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Characterization of high-energy neutron standard fields and study of calibration methods

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nBHEAM 2025: Neutron Beams at High Energy: Applications and Metrology

Outline

1. Development of high-energy neutron standard field [at TIARA]
    1. Neutron beam line, facility
    2. Fluence measurement
    3. Spectrum measurements
    - Facility outline of TIARA
2. Study of two-angle differential calibration method [at RCNP]
    1. Two-angle differential method
    2. Reference spectra
    3. Calibration results and discussion

- Summary

TIARA: High-energy neutron standard field

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TIARA cyclotron facility

- NMIJ-AIST developed the 45-MeV high-energy neutron standard field collaborating with TIARA facility of QST.

Proton beam

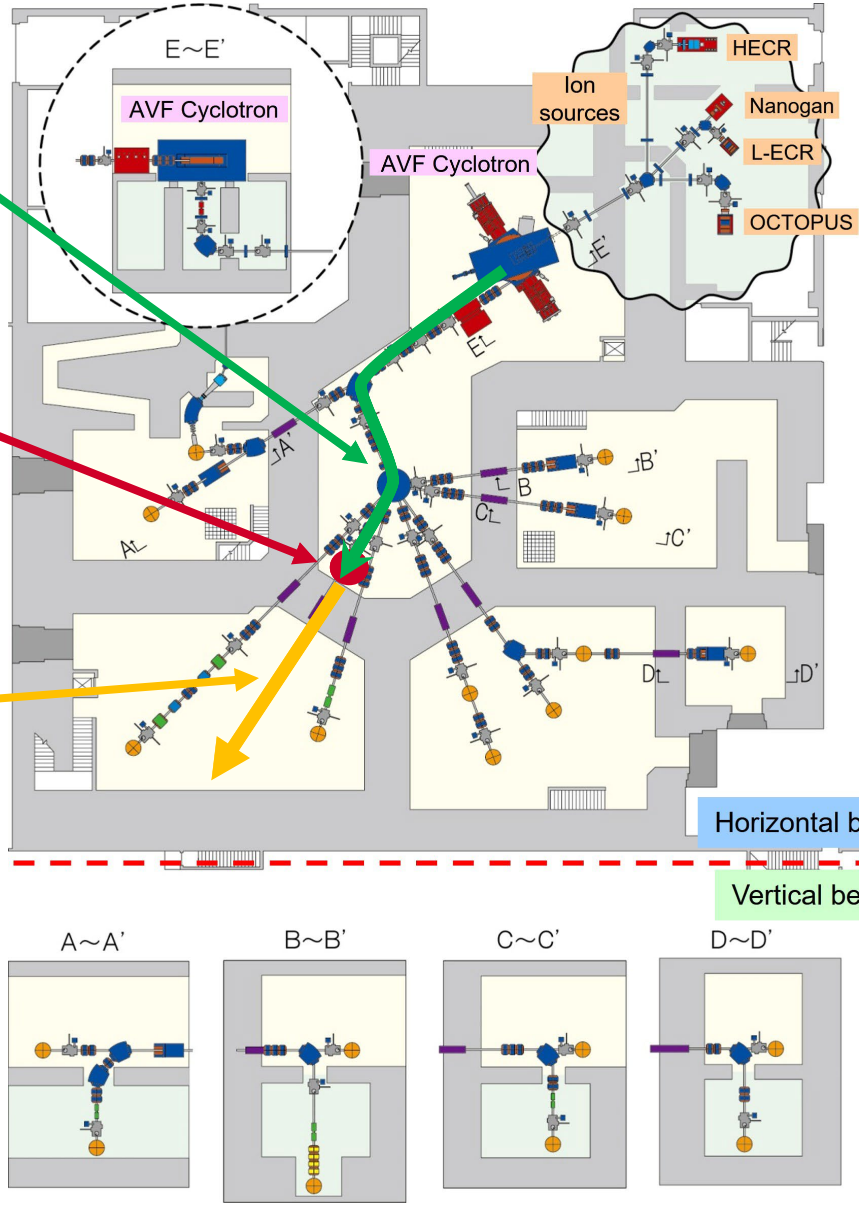
LC beam line
50 MeV
Few nA – 2 μA

Lithium target

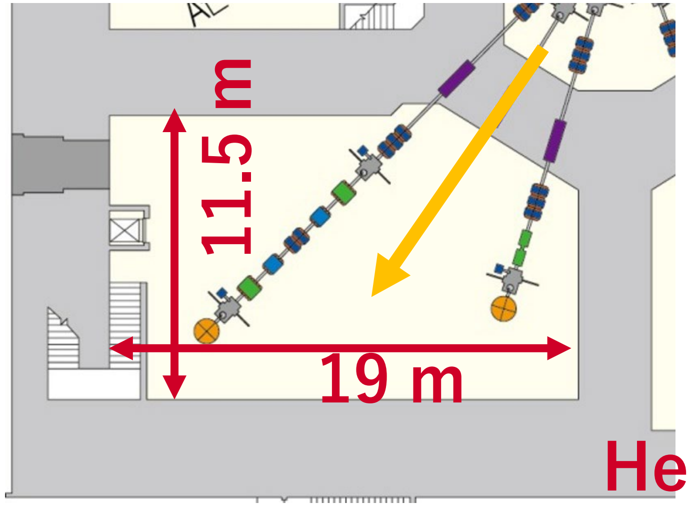
3.7 mm thick
>95 % enriched ^{7}Li

Neutron beam

45 MeV



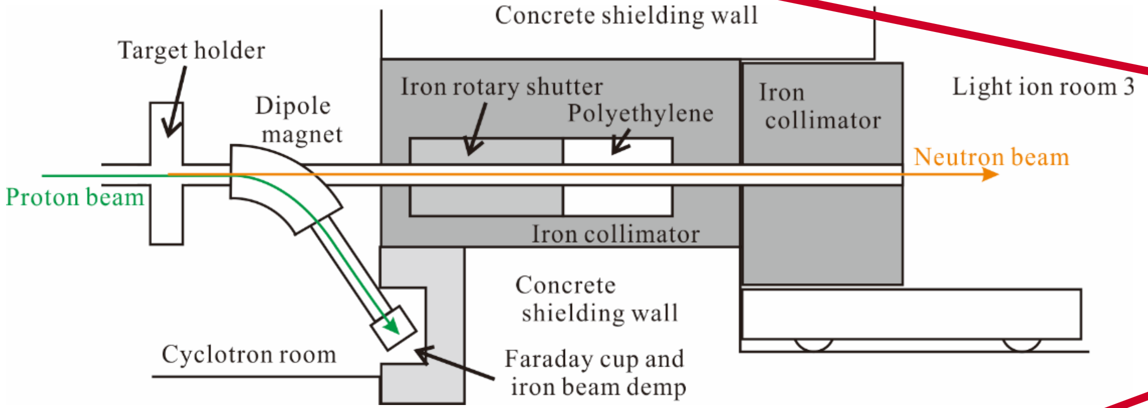
