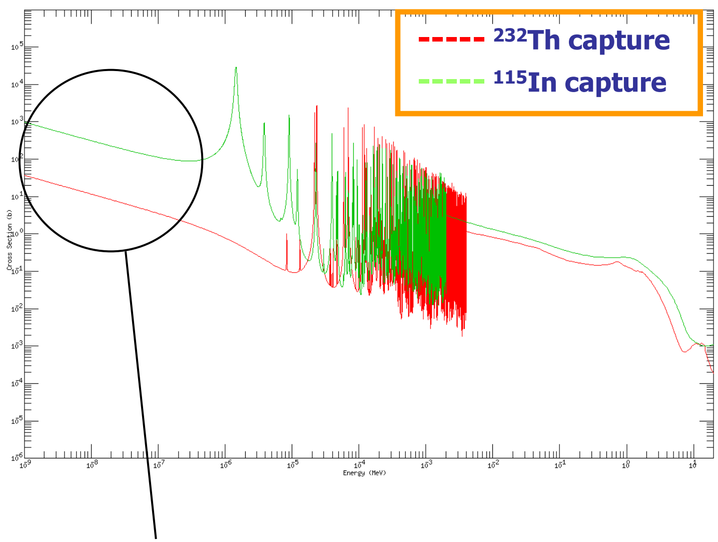



Fig. Proportionality of X secs. of $^{232}$Th and $^{115}$In in thermal neutron range

