Nuclear data (p+9Be) for compact neutron sources

RANS
RIKEN Accelerator-driven compact Neutron Sources

31 Aug. 2023 International Nuclear Data Evaluation Network for Light Elements (INDEN-LE), IAEA

RANS-RIKEN Accelerator-driven compact Neutron Systems-

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T-RANS、president Technology Research Association for Neutron Next Generation System

T-RANS Technology Research Association for Neutron Next Generation System

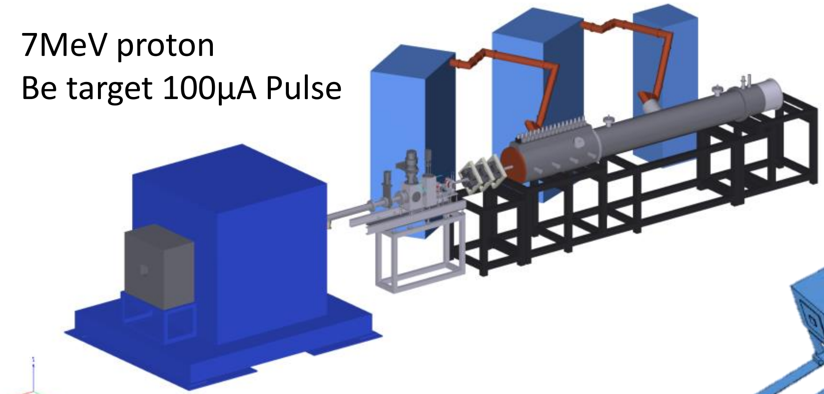
Y.OTAKE, Yujiro IKEDA, Yasuo Wakabayashi, Mingfei Yan, ★

COMPACT NEUTRON SYSTEMS at RIKEN: *RANS-I,-II,-III & μ*

- In operation, RANS and RANS-II

RANS

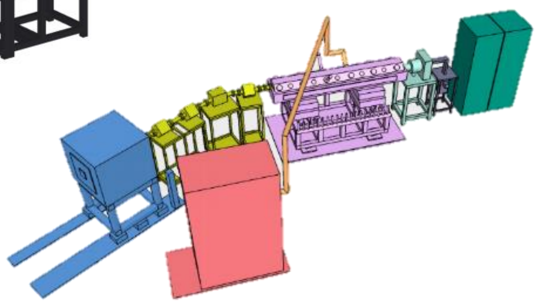
7MeV proton
Be target 100μA Pulse



Up-grade of moderator-reflector system 2020-2021

RANS-II

2.49MeV proton
Li target 100μA Pulse

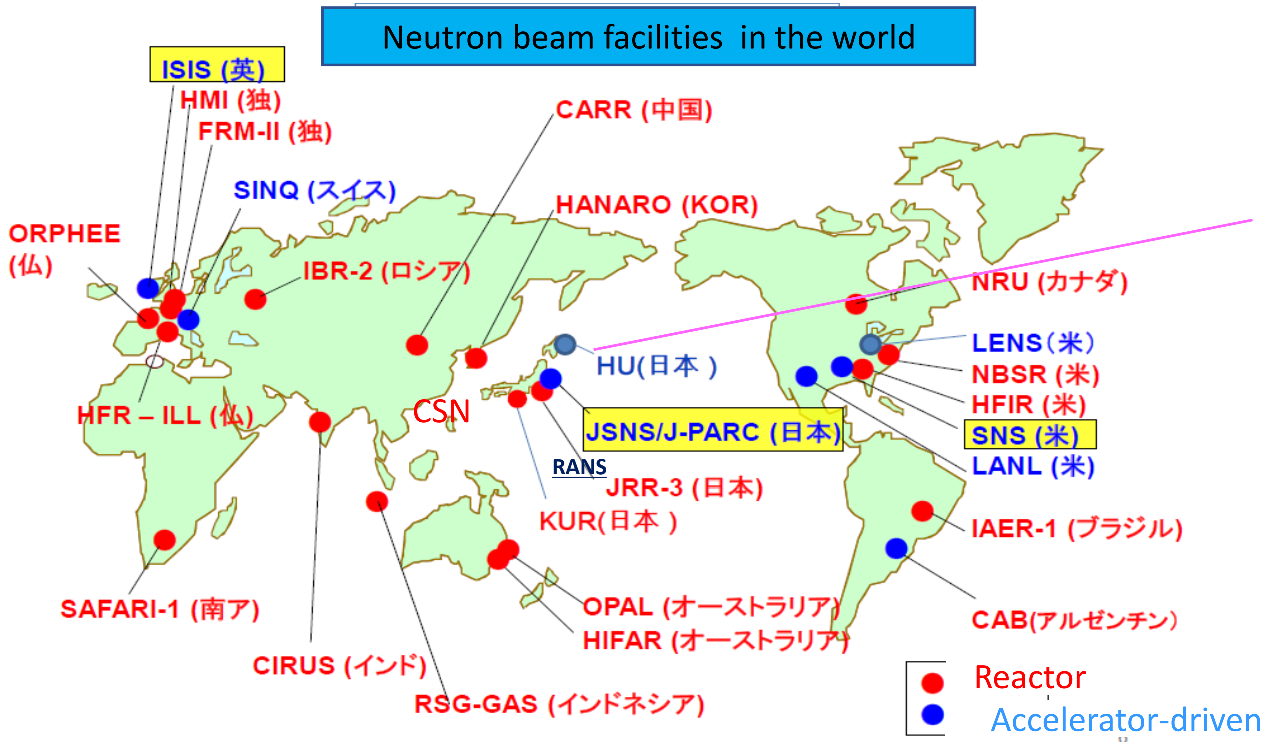


RANS-μ

Under development

RANS-III

Solving problems in large facilities concerning issues of a few chances for non-destructive test users, and few occasion for a new trial experiments with neutrons



RIKEN RANS Development

Compact neutron systems for practical use !

neutrons, anytime, anywhere

Source and instrumentation are inseparable relationship

The development purpose

in order to respond to the needs! New needs

→Standard Model of non-destructive test as evaluation analyzer

Neutron Source development

RANS, RANS-II, RAS-III
(Accelerator-based)
RANS-μ (RI)
+ Moderator, reflector, shielding

R&D

Instruments design, analytical methods should be based on strong demand from the society

The most critical need is non-destructive diagnostic system for infrastructure:
To meet needs : preventive maintenance

Salt damage->bridges collapse

USA I-70 Concrete bridge collapse

Dec. 2005 , 45 years after the construction Pennsylvania. Rebar corrosion because of **ant freezing agent**

From：Pittsburg Post-Gazette

Initial construction failure

Canada Collapse of a Portion of de la Concorde Overpass

Sept, 2006, 35 years after construction, Montreal

Initial construction failure

出典：落橋に関する委員会報告書

Message from Dr. Banthia to Japanese researchers:
The novel non-destructive test methods such as x-ray, electromagnetic induction method, elastic wave method.出典：六郷ら、カナダのデラコンコルド跨道橋の崩落事故に学ぶ、コンクリート工学,2008.12