Light Ion Room 3



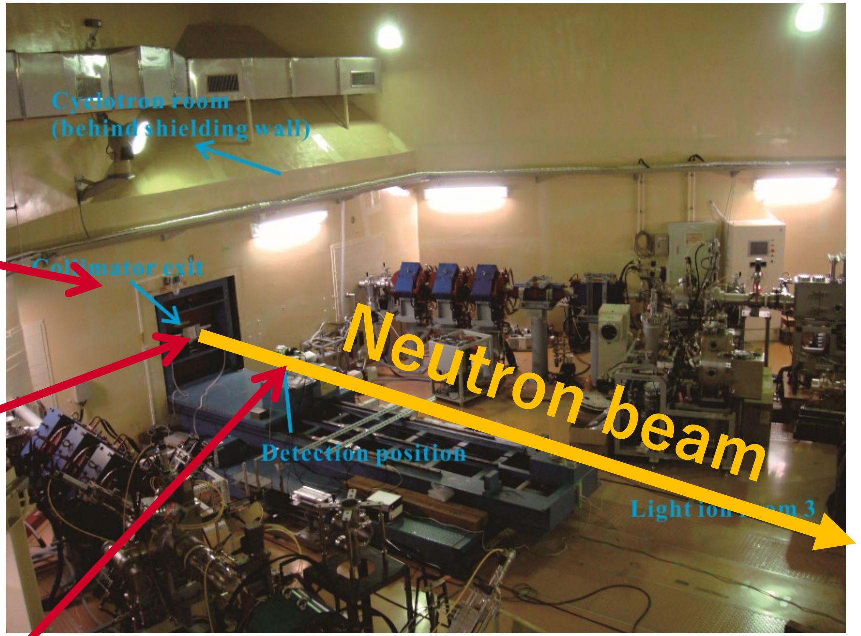
Height: 6 m

TIARA: High-energy neutron standard field at TIARA

Target and collimator



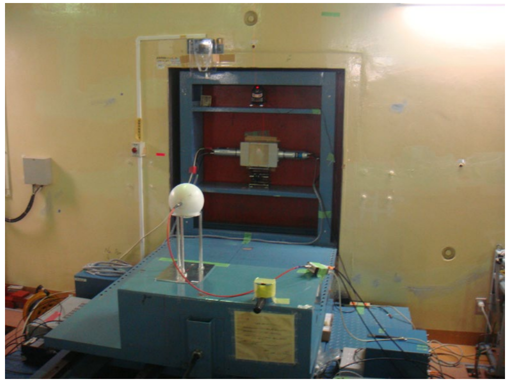
Side view of the target and collimator system



Neutron fluence monitor (at collimator exit)

Plastic scintillator detector as fluence monitor

Reference measurement point (6.5 m from target)



Example of measurement at the reference point

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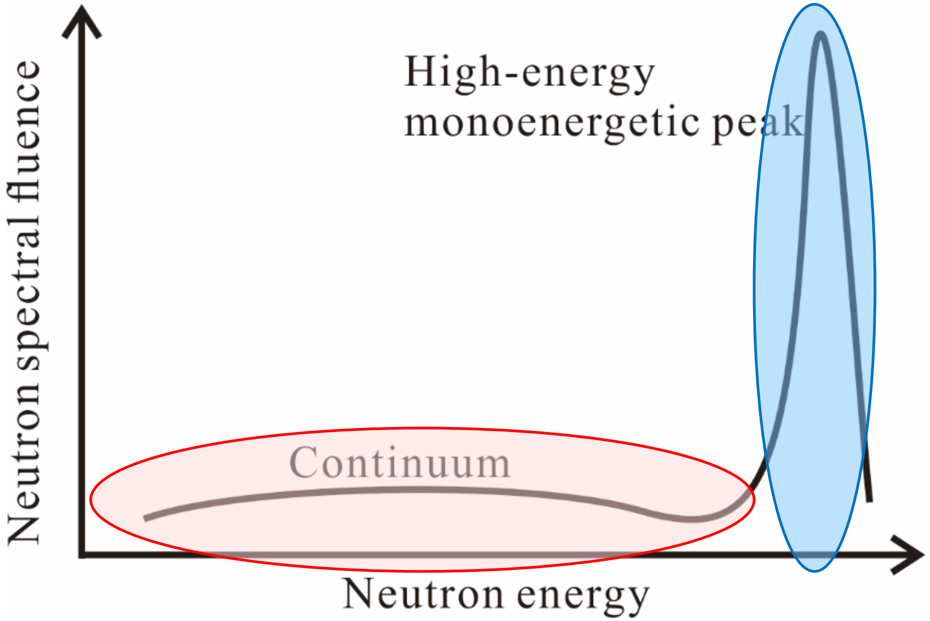
High-energy neutron spectrum by $^{7}Li(p,n)$ reaction: quasi-monoenergetic



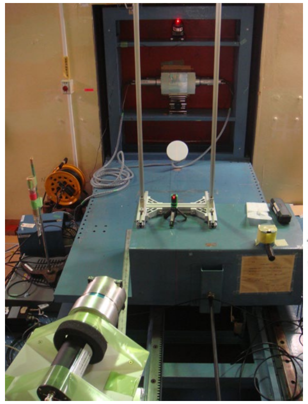
High-energy monoenergetic peak: main component to be reference for calibration

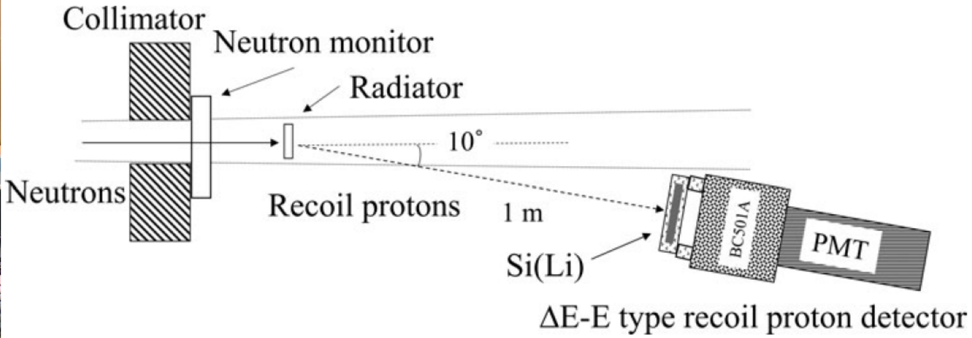
Neutron fluence of high-energy monoenergetic peak is determined using a proton recoil telescope.

Continuum: a kind of background

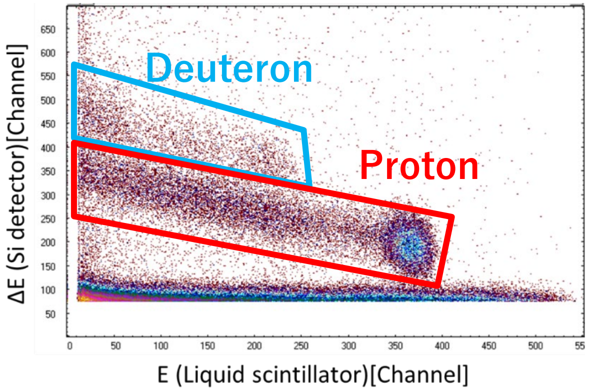
The continuum can have a significant effect on the calibration results depending on the energy characteristics of the sensitivity of the DUT.

