New opportunities and challenges in nuclear physics with high power lasers
1 July 2024, Trento, Italy

Advances in Laser-driven Neutron Sources and Applications at Osaka University

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Neutron characteristics

Compared to X-rays…

Higher ability to penetrate matter ⇒**Transmission measurement**

High sensitivity to light elements (especially hydrogen)

⇒**Detecting water, hydrogen, biomolecules, oil**

Reaction differs depending on the element ⇒ **Element identification**

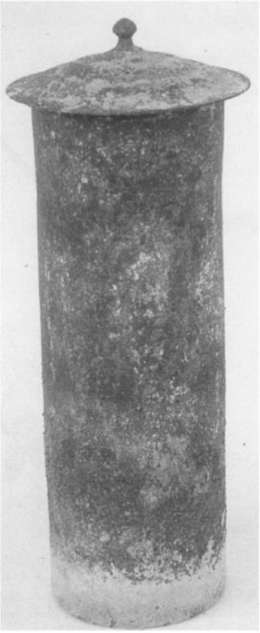


図１　一乗寺経塚出土経筒の概観[5]

Neutron

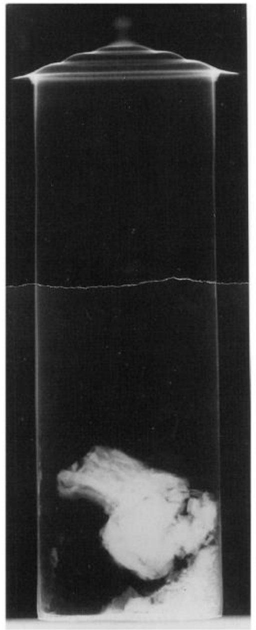


図２　経筒の NR 画像[5]

X-ray

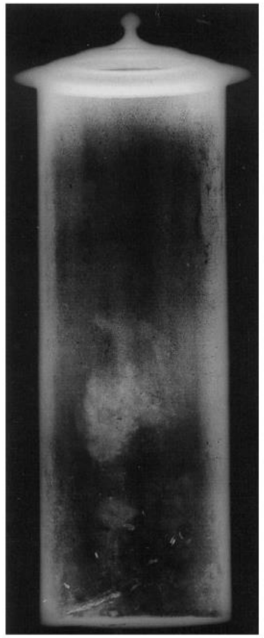


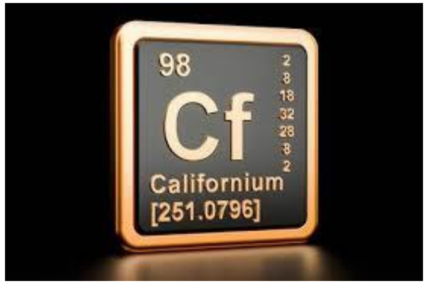
図３　経筒の XR 画像[5]

Reactor (JRR-3)

Neutron Sources

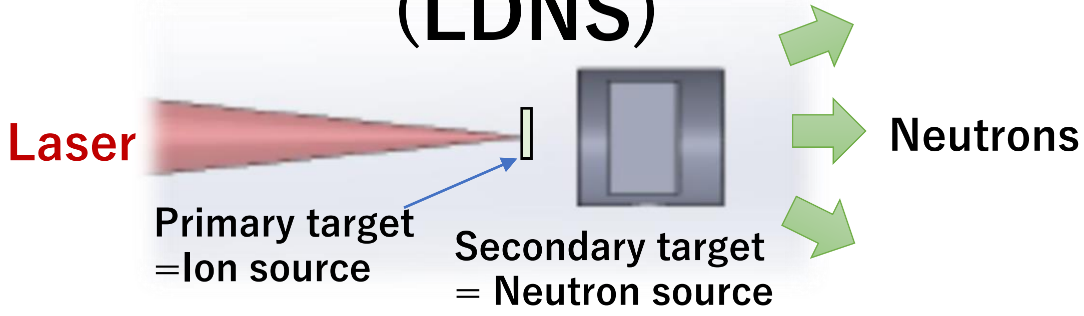
Reactor
Large facility
Continuous beam

Accelerator
Large facility
Pulsed beam



Radioisotope
Small, Expensive
Continuous beam
Temporal decay

Laser-driven Neutron Source (LDNS)



High Neutron number
~$10^{10\text{-}11}$ n/pulse

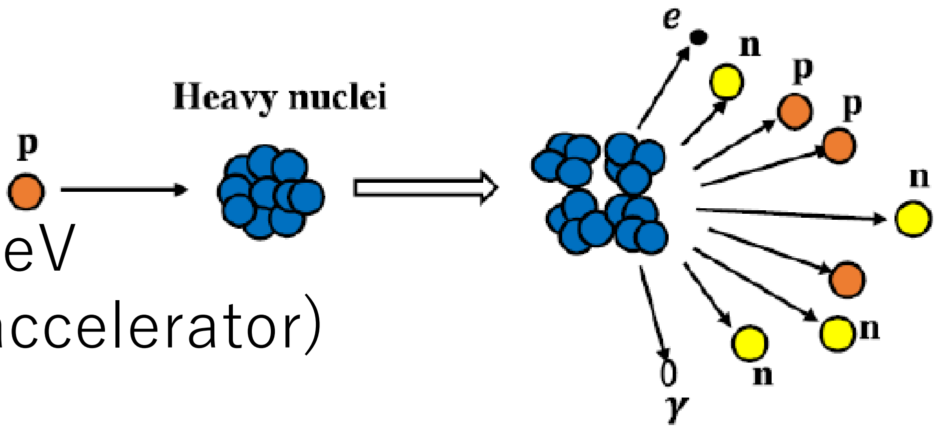
Short Pulse
< 1ns

Small Size
~1 cm^3

Main current scientific question
What are the characteristics of LDNS that make it possible to provide science and applications that are not possible with accelerator neutron sources?

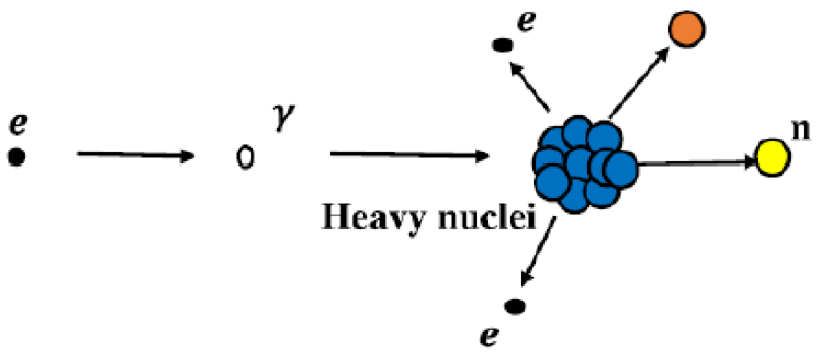
Nuclear reactions to generate neutrons by laser

(a) Spallation Nuclear Reaction

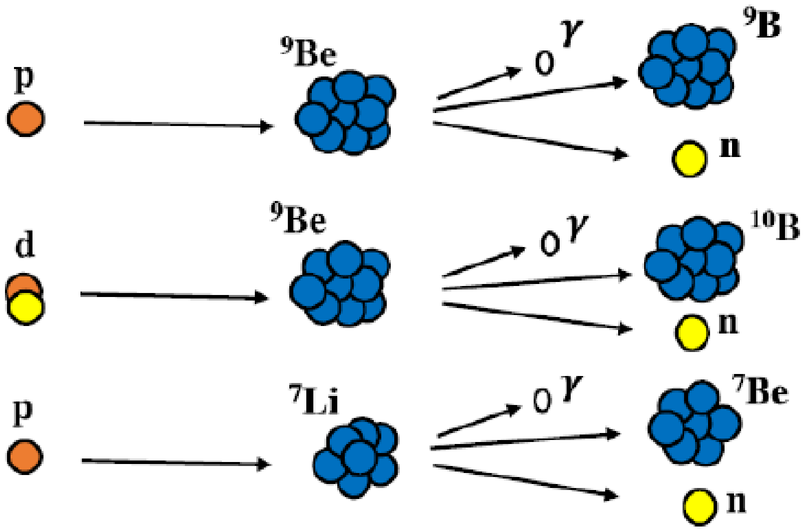


GeV
(J-PARC accelerator)

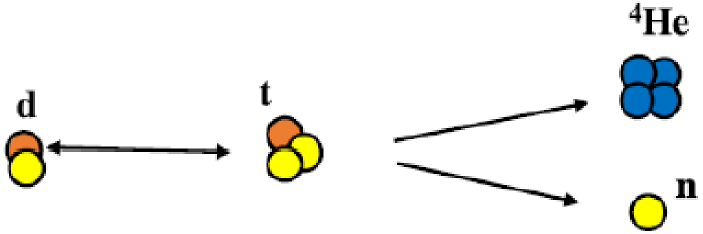
(b) Photo Nuclear Reaction



(c) Low Energy Nuclear Reaction



(d) Thermo-nuclear Fusion



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Literatures on LDNS

2004 — 10^8 n/sr

Author	Reaction	Target primary	Target secondary	Laser configuration: Energy [J]	Intensity [$\mathrm{Wcm^{-2}}$]	Duration [ps]	Neutron Yield [n/sr]	[n/sr/J]
Lancaster	Li(p,n)Be	CH	LiF	80	3×10^{19}	1	3.0×10^8	3.75×10^6
Higginson	Li(p,n)Be	Cu	LiF	140	1×10^{20}	0.7	1.0×10^8	7.1×10^5
Higginson	Li(d,n)Be	CD_2	LiF	360	2×10^{19}	9	8.0×10^8	2.2×10^6
Willingale	D(d,n)He	CD	CD	6	2.6×10^{19}	0.4	5.0×10^4	8.3×10^3
Jung	Be(p,n)B, Be(d,n)	CD_2, CH	Be	80	5×10^{20}	0.6	4.4×10^9	5.5×10^7
Roth	Be(p,n)B, Be(d,n)	CD_2	Be	80	5×10^{20}	0.6	5.0×10^9	6.3×10^7
Zulick	Li(p,n)Be	CH_2	LiF	1.1	2×10^{21}	0.04	1.0×10^7	9.1×10^6
Maksimchuk	D(d,n)He	D_2O ice on Cu	CD	6	2×10^{19}	0.4	4.0×10^5	6.7×10^4
Storm	Li(p,n)Be	Si_3N_4	Li	60	2×10^{20}	0.18	1.6×10^7	2.7×10^5
Pomerantz	photo-nuclear	plastic	Cu	90	-	0.15	1.0×10^7	1.1×10^5
Kar	D(d,n)He	CD	CD	220	3×10^{20}		8.0×10^8	3.6×10^6
Alejo	D(d,n)He	D_2O ice on Cu	CD	200	2×10^{20}	0.75	2.0×10^9	1.0×10^7
Kleinschmidt	Be(p,n)B, Be(d,n)	CD	Be	175	2×10^{20}	0.5	1.42×10^{10}	8.1×10^7
Zimmer	(p,n), (d,n)	CD	LiF-Be	100	2×10^{20}	0.6	1.43×10^9	1.4×10^7
Günthe	photo-nuclear	CHO foam + Au	-	20	$\sim 10^{19}$	0.75	1.11×10^9	5.5×10^7
	(p,n)	CHO foam + Au	-	20	$\sim 10^{19}$	0.75	4.93×10^9	2.5×10^8
Yogo	Be(p,n)B, Be(d,xn)	CD	Be	900	1×10^{19}	1.5	2.3×10^{10}	2.6×10^7