From Mr. R.Ooishi (Institute Public Work)

Italy ·Moradi bridge collapse （14 Aug.2018.） Salt damage

Vigili del Fuoco/AFP

Taiwan bridge collapse1 Oct. 2019)

写真:https://udn.com/news/story/7321/4078135

Some crtical needs to CNS from industrial applications on-site use

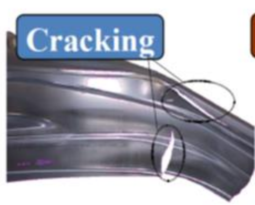
Ex. iron and steel:

・non-destructive test,

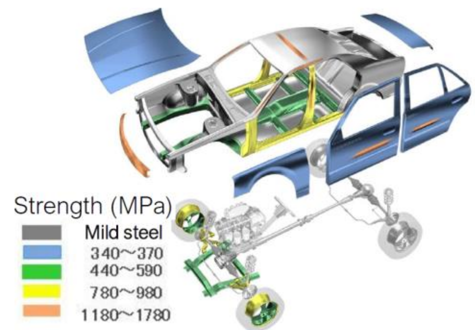
・development of material engineering diffraction

I. Non-destructive test: transmission imaging for such large area as 10cm2 with *100μm resolution

II. Material development towards high strength-formability for weight reduction
   I. volume fraction evaluation
   II. texture evolution estimation

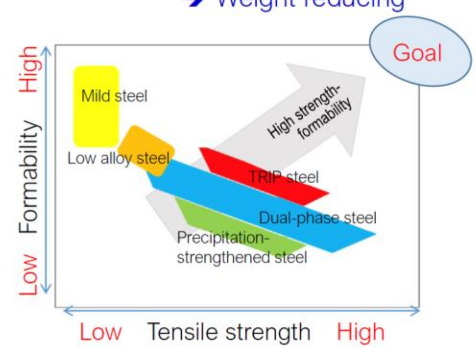


Steel parts and tensile strength for a car body.



http://www.nssmc.com/tech/nssmc_tech/car/car_01/index.html

High strength-formability
➔ Weight reducing



Nondestructive test **on site** use need two ways; **Stational system on floor**, and **transportable compact system**

1. Lower radiation level during operation
2. Easy to operate, and easy and safe for maintenance
3. Good S/N measurements for quantitative analysis (No powerful source, but proper technology for compact source including shielding design, pulse structure, etc.)
4. As f… ctivation products

On-site non-destructive test
Floor-standing type

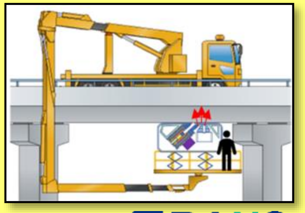
X-ray, Electron, SEM, TEM,EBSD

Neutron

RANS-II MODEL

RANS-II

On-site non-destructive test
Transportable type



RANS-μ

RANS-μ
Neutron Salt-meter

RANS-III MODEL

RANS-III

The most suitable neutron production in terms of high neutronnyield and stable oeration, we have chosed the ^{9}Be (п,n) reaction for RANS

1. **High efficiency and small system including shielding-**

-> accelerated ion beam energy should be less than 12MeV

Neutron flux at target position 4π ~10^{12}/sec

Li (p,n)
Be (p,n)
Li (d,n)
Be (d,n)

small system=> Proton or deuteron E> 2 MeV
few activation waste, proton Energy < 12MeV

Be (γ,n)
Pb (γ,n)
Ta (γ,n)

Electron > 30MeV is needed, too high energy for compact source
Easy to operate

Higher energy proton beam,

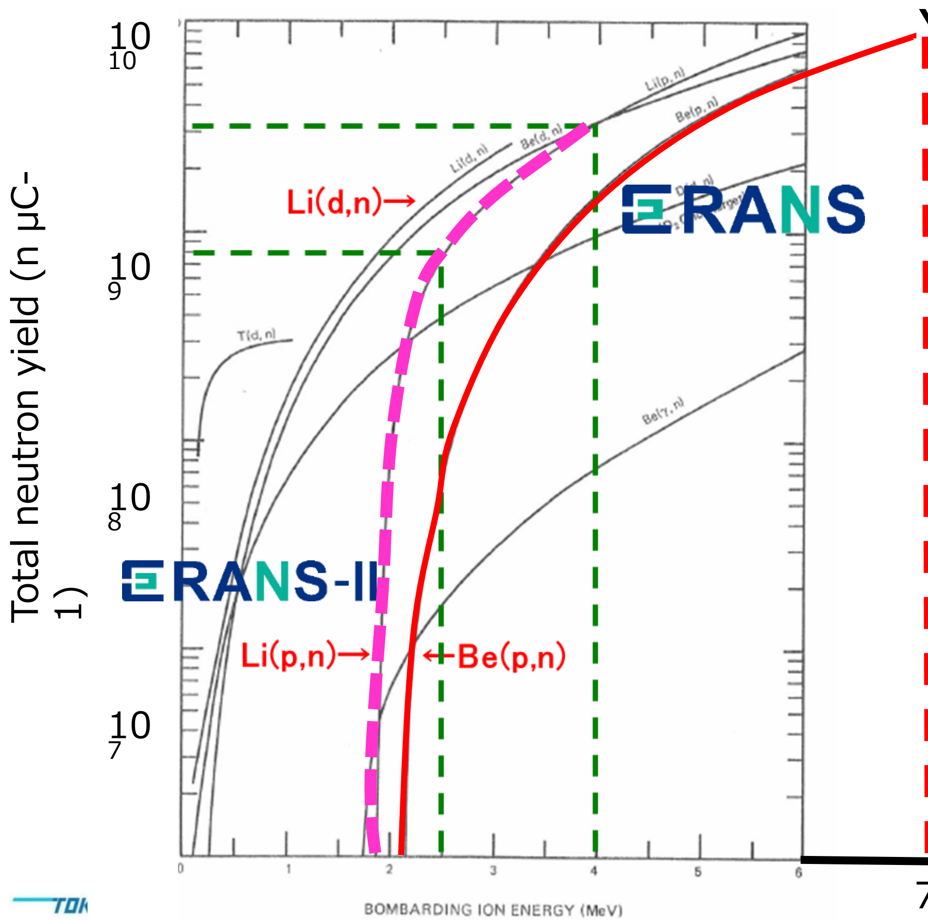
Target: W, Ta, etc.
Please refer **HBS report from JCNS**

- Nuclear fusion

DD neutron tube: too small amount
DT: neutron energy is too high, and Tritium is not favarable for compact source

Neutron yield curves of right elements with low energy charged particle injection

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



RANS:7MeV proton
Be target
10^{12} neutron/s

RANSII:2.5MeV proton
Li target
10^{11} neutron/s

Deuteron low energy nuclear reaction with (Be, Li)

