QST

INDEN Cu and Fe Benchmark tests

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Introduction

- We performed INDEN benchmark tests using JAEA/FNS Cu and Fe experiments and QST/TIARA Fe experiments.

  - Cu & Fe: JAEA/FNS experiments for DT neutrons
  - Fe: QST/TIARA experiments for 40 and 65 MeV neutrons

- We report all results and some remarks for further INDEN improvement.

Methodology

- Code: MCNP-6.20
- Nuclear data library: INDEN (Nov.2024), FENDL-3.2b and JENDL-5

Iron (Fe)	FENDL-3.2b (INDEN-1.0)	recommended, INDEN (Nov.2024) in this study
54Fe	f54e80o	f54e80p
56Fe	f56e80X29r48	f56e80X29r67d
57Fe	f57e80m	f57e80o
58Fe	ENDF/B-VIII.0	-

Copper (Cu)	FENDL-3.2b	recommended, INDEN (Nov.2024)	latest (no ACE)
63Cu	ENDF/B-VII.0	cu63e81b2_PopWe2TotIn6RB	cu63e81b2_PopWe2TotIn7
65Cu	ENDF/B-VII.0	cu65e81b2_PopWe2TotIn6RB	cu65e81b2_PopWe2TotIn7

- Nuclear data processing code: NJOY2016.76
- Files downloaded from the official webpage https://www-nds.iaea.org/INDEN/.

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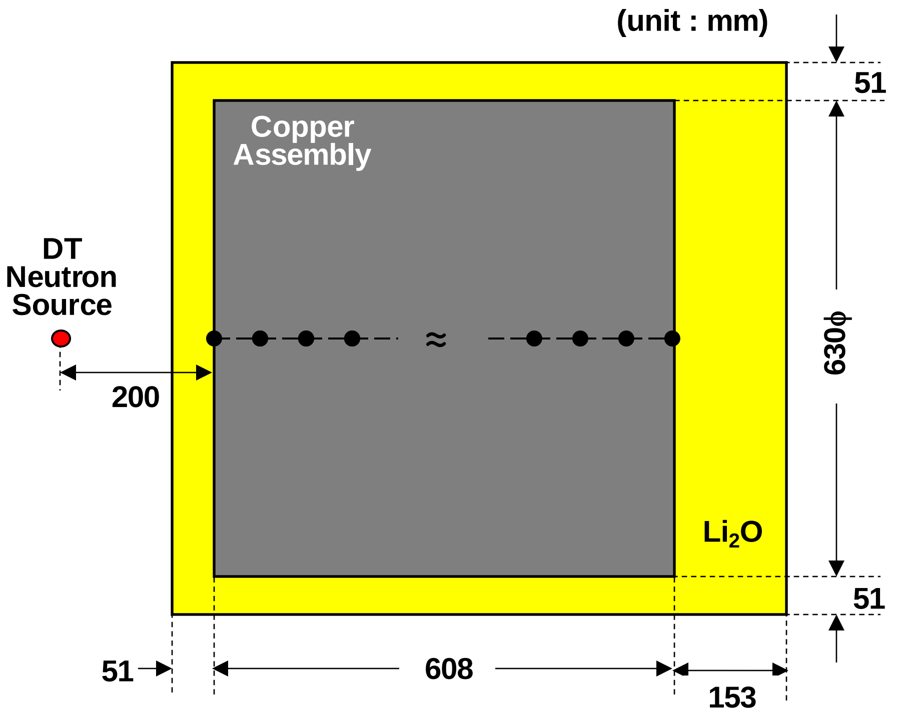
JAEA/FNS Cu experiment

Basic information

- The newly performed experiment by using Cu assembly covered with Li_2O blocks (ref) has been conducted in this study.
- Fission (MFC) and several reaction rates (activation foils) were measured every 5 cm inside Cu assembly.