Proton recoil telescope (PRT)

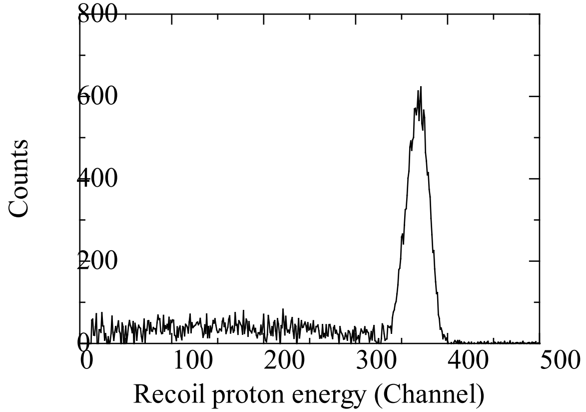




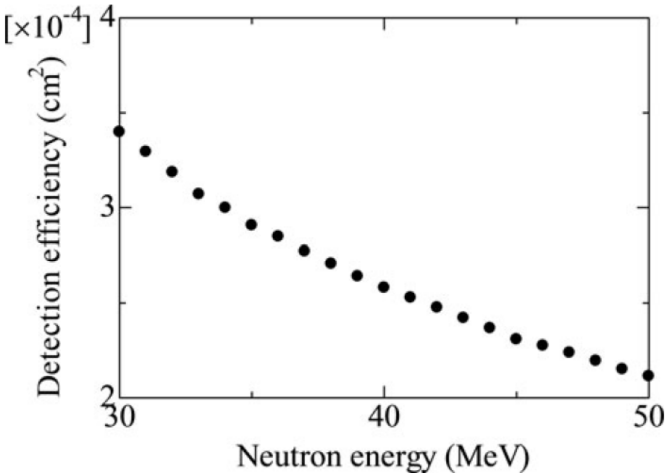
PRT detector consists of HDPE radiator, organic liquid scintillator (E), and Si detector (dE).



PH spectra of dE and E detectors of PRT.



PH spectrum for proton signals of BC501A.



Detection efficiency of PRT, calculated using MCNPX.

High-energy-peak neutron fluence at the reference position (6.5 m from the target) per monitor count

8.97 ± 0.57 cm^{-2}

T. Matsumoto, et al., J. Nucl. Sci. Technol. 54, 529-538, 2017.

TIARA: Spectrum measurements

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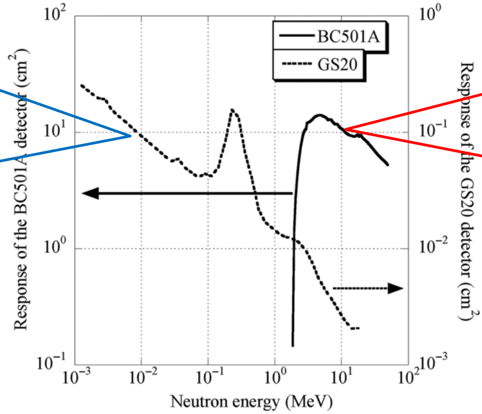
TOF measurements

- Organic liquid scintillator BC501A
- Lithium-glass scintillator GS20

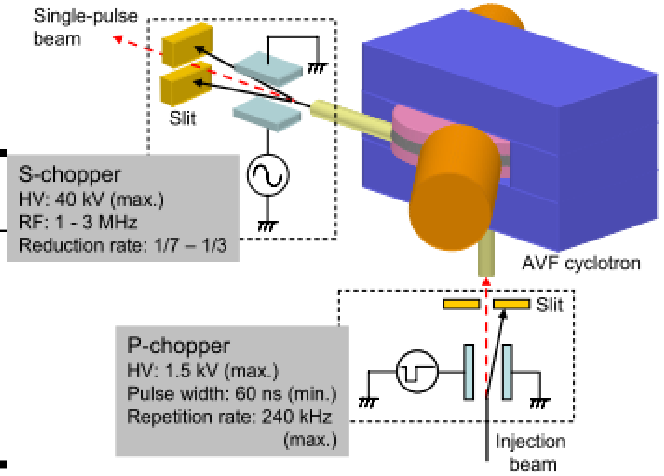


Response function of the BC-501A and GS20 scintillators calculated by SCINFUL-QMD and MCNPX, respectively

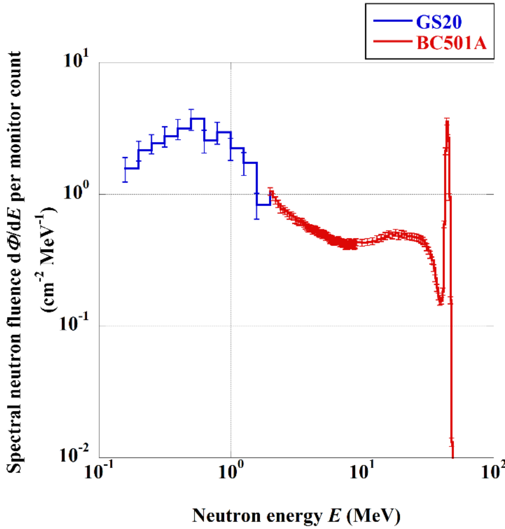
Single pulse beams available in TIARA cyclotron enabled TOF measurements down to the low-energy

Lower limit of TOF measurement due to overlapping of the next pulse

	Freq.	Interval	Neutron energy
Original	16.234 MHz	62 ns	63 MeV
1/6	2.706 MHz	370 ns	1.6 MeV
1/80	**202.9 kHz**	**4.9 μs**	**9 keV**



Single pulse beam system of the TIARA cyclotron.
S. Kurashima, et al., Proceedings of CYCLOTRONS 2010, Lanzhou, China, MOPCP090



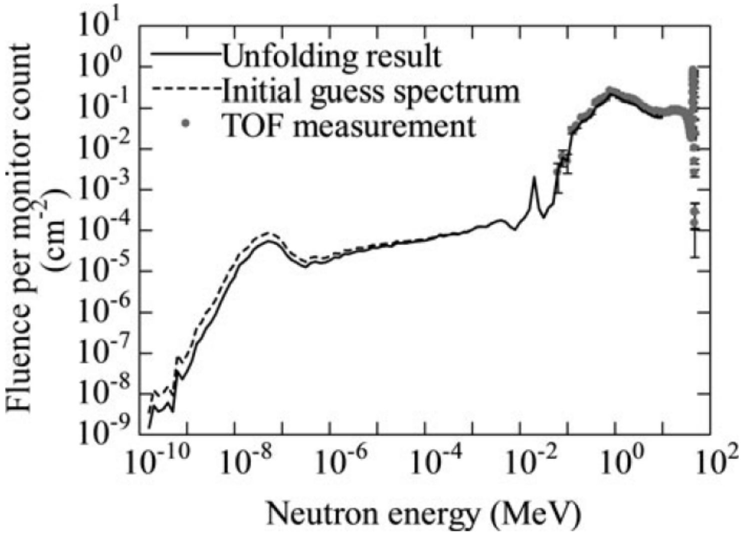
Results of spectrum measurements by TOF method
A. Masuda, et al., IEEE Trans. Nucl. Sci. 62, 1925-1300, 2015.

Bonner unfolding

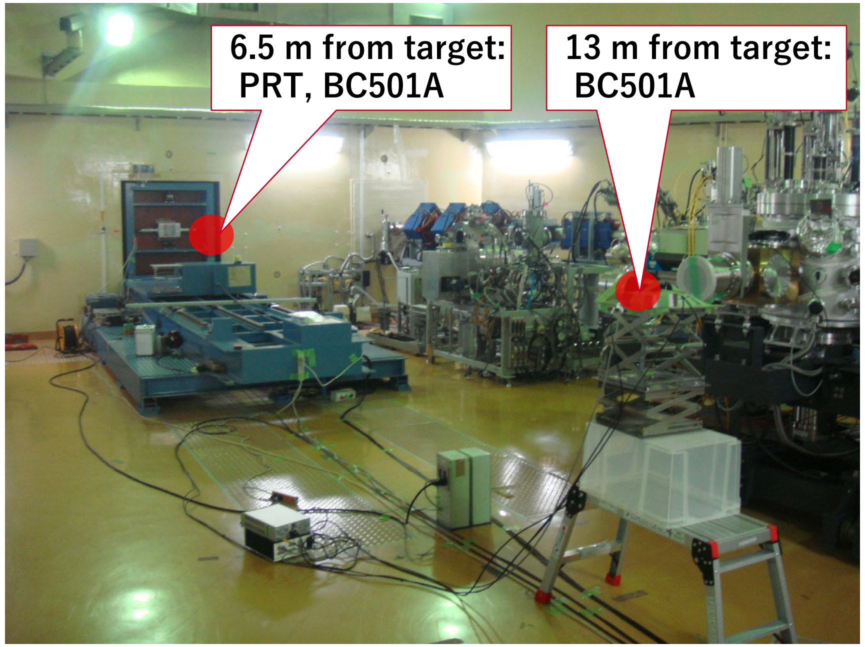
Low-energy neutrons below TOF measurements were evaluated by Bonner sphere spectrometer.