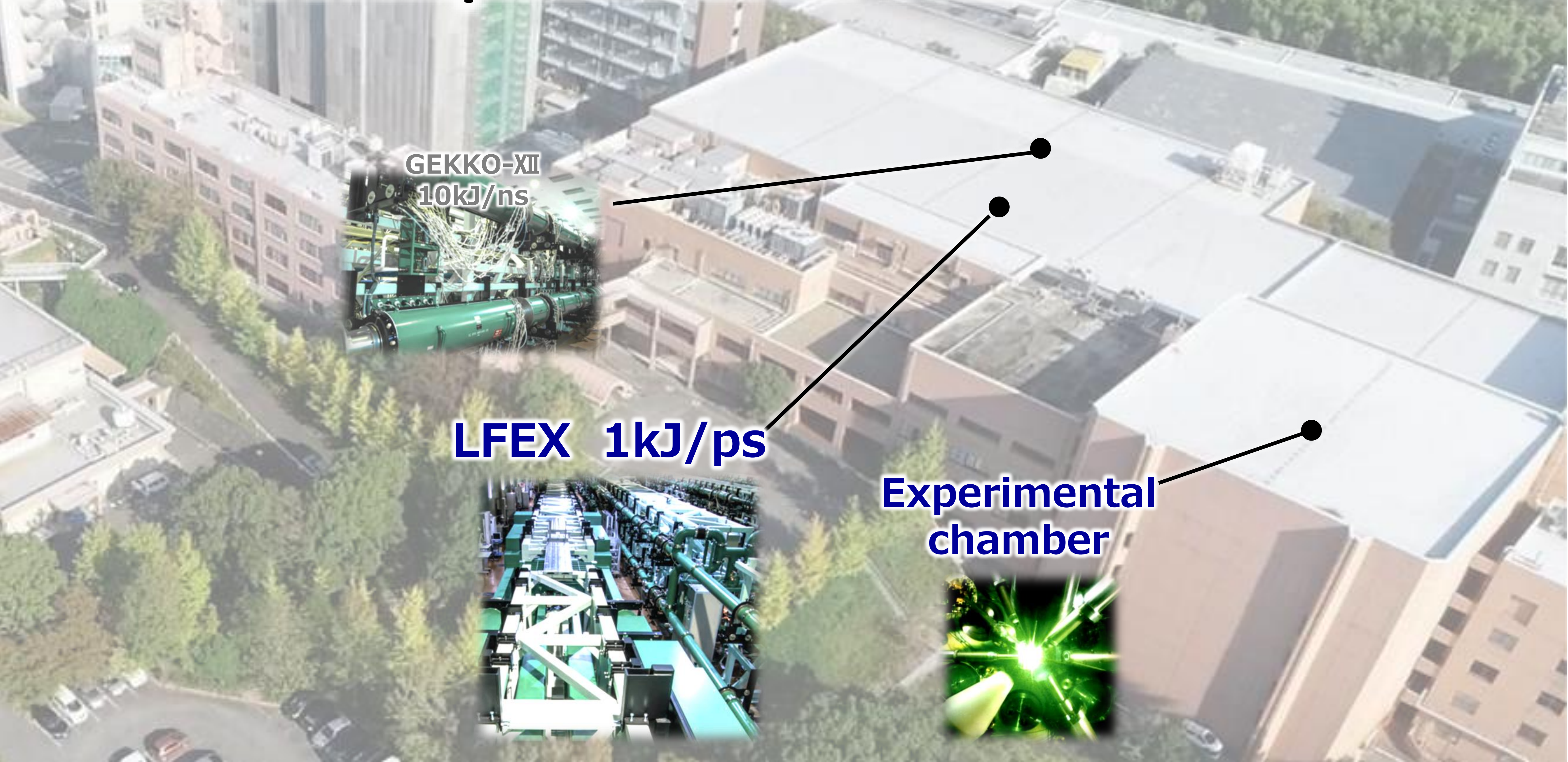
2023 — 10^{10} n/sr

Yogo, A. *et al. Eur. Phys. J. A* **59**, 191 (2023), *Review Article*, OPEN ACSESS

>10^9 neutrons/steradian enables applications

in the fields of **Neutron Analysis**

LDNS Developments at ILE Osaka



Experimental conditions

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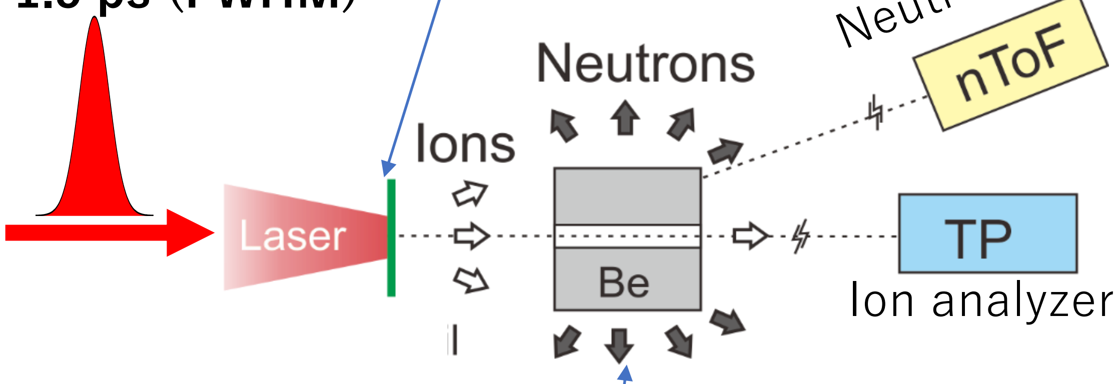
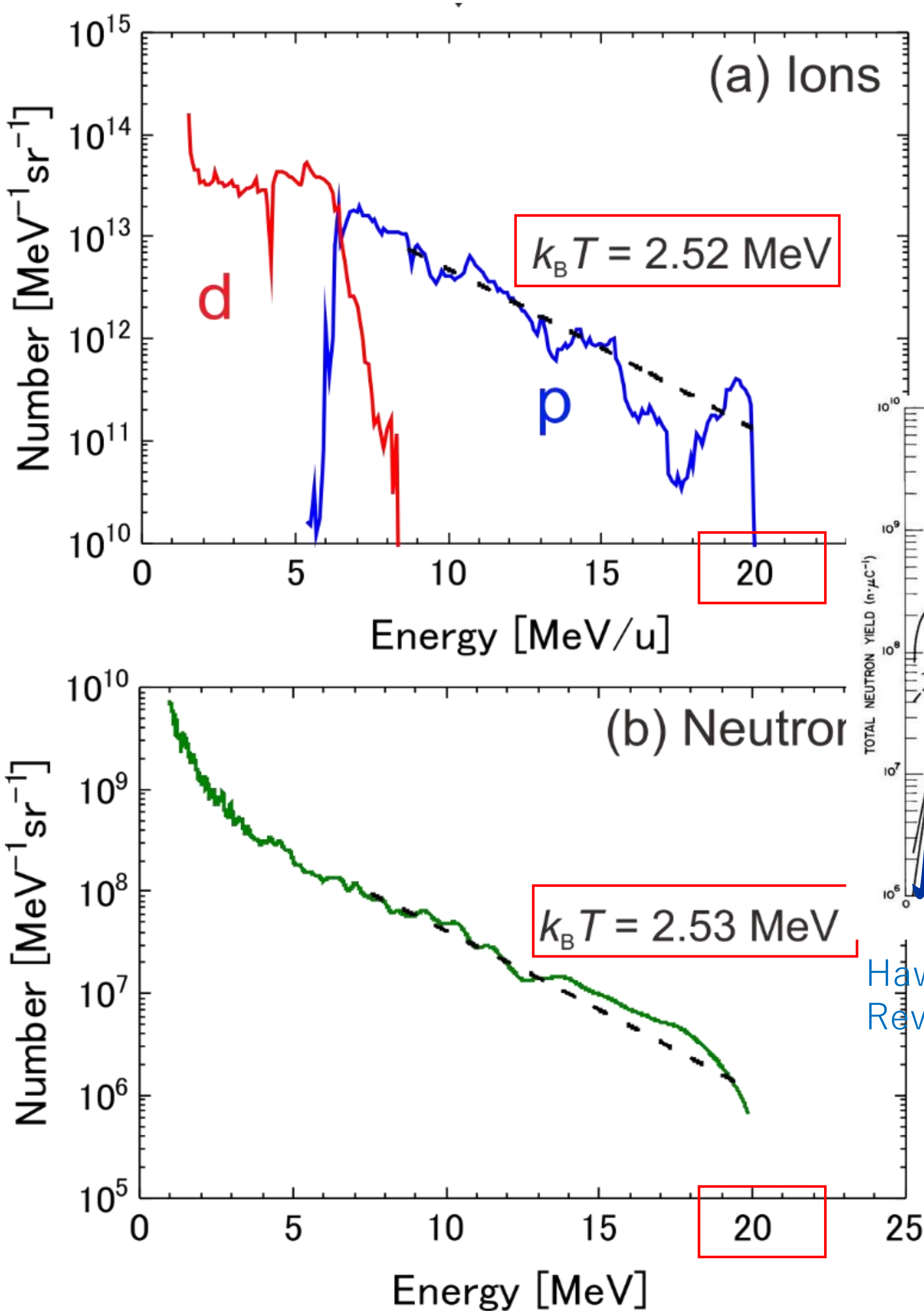
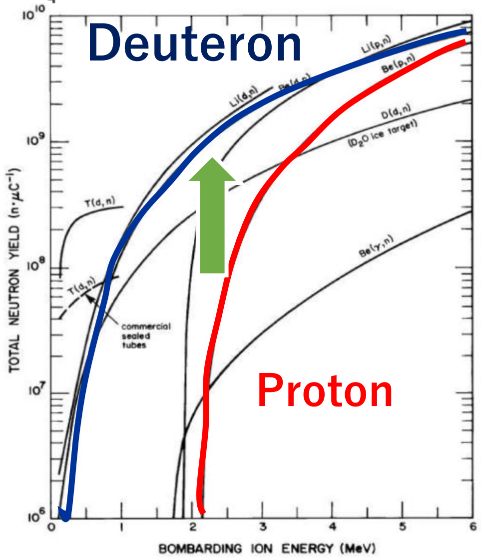
Primary target: Deuterated Polystyrene
-$(C_8D_8)_n$- 1.5 or 5 μm thickness

1×10^{19} Wcm^{-2}
1.5 ps (FWHM)



Secondary target: **Be block**
1 cm in thickness





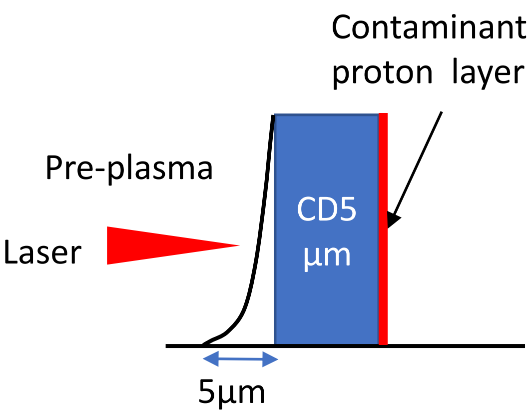
Hawkesworth, Atomic Energy Review 15, 169-220 (1977).