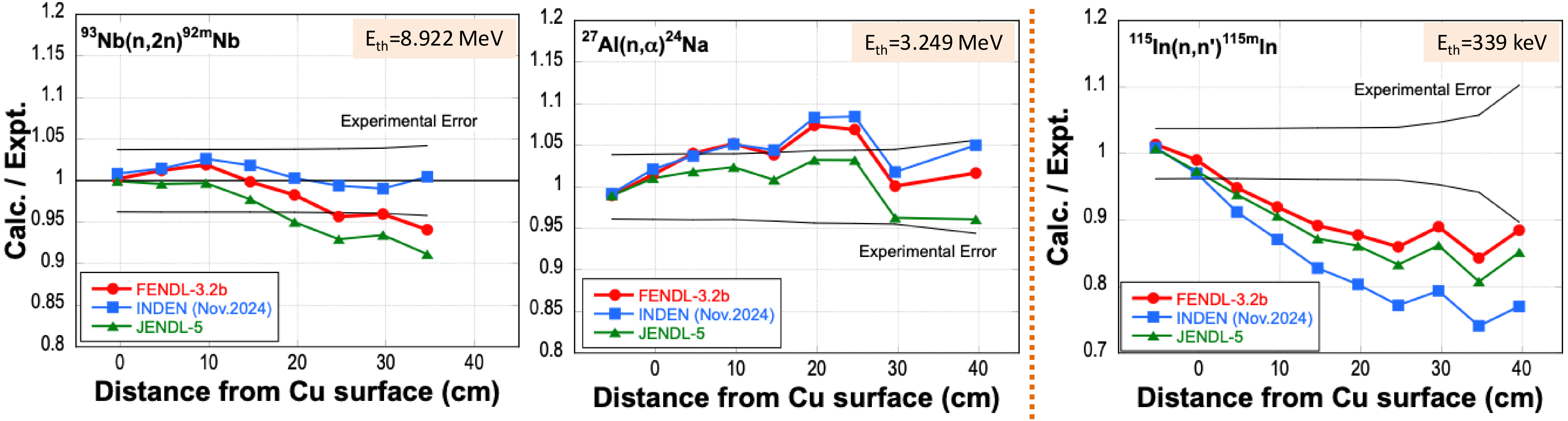
Details of the new experiment:
[ref] S. Kwon et al., FED109/111, p.1658 (2016).

Reaction rates used for this study

- ^{93}Nb(n,2n)^{92m}Nb
- ^{27}Al(n,α)^{24}Na
- ^{115}In(n,n')^{115m}In
- ^{197}Au(n,γ)^{198}Au
- ^{186}W(n,γ)^{187}W

Calc./Expt. of reaction rates

Results on the reaction rates sensitive to higher energy neutrons (threshold reaction)



- FENDL-3.2b and INDEN show a good agreement with the measured ones.
- JENDL-5 underestimates the measured $^{93}Nb(n,2n)^{92m}Nb$ reaction rate slightly.

- All libraries underestimate the measured data more with depth of Cu assembly.
- INDEN is worse than FENDL-3.2b.

Calc./Expt. of reaction rates (cont.)