Default spectrum including penetrated / scattered neutrons was calculated based on the TOF spectrum.

Unfolding code: MAXED in UMG3.3 package



Consistency of peak-neutron fluence



Detector	Measurement position	Peak neutron fluence at 6.5 m / monitor count
PRT	6.5 m	8.97 ± 0.57 cm^{-2}
BC501A	6.5 m	9.4 ± 1.9 cm^{-2}
BC501A	13 m	9.3 ± 1.9 cm^{-2}

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National Institutes for Quantum Science and Technology (QST)
└ Takasaki Institute for Advanced Quantum Science (TIAQ)
└ Takasaki Ion Accelerators for Advanced Radiation Application (TIARA)

Available ions

H^{+}, $^{4}He^{2+}$, $^{12}C^{3+}$, $^{12}C^{5+}$, $^{12}C^{6+}$, $^{15}H^{3+}$, $^{16}O^{4+}$, $^{16}O^{6+}$, $^{20}Ne^{4+}$, $^{22}Ne^{6+}$, $^{20}Ne^{7+}$, $^{20}Ne^{8+}$, $^{40}Ar^{8+}$, $^{40}Ar^{10+}$, $^{40}Ar^{13+}$, $^{40}Ar^{14+}$, $^{84}Kr^{17+}$, $^{129}Xe^{25+}$, $^{129}Xe^{26+}$, $^{192}Os^{30+}$

D^{+}, $^{3}He^{2+}$, $^{11}B^{3+}$, $^{14}N^{3+}$, $^{14}N^{5+}$, $^{16}O^{3+}$, $^{16}O^{5+}$, $^{16}O^{7+}$, $^{20}Ne^{6+}$, $^{28}Si^{5+}$, $^{28}Si^{10+}$, $^{36}Ar^{8+}$, $^{40}Ar^{11+}$, $^{56}Fe^{15+}$, $^{58}Ni^{15+}$, $^{84}Kr^{18+}$, $^{84}Kr^{20+}$, $^{102}Ru^{18+}$, $^{102}Ru^{22+}$, $^{129}Xe^{24+}$

Beam energy

5 - 80 MeV (in case of H^{+})

Beam current

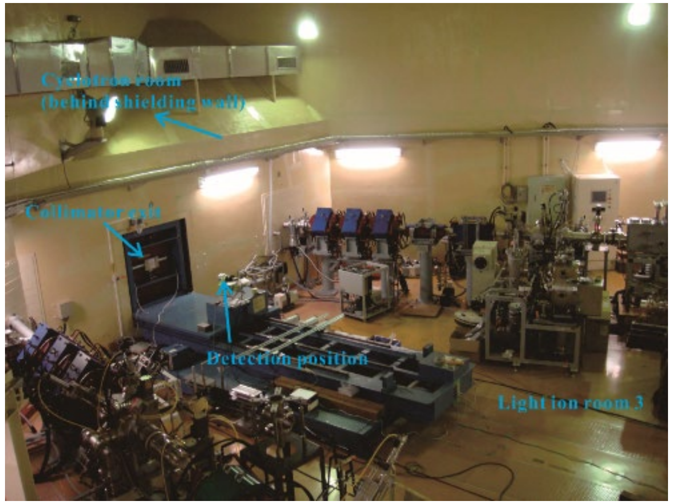
few nA – 2 μA (in case of H^{+}, LC course)

Lithium target

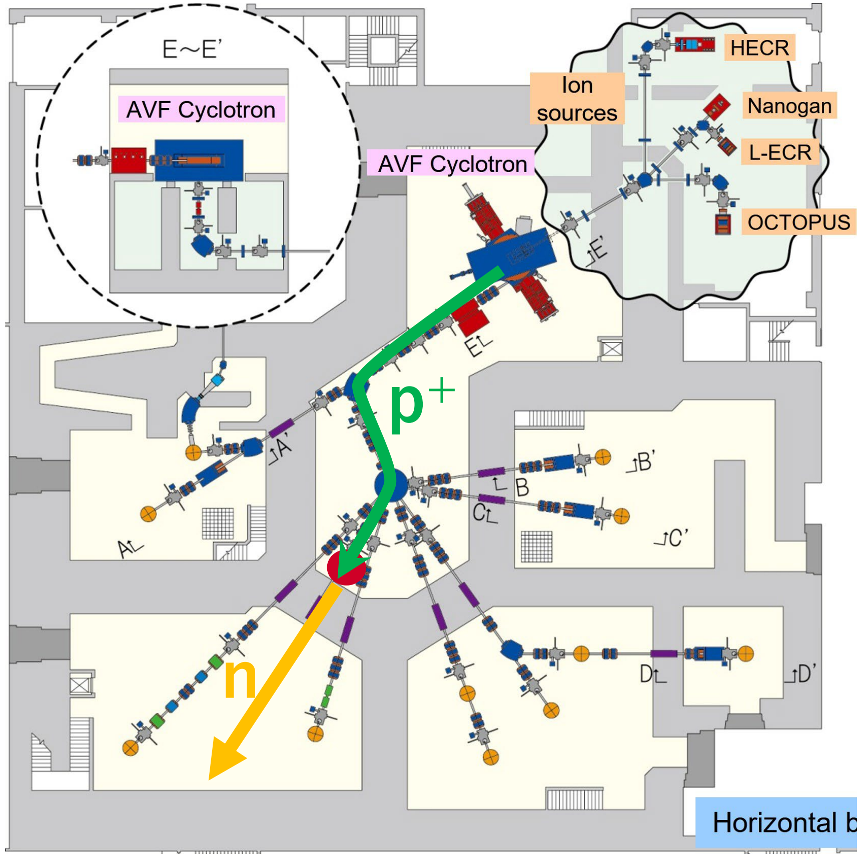
3.7 mm thick for 45 MeV

3.5 cm diameter

>95 % enriched ^{7}Li



Light Ion Room 3

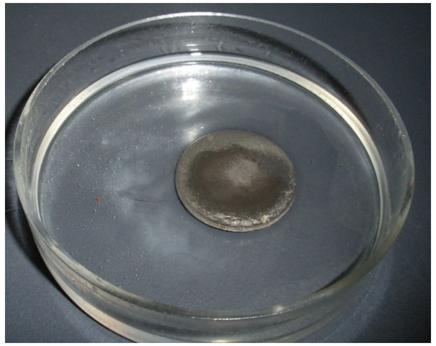


Cyclotron facility of TIARA

Supplement: TIARA facility information

How to use the high-energy neutron standards established at TIARA:

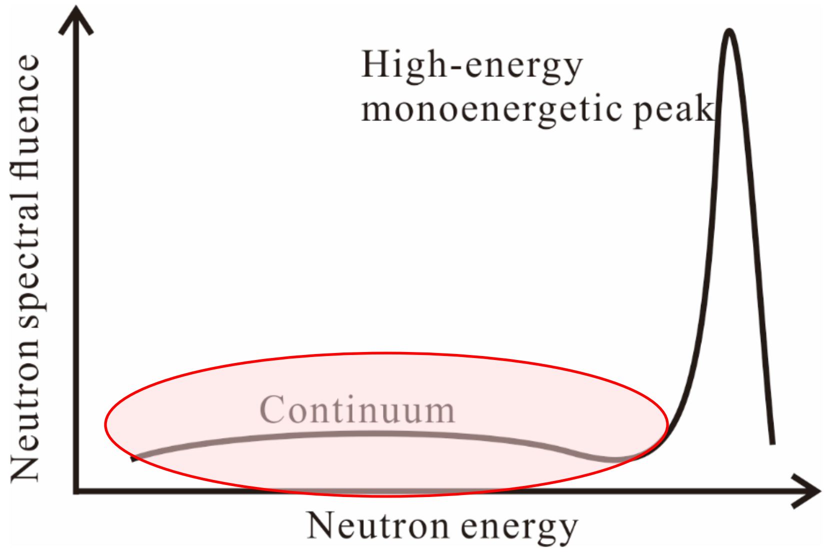
- **Customers of the calibration service reserve beam time by applying for QST's paid Facility Use Program.**
- **NMIJ-AIST accompanies the experiment for technical preparations for neutron generation, measurements, and providing references.**
  - Target fabrication and installation
  - Coordination with cyclotron operators
  - Beam order and tuning in cooperation with operators
  - Measurements and providing references
- **NMIJ-AIST can support in coordinating with TIARA-QST, including beam time application.**



Lithium target

Target installation by NMIJ-AIST

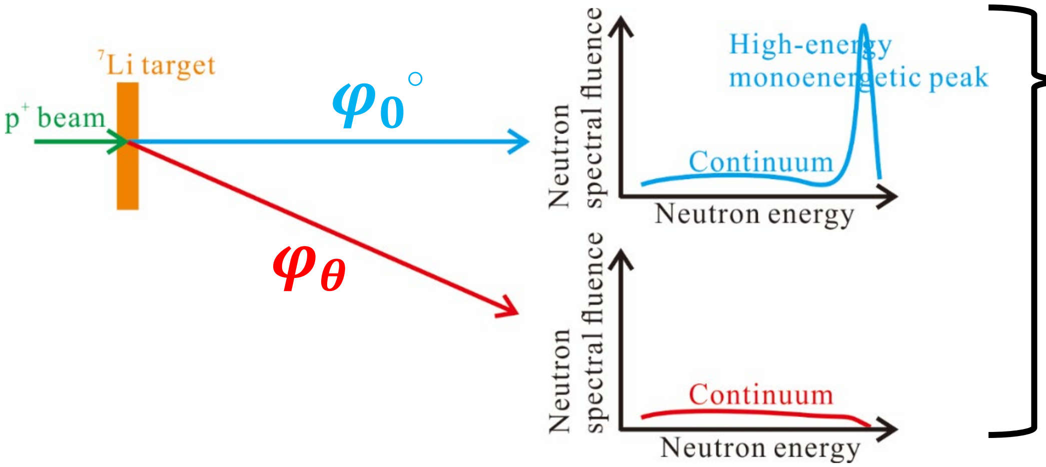
RCNP: Two-angle differential calibration method



Continuum: a kind of background

Option 1: Understand the neutron spectral fluence down to the low-energy, estimate its impact, then make corrections for calibration result. ➡ **TIARA**

Option 2: Canceling out the effect of continuum experimentally



$\varphi_{0^\circ} - \varphi_\theta$: artificial monoenergetic neutrons

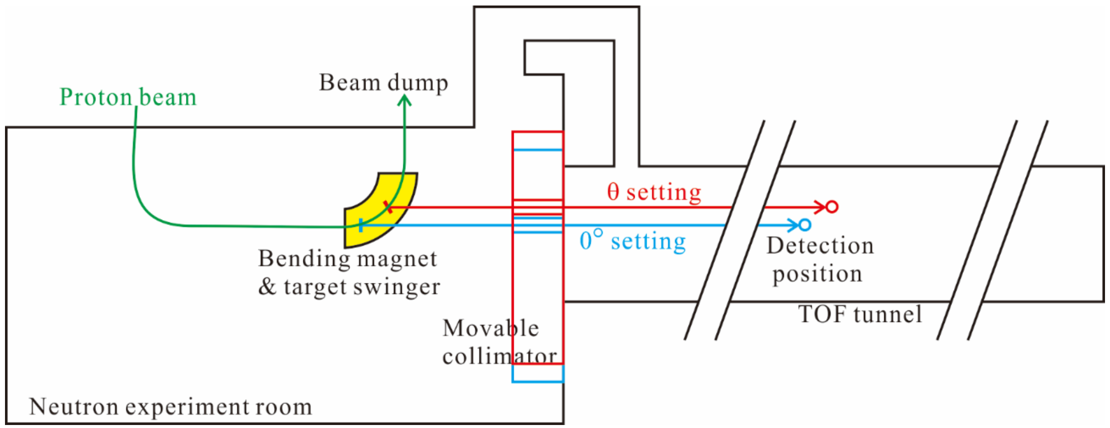
Originally proposed by R. Nolte, et al., for 20-100 MeV neutrons.

R. Nolte, et al., Nucl. Instr. Meth. A 476, 369-373, 2002.

We studied applicability of the two-angle differential method at RCNP cyclotron facility.

RCNP: Two-angle differential method

Target swinger and movable collimator system at RCNP



Quasi-monoenergetic high-energy neutron facility of RCNP

Any angular (0 – 30 deg) component of the generated neutrons can be extracted to the tunnel.

(Detailed information about RCNP facility will be given in the next presentation by Prof. Shima.)

Demonstration for response calibration of Bonner sphere detectors

- Easy to calculate response by Monte Carlo simulations
- Various response characteristics
  - Small sphere
  - Large sphere
  - Metal-induced sphere