A. Yogo et al. Appl. Phys. Express 14, 106001 (2021).

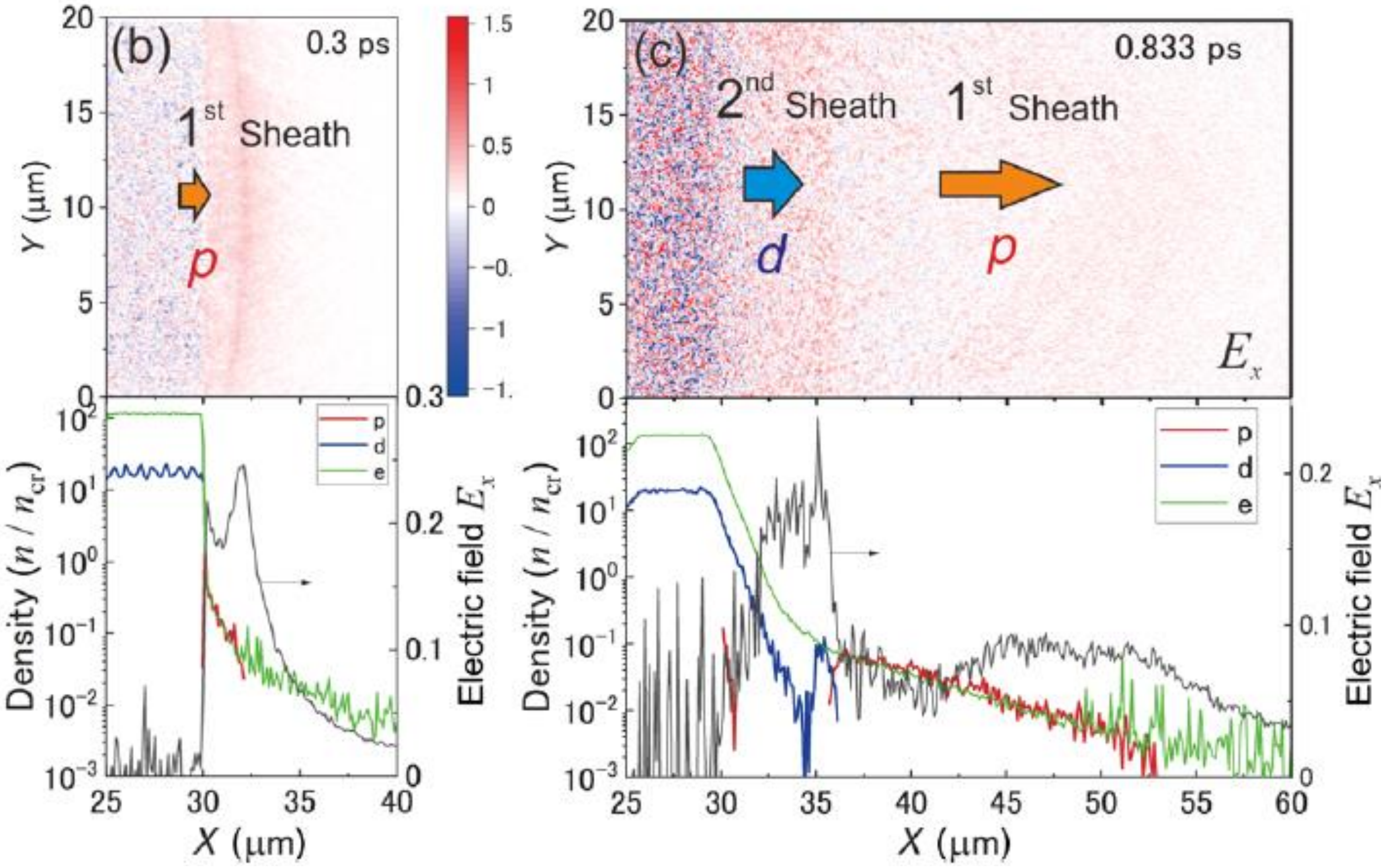
ps relativistic laser

is advantageous for deuteron acceleration

2D PIC by PICLS



Φ_L = 60 µm
space: 20mm × 200mm

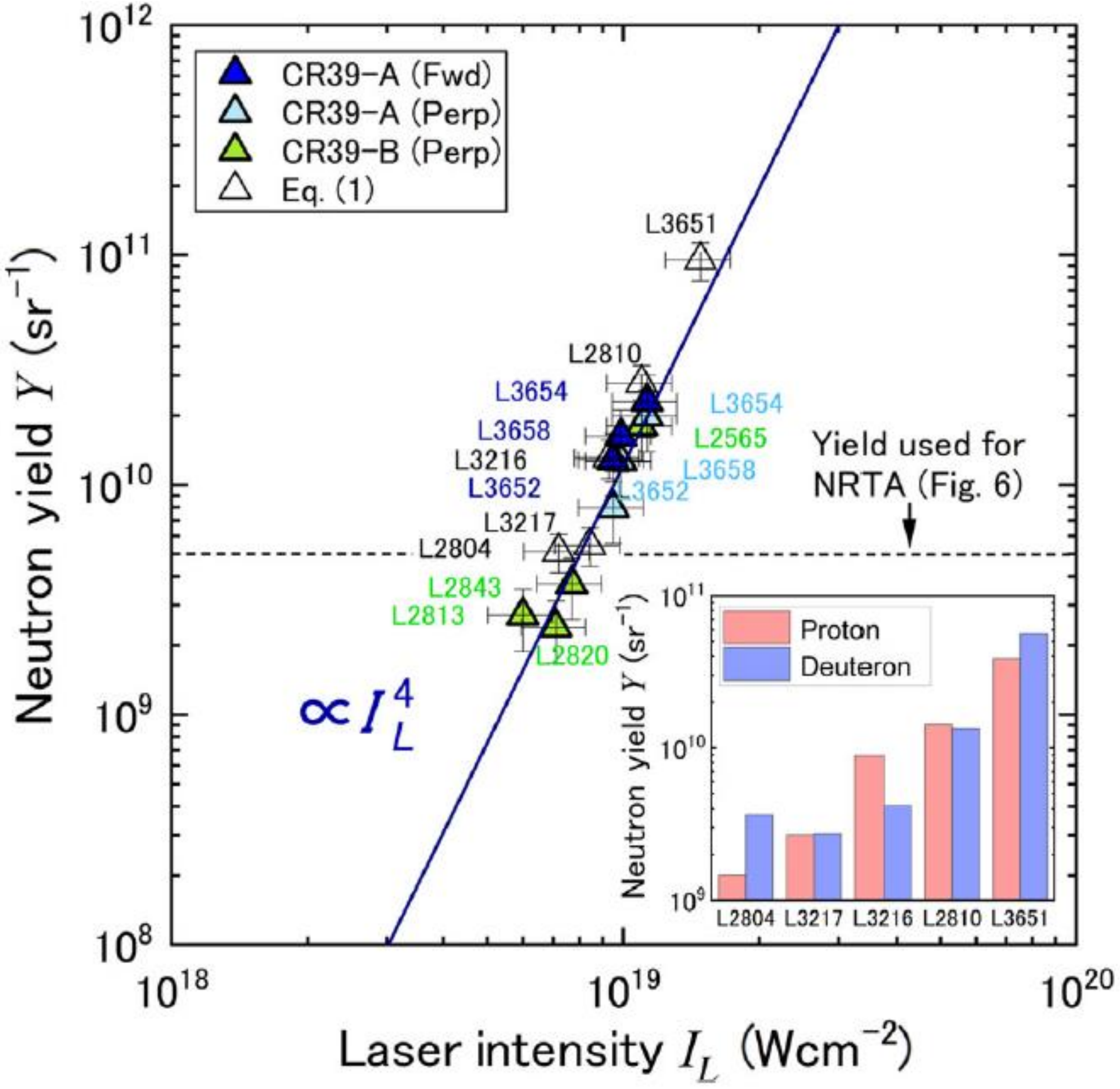


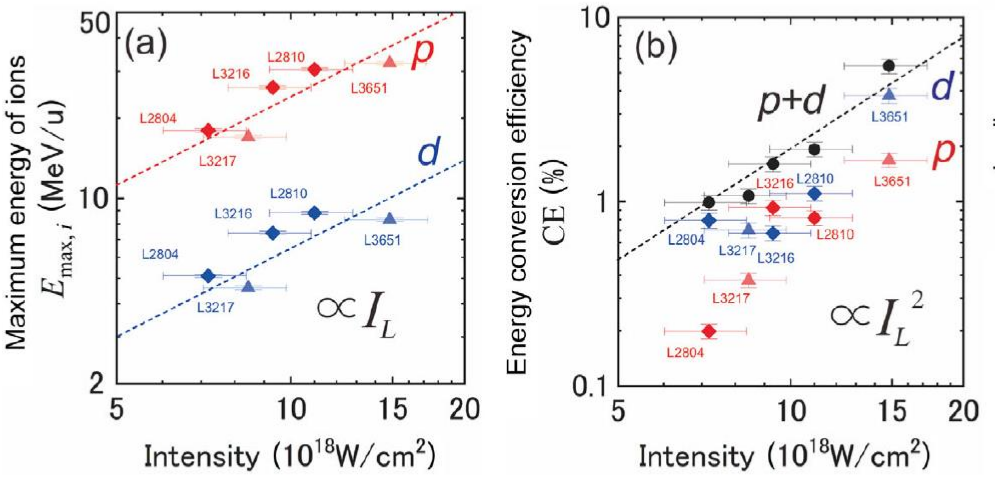
Protons detach from the surface and deuterons begin to accelerate after 0.8 ps.

Boosted-TNSA mechanism

A. Yogo, et al., Phys. Rev. X 13 011011 (2023).

Neutron Yield enhanced as the 4th power of laser intensity





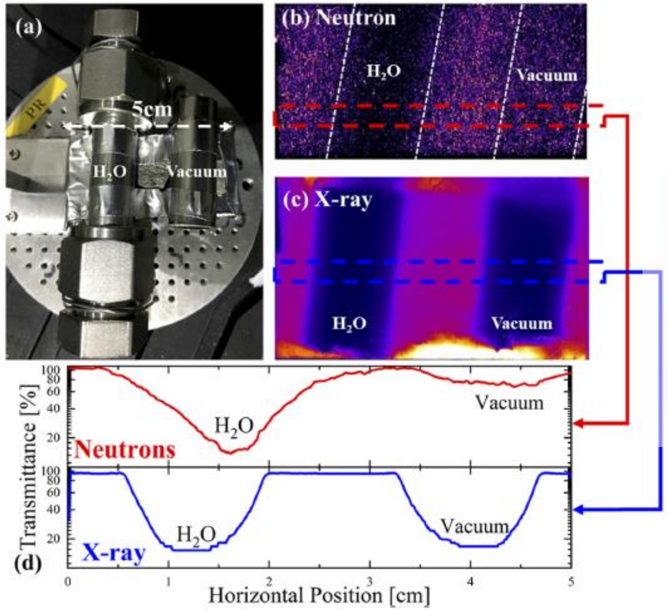
$$E_{\max,i} \propto I_L^k \qquad \mathrm{CE} \propto I_L^m \quad \Rightarrow \quad Y \propto I_L^{k+m+1}$$

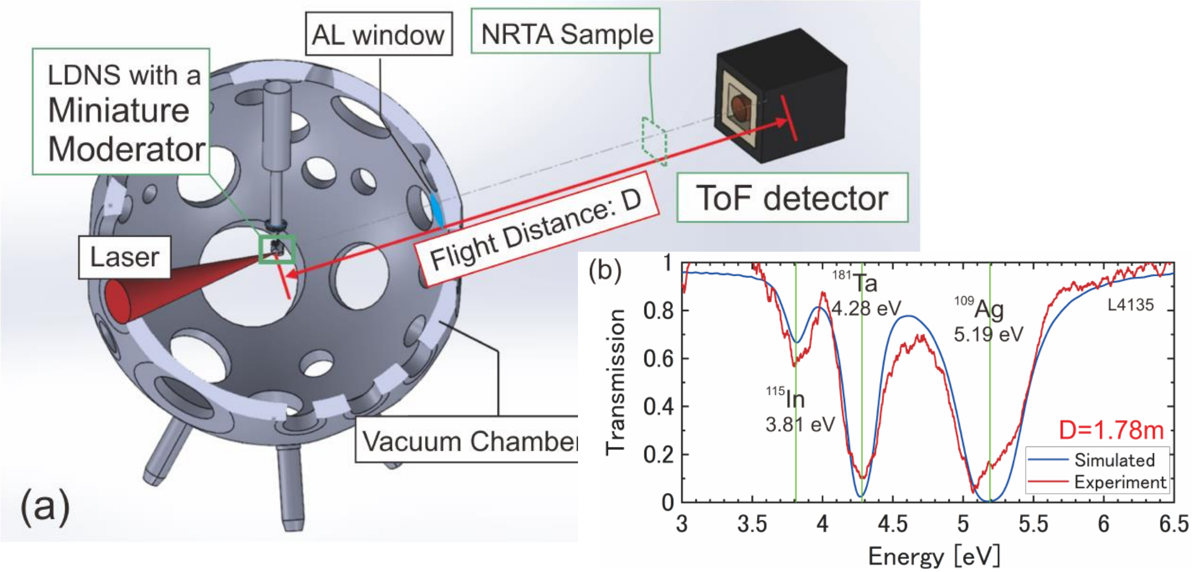
$k = 1$ ($E_{\max,i} \propto I_L$) and $m = 2$ ($\mathrm{CE} \propto I_L^2$)

$$Y \propto I_L^4$$

A. Yogo, et al., Phys. Rev. X 13 011011 (2023).

Applications of LDNS





Neutron applications depending on the energy

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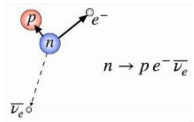
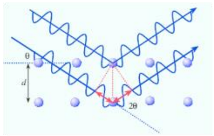


