BNCT lithium beam driver (LDRD 24-046)

Masahiro Okamura

December 18th, 2025

Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

@BrookhavenLab

Recommendations:

12. For MAC-22, clarify the scope of responsibilities among collaborators and highlight the BNL part.

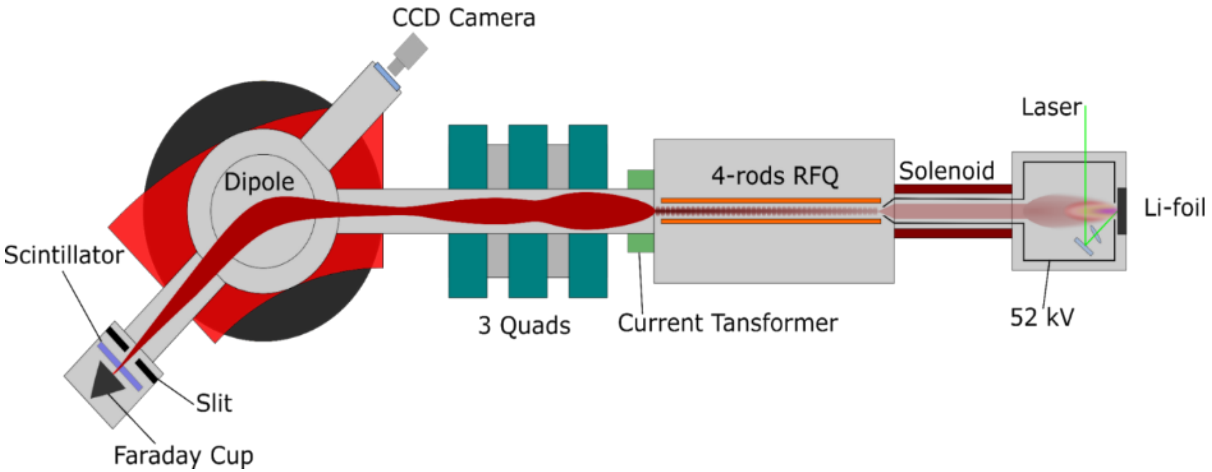
ANSTO, Wollongong Uni.	Monte Carlo Simulation for BSA(BNCT moderator)
GSI,	RFQ beam dynamics design
Institute of Science Tokyo	RFQ fabrication including RF simulation
Osaka Uni.	Production of Nuclear data for inverse kinematics
Nagaoka UT	DPIS Mechanical design, Tape target scanning system
Columbia U.	High current lithium beam acceleration test
Darmstadt Tech.	Neutron measurement
Okayama Uni.	Application to BNCT

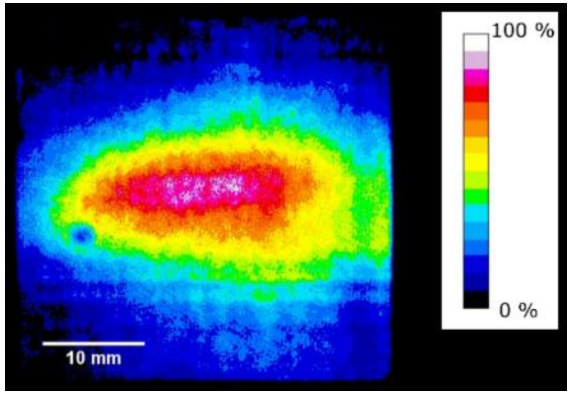
For all items, the core part is being carried out by BNL members.
T. Sakabe, S. Ikeda, T. Kanesue

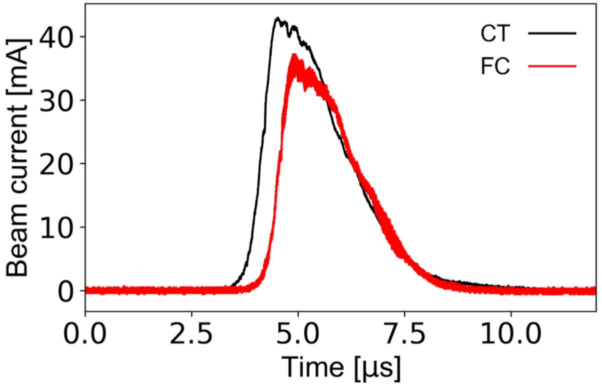
Background of the project

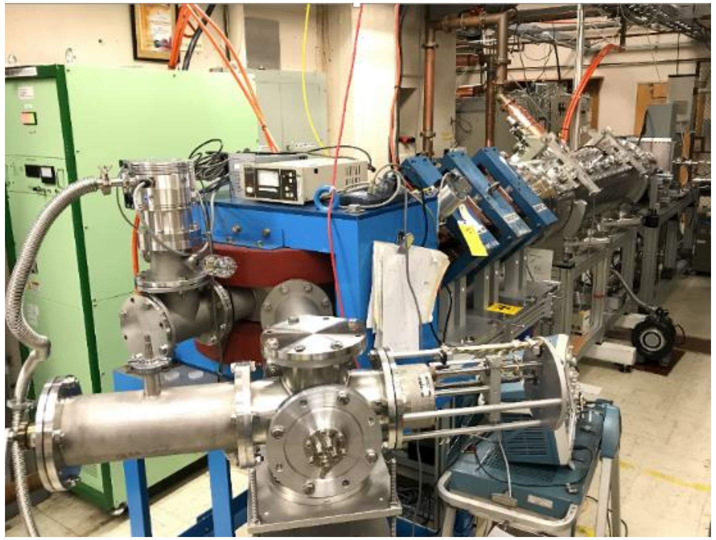
Background

Success of 35 mA beam acceleration by first stage accelerator (RFQ linac)*









<u>Our group achievement</u>

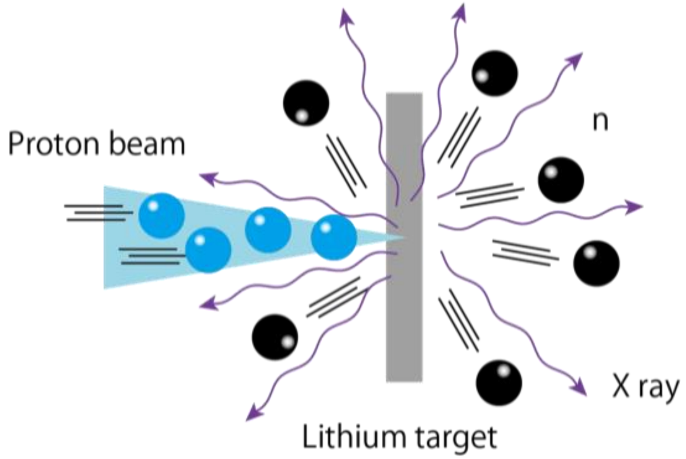
35 mA of $^{7}Li^{3+}$ was accelerated (world record).
$^{7}Li^{3+}$ energy was 1.43 MeV.

*M. Okamura, et al. Demonstration of an intense lithium beam for forward-directed pulsed neutron generation. *Sci. Reports* 12, DOI: 10.1038/s41598-022-18270-0 (2022).

Background

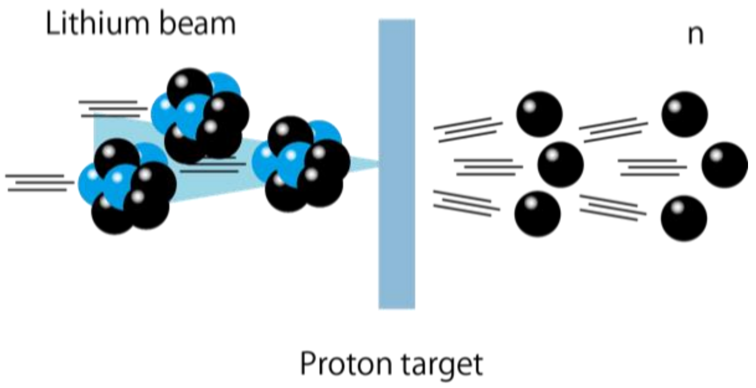
Neutron source with Li ion driver

Non-Inverse kinematic reaction (conventional type)



$$^{7}Li + p \rightarrow {}^{7}Be + n - 1.64\ MeV$$
$$^{9}Be + p \rightarrow {}^{9}B + n - 1.85\ MeV$$

Inverse kinematic reaction*



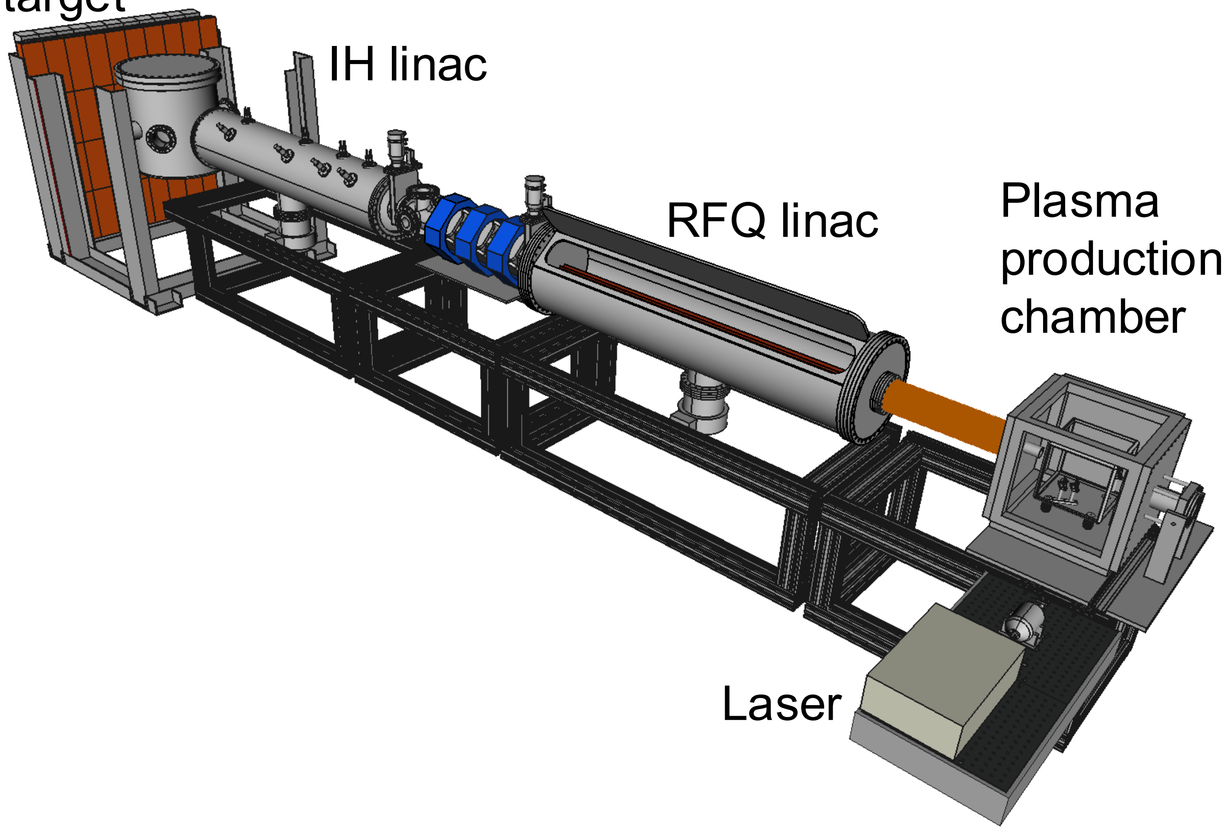
- In the non-inverse kinematic reaction case, the neutrons are produced in the 4 π direction.