It is possible to make the high production of the neutron with low energy beam, but, the activation of the accelerator←difficult for maintenance

Technical difficulty of the target lifetime

$Y_N(E_p) = 3.42 \times 10^8 (E_p - 1.87)^{2.05}$ (n/μC)

＊＊C.M. Lavelle, et al, Nuclear Instruments and Methods in Physics Research A 587 (2008) 324–341

10^{6}

RANS

Major parameters of RANS

RANS
RIKEN Accelerator - driven compact Neutron Sources

1.Proton 7MeV 100 μA (max. av.) Daily use

Be (p,n)reaction: Be (Dr. Y.Yamagata)

2012 7MeV proton linac was installed (Accsys co.)
2013 Operation starts with fast and thermal neutron

•Neutron max total flux ~10^{12}/sec

- 7MeV 100 μA 700W
- Pulse condition
- 10-180μs pulse width
- 20-180Hz repetition rate

Choose them under the condition 1.3 %duty, 100μA

2.compact and low cost

proton linac: in our case less than <2億円=2*10^8 yen=2 million US$

shielding design Multilayer shielding of target station

７MeV、100μA、Rf power supply.: 350kW(peak) duty 1.3%,Electric power peak 40kVA, Cooling water：75L/min ,**pulse width** (**30～200μs**)repetition frequency～**20～180Hz** RF power 425MHz, Injection energy0.030-3.5MeV

RANS and RANS-II neutron instruments

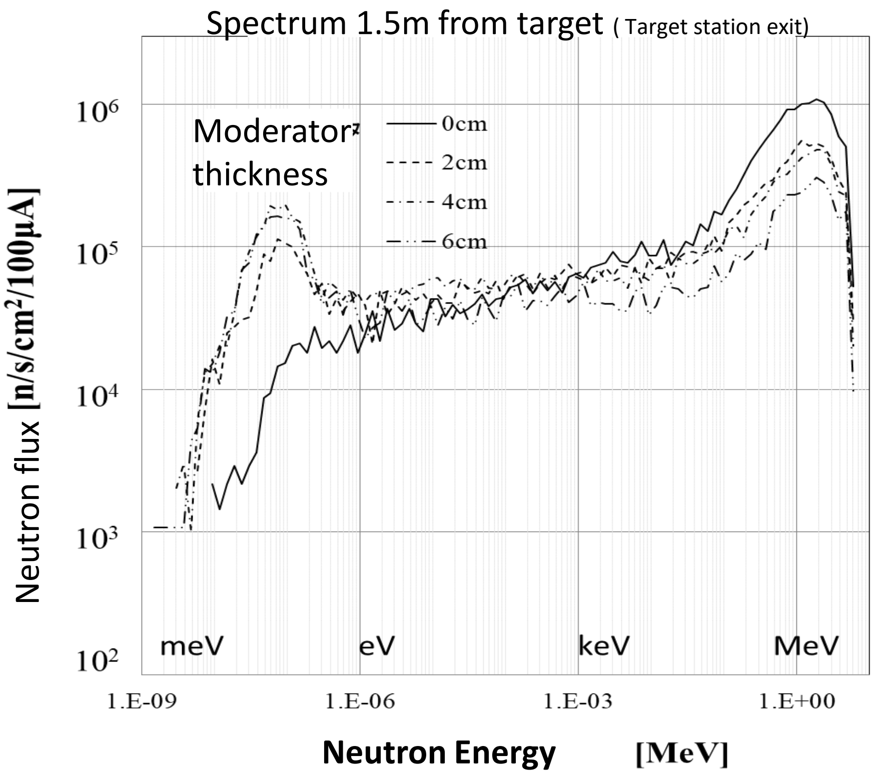
RANS

RANS-II

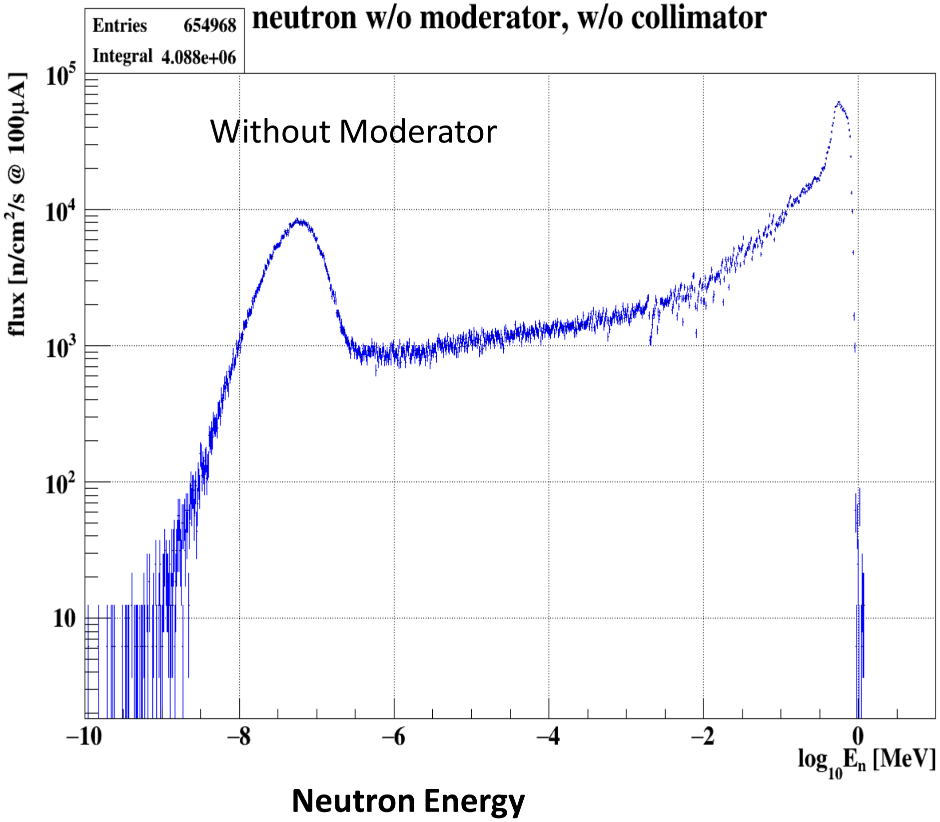
1. Imaging experiments special resolution, 0.5mm, 0.2mm, Non-destructive test
2. Diffraction, iron steel samples, residual **austenite phase fraction**
3. Prompt gamma-ray Neutron Activation Analysis, PGNAA, elemental analysis
4. SANS with Ibaraki Univ. (Small Angle Neutron Scattering) nano, sub-mic.
5. Fast neutron transmission imaging for thick samples
6. Fast neutron **scattered imaging** from the surface layer with 6~20cm
7. Phase contrast imaging with Tohoku Univ. Prof. A. Momose
8. Polarized neutron experiment for fundamental physics, with Nishina-center, Tohoku Univ. Kyushu- Univ.