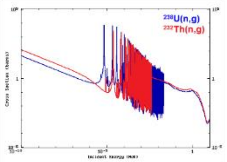
Life time of neutrons

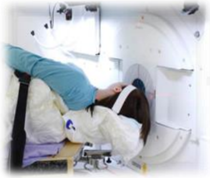

Crystallography of proteins


Neutron Diffraction Analysis

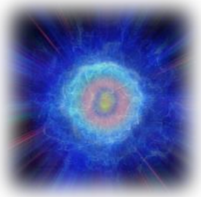

Light water reactor


Radiography


Resonance spectroscopy


Neutron therapy (BNCT)


He burning inside stars (s-process etc)


Supernova (r-process etc)


Neutron stars merger (r-process etc)

Steller nucleosynthesis

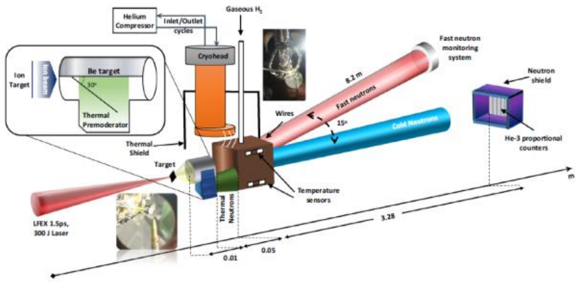
100 neV | 1 meV | 25 meV (300K) | 1 eV | 1 keV | 1 MeV | Energy

Ultra-Cold | Cold | Thermal | Epi-thermal | Fast

LDNS results at Osaka Univ

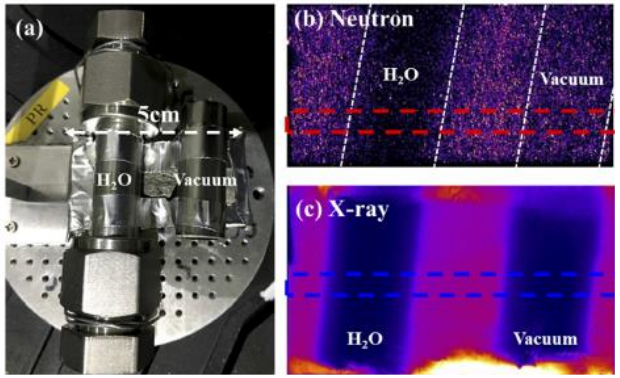
Cold neutron generation

Mirfayzi, Sci. Rep. 10, 20157 (2020)



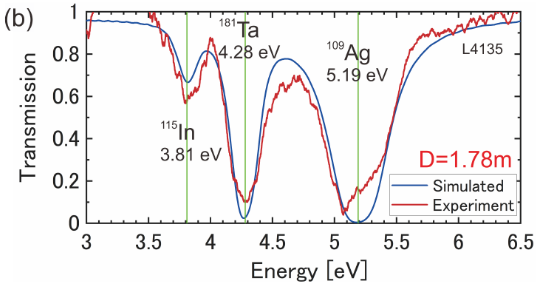
Radiography

Yogo, Appl Phys Express 14 106001 (2021)
Wei AIP Adv. 12, 045220 (2022)



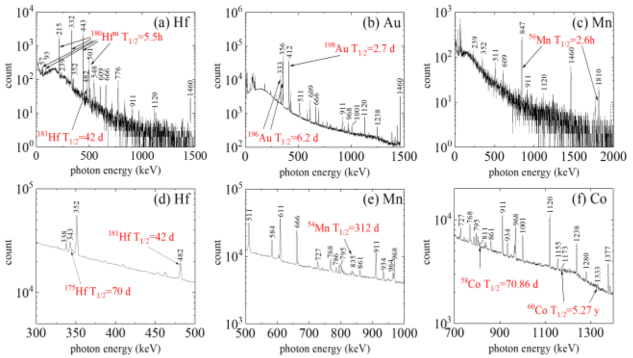
Resonance spectroscopy

Yogo, Phys Rev X 13, 011011 (2023)
Lan, accepted by Nat. Comm.



Nucleosynthesis

Mori, Phys Rev C 104, 015808 (2021)
Mori, J Phys G, 49 065103 (2022)
Mori, High Pow. Las. Sci. Eng, 11, E20



Neutron moderation (deceleration)

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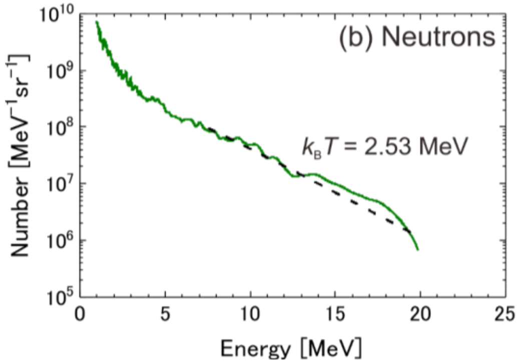
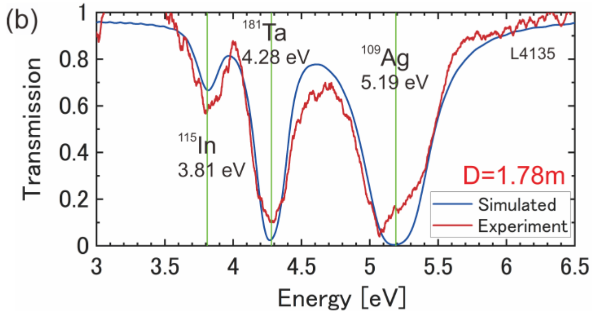


MeV Fast neutrons

Moderator

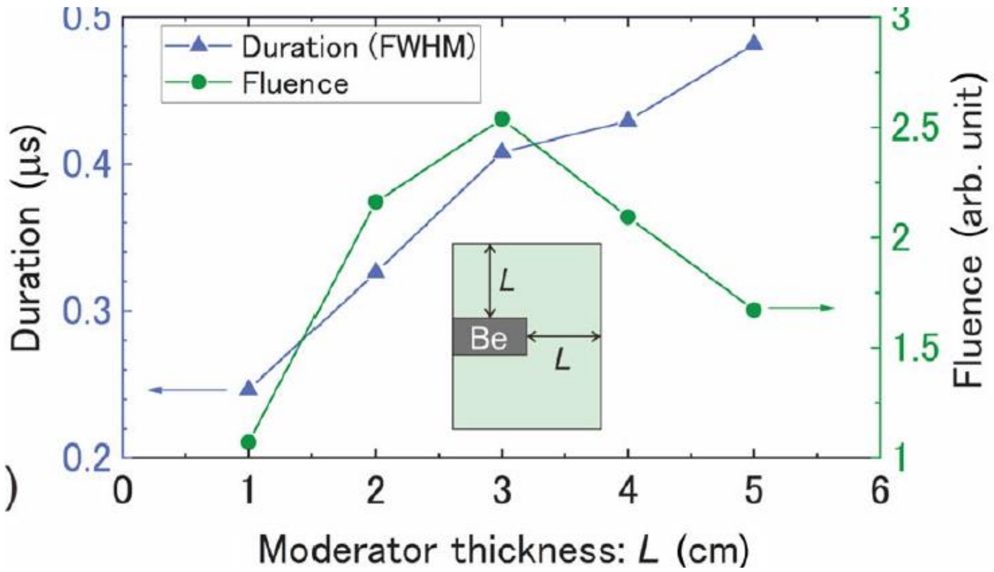
Light water in nuclear reactors



eV Epi-thermal

meV Thermal

Problem: temporal broadening after the moderation

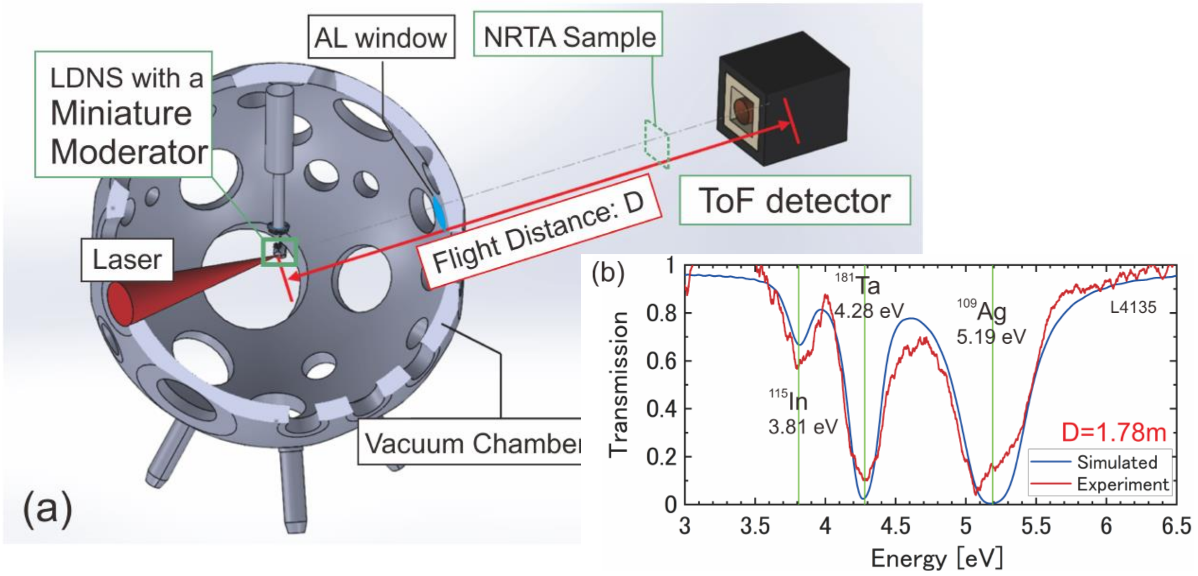


Our approach

Minimize the moderator size

→ **3 cm thick High-density Polyethylene**

Neutron Resonance Spectroscopy



Neutron Resonance Spectroscopy (NRS)