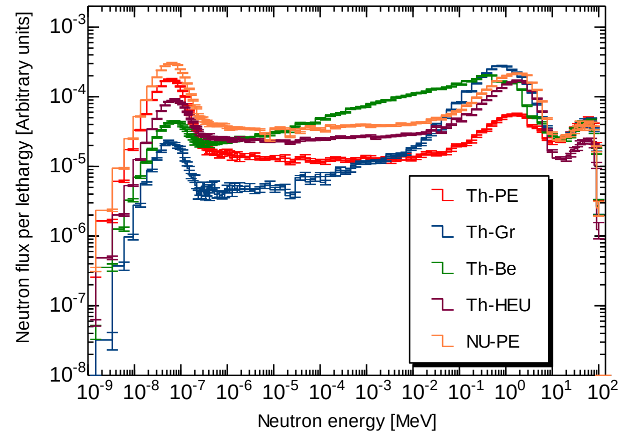



Fig. Neutron spectrum in injection of **100 MeV protons**

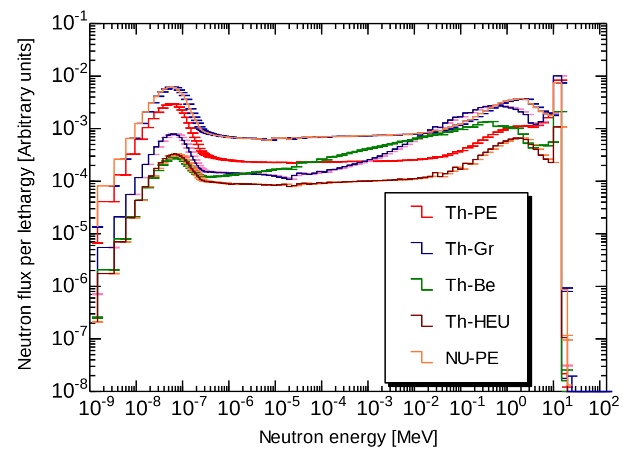



Fig. Neutron spectrum in injection of **14 MeV neutrons**

## - Measurement (Foil activation method)

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

# $^{232}$Th-loaded ADS with 14 MeV neutrons

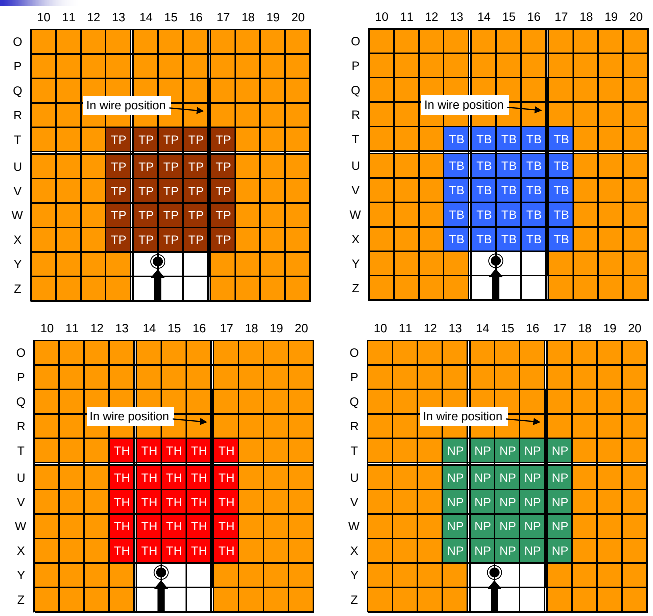



Fig. Core configuration of $^{232}$Th-loaded cores

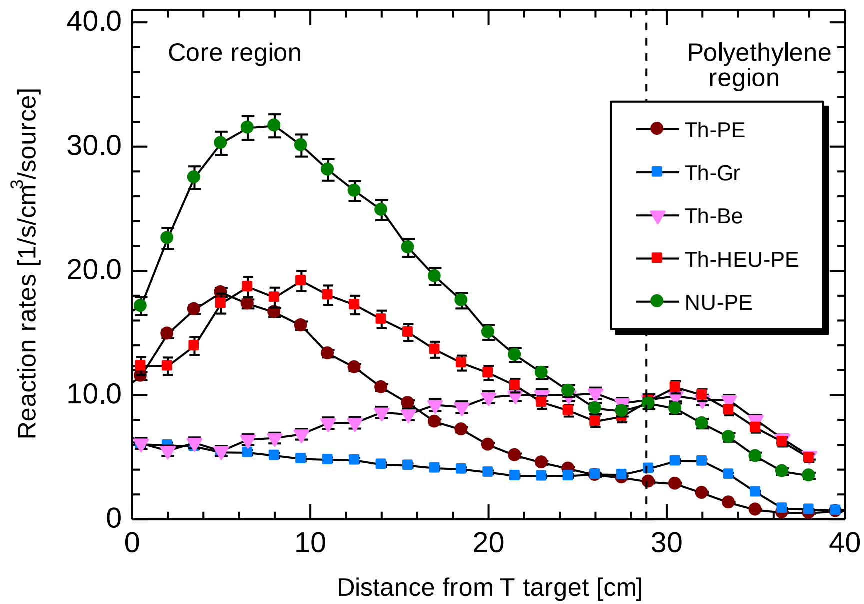



Fig. Comparison of measured $^{115}$In (n, $\gamma$)$^{116m}$In reaction rates in $^{232}$Th-loaded cores

Fig. Th-PE cells

Fig. Th-Be cells

**Confirmed**

Effect of neutron spectrum on profile of $^{232}$Th capture reactions for 14 MeV neutrons