Typical Neutron Spectra for p-Be and p-Li with respective proton energy of 7 MeV and 2.5 MeV

RANS



RANS-II



To design RANS, we **needed** reliable data for accurate neutron yield. But we found that a lack of nuclear data base suitable for it as follows:

Although there have been amounts of nuclear data of nuclear reactions as Be(p,n), Li(p,n), Be(d,n),etc., no suitable data library was available for low-energy protons.

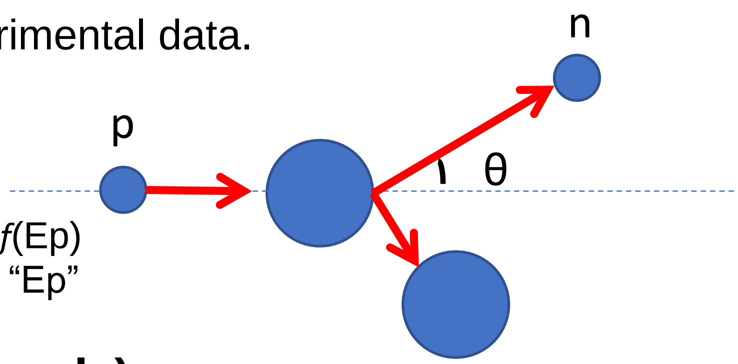
Then,

- We, RIKEN team proposed a new analytical function to give neutron spectrum for p-Be source neutron production reaction. We call it as ”Func.”
- The function enable to provide the total production cross section, angular distribution along with double differential cross sections of the p-Be reaction with proton energy below 12MeV.

Steps to create the function for the p-Be reaction

From 2015-, Dr.Y.Wakabayashi et al

- Thick target is sum of thin target.
- Make the function to reproduce the experimental values of neutron spectrum (total cross section, angular distribution, and energy spectrum) using thin Be target.
- Use EXFOR [1] and ENSDF [2] to search available experimental data.



Steps to make the function

①Total cross section (σ(Ep))

Make a function following incident proton energy “Ep” --- σ(Ep) = *f*(Ep)

↓ Get total cross section σ(Ep) with certain “Ep”

②Angular distribution (dσ(θ, Ep) θ：scattering angle)

Make a function following “Ep” using σ(Ep) --- dσ(θ, Ep) = σ(Ep) x *f*(θ,Ep)

↓ Get dσ(θ) with certain ”Ep”

③Energy spectrum (dσ(En, θ, Ep))

Maximum outgoing neutron energy (En_max) is determined from kinematics at certain “Ep” and ”θ”.

Make a function following “En_max” using dσ(θ, Ep) --- dσ(En, θ, Ep) = dσ(θ, Ep) x *f*(En, En_max(θ, Ep))

↓ Get En with certain ”Ep” and ”θ”

“Ep” proton energy ⇒ neutron spectrum (①～③) is obtained

[1] http://www.nndc.bnl.gov/exfor/exfor.htm
[2] http://www.nndc.bnl.gov/ensdf/

Y. Wakabayashi et al."A function to provide neutron spectrum produced from the 9Be + p reaction with protons of energy below 12 MeV", J. Nucl. Sci. Technol. Vol. 55 (2018) pp.859-867

Cross section derived by Func. for Be(p,n) with Ep<12MeV

total cross section

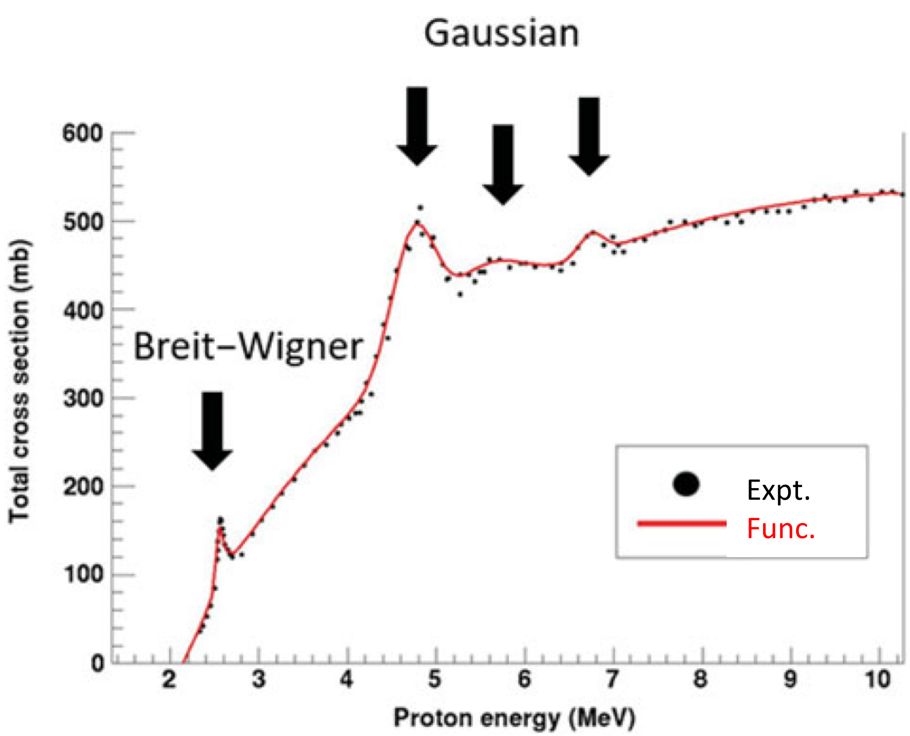
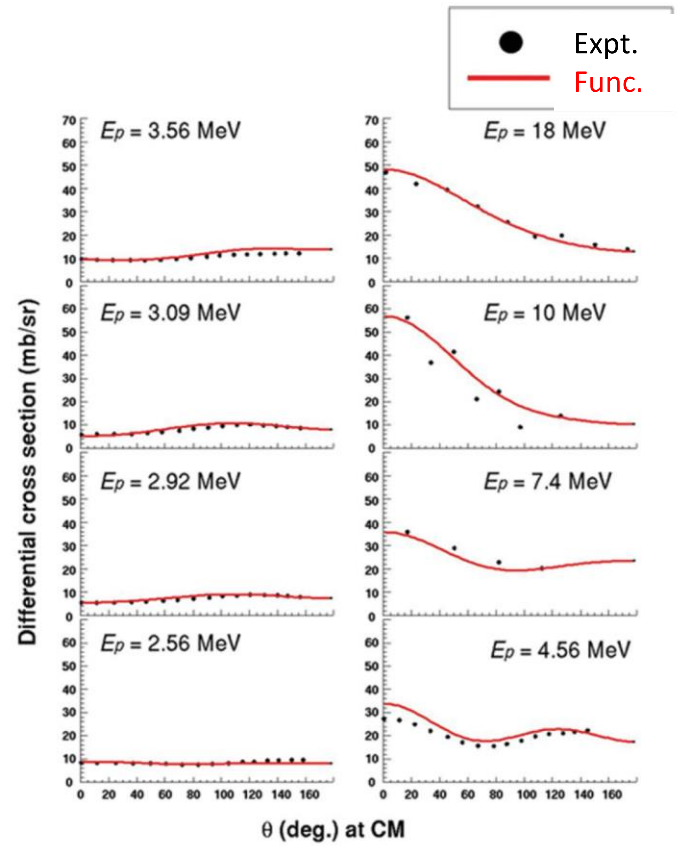