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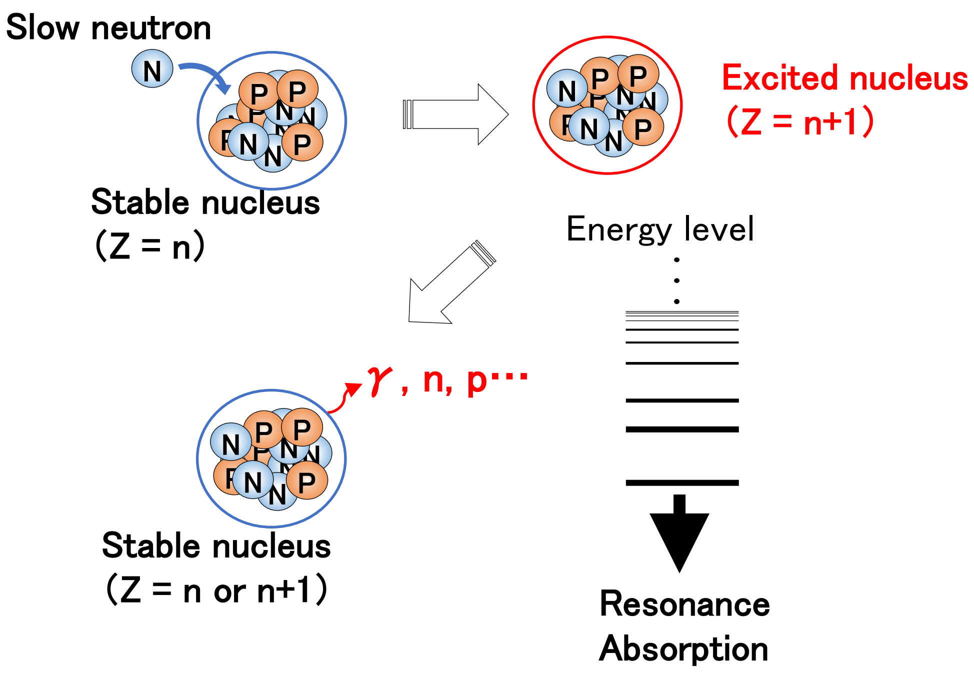
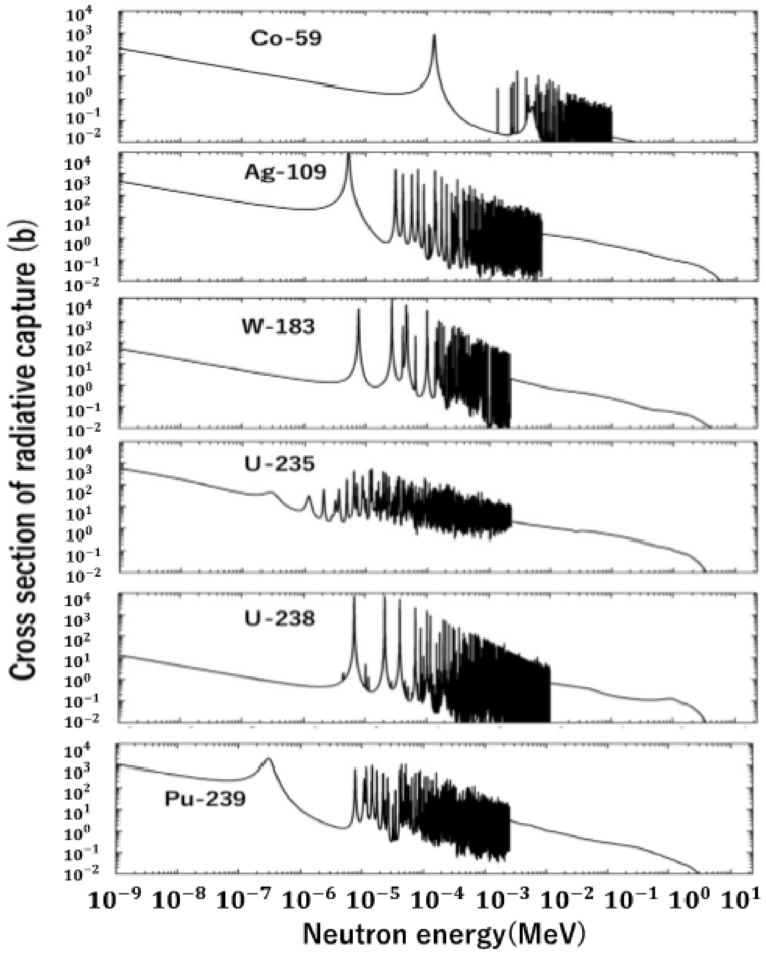
NRS is based on the nuclear resonance absorption process, where a neutron is efficiently captured at the resonance energy of a nucleus in the energy region of eV.

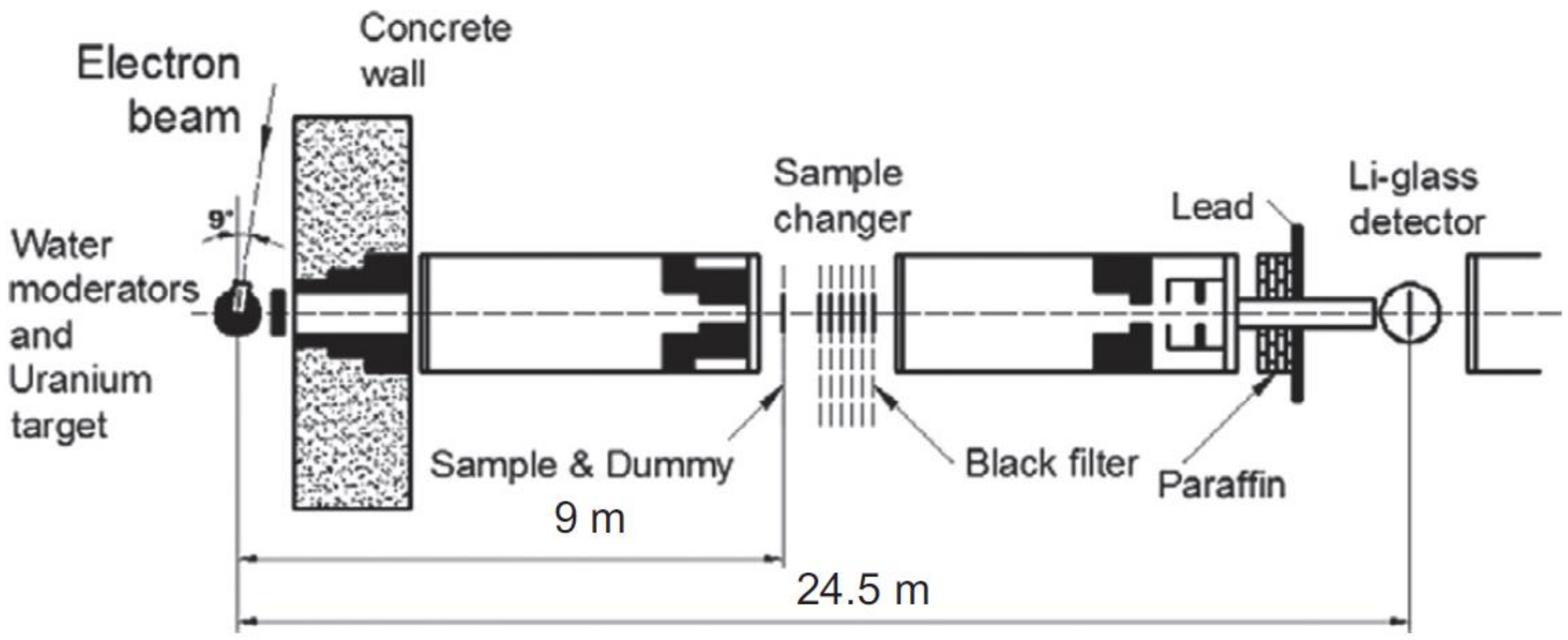




The resonance energy depends on the nuclear species.

Fingerprint of isotopes

NRS measured at accelerators



B. Becker et al., Eur. Phys. J. Plus 129, 58 (2014).

The neutron energy is analyzed by time-of-flight (ToF) method using a 25 m beamline.

NRS measured by LDNS: 1.8 m beamline

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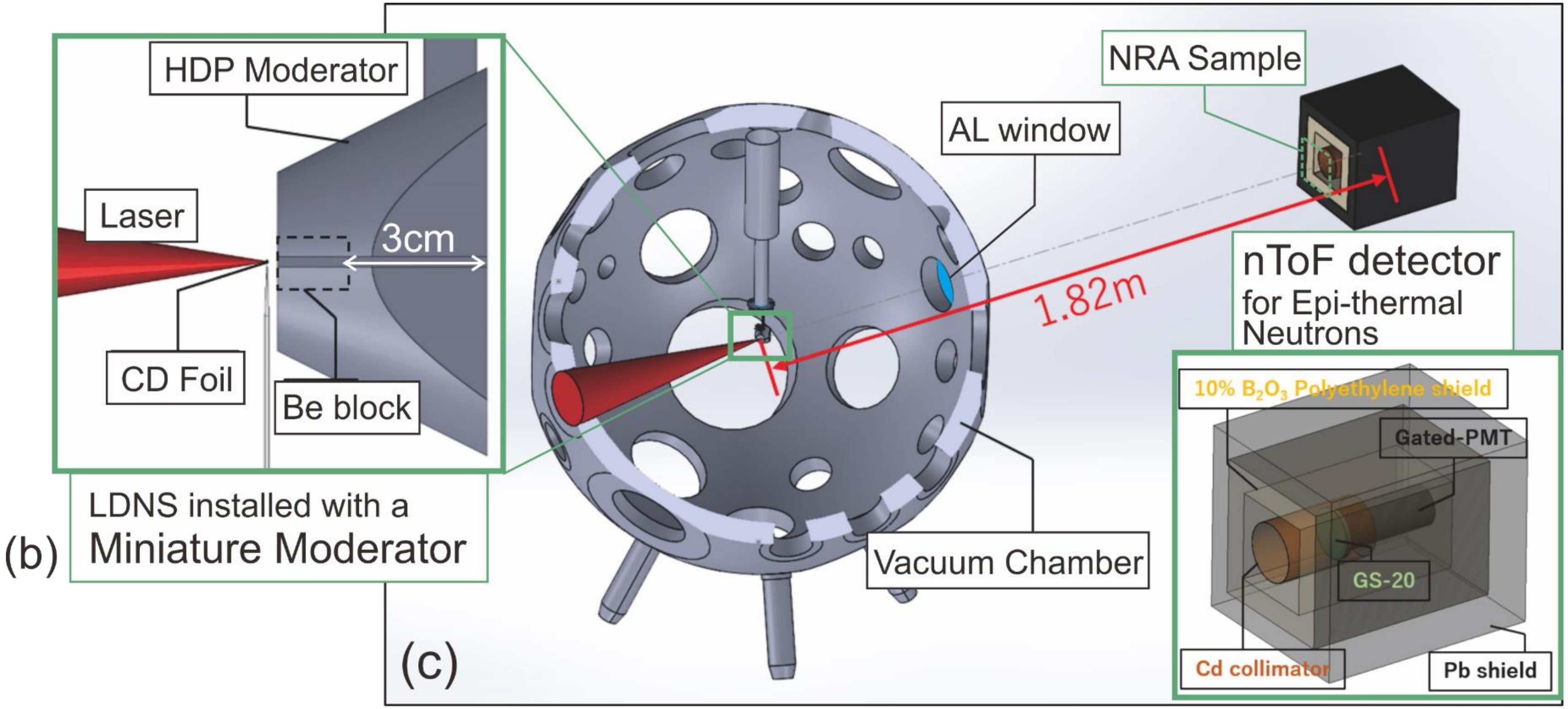
A. Yogo, et al., Phys. Rev. X 13 011011 (2023).



N-ToF resolution $$\Delta E_n / E_n = 2\Delta\tau\sqrt{2E_n/m}/D$$

The temporal spread **Δτ** at the moderator exit linearly shortens the distance **D**.