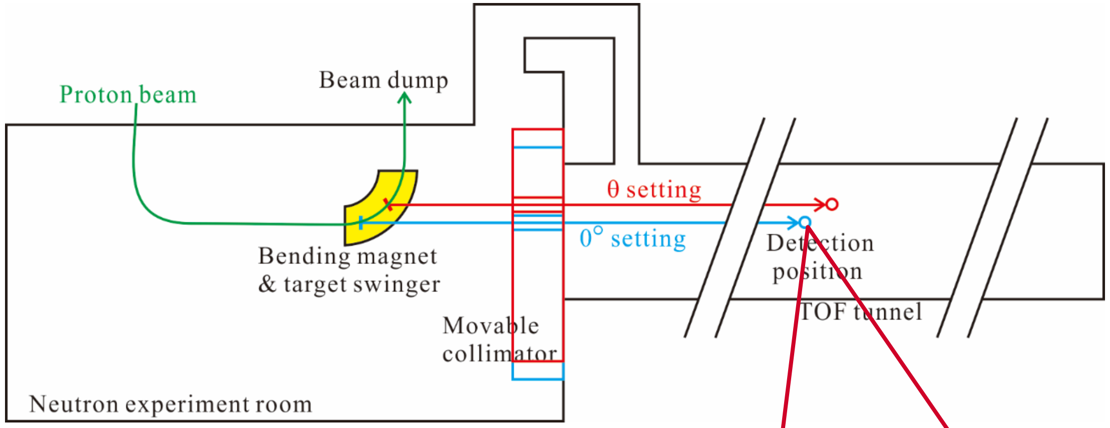


Bonner sphere detectors

RCNP: Two-angle neutron spectra

Measurements

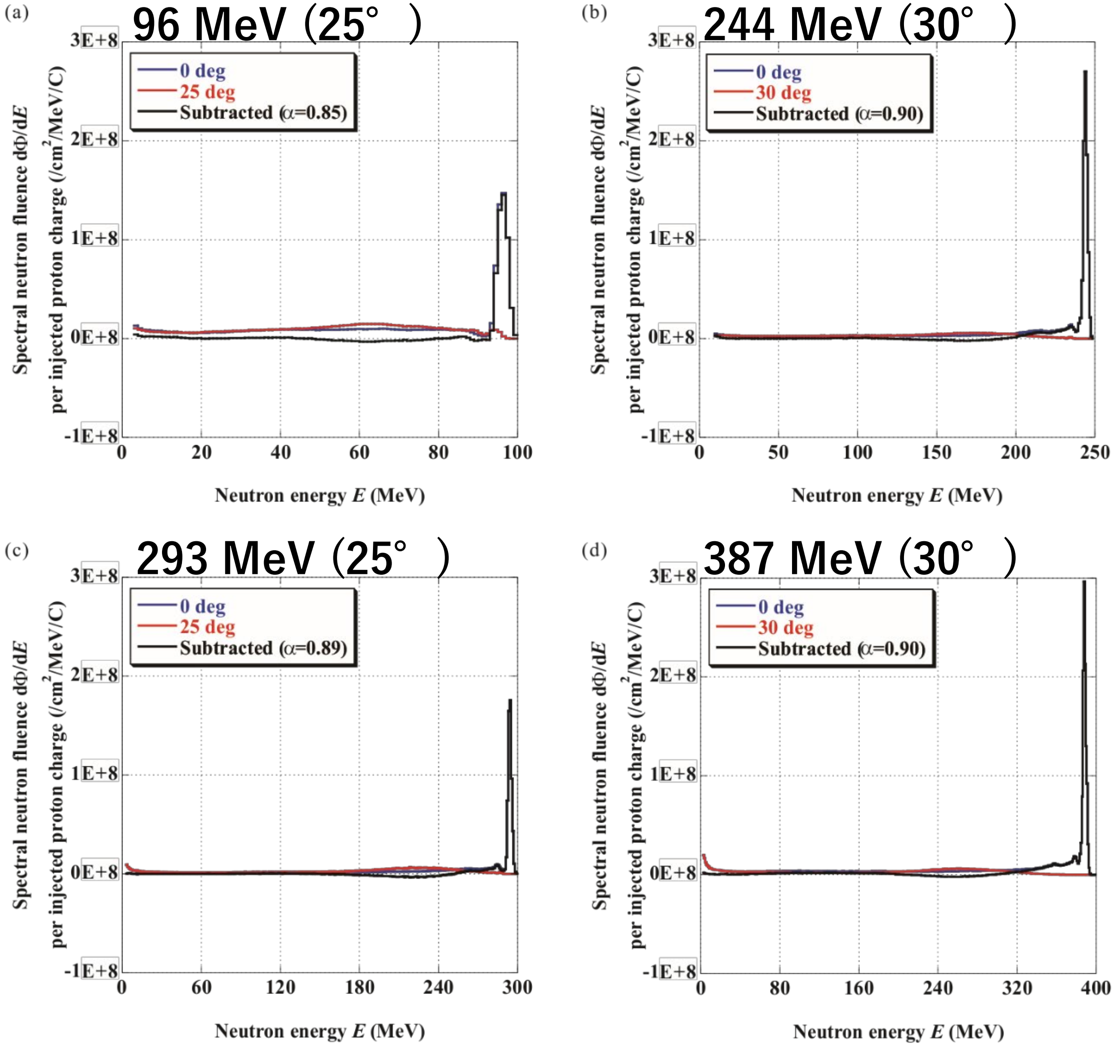
Bonner sphere detectors were set at 30 m from the target.



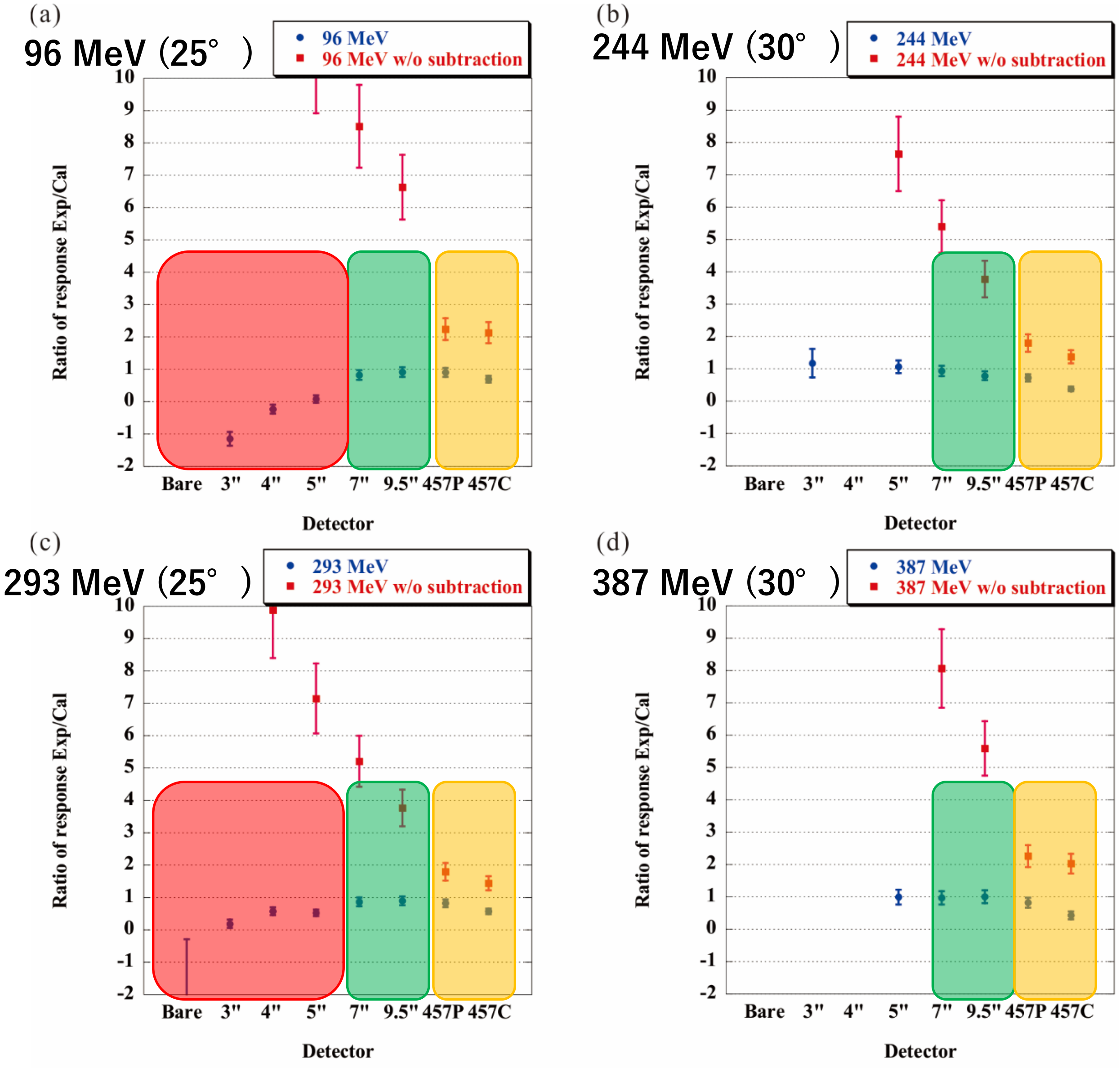
Measurements of Bonner sphere detectors

Reference spectra (NE213, TOF)

Y. Iwamoto, et al., Nucl. Instr. Meth. A 804, 50-58, 2015.



RCNP: Results & discussion



- **General:** Two-angle differential method significantly improves calibration results.
- **Large spheres:** Results agreed with calculated response well.
- **Small spheres:** Smaller spheres' response were more underestimated when 25 deg is used due to the effect of penetrated neutrons.
- **Metal layered spheres:**
  Underestimated?
  → Calculations overestimated the response due to used cross-sections.
  Calibration method worked well.