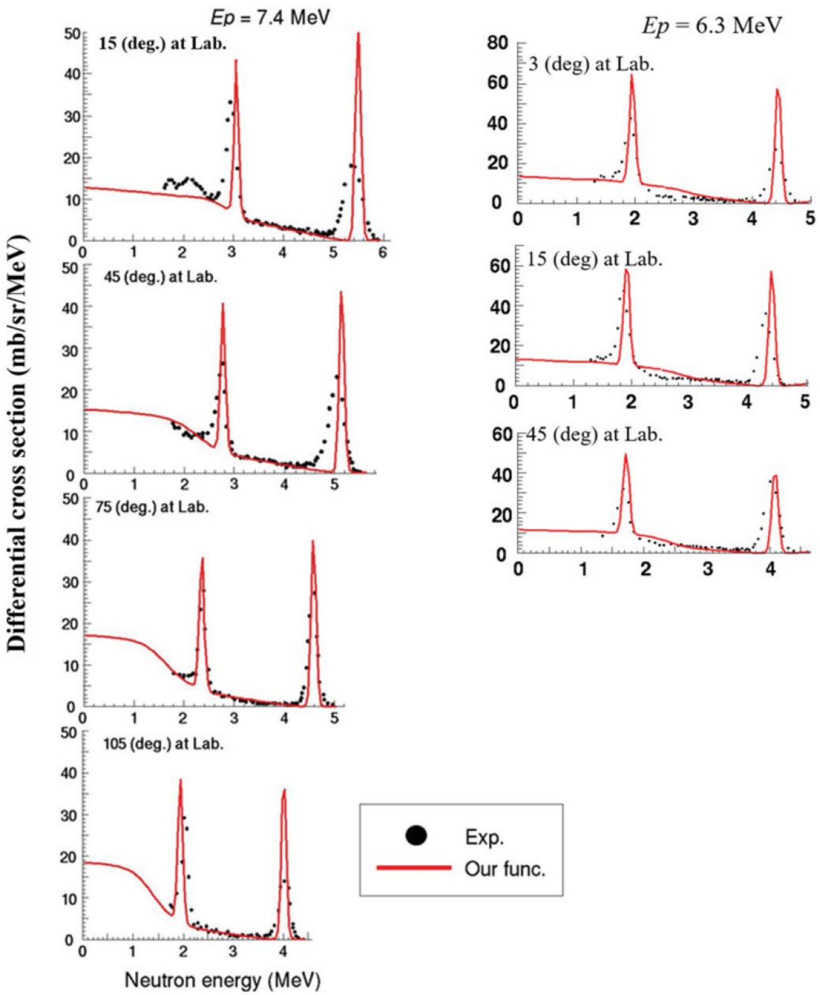
Figure 1. Total cross section of neutron production by p–Be. Dots are the available experimental data [18,19]. The solid line was obtained using the function.

Angular distribution of neutrons

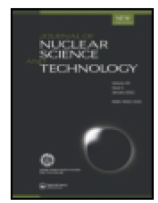


ɿular distribution. Dots are the available experimental data [7,20–22]. The solid line was obtained using the function.

Double differential Cross-sections for Be(p,n) reaction with different proton energies Ep<12MeV



igure 3. Energy spectrum. Dots are the available experimental data [21]. The solid line was obtained using the function.



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A function to provide neutron spectrum produced from the ^{9}Be + p reaction with protons of energy below 12 MeV

Yasuo Wakabayashi, Atsushi Taketani, Takao Hashiguchi, Yoshimasa Ikeda, Tomohiro Kobayashi, Sheng Wang, Mingfei Yan, Masahide Harada, Yujiro Ikeda & Yoshie Otake

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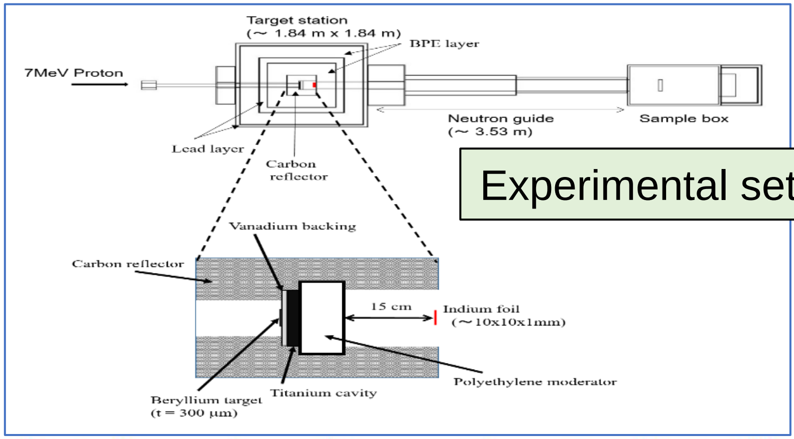
To link to this article: https://doi.org/10.1080/00223131.2018.1445566

Experimental validation of the Function with ^{115}In(n,n')^{115m}In reaction rate

RANS, Be target = p-Be : Ep=7MeV



To evaluate total neutron flux > about 1MeV, the experimental ^{115}In(n,n')^{115m}In reaction rate was compared with calculated ones.

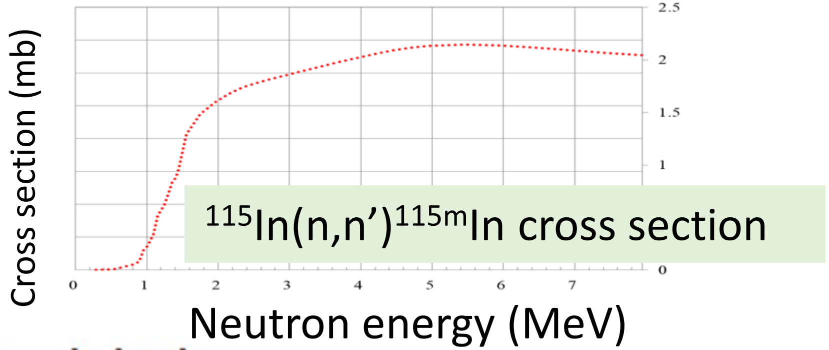


Table 1. Comparison of the reaction rate of In5n. The C/E ratio is the calculated result divided by the experimental value.