NRS measured by LDNS: 1.8 m beamline

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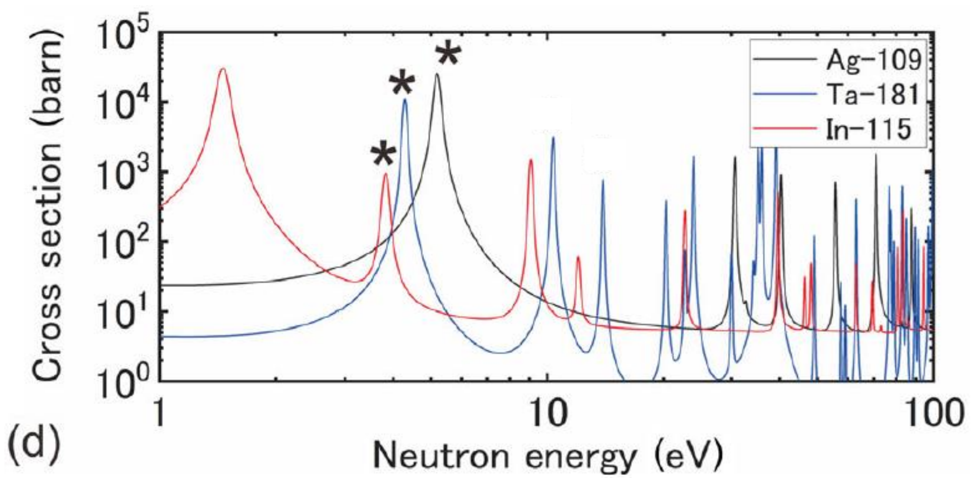
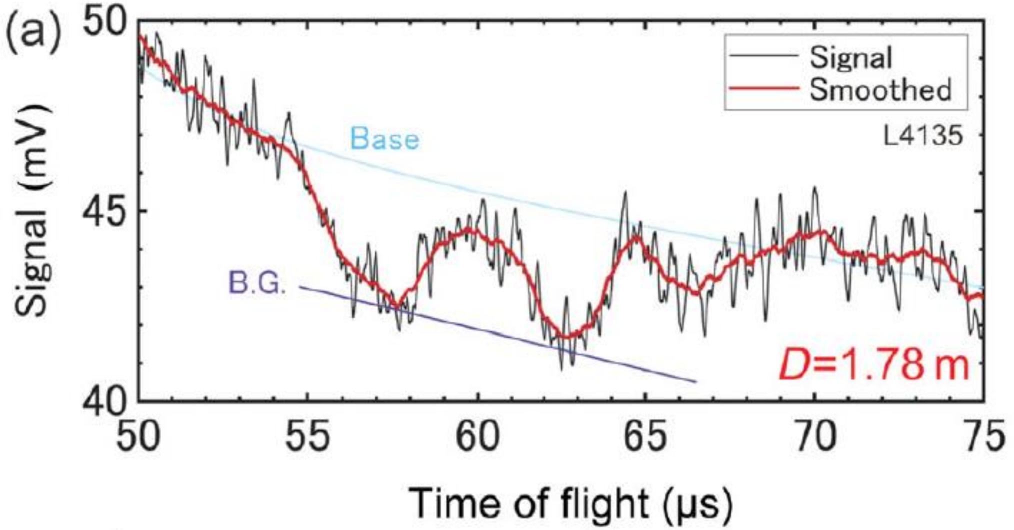
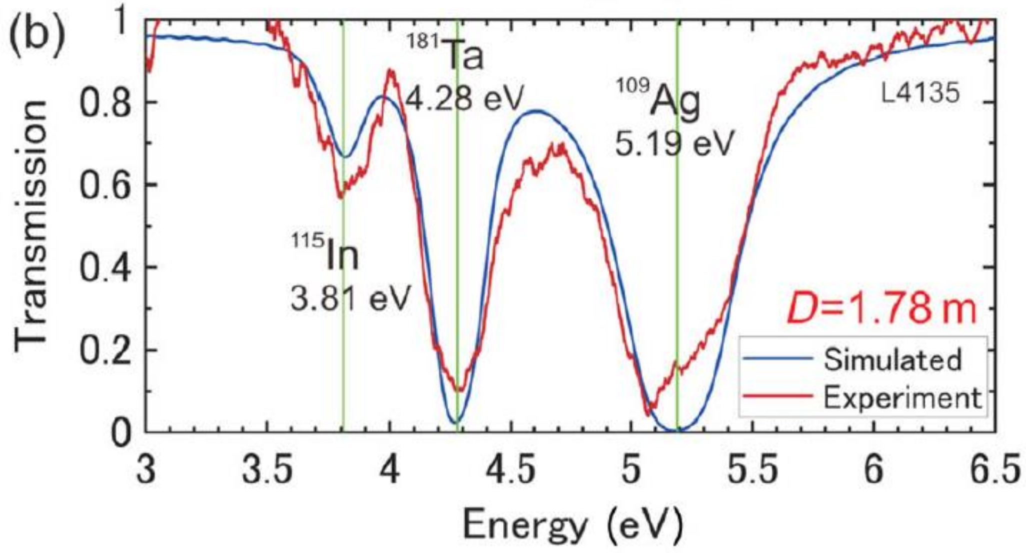
We located plates of **In, Ta, Ag** (t 0.1 mm) on the beamline and measured transmitted neutrons.

Large cross section in 1-10 eV range







The dips attributed to the absorption by In-115, Ta-181, Ag-109 are clearly identified.

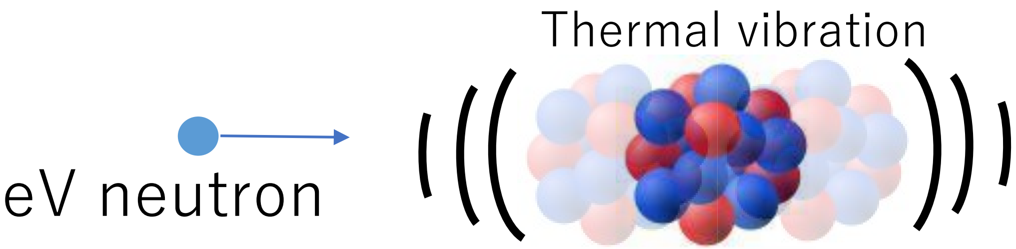
$$\Delta E_n / E_n = 2.3\%$$

10^2–10^3 cm^{-2} neutrons of 1–20 eV

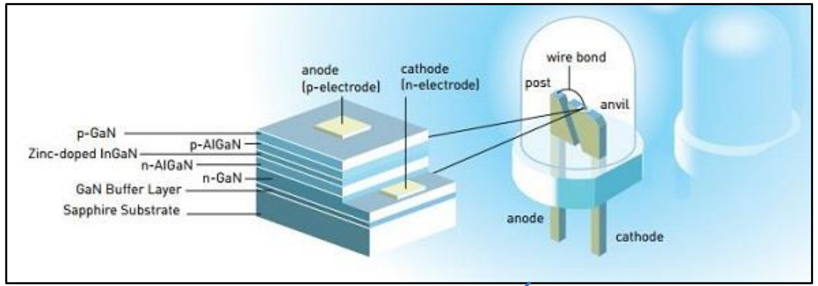
at a sample position

A. Yogo, et al., Phys. Rev. X 13 011011 (2023).

Neutron thermometer

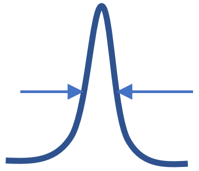


The resonance peak is broadened by the thermal vibration of the nucleus according to the **Doppler Effect**.

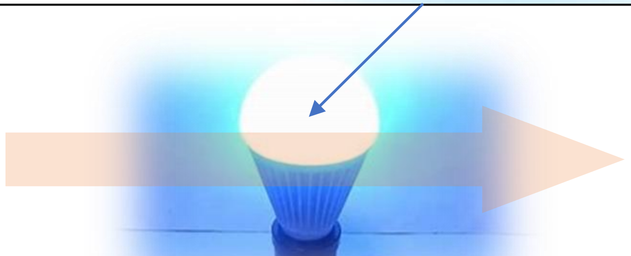


Element-selective and transparent thermometer for dynamic objects

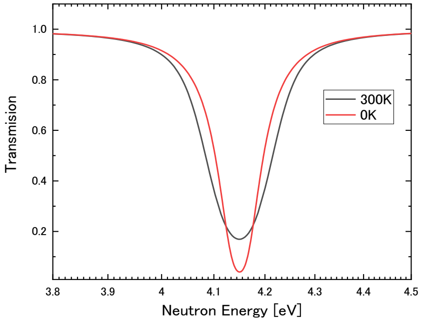
Neutron pulse



100 ns



Electronic device in operation



Bringing time resolution to neutron resonance spectroscopy

Single-shot Neutron thermometer

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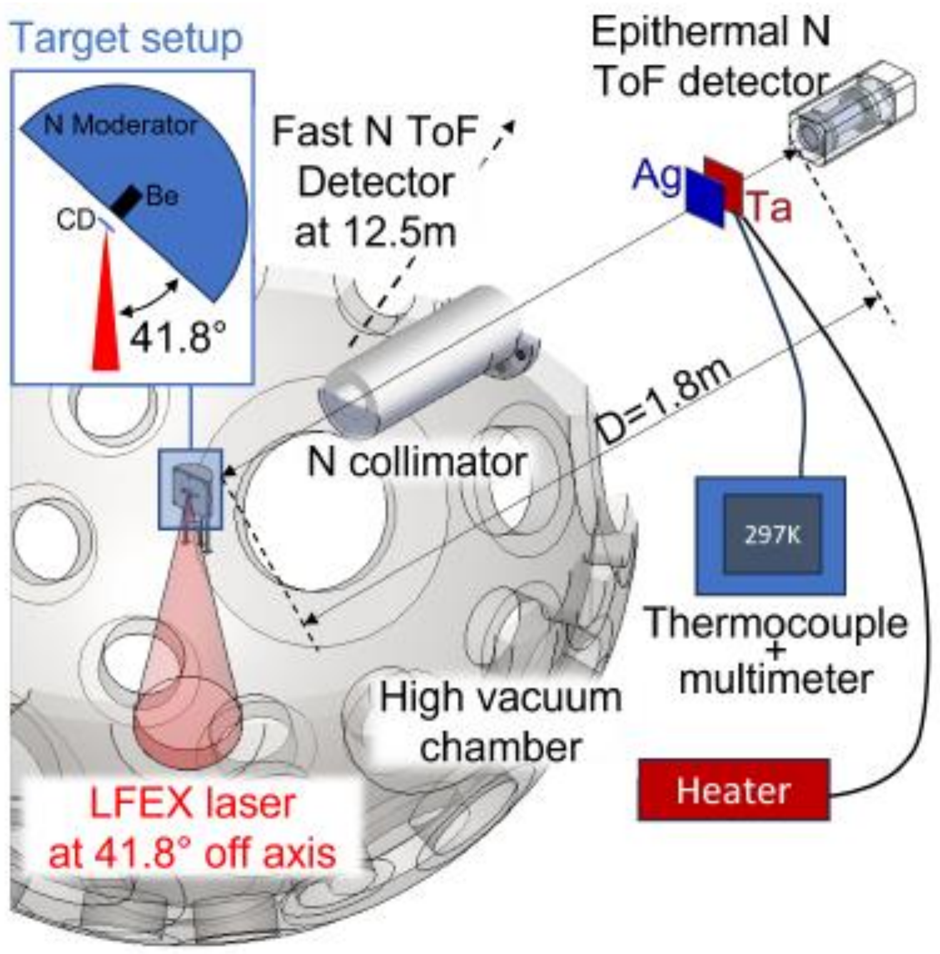