<u>Inverse kinematic reaction case</u>

- Neutrons are directed forward thanks to the momentum of the heavier ions compared to the proton target.
- Neutron flux at large angles is reduced drastically.
  -> Smaller number of unwanted radiation and smaller shielding.

*M. Okamura, et al. Demonstration of an intense lithium beam for forward-directed pulsed neutron generation. *Sci. Reports* 12, DOI: 10.1038/s41598-022-18270-0 (2022).

Compact neutron source using intense Li ion beam driver



We achieved 35 mA and 1.43 MeV of $^{7}Li^{3+}$ beam (World record!!) [1].
The threshold energy of the inverse kinematic reaction is 13.098 MeV [2].
⇒ Further acceleration is necessary and will be achieved using an IH-Linac.

Expected specification

Ion	$^{7}Li^{3+}$
Ion beam energy	14-20 MeV
Beam pulse width	0.1-5 us
Repetition rate	100 Hz – 1kHz
Peak ion beam current	10 - 100 mA
Average ion beam current	10 - 100 μA
Neutron energy	0.5 MeV - 5.5 MeV
Average neutron flux	Up to 1 x 10^{9} n/cm^{2}/s
Length	< 8 m

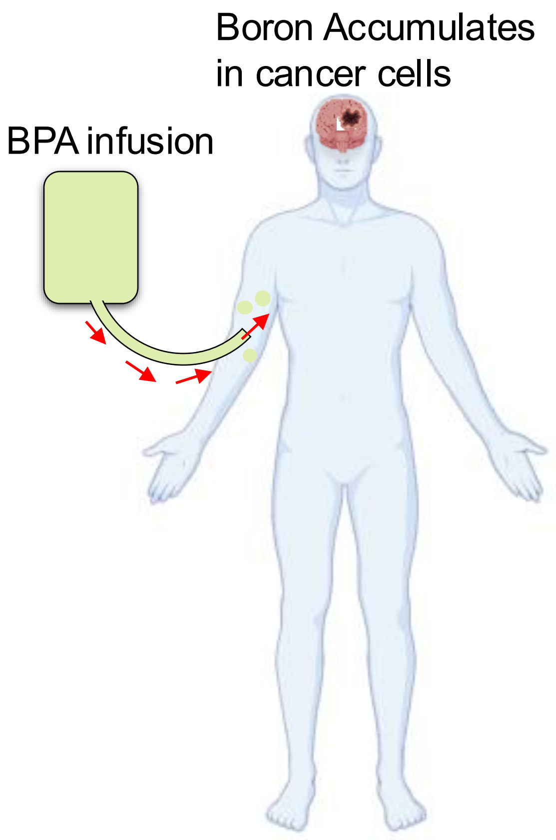
Advantage: Forward-directed neutrons ⇒ very small number of unwanted neutrons, small shielding

[1] M. Okamura, et al. Demonstration of an intense lithium beam for forward-directed pulsed neutron generation. *Sci. Reports* 12, DOI: 10.1038/s41598-022-18270-0 (2022).
[2] M.Lebois, et al. Development of a kinematically focused neutron source with the p(7Li,n)7Be inverse reaction. Nuclear Instruments and Methods in Physics Research-A, 735(2014)145–151, DOI: 10.1016/j.nima.2013.07.061

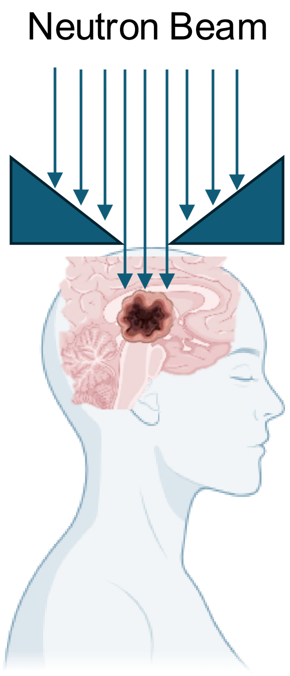
Background

Boron Neutron Capture Therapy (BNCT)

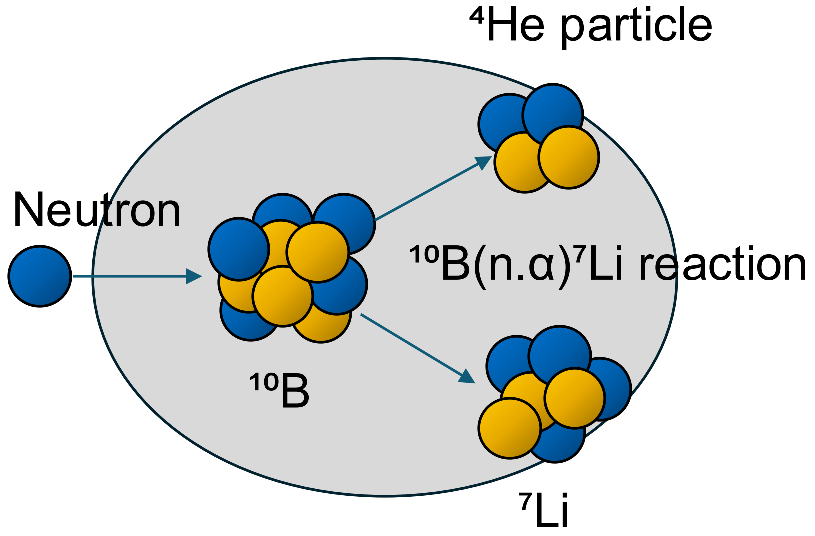
1. Boron compound IV infusion



2. Neutron beam irradiation



3. Transmuted particles destroy tumor cell nuclei



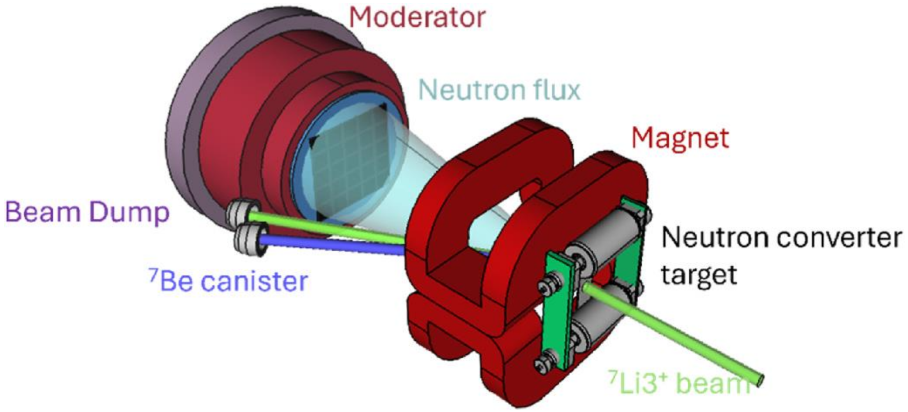
- Neutron Beam reacts with boron-10
- Destroy tumor cells from inside
- Safety passes through surrounding tissue
- Treatment time ~ 1 hour

BNCT is one of the promising applications of the compact neutron source using an intense Li ion beam driver.

Background

BNCT with the inverse kinematic scheme

Our concept of the BNCT using a high-intensity lithium beam has been proposed. This system is expected to achieve a safer and more efficient BNCT system.



Conceptual diagram of a neutron target system assuming a neutron source using inverse kinematics*.

Interior of the RFQ linear accelerator*.

A new paper about our concept was released in public.