	Reaction rate [1/s/100 μA]	C/E ratio
Experimental value	2.55±20X10^{-17}	----------
Calculation with the CF	2.91X10^{-17}	1.14±0.07
Calculation with ENDF/B VII.0	1.66X10^{-17}	0.65±0.04

The reaction rates calculated with GEANT4 by using **the new function and ENDF/B-VII (C) were compared with Experiment (E)**

From results of C/E for the reaction rates, calculation with the new function gives reasonable agreement with experiment compared to that of ENDF/B-VII. Nevertheless, there was about 15 % overestimation remained.

Recent progress in neutron source characteristics at RANS

1. Concerning the p-Be reaction, a new data library becomes available in JENDL-5, the same experimental measurements with the In foil were carried out to confirm the adequacy of source neutron production by using the data.

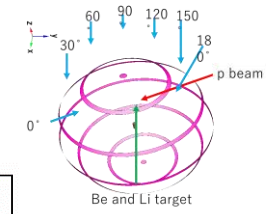
   This program is to have a better and reliable neutron source such as described in previous slide the Function still overestimated the experiment by 15 %.

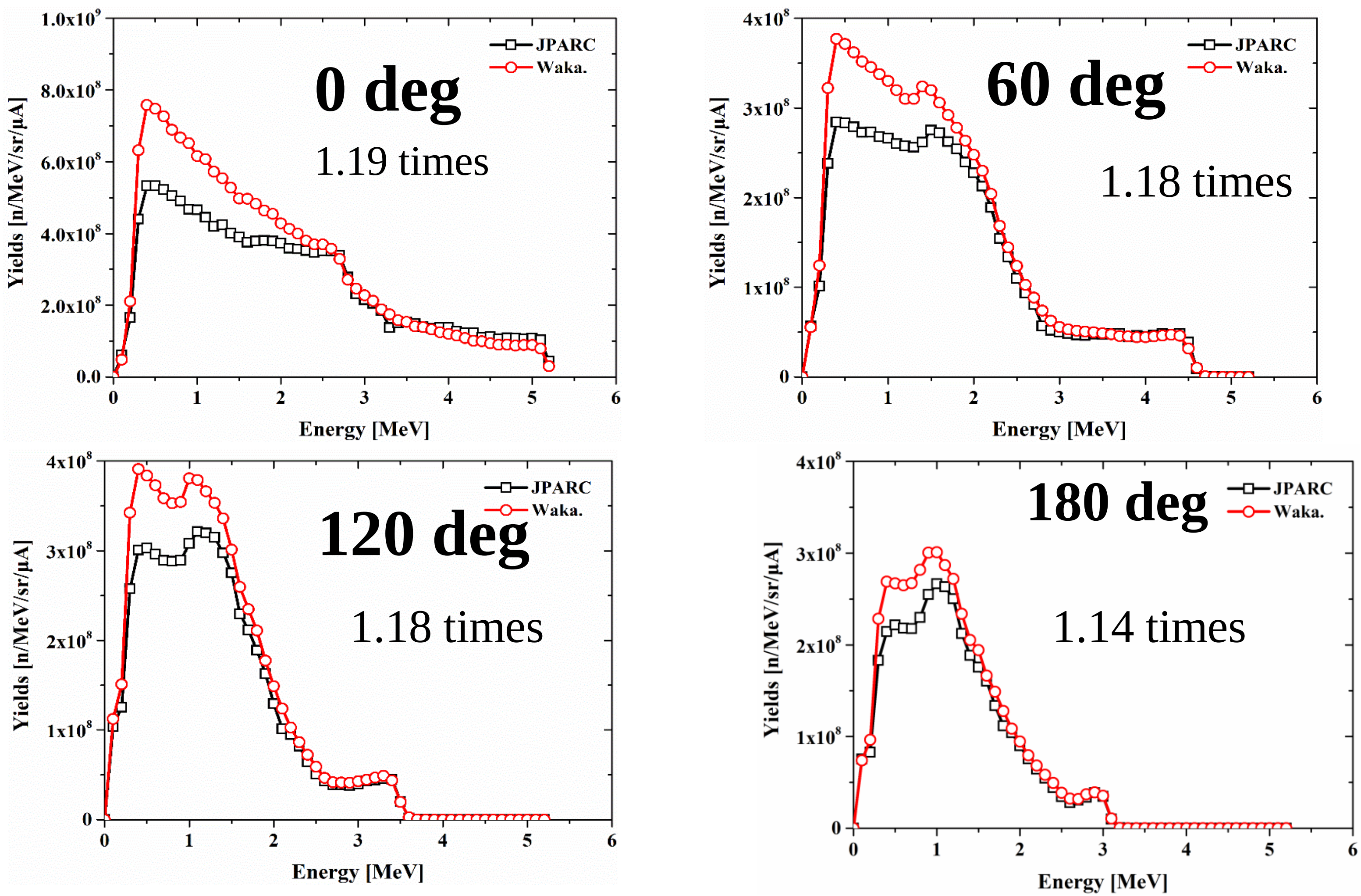
   Func. was compared with JENDL

2. **RANS-II** with the **p-Li started** neutron production operation. We do need the validate neutron source characteristics in terms of neutron yield and angular distribution.