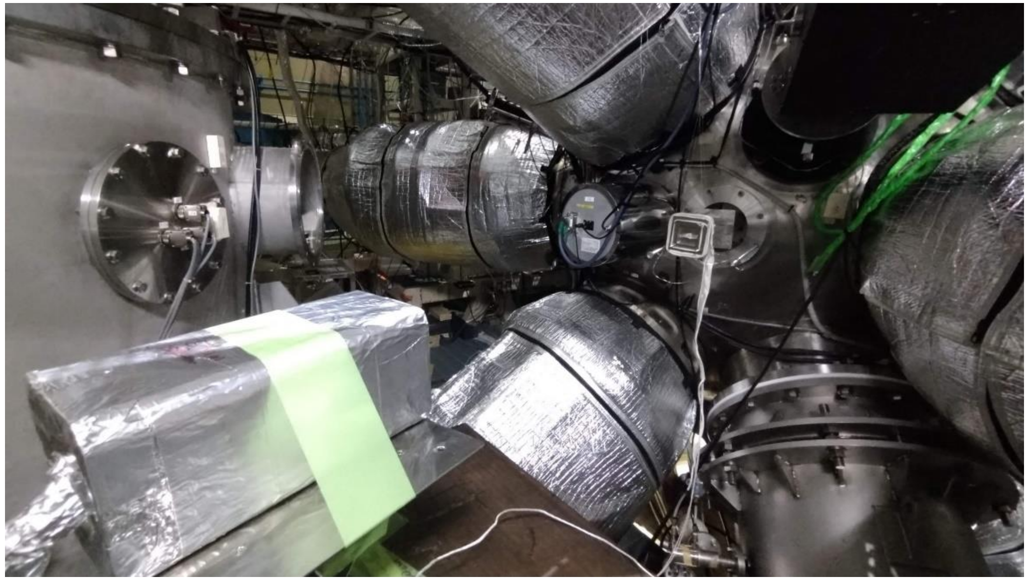

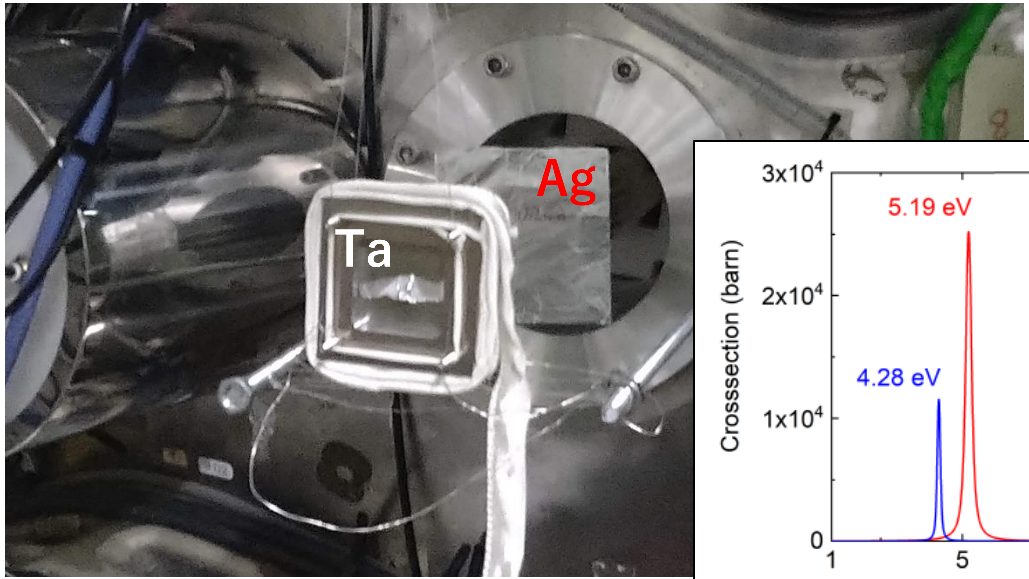

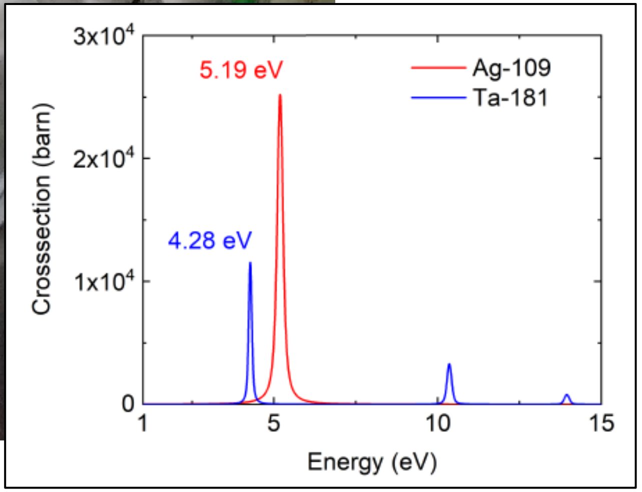

Z. Lan e al., Nat. Comm. (accepted)

Single-shot Neutron thermometer

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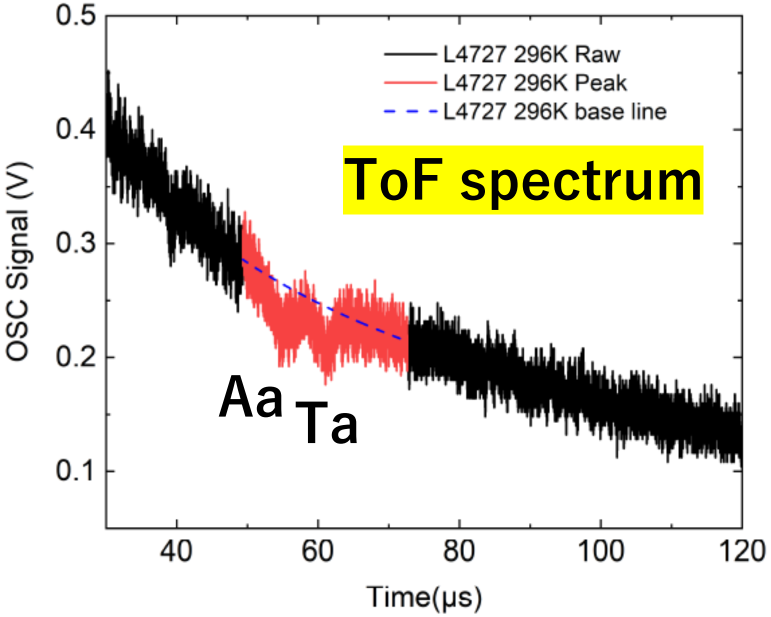
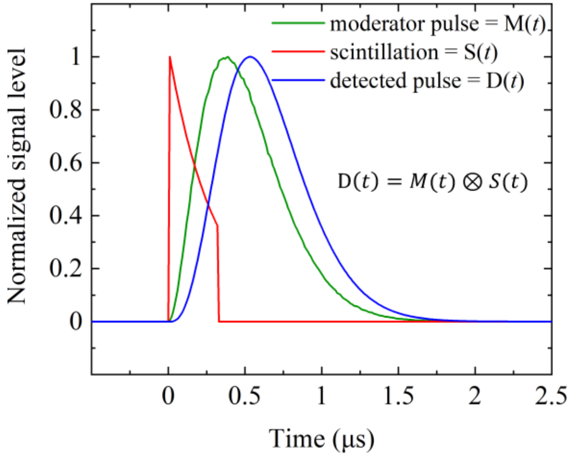
Osaka University

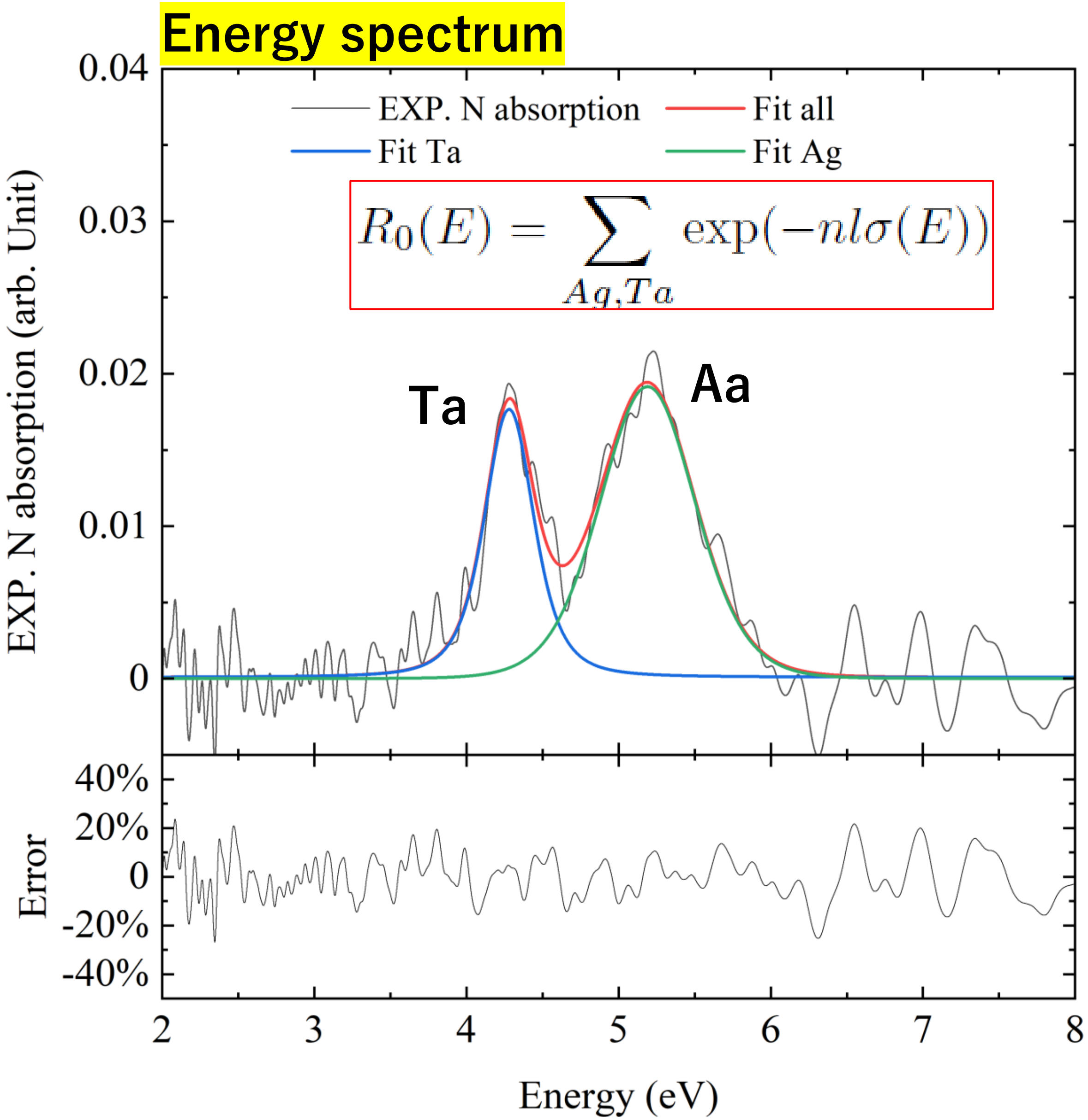
At a room temp. (296 K)





$$t_{raw} = t \otimes D(t)$$

Pulse broadening at
Moderator
Detector (^{6}Li scintillator)



Single-shot Neutron thermometer

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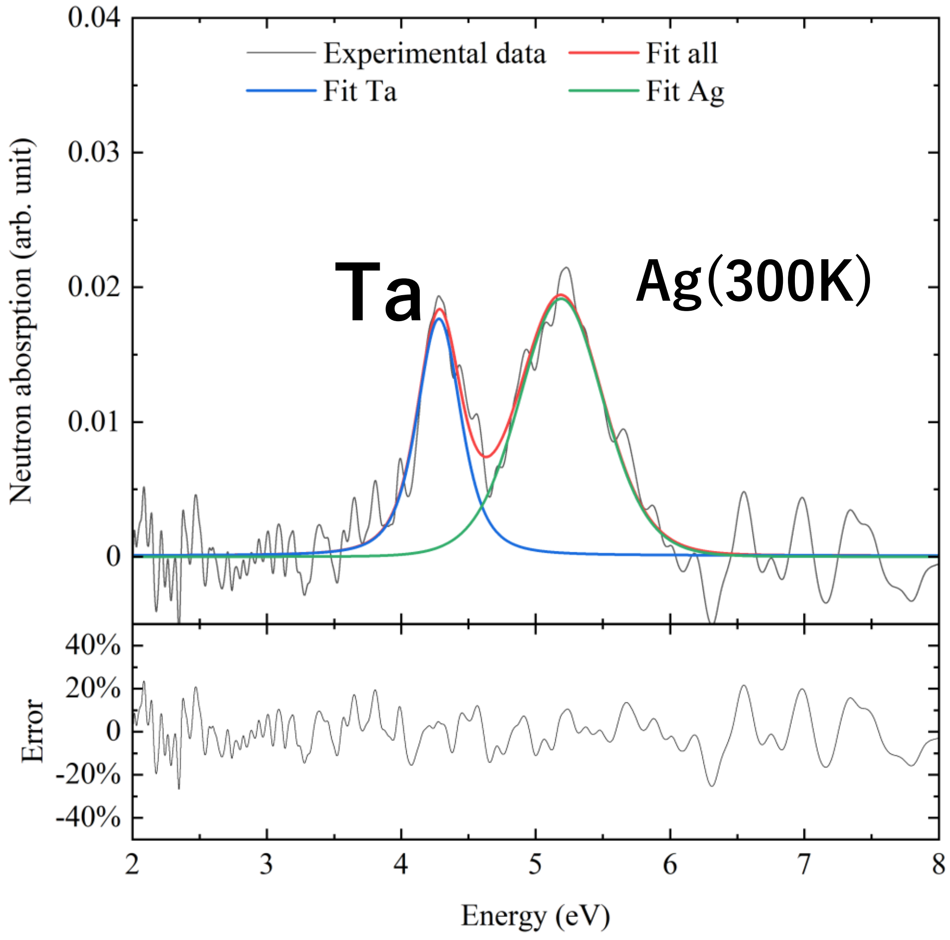

B-W Model fitting,

$$\sigma_T\,(E,T) = \sigma(E) \otimes \exp\left(-\frac{(E-E_r)^2}{2\Gamma_D^2(T)}\right)$$

Absorption for each sample

$$R_i\,(E,T) = \exp(-nl\sigma_i(E,T))$$
$$i = Ag\ or\ Ta$$

The broadening effects induced by **laser randomness** are assumed as

$$F(E) = a \times exp\left(-\frac{(E-b)^2}{c^2}\right)$$

$$R_{EXP}\,(E,T) = \exp(-nl\sigma_i(E,T)) \otimes F(E)$$

Ag reference to compensate laser randomness.

$$R_{EXP,Ag}\,(E,300K) = \exp(-nl\sigma_i(E,300K)) \otimes F(E)$$
$$= \sigma_{Ag}(E) \otimes \exp\left(-\frac{(E-E_r)^2}{2\Gamma_D^2(300K)}\right) \otimes F(E)$$

We determine the shot-by-shot randomness $F(E)$ by fitting the reference (Ag) signal.