Applied Radiation and Isotopes 223 (2025) 111872

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

ELSEVIER

Study of directional pulsed neutron flux generation for BNCT using a high-intensity lithium beam

Masahiro Okamura [a,b,*], Antonino Cannavo [a], Shunsuke Ikeda [a], Takeshi Kanesue [a], Toshiro Sakabe [a], Kazumasa Takahashi [c], Giovanni Ceccio [d], Madhawa Horana Gamage [e]

[a] Brookhaven National Laboratory, NY, USA
[b] Institute of Science Tokyo, Tokyo, Japan
[c] Nagaoka University of Technology, Niigata, Japan
[d] Nuclear Physics Institute of the Czech Academy of Science, Husinec-Rez, Czech Republic
[e] Columbia University, NY, USA

* M. Okamura, et al., Appl. Radiat. Isot.,2025, https://doi.org/10.1016/j.apradiso.2025.111872

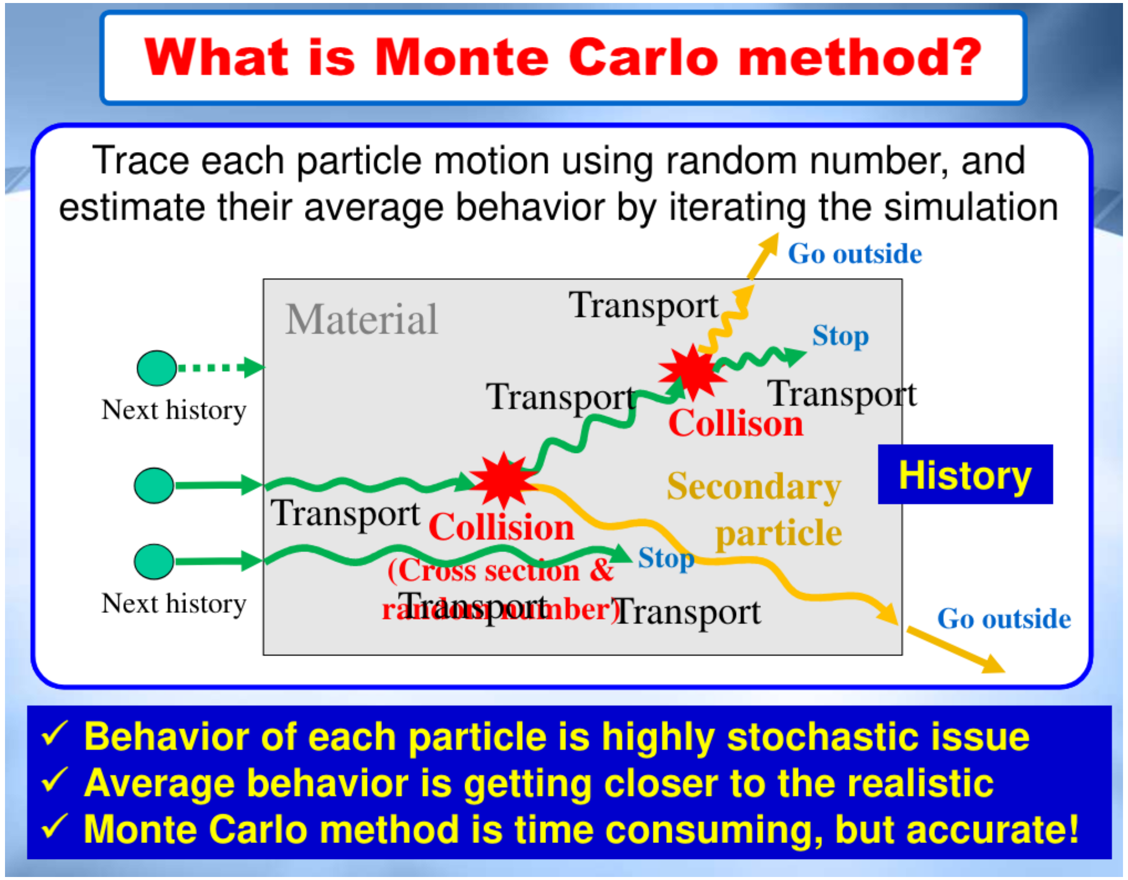
Neutronics simulation

Background of the neutronics simulation for the inverse kinematic reaction

Monte Carlo simulations are essential for developing the neutron source and its applications.
However,

- General nuclear reaction models, incorporated Monte Carlo simulations, can not be used for the inverse kinematic reaction.
- There are no evaluated nuclear cross section data for the inverse kinematic reaction in public.

⇒We need to make the cross-section data for the inverse kinematic reaction, which can be used in a Monte Carlo simulation.

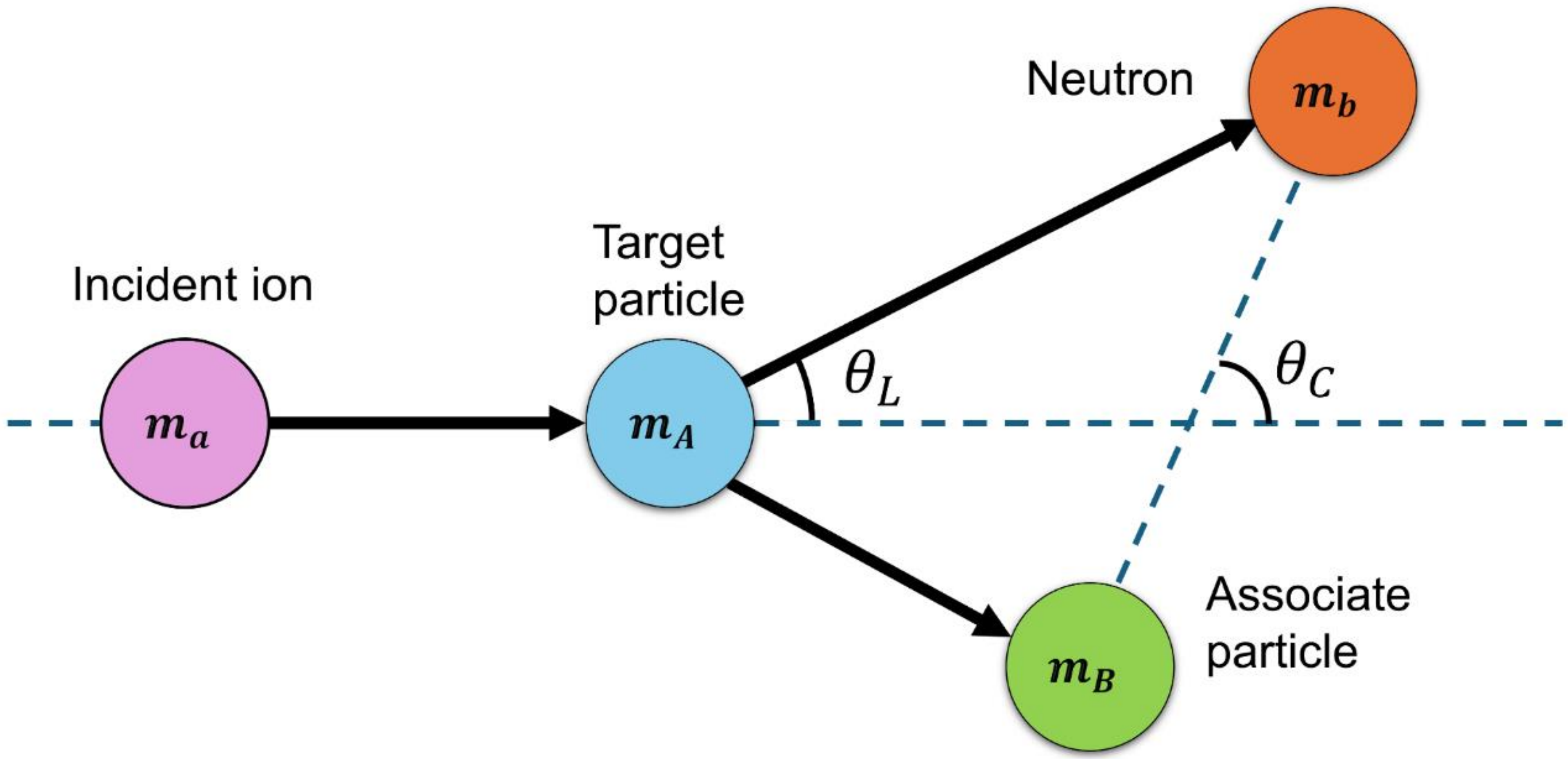


"What is Monte Carlo method?"
https://phits.jaea.go.jp/lec/phits-introduction-en.pdf

Summary of making process for the cross-section data

The cross-section data for the inverse kinematic reaction, $p(^{7}Li,n)^{7}Be$, was made based on evaluated cross-section data of the proton beam case.

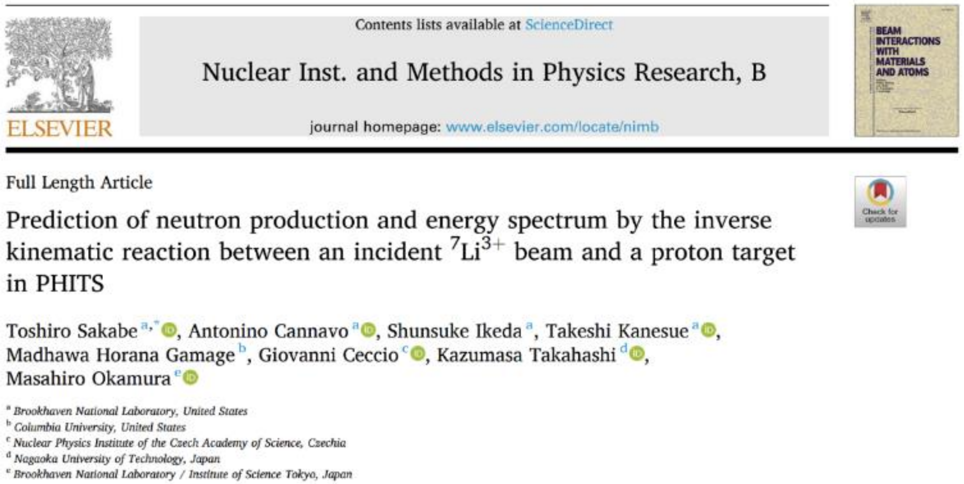
The transformation between the center-of-mass frame and the laboratory frame was performed using two-body kinematics.



Monte Carlo simulation for the inverse kinematic reaction

The Monte Carlo simulation with the new cross-section data showed reasonable results that well describe the feature of neutrons from the inverse kinematic reaction.

A new paper about our initial simulation study was released in public.