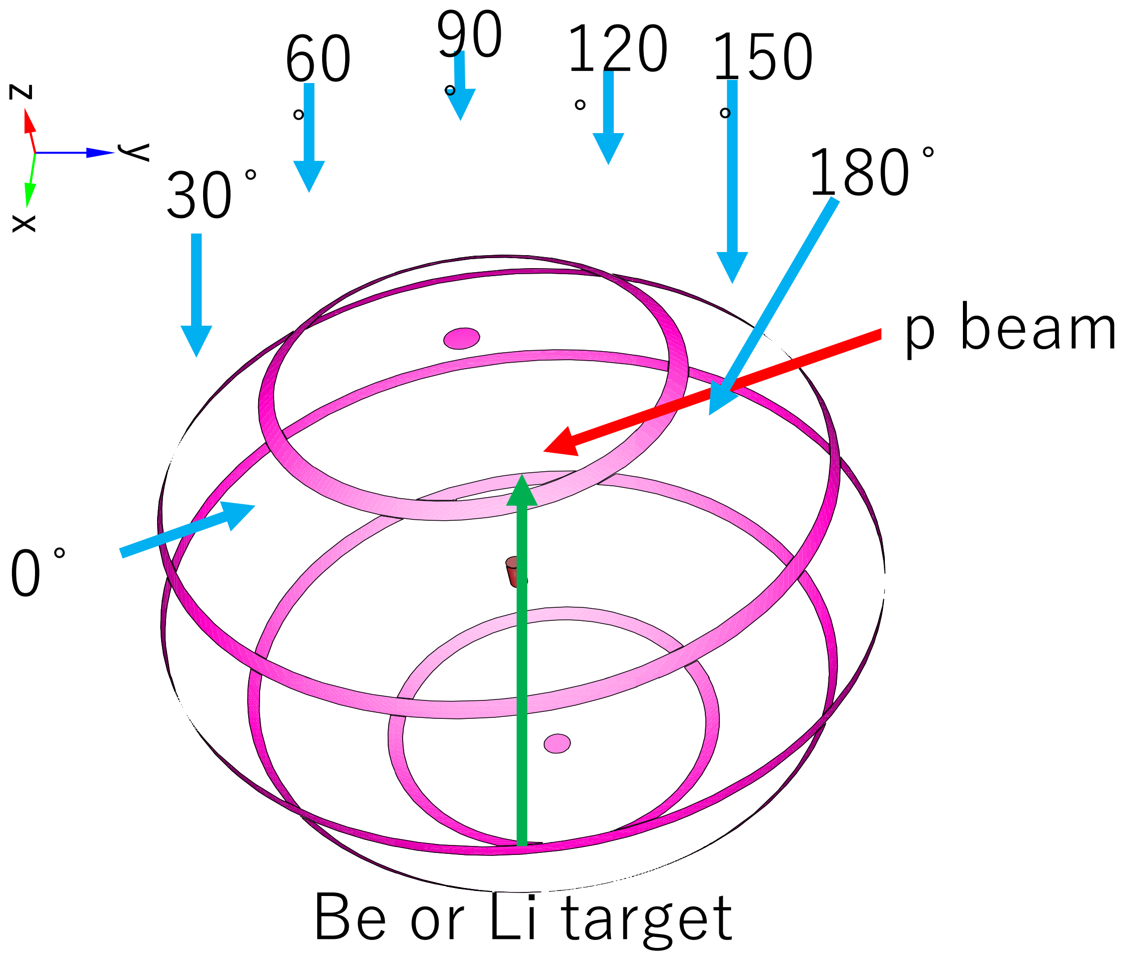
   Experimental validation of simulation calculation with available nuclear data, e.g., JENDL, ENDF, etc.

Comparison of Func. and JENDL-5





Overestimation by Func. could significantly be mitigated by JENDL-5 in all angles.



60°
90°
120°
150°
180°
30°
0°
z
y
x
p beam
Be or Li target

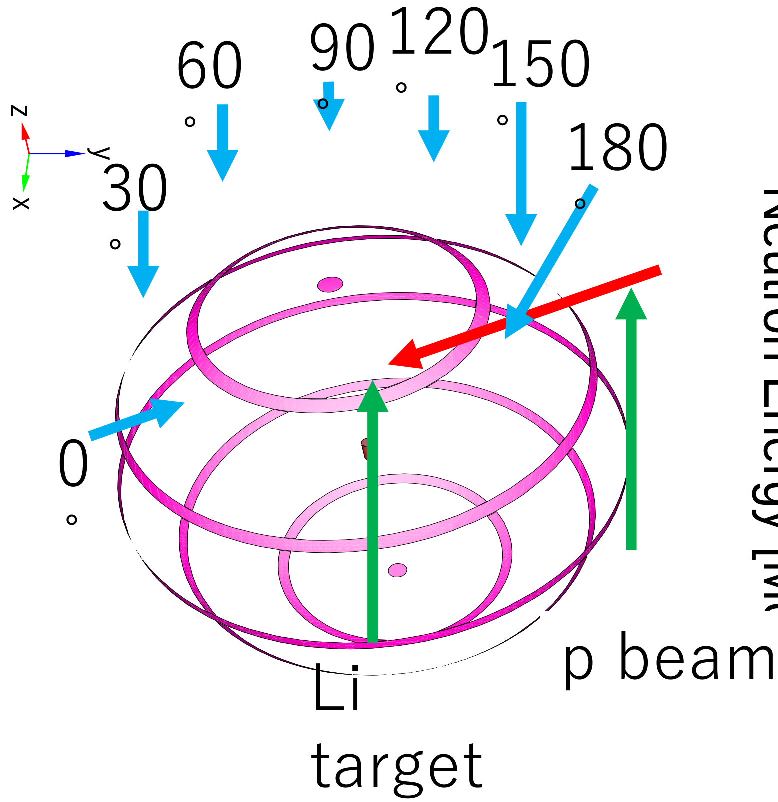
In addition to RANS, present status of the p-Li source for RANS-II is worth to be shown briefly in this particular occasion.

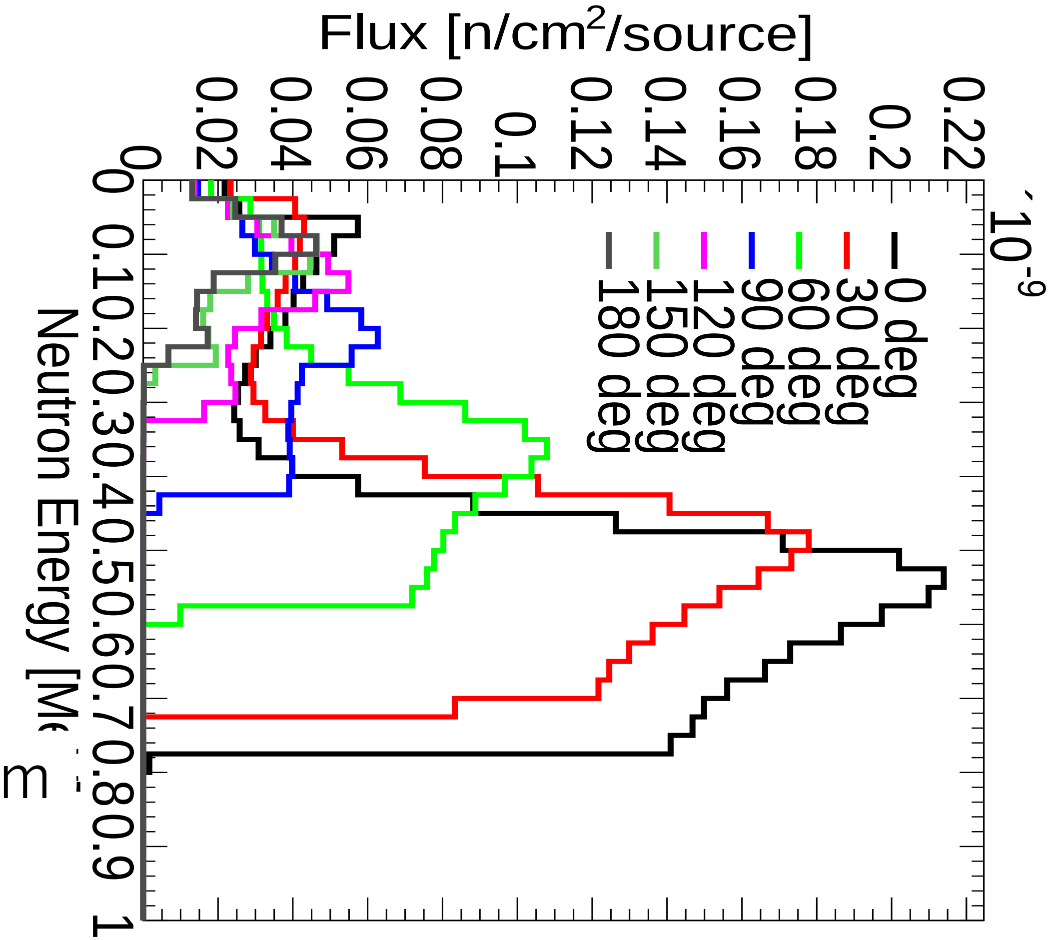
RANS-II: two function

・Proto-type of transportable compact neutron systems
・Standard Model of floor standing compact neutron system: can be easily introduced into public inspection stations, companies and universities.
-> Neutron Tomography system is now being developed with RANS-II based on the collaboration with AIST.