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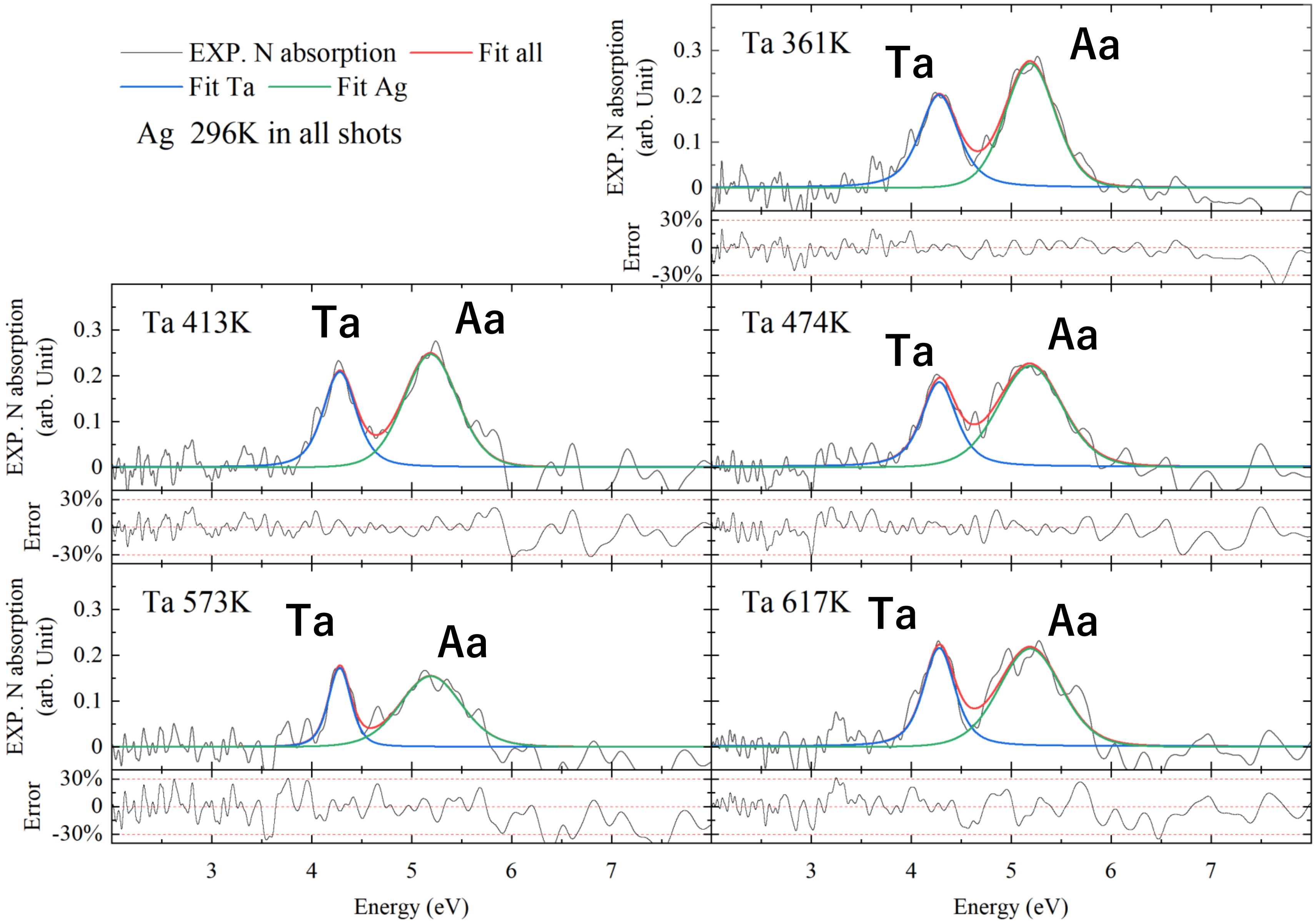
Temperature dependency



Temperature-dependent cross-section for the resonance absorption

$$\sigma_T(E) = \sigma_{BW}(E) \otimes G(E)$$

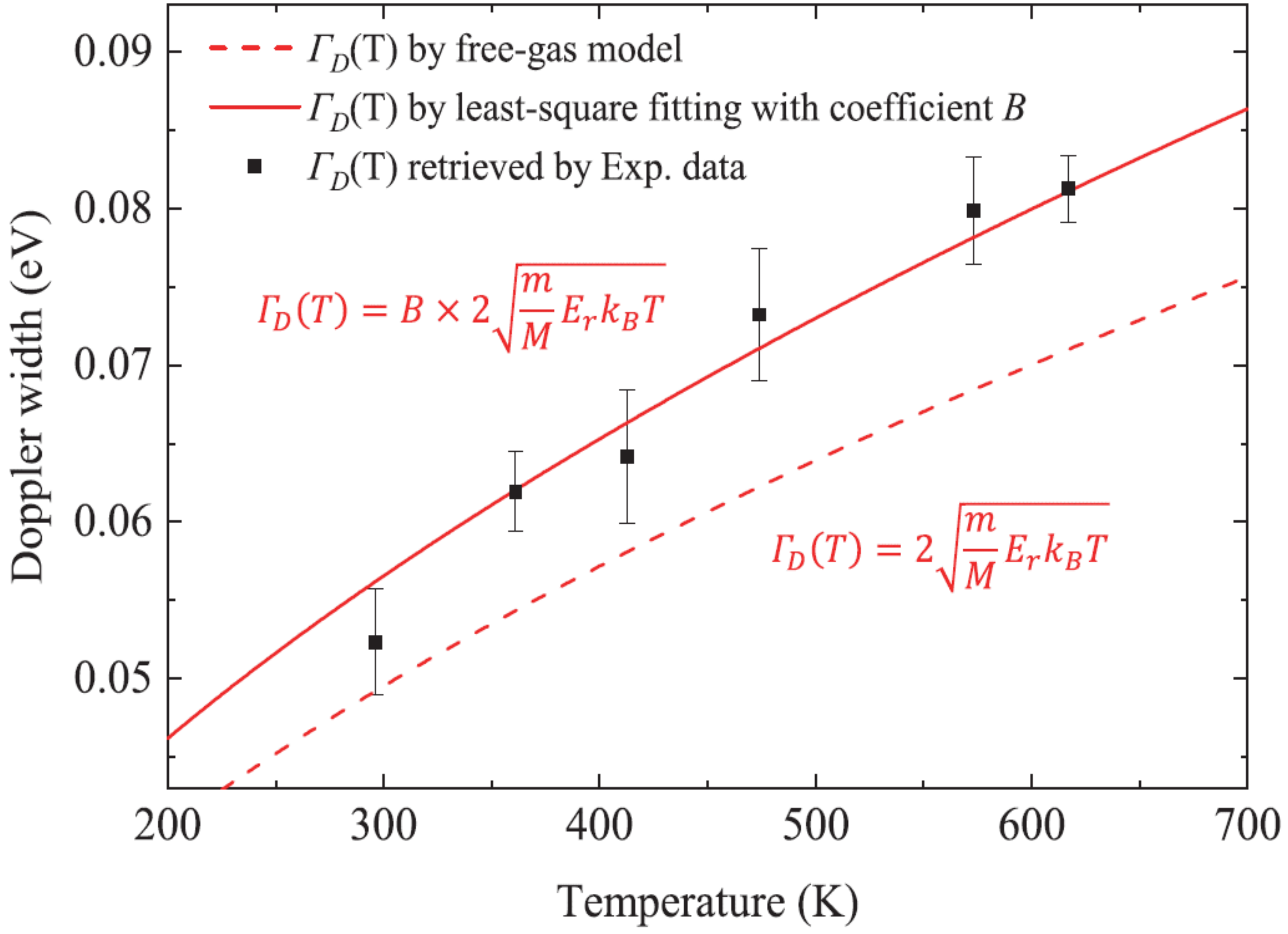
$$\sigma_{BW}(E') = \pi \lambda\!\!\!^{-} g_j \frac{\Gamma_n \Gamma_\gamma}{(E' - E_r)^2 + (\Gamma_n + \Gamma_\gamma)^2/4}$$

Breit-Wheeler single-level formula
= cross-section at 0 K

$$G(E) = A \exp[-\frac{(E - E_r)^2}{2\Gamma_D(T)^2}]$$

Doppler effect (Gaussian)

Single-shot Neutron thermometer



A free-gas model by Bethe was used for investigating the relationship between temperature and Doppler width.

The experimental data shows a good agreement with the theoretical curve.

Proof-of-principle result of
Temperature Profiling by Laser-driven NRS

Transparent, Isotope-selective, single-shot thermometer

Summary

Institute of Laser Engineering
Osaka University

High Neutron Number
~$10^{10\text{-}11}$ n/pulse

Small Size
~1 cm^3

Short Pulse
< 1ns

→

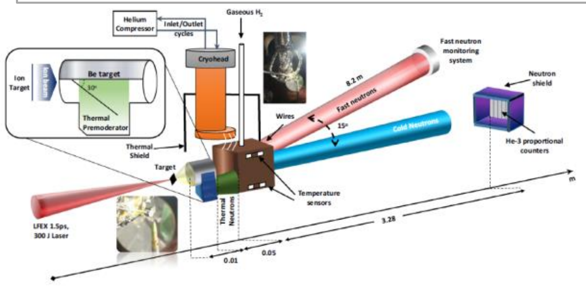
Short Beamline for Neutron Analysis
20 m (Accelerator) → 2 m (LDNS)

Single Shot Neutron Analysis
1-10 h (Accelerator) → 1 shot (LDNS)

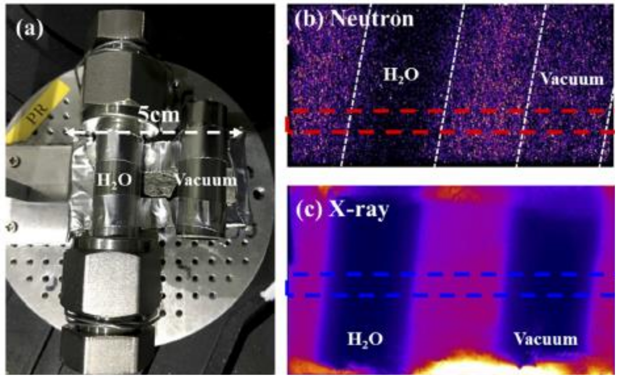
100 neV | 1 meV | 25 meV (300K) | 1 eV | 1 keV | 1 MeV | Energy

Ultra-Cold | Cold | Thermal | Epi-thermal | Fast

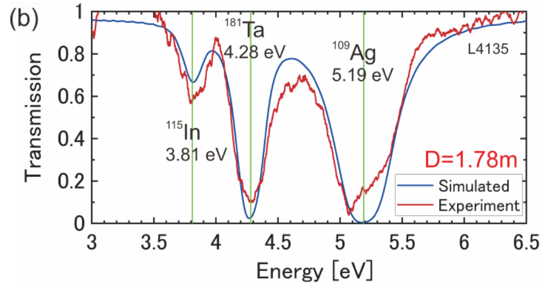
Cold neutron generation



Radiography



Resonance spectroscopy



Nucleosynthesis