C. H. Pyeon, *et al.*, *Nucl. Sci. Eng.*, (2013). [in print]

# Exp. vs. Cal. (14 MeV neutrons)

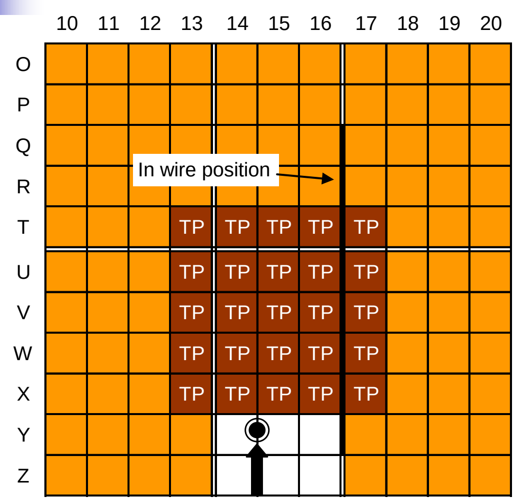



Fig. Core configuration of $^{232}$Th-Poly. cores

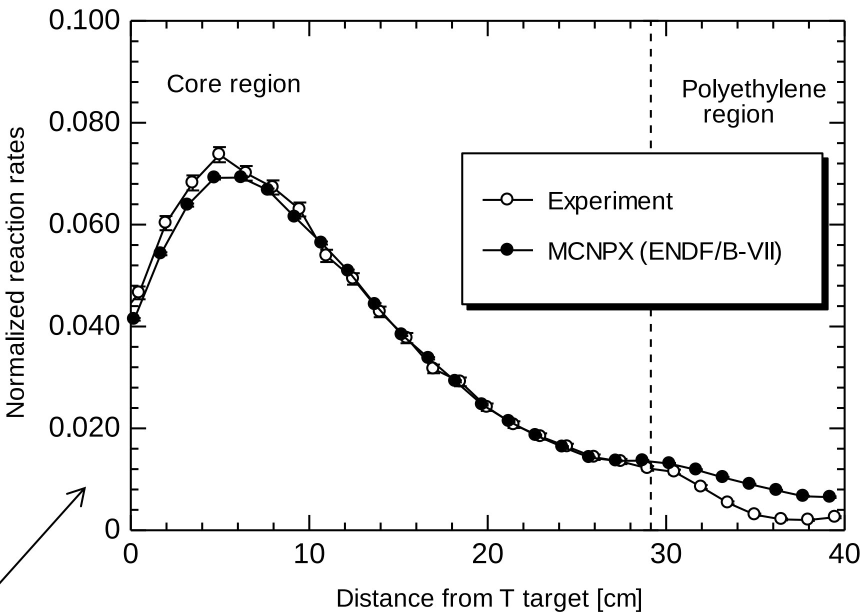



Fig. Comparison between measured and calculated $^{115}$In (n, γ)$^{116m}$In reaction rates in Th-PE core

Table MCNPX results of keff in Th cores

| Core | $k_{eff}$ |
|---|---|
| **Th-PE** | **0.00613** |
| **Th-Gr** | **0.00952** |
| **Th-Be** | **0.00765** |
| **Th-HEU-PE** | **0.58754** |
| **NU-PE** | **0.50867** |

**Results**

- Good agreement with measured and calculated (MCNPX) reaction rates
- No difference between ENDF/B-VII.0 and JENDL-3.3

# Profile of $^{232}$Th capture reaction rates

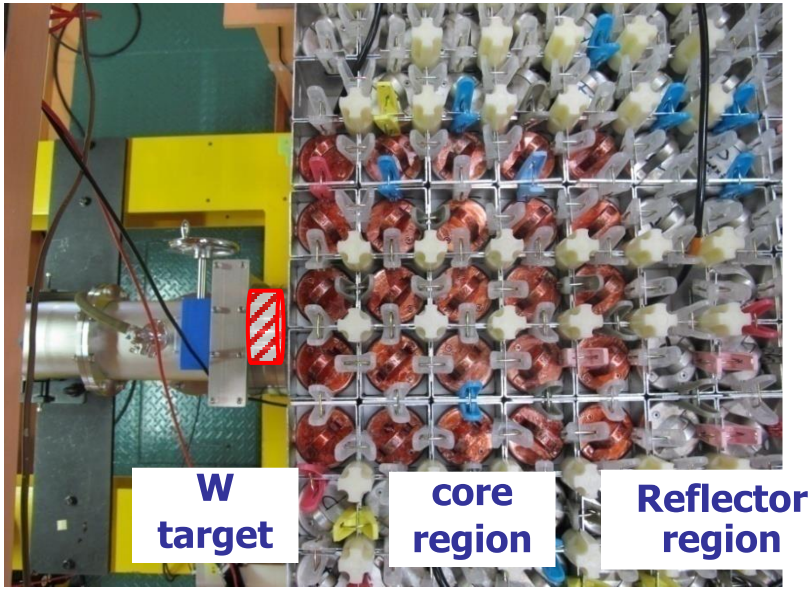



Fig. Core configuration of $^{232}$Th-loaded core

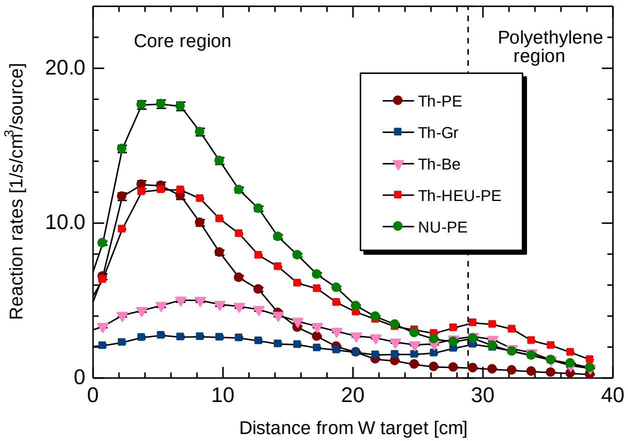



Fig. Measured $^{115}$In (n, $\gamma$)$^{116m}$In reaction rates (**100 MeV protons**)