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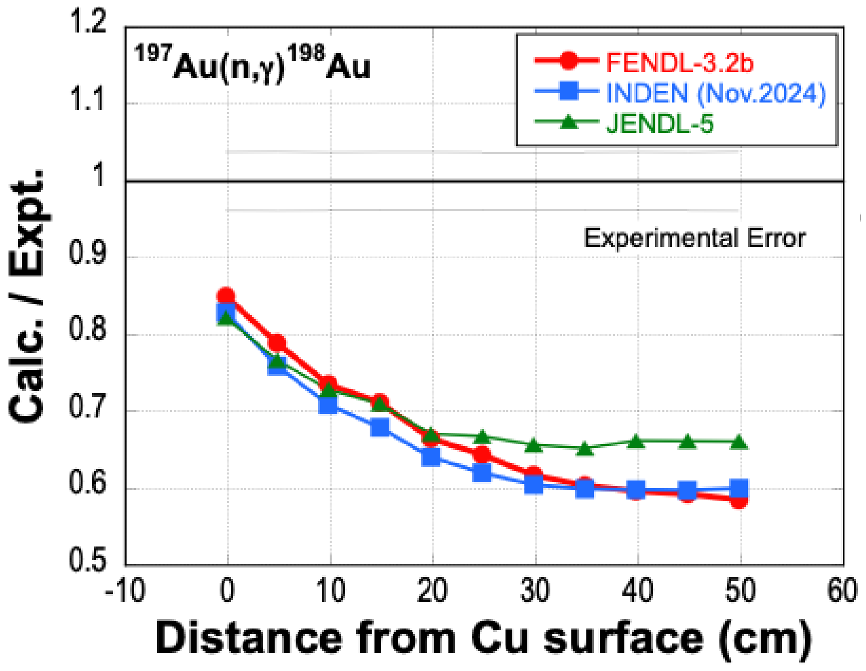
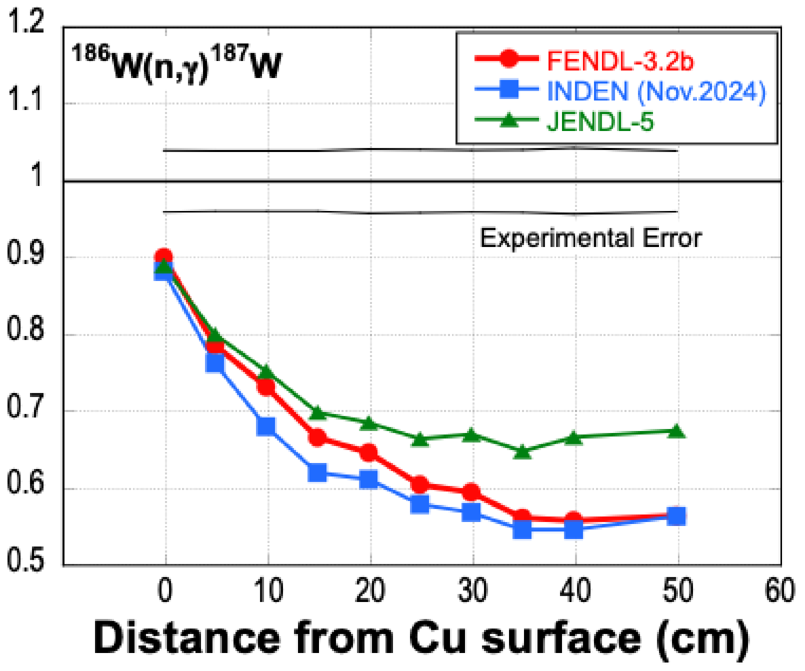
Results on the reaction rates sensitive to lower energy neutrons



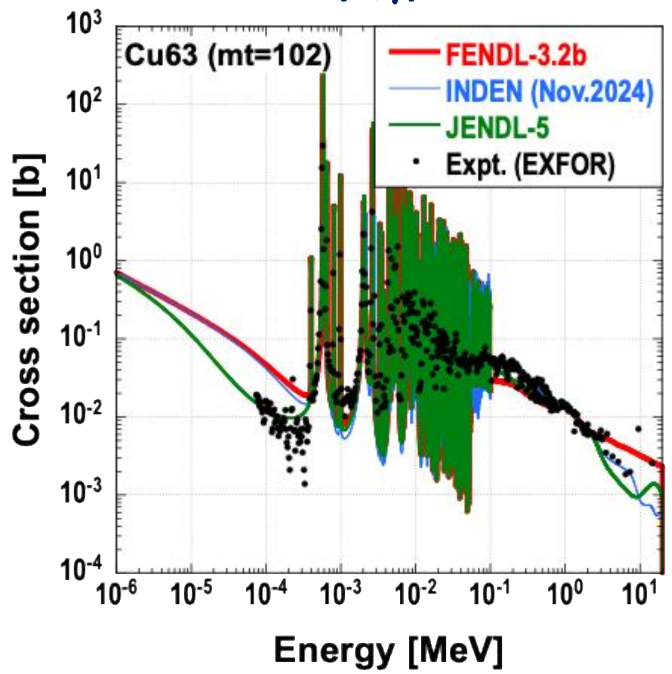


Underestimation tendency still appears:

- $^{197}Au(n,\gamma)^{198}Au$ and $^{186}W(n,\gamma)^{187}W$ reaction rates are sensitive to lower energy neutrons.
- All libraries underestimate drastically, though JENDL-5 is better.

[ref] C. Konno et al., J. Nucl. Sci. Technol. 60 (9), 1046–1069 (2023)

Cross sections of (n,γ) reaction



- JENDL-5 has modified the neutron capture reaction data, mt=102 based on the recent experiment data (via 25 keV measured by M.Weigand 2017).
- This is the reason of the improvement [ref].