Nuclear Instruments and Methods in Physics Research B 566 (2025) 165783

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, B

journal homepage: www.elsevier.com/locate/nimb

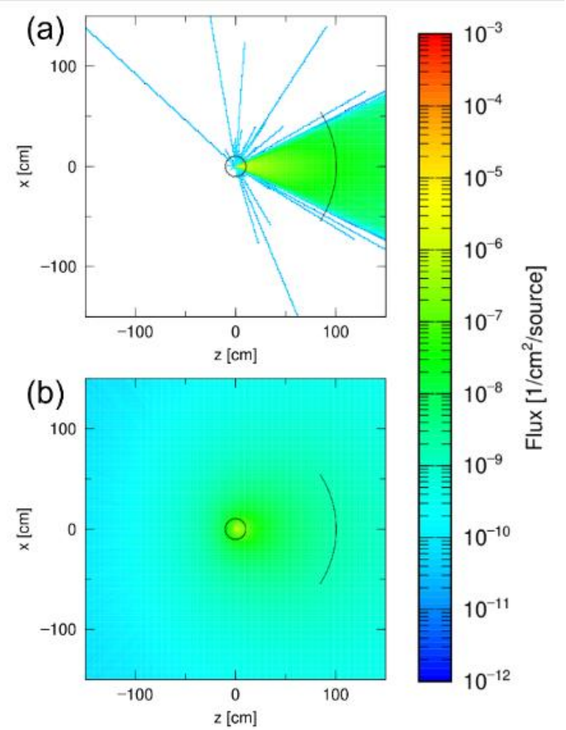
Full Length Article

Prediction of neutron production and energy spectrum by the inverse kinematic reaction between an incident $^{7}Li^{3+}$ beam and a proton target in PHITS

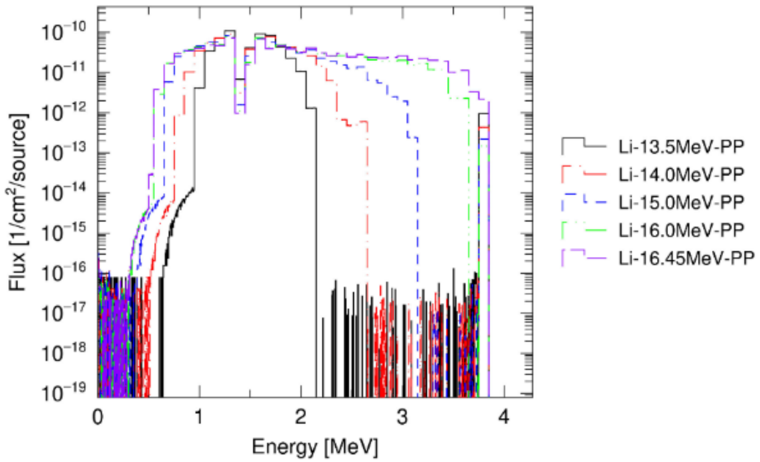
Toshiro Sakabe [a,*], Antonino Cannavo [a], Shunsuke Ikeda [a], Takeshi Kanesue [a], Madhawa Horana Gamage [b], Giovanni Ceccio [c], Kazumasa Takahashi [d], Masahiro Okamura [e]

[a] Brookhaven National Laboratory, United States
[b] Columbia University, United States
[c] Nuclear Physics Institute of the Czech Academy of Science, Czechia
[d] Nagaoka University of Technology, Japan
[e] Brookhaven National Laboratory / Institute of Science Tokyo, Japan

* T. Sakabe, et al., Nucl. Instrum. Methods Phys. Res. B, 2025, https://doi.org/10.1016/j.nimb.2025.165783



(a) The inverse kinematic reaction, p (^{7}Li, n)^{7}Be.
(b) The non-inverse kinematic reaction, ^{7}Li (p, n)^{7}Be. The incident particle energies were 2.286 MeV/n for both simulations. A polypropylene target is defined.

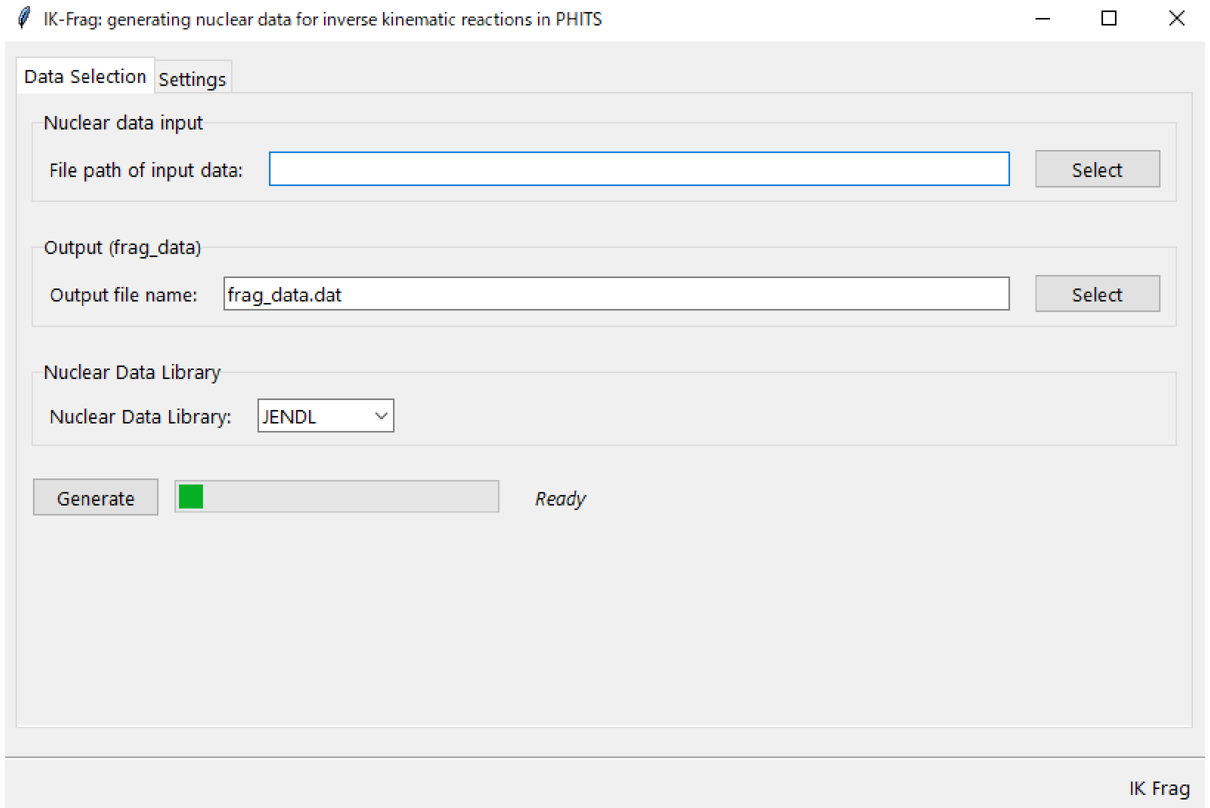


Neutron energy spectra of p (^{7}Li, n)^{7}Be. In the legend, "Li" and "PP" mean a lithium-ion beam and a polypropylene target, respectively. The energy values in the legend mean the incident lithium-ion energy*.

Cross-section data generator for the inverse kinematic reaction

We developed an automated tool that produces cross-section data for inverse-kinematics reactions, in collaboration with a graduate student at the University of Osaka.

This software tool has been released to the public on GitHub: https://github.com/furiwara19/IK-Frag



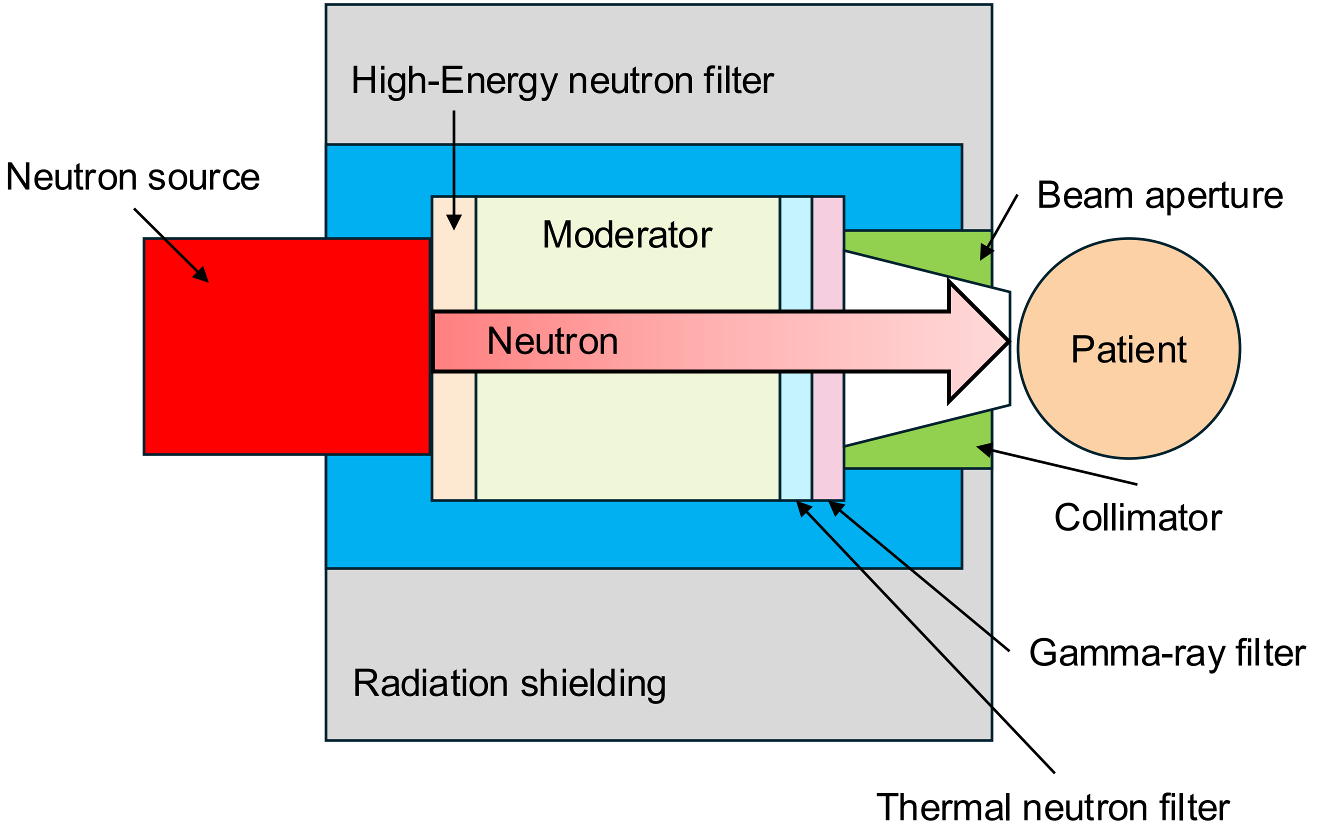
Graphic user interface of the software

This software tool can process major evaluated nuclear cross-section libraries (ENDF, TENDL, and JENDL) and select the key parameters used to generate new data.