A. Masuda, et al., IEEE Trans. Nucl. Sci. 59, 5161-166, 2012.
A. Masuda, et al., Nucl. Instr. Meth. A 849, 94-101, 2017.

Summary

- **Development of high-energy neutron standard field [at TIARA]**
  - NMIJ-AIST developed high-energy neutron standard at TIARA.
  - High-energy peak neutron fluence was determined using PRT.
  - Neutron spectral fluence down to the low-energy was measured by TOF and Bonner unfolding methods.
  - Brief introduction to the TIARA facility was given.
- **Study of two-angle differential calibration method [at RCNP]**
  - Two-angle differential calibration method was demonstrated at RCNP.
  - It is effective to calibrating neutron detectors with sufficient moderator.
  - Care should be taken for detectors mainly sensitive to low-energy neutrons.
- We also working on some application experiments related to high-energy neutrons. e.g., to be presented this afternoon by Dr. Lee

Acknowledgement: Contributors

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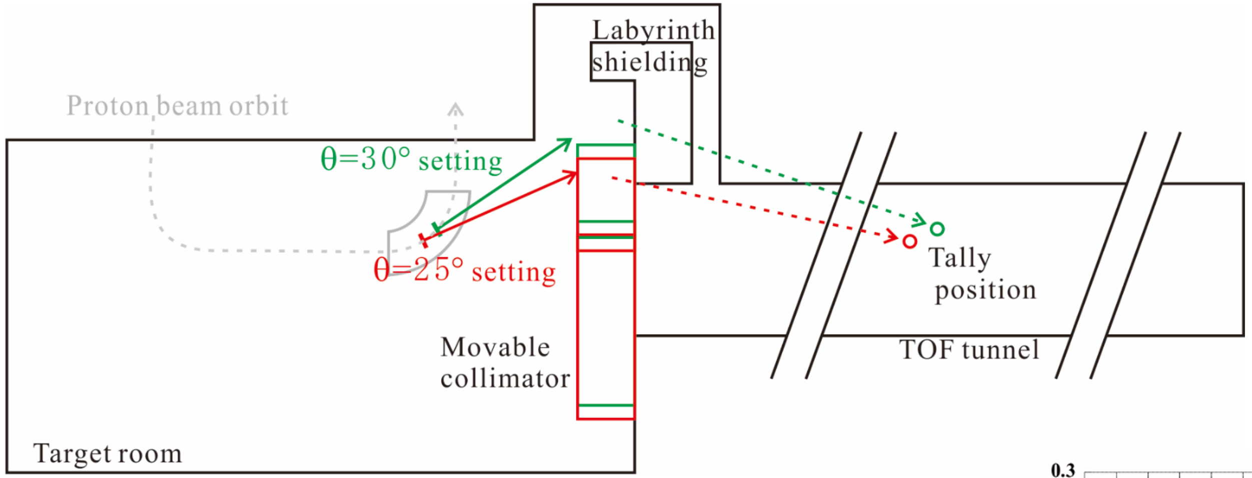
Tohoku University

Takashi NAKAMURA

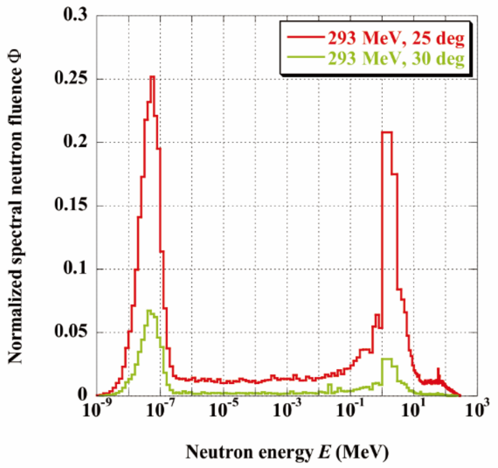
Backup/ RCNP: Results & discussion – Small sphere

Generated neutrons hit the collimator shallower in the 25 deg measurement than in the 30 deg measurement.



Calculation of neutrons that penetrate the collimator and reach the calibration point.

- For simplicity, only 0-deg neutrons are incident on the collimator.



Low-energy neutrons increase in 25-deg measurement.

Excessive subtraction

Underestimated calibration result

Care is required for detectors that are highly sensitive to low-energy neutrons.

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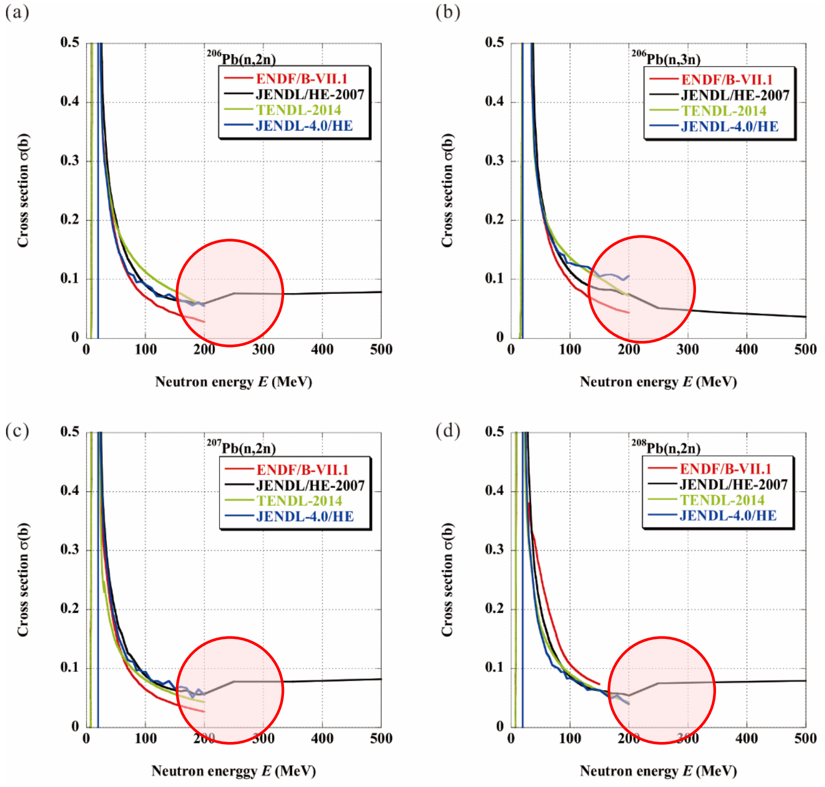
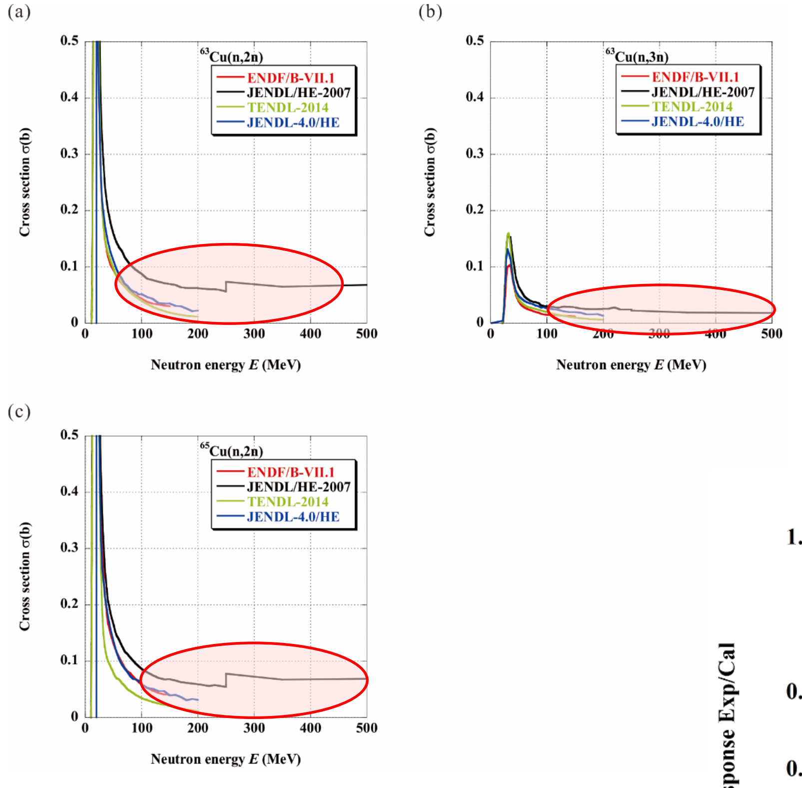
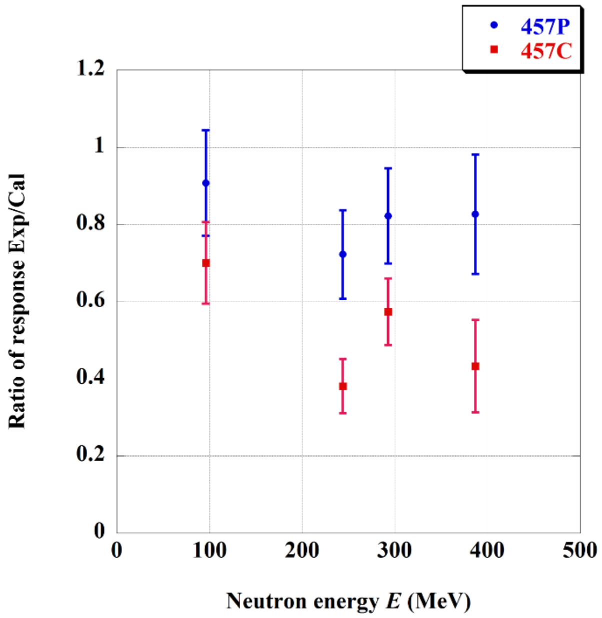
Cross-sections used in the calculation (JENDL/HE-2007) were overestimated