**Effects**

1) Neutron spectrum in core
2) External neutron source at target
   (14 MeV neutrons vs. 100 MeV protons)

Note: Protons; 100 MeV, 50 mm dia., 0.1 nA
Target; W, 50 mm dia., 9 mm thick

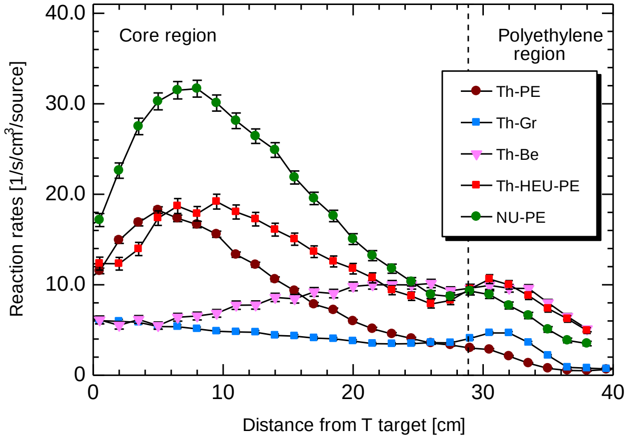



Fig. Measured $^{115}$In (n, $\gamma$)$^{116m}$In reaction rates (**14 MeV neutrons**)

# Pulsed neutron method ($^{232}$Th-loaded ADS)

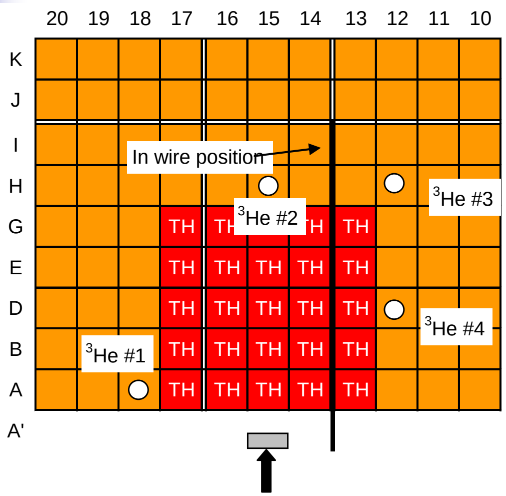



Fig. Core configuration of $^{232}$Th-Poly. Cores (**100 MeV protons**)

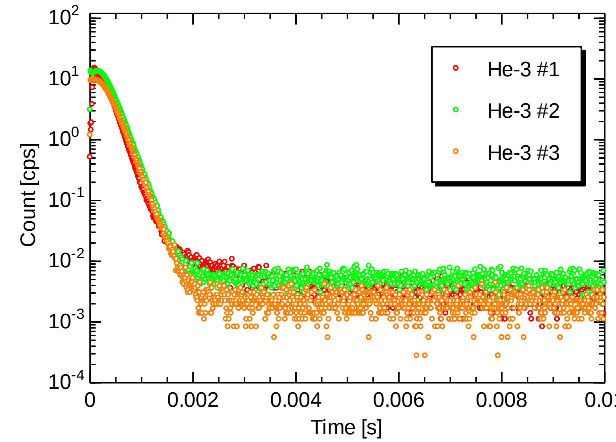



Fig. Results in **Th-HEU-PE** with **100 MeV protons**

Table Results in keff ($^3$He #3; Area ratio method)

| | Cal. | Exp. | |
|---|---|---|---|
| Core | MCNPX | 100 MeV Protons | 14 MeV Neutrons |
| **Th-HEU-PE** | **0.5876** | **0.7346** | **0.6577** |