Beam shaping Assembly（BSA）

A Beam Shaping Assembly (BSA) is a key component of a BNCT system that modifies the primary neutron beam from an accelerator. It adjusts the energy, intensity, and direction of the neutrons to produce an epithermal or thermal neutron beam suitable for medical treatment. **We initiated the design of BSA.**

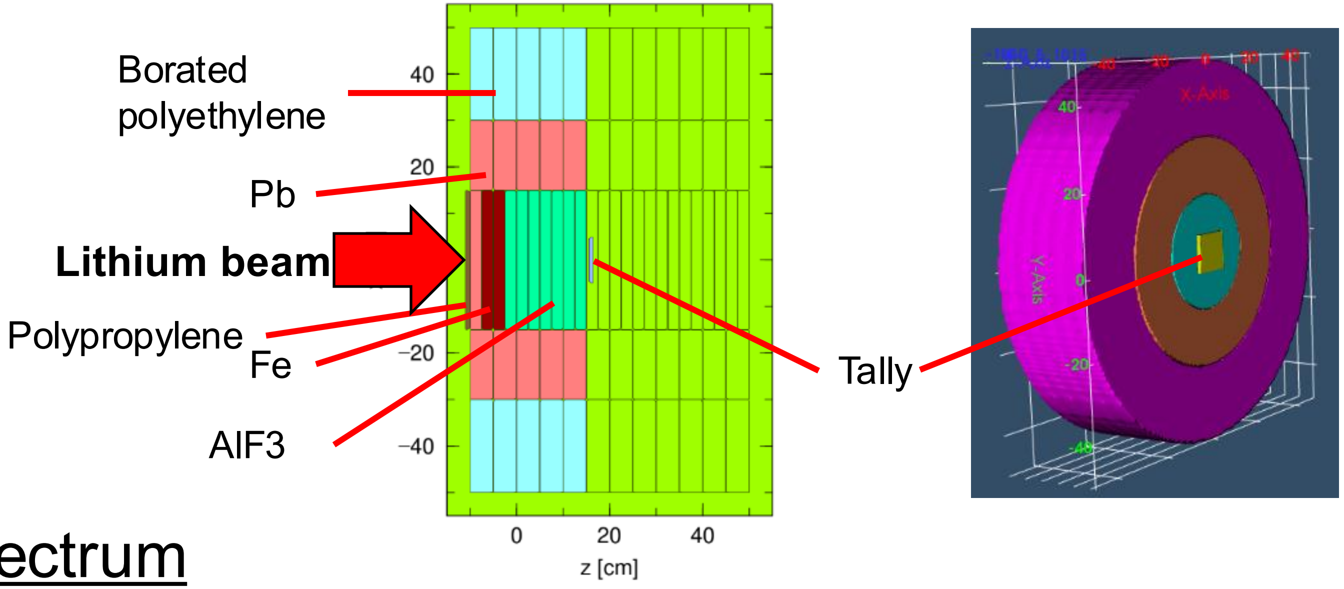
Conceptual diagram of a BSA



Initial trial about the BSA design for the inverse kinematic system

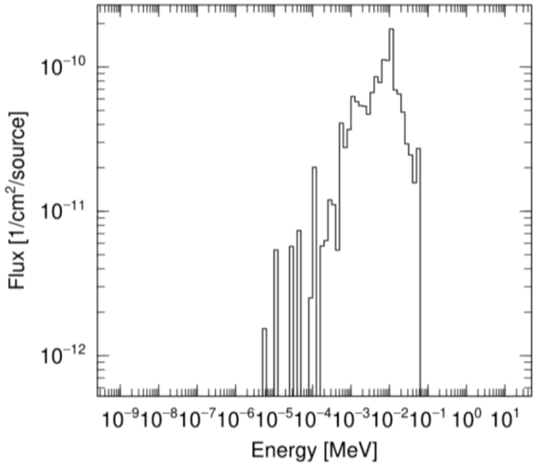
Geometry

^{7}Li-ion hits the polypropylene target and then neutrons are produced.

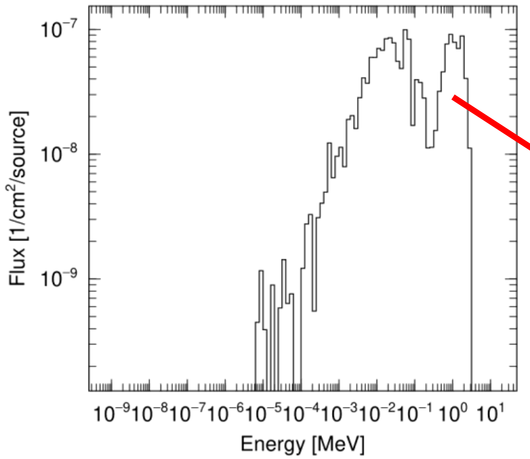


Neutron energy spectrum

Proton 2.5 MeV + Li target
(non-inverse kinematics)



Li 15 MeV + plastic target
(inverse kinematics)

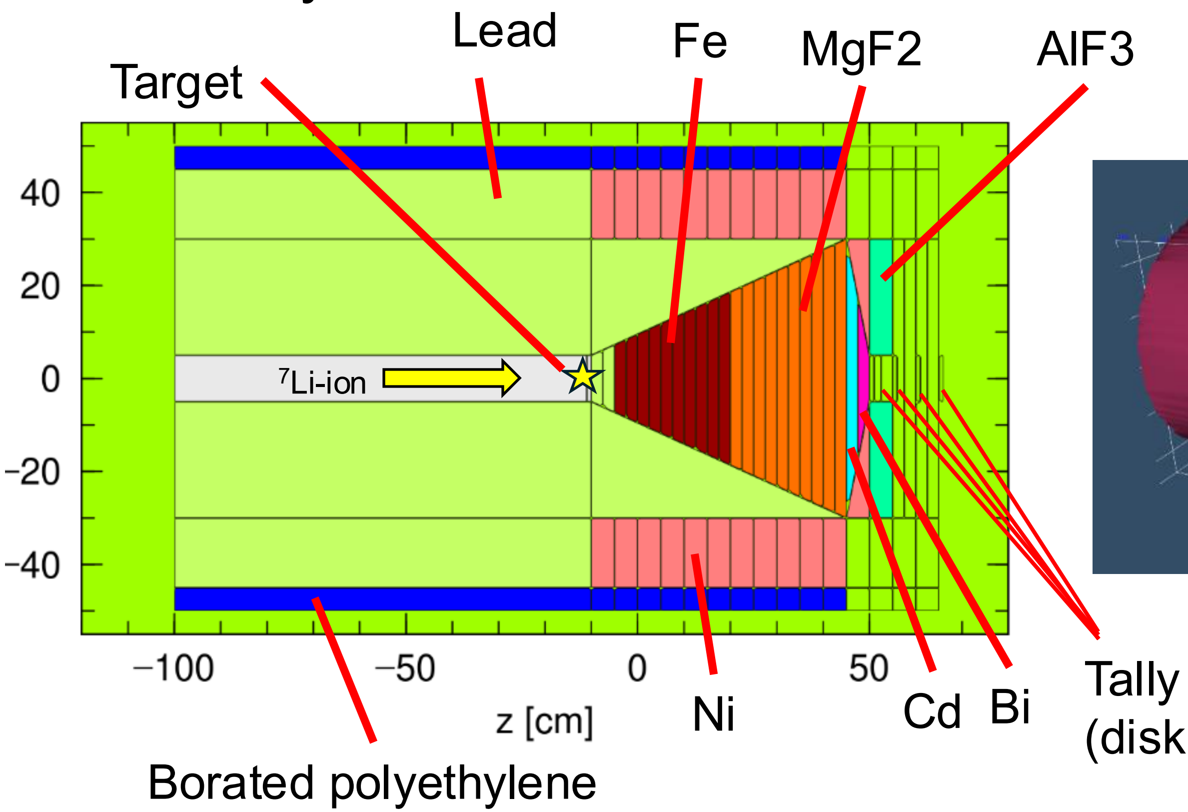


Fast neutrons exist after the moderator.
⇒Further moderation is required.

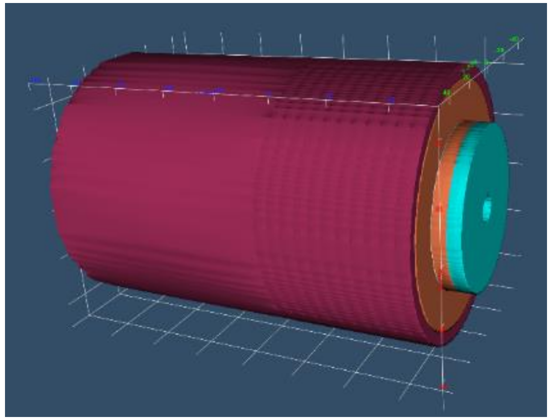
BSA design for the inverse kinematic system

We defined a thicker BSA system to moderate neutrons sufficiently.

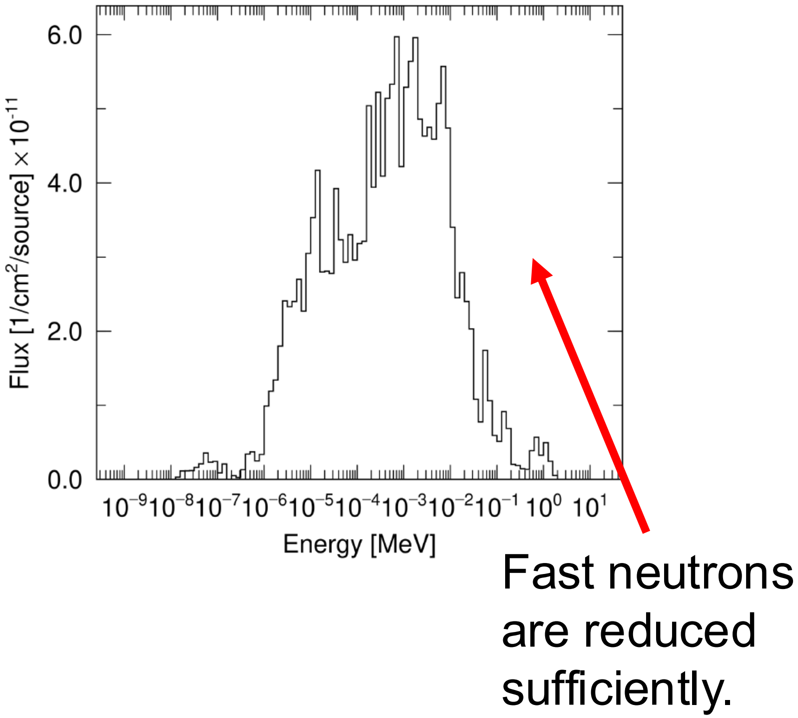
Geometry



3D image



Results
(Neutron energy spectrum)



Summary of the neutronics simulation study

- A cross-section dataset for the inverse kinematic reaction was developed for use in Monte Carlo simulations.
- The simulations incorporating this dataset produced results that were consistent with expectations for the neutron yield, angular distribution, and energy spectrum.
- These results also match theoretical predictions for neutrons generated via inverse kinematics and agree with values reported in previous studies.
- The initial study for the BSA design indicates that the neutron energy can be tuned for BNCT with an appropriate BSA configuration.