Power	Neutron Yield @target	Target ST shielding	Beamline	Neutron @ sample position	Acce. Duty
RANS 7MeV 700W	10^{12} n s^{-1}	Volume：~ $8m^3$ weight～23ton	1.5m	*10^5 n cm^{-2} s^{-1}	RANS 1.3% (RF Duty cycle)
			5m	*10^4 n $cm^{-2}s^{-1}$	
RANS-II 2.49MeV 250W	*10^{11} n s^{-1}	V~$1m^3$ W~ 3.5ton	0.5m	*10^4~10^5 n cm^{-2} s^{-1}	RANS-II 3% (RF Duty cycle)
			1.5m	*10^4 n cm^{-2} s^{-1}	

Neutron spectra of the p-Li reaction calculated by using JENDL

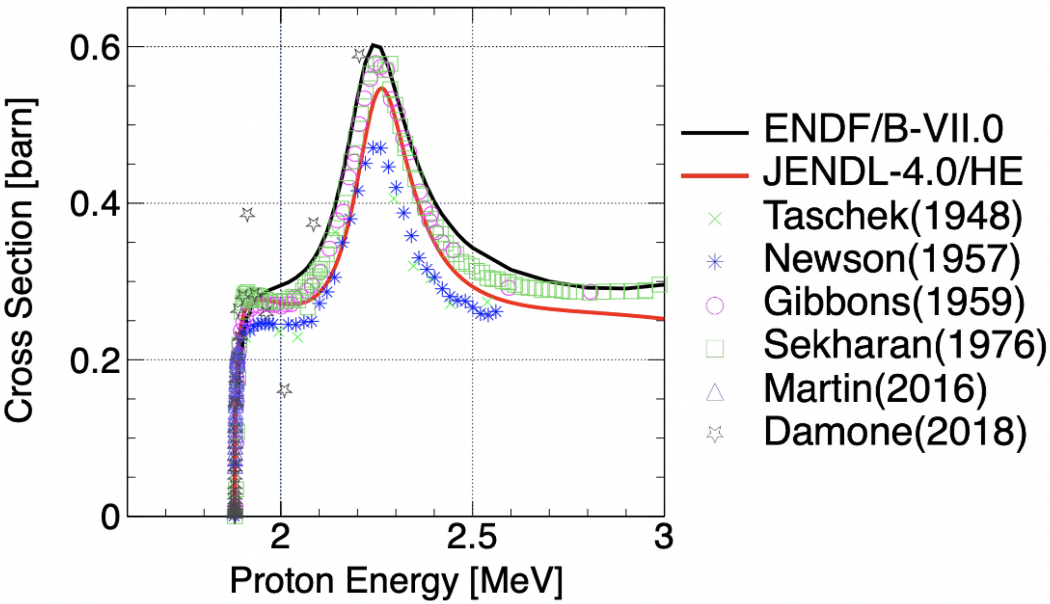




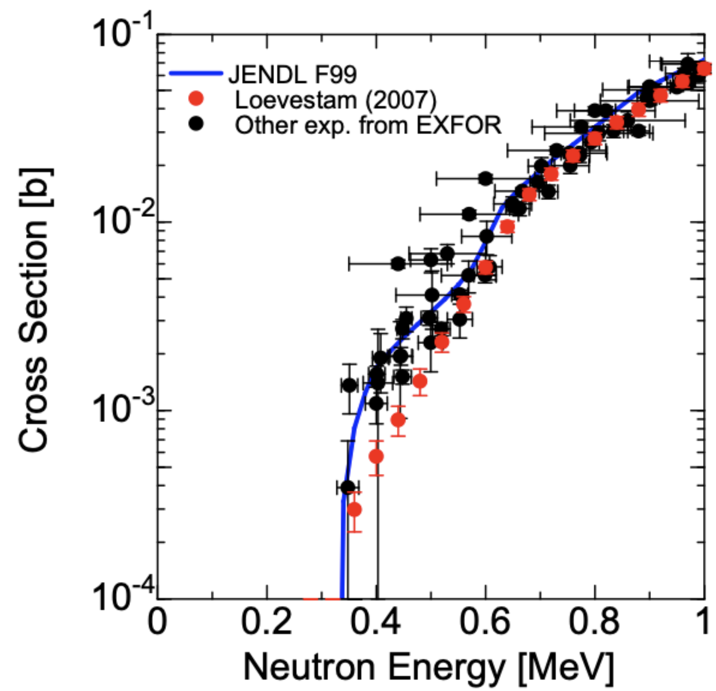
The reaction rate of $^{115}In(n,n')^{115m}In$ reaction was measured in a forward position to the Li target.

The experimental data was compared with simulations, resulted in overestimation of more than 30 % up to 50 %.

At this moment, it could be reasonable agreement from neutron source utilization point of view, however, the overestimation needs to be investigated.



There is systematic deviations between JENDL and ENDL, which gives about 5 % difference in neutron yield.



Cross sections of $^{115}In(n,n')^{115m}In$ reaction detector Near the threshold at 0.36 MeV, some scattered experimental data are distributed. a part of the overestimation could be attributable.

Critical impact of RANS-II 2.5 MeV proton beam profile on neutron production

Beside nuclear reaction aspect, proton beam profile has significant influence on the neutron production evaluation in terms of,

1. Proton energy distribution on the Li target,
   (energy dependent neutron yield curve shown in Page 9)
2. Proton beam footprint
   (Some of protons are out of Li area so that not all collected beam current interacts with Li target.)
3. Proton beam position

All aboves should be taken into account in the next analysis.

Concluding remarks.

- Concerning the p-Be RANS source, we have established a powerful simulation system for neutron field and associated reaction environment at RANS.
Currently, a precise neutron yield determination system is under installation by introducing a Solar panel detector to give absolute neutron production data.
- Concerning the p-Li RANS-II source, although there is reasonable agreement between simulation and experiment, still we do need to do deep analysis by taking account of the proton beam profile.
- For the development of “Accelerator-driven “compact” neutron systems”, the lack of nuclear data with accelerated proton beam is a serious issue in the world.

Thank you for your kind attention!!!