$\beta_{eff}$ = 8.491E-03; SRAC-CITATION 107-G, 3-D

$\alpha$ = **5065** ± 28 (100 MeV Protons)

**5288** ± 13 (14 MeV Neutrons)

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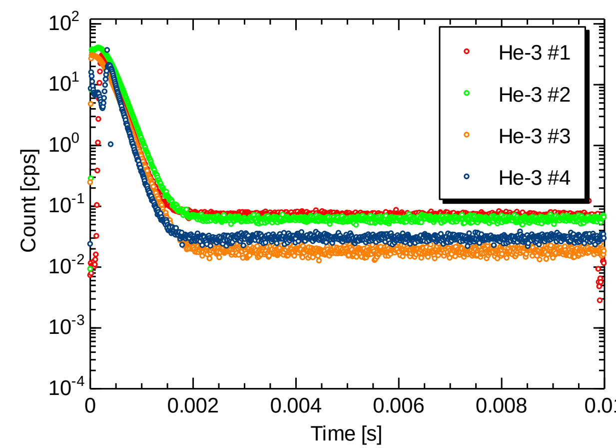


Fig. Results in **Th-HEU-PE** with **14 MeV neutrons**

# Th-loaded ADS benchmarks

**Table List of Th-loaded ADS cores**

| Core | Cell patter | $k_{eff}$ |
|---|---|---|
| Th-PE | 1/8”Th+1/2”PE | 0.00613 |
| Th-Gr | 1/8”Th+1/2”Gr | 0.00952 |
| Th-Be | 1/8”Th+1/2”Be | 0.00765 |
| Th-HEU-PE | 1/8”Th+1/16”HEU+3/8”PE | 0.58754 |
| NU-PE | 1/8”NU+1/2”PE | 0.50867 |
| Th-HEU-5PE | 1/8”Th+5*(1/16”HEU+3/8”PE) | 0.85121 |
| Th-HEU-Gr-PE | 1/8”Th+4*(1/16”HEU+1/2”Gr)+1/8”PE | 0.35473 |

* Contributed for IAEA on Feb. 2013

# Subcriticality measurements

**Table List of subcriticality data in all the cores shown in previous page**

| Core | 14 MeV neutrons | | 100 MeV protons | |
|---|---|---|---|---|
| | PNS method | Noise method | PNS method | Noise method |
| Th-PE | Available | Available | - | - |
| Th-Gr | Available | Available | - | - |
| Th-Be | Available | - | - | - |
| Th-HEU-PE | Available | Available | Available | Available |
| NU-PE | Available | - | - | - |
| Th-HEU-5PE | Available | Available | Available | Available |
| Th-HEU-Gr-PE | Available | Available | Available | Available |

* Contributed for IAEA on Feb. 2013

# Summary

- **ADS project in Kyoto Univ. Research Reactor Institute**
  - Energy amplifier system using ADS with high-energy protons

- **$^{232}$Th plate irradiation experiments**
  - Conversion study on $^{232}$Th fission and capture reactions in critical state:
    -> Discrepancy between experiments and calculations

- **Thorium-loaded ADS experiments**
  - ADS experiments with 100 MeV protons and 14 MeV neutrons
  - Static: Reaction rate analyses of $^{232}$Th capture reactions
  - Kinetic: Subcriticality by the Pulsed neutron method by varying
  - Neutron spectrum in the core
  - External neutron source at the target

- **Future plans**
  - Subcritical multiplication analyses of M and k-source
  - Critical experiments on investigation of further captures ($^{232}$Pa -> $^{233}$U) and fissions ($^{233}$U)
  - Investigate the probability of conversion analyses in subcritical states

# PHYSOR2014 in Kyoto

- Int. Conf. Physic of Reactor in 2014 (PHYSOR2014; ANS Topical Mtg.)
  **28$^{th}$ Sep. to 3$^{rd}$ Oct. 2014**

- Sub-title: "The Role of Reactor Physics towards a Sustainable Future"

- Key dates
  - Start "Paper submission" and "Registration" on **25$^{th}$ Oct. 2013**
  - Deadline of paper submission on **20$^{th}$ Dec. 2013**

- Technical sessions
  15 Tracks, 8 Special sessions,
  One-day Workshop (such as ADS )

- Access to, http://physor2014.org/