Neutron measurement

Neutron measurement experiment at BNL

The experimental study aims to:

- characterize neutrons from the inverse kinematic reaction; $p(^{7}Li, n)^{7}Be$.
- validate the PHITS simulation system for the inverse kinematic reaction.

The Tandem Van de Graaff accelerator at BNL was used for the experiment.

<u>Basic information on the experiment</u>

- Beam ion: $^{7}Li^{3+}$
- Target material: Polypropylene $(C_3H_6)_n$
- 15 MeV

The Tandem Van de Graaff accelerator at BNL

https://www.bnl.gov/tandem/

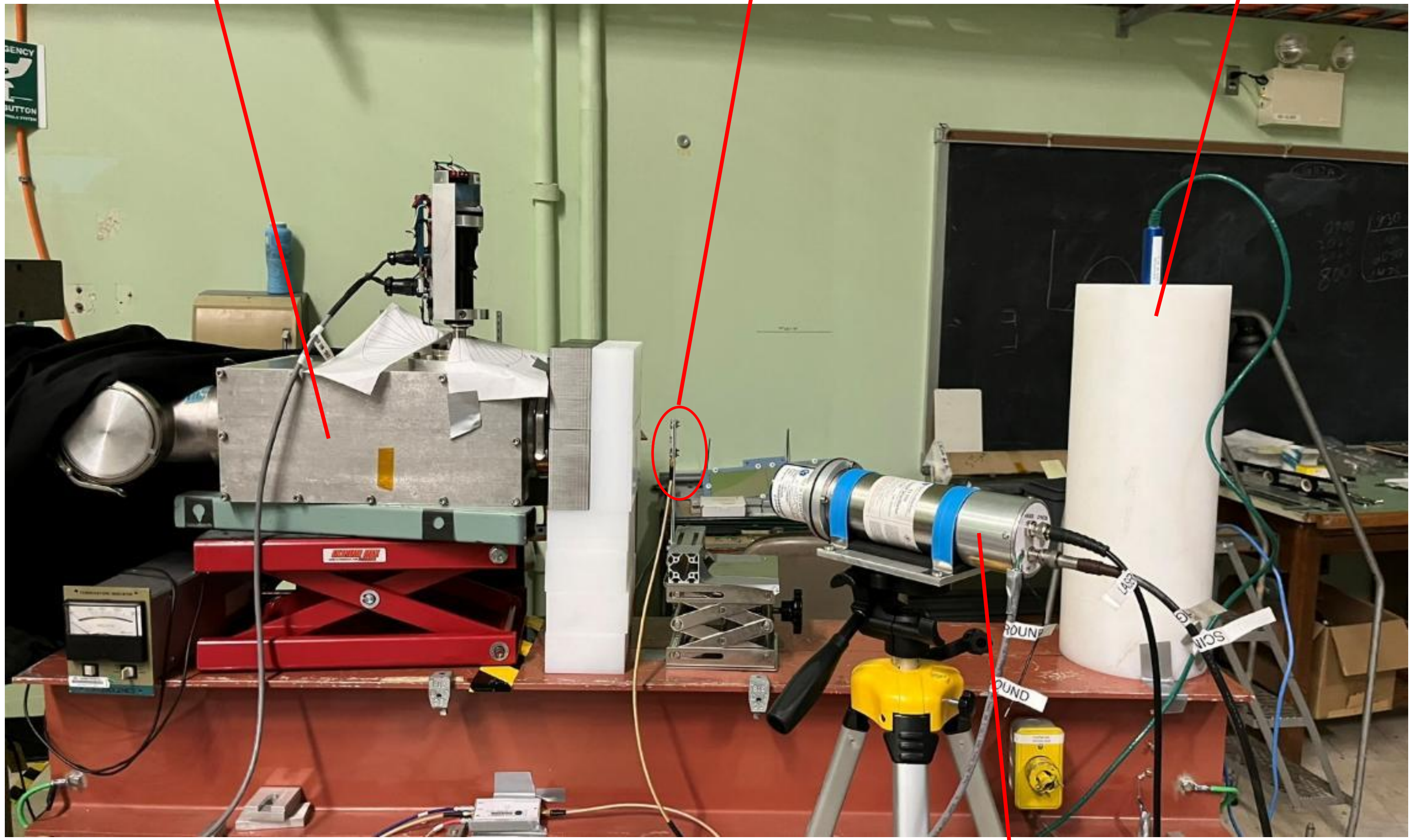
Setup of the chamber and the detector

The target chamber was installed at the end of the beamline. The detectors were located near the chamber.

Vacuum chamber

Diamond detector

BF_3 detector



Liquid scintillator

<u>Diamond detector</u>

- 0 degrees
- 15 cm away from the surface of the chamber
- Bias voltage: - 400 V (negative voltage)

<u>BF_3 detector</u>

- 0 degrees
- 90 cm away from the target
- Bias voltage: +1275 V (positive voltage)

<u>Liquid scintillator</u>

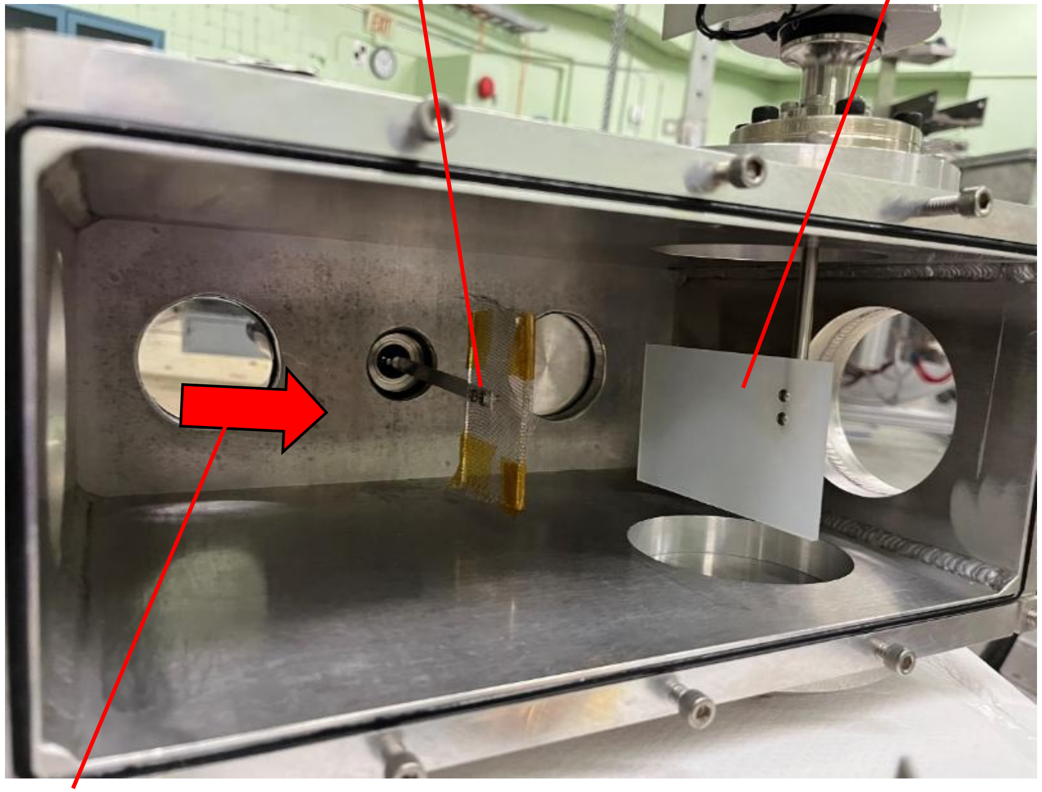
- 40 degrees
- 55 cm away from the target
- Bias voltage: - 750 V (negative voltage)

Setup of the target and the scintillator for the beam monitor

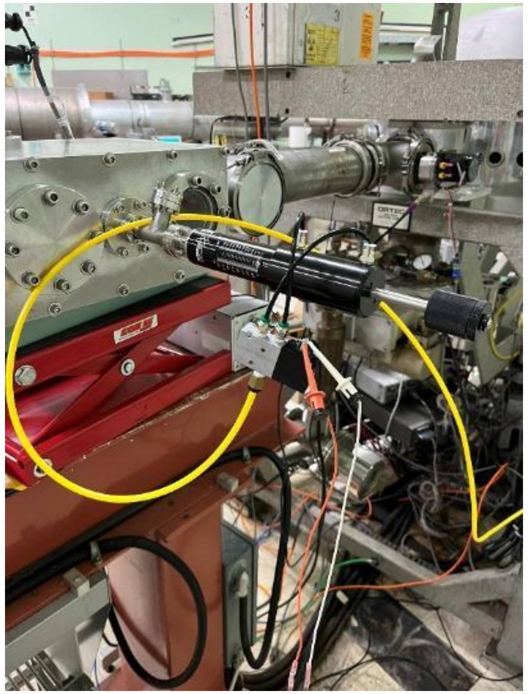
The polypropylene target was installed in the chamber. The thickness was 3.175 mm.