Pb



Cu





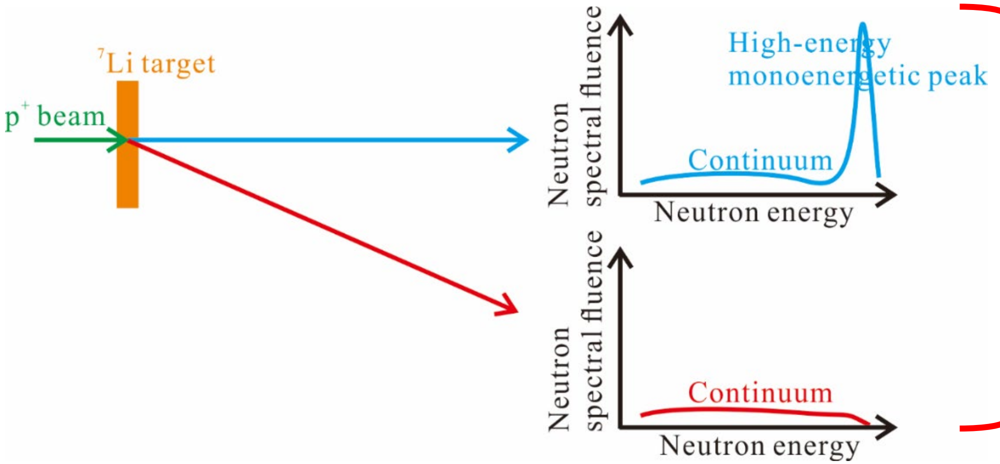
Discrepancies between calculations and measurements

(Pb: 10%, Cu: 30% @96 MeV ; Pb:20%, Cu:50% >200 MeV)

consist with the cross-section trends.

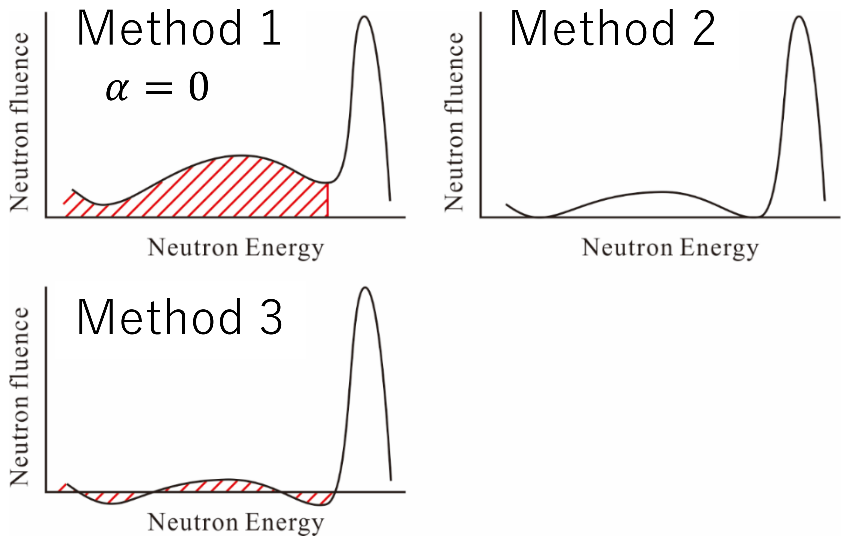
→ **Calculations overestimated; calibration method worked well.**

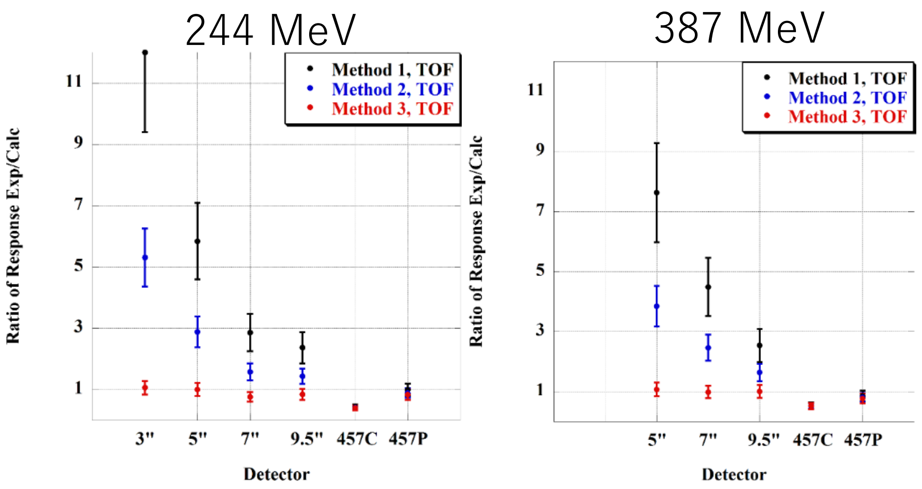
Backup/ RCNP: Determination of the artificial monoenergetic neutron



The continuums are not exactly the same.

$\varphi_{0^\circ} - \alpha \cdot \varphi_\theta$: How to determine α





Dependence of results on α determination