Scintillator for the beam monitor (BC-408, Saint-Gobain)

Polypropylene target



Beam direction

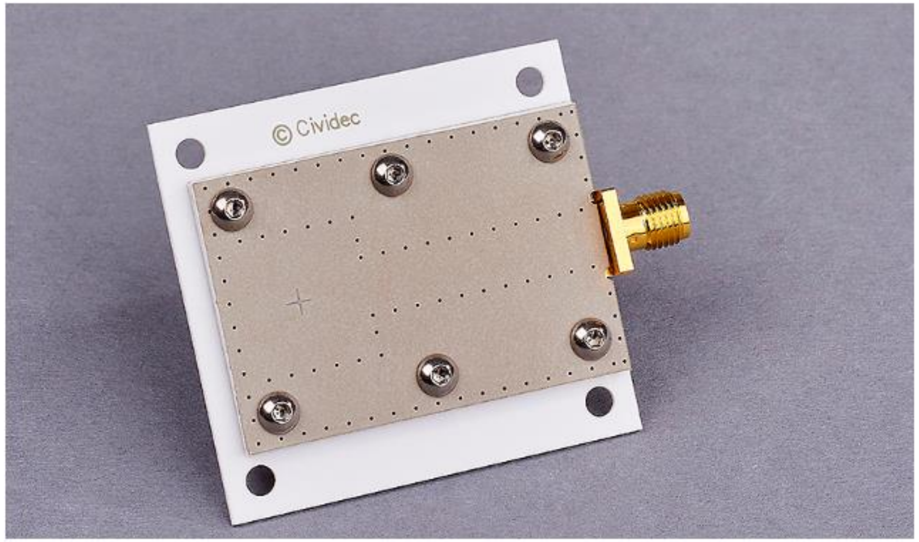


A scintillator was inserted into the vacuum chamber via the pneumatic feedthrough.

Before the experiment, the beam size and shape were observed using the scintillator.

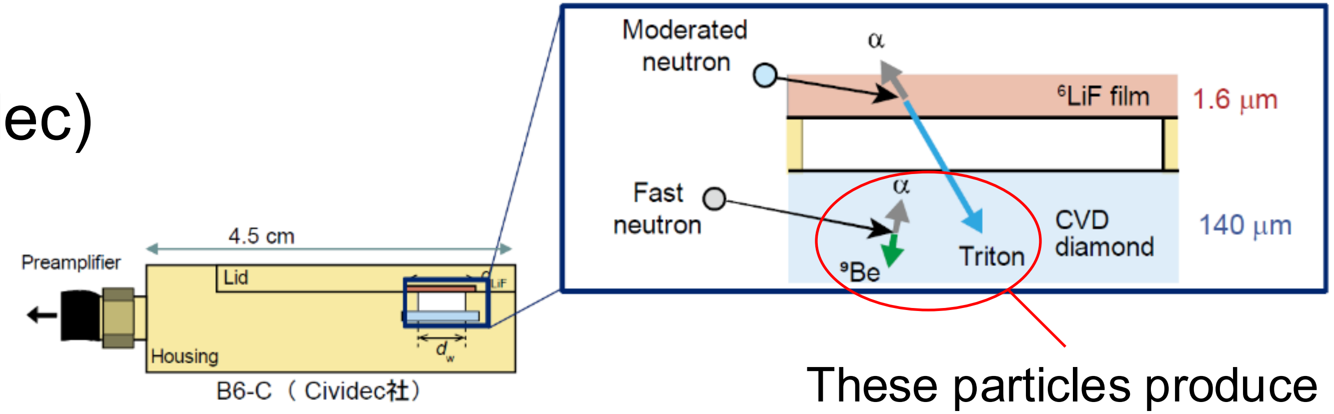
During the neutron production, the scintillator was withdrawn from the beam path.

Diamond neutron detector(B7, Cividec)



Sensor material:	sCVD diamond
Active area:	4 mm x 4 mm
Sensor thickness:	500 µm
Neutron energy range:	E_n > 1 MeV
Calibration Aperture:	1 mm in diameter

https://cividec.at/detectors-B7.html



*K. Mukai *et al. Nucl. Fusion*2021

These particles produce electron-hole pairs inside the diamond.

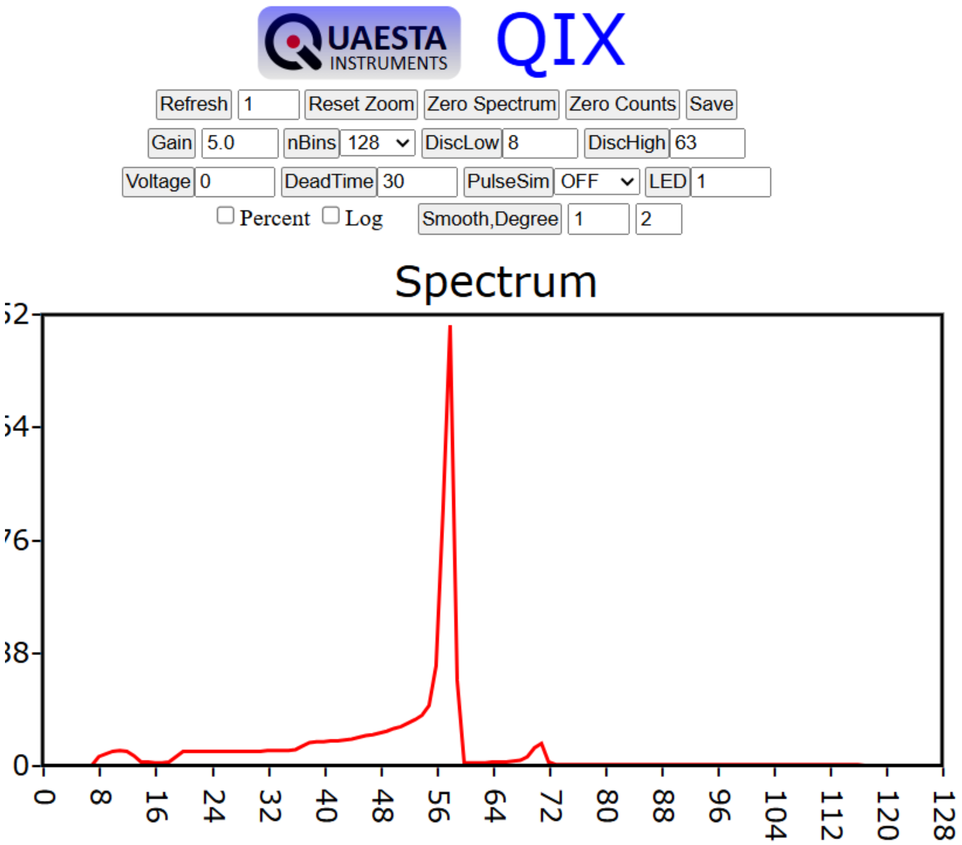
The number of the produced electron-hole pairs is proportional to the energy loss of the incident particle.
The energy per signal e-h pair creation in diamond is 13.6 eV.*
⇒ We can obtain information on deposited energy to the diamond by collecting signals of electrons or holes.

*Kavrigin, P. (2018). *Neutron spectroscopy with sCVD diamond detectors* [Dissertation, Technische Universität Wien]. reposiTUm. http://hdl.handle.net/20.500.12708/78506

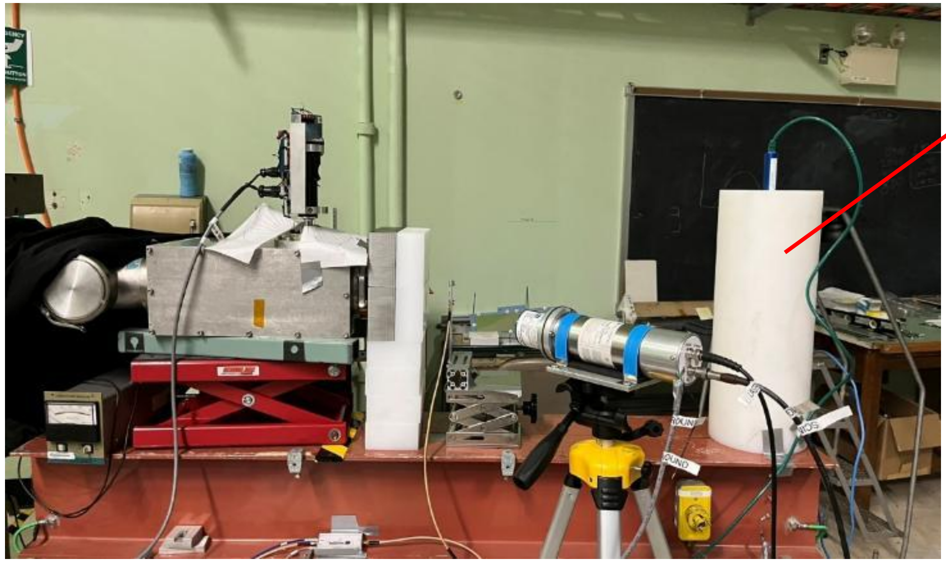
Results: BF3 neutron detector

A typical shape of the spectrum data was obtained with the BF_3 neutron detector.

The spectrum at 15 MeV, 45 nA



Spectrum Counts = 9148197
Spectrum Time = 1882.603, CPM = 291560.0
Total Counts = 8635234, CPS = 4342



BF_3 detector

Reactions for the neutron detection

$$n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li^{*} + {}^{4}_{2}He \ (Q = 2.30\ MeV, 93\%)$$

$$n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He \ (Q = 2.78\ MeV, 7\%)$$

Results: Comparison between the experiment and the simulation

A PHITS simulation was also conducted for the comparison between the experimental data and the simulation data.

Results of the BF_3 detector: Helium-production reaction rate at 15 MeV of Li-beam

	Experiment	JENDL (C/E)	TENDL (C/E)	ENDF (C/E)
Setting 1 (without block)	4.57.E+03	5.84.E+03 (1.28)	5.24.E+03 (1.15)	5.52.E+03 (1.21)

C/E: Calculation(Simulation) / Experiment

Unit: Count per second

Results of the diamond detector: Elastic scattering rate at 15 MeV of Li-beam

	Experiment	JENDL (C/E)	TENDL (C/E)	ENDF (C/E)
Setting 1 (without block)	2.90.E+01	3.82E+01 (1.32)	2.88E+01 (0.994)	2.99E+01 (1.03)

C/E: Calculation(Simulation) / Experiment

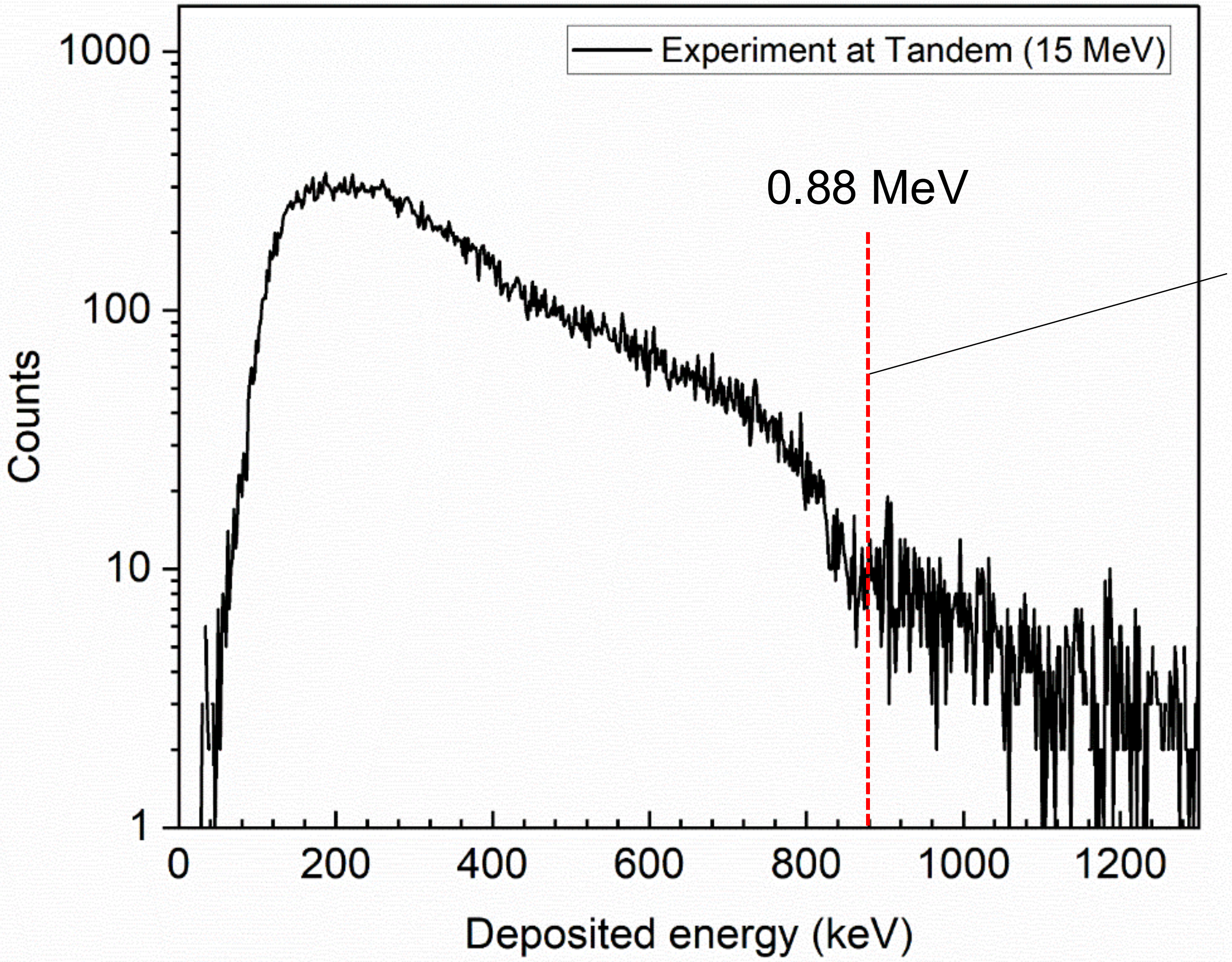
Unit: Count per second

The same order of the reaction rates was observed. There is a good agreement between the experimental results and the simulation.

Results: Deposited energy into the diamond

The spectrum of the deposited energy was obtained by the measurement with the diamond detector.

15 MeV, 45 nA of the Li-ion beam without the moderator block



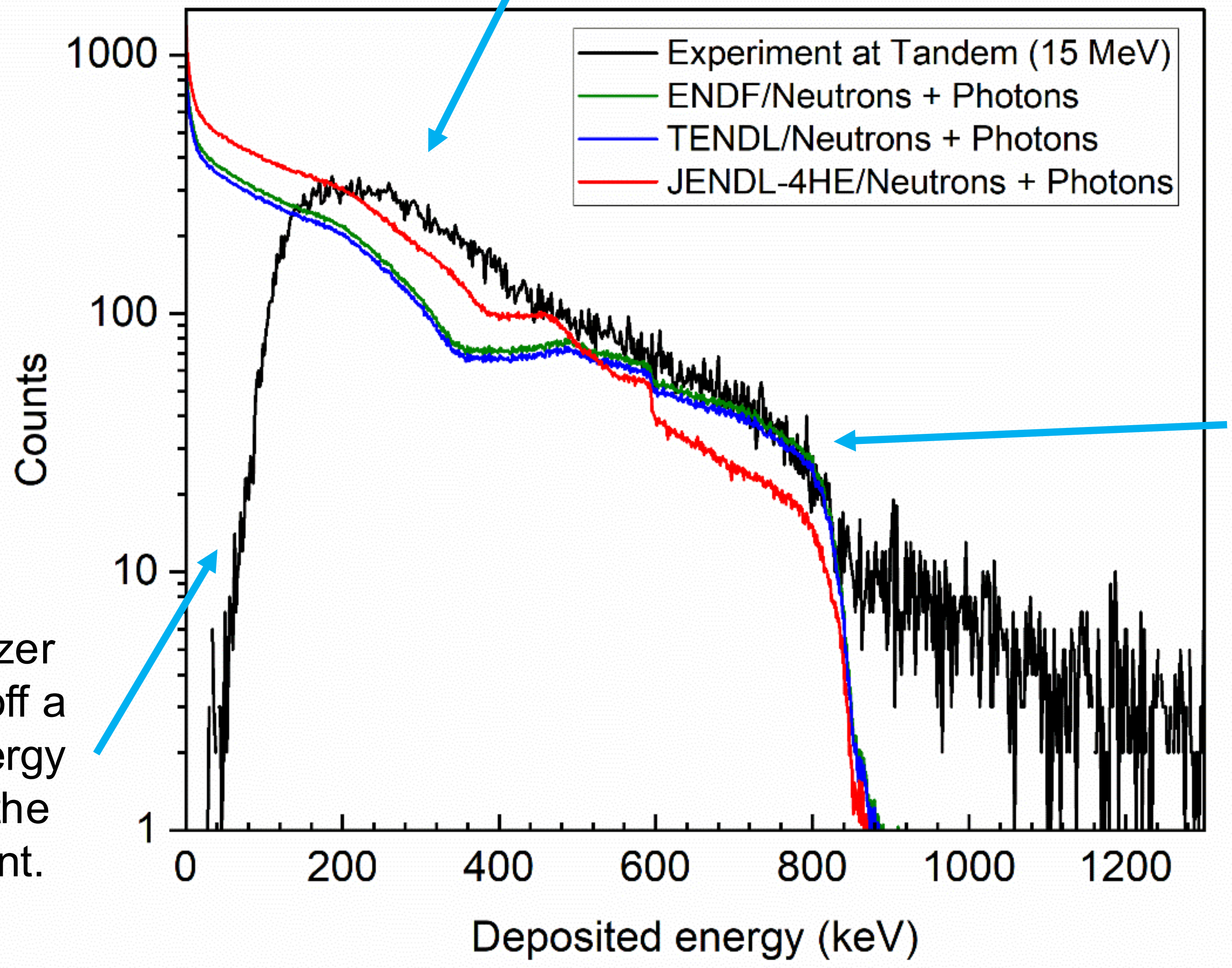
15MeV Li ion: Max neutron 3.1 MeV

The drop point is the same as the maximum deposited energy by the elastic reaction (0.88 MeV).

The maximum neutron energy, estimated from the experiment data, agrees with the calculated value.

Results: Comparison of deposited energies between the experiment and the simulation

The JENDL-based showed a better agreement in a lower energy region.



The energy deposition by the elastic reaction between carbon and a neutron is dominant.
The photon contribution to the energy deposition is negligibly small.

The ENDF-based data and the TENDL-based data showed a good agreement around a higher energy region.

The digitizer may cut off a lower energy signal in the experiment.

Good agreement between the experimental results and the simulation was observed.

Summary of the neutron measurement study

- Fast neutrons from $p(^7Li,n)^7Be$ were measured by using the diamond detector. The maximum neutron energy from the experiment is estimated to be the same as the theoretical value.

- The BF_3 neutron detector also detected moderated thermal neutrons from $p(^7Li,n)^7Be$. The nuclear reaction induced in the BF_3 neutron detector is identical to the $^{10}B(n,\alpha)^7Li$ reaction used in BNCT.

- The simulated deposited-energy spectrum in the diamond showed good agreement with the experimental results.

- Further validation for the simulation is required.

Recent publication

2 full papers and 1 conference paper were published.

- Masahiro Okamura, et al., “Study of directional pulsed neutron flux generation for BNCT using a high-intensity lithium beam”, *Applied Radiation and Isotopes*, 223 (2025) 111872, https://doi.org/10.1016/j.apradiso.2025.111872

- Toshiro Sakabe, et al., “Prediction of neutron production and energy spectrum by the inverse kinematic reaction between an incident 7Li3+ beam and a proton target in PHITS”, *Nuclear Instruments and Methods in Physics Research B* 566 (2025) 165783, https://doi.org/10.1016/j.nimb.2025.165783

- Toshiro Sakabe, et al., “Measurement of forward-directed neutrons generated by an inverse kinematic reaction using incident 7Li3+ beam”, 16th International Conference on Heavy Ion Accelerator Technology (HIAT2025), conference paper, 2025, https://doi.org/10.18429/JACoW-HIAT2025-WEX05

Summary of the project

- In this project, we are advancing our research using both simulation and experiments to guide the design of the accelerator and the neutron beam shaping assembly.

- The cross-section data set was prepared for the inverse kinematic reaction and used in the Monte Carlo simulation. The simulation results well described the feature of neutrons from the inverse kinematic reaction.

- In the experiment, fast neutrons and moderated thermal neutrons were measured using the diamond detector and the BF_3 neutron detector. The experimental data showed good agreement with the simulation results.