Short remarks on Cu data

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- INDEN Cu data showed the better agreement with the measured $^{93}Nb(n,2n)^{92m}Nb$ reaction rate sensitive to neutrons above 10 MeV than FENDL-3.2b, but it underestimated the measured reaction rate of $^{115}In(n,n')^{115m}In$ more than FENDL-3.2b.

- The issue on lower energy neutrons should be improved [ref].

- The neutron capture reaction, (n,γ), in ^{63}Cu data of JENDL-5 has been re-evaluated based on the recent experimental data, but the improvement is around 10%.

About the issue on lower energy neutrons;
[ref] S. Kwon et al., FED109/111, p.1658 (2016).

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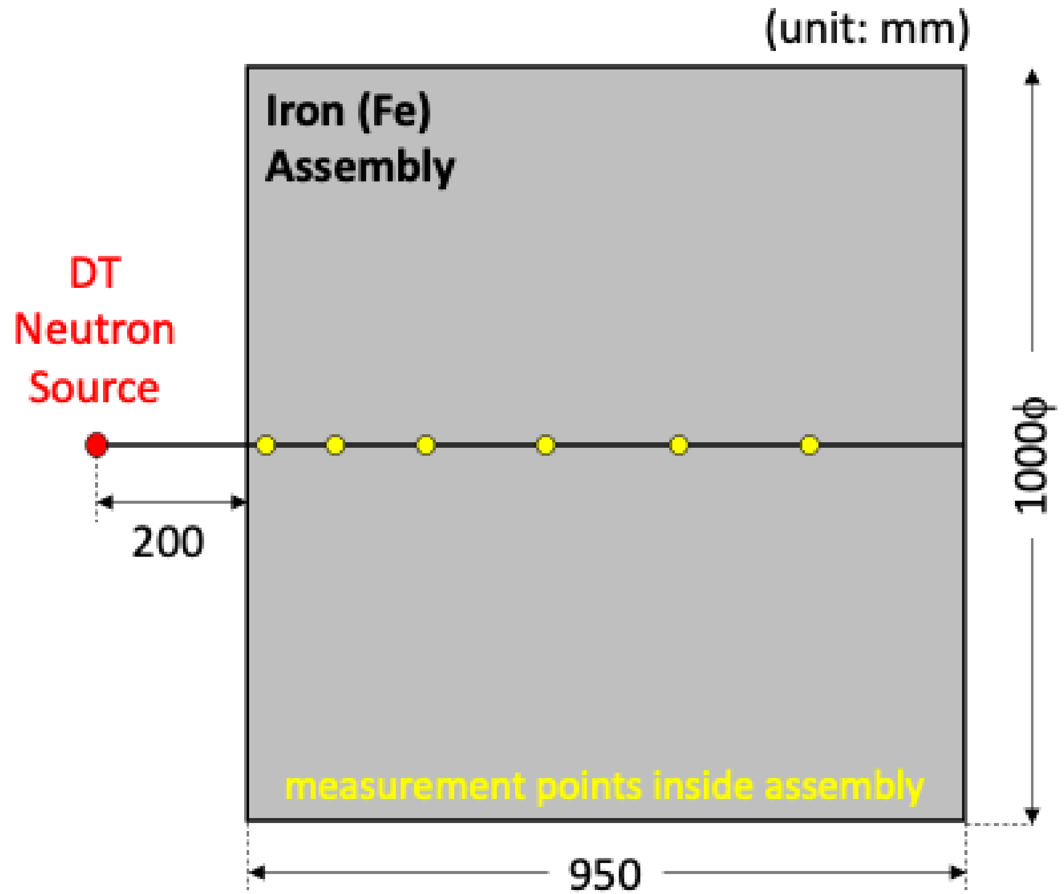
JAEA/FNS Fe experiment

Basic information

- Experiment performed only for Fe assembly [ref] is conducted in this study.
- Several reaction rates (activation foils) measured were not used in this study.
- Neutron spectra by scintillators, proton recoil counters and slowing down time method to cover wide range of neutron energies were used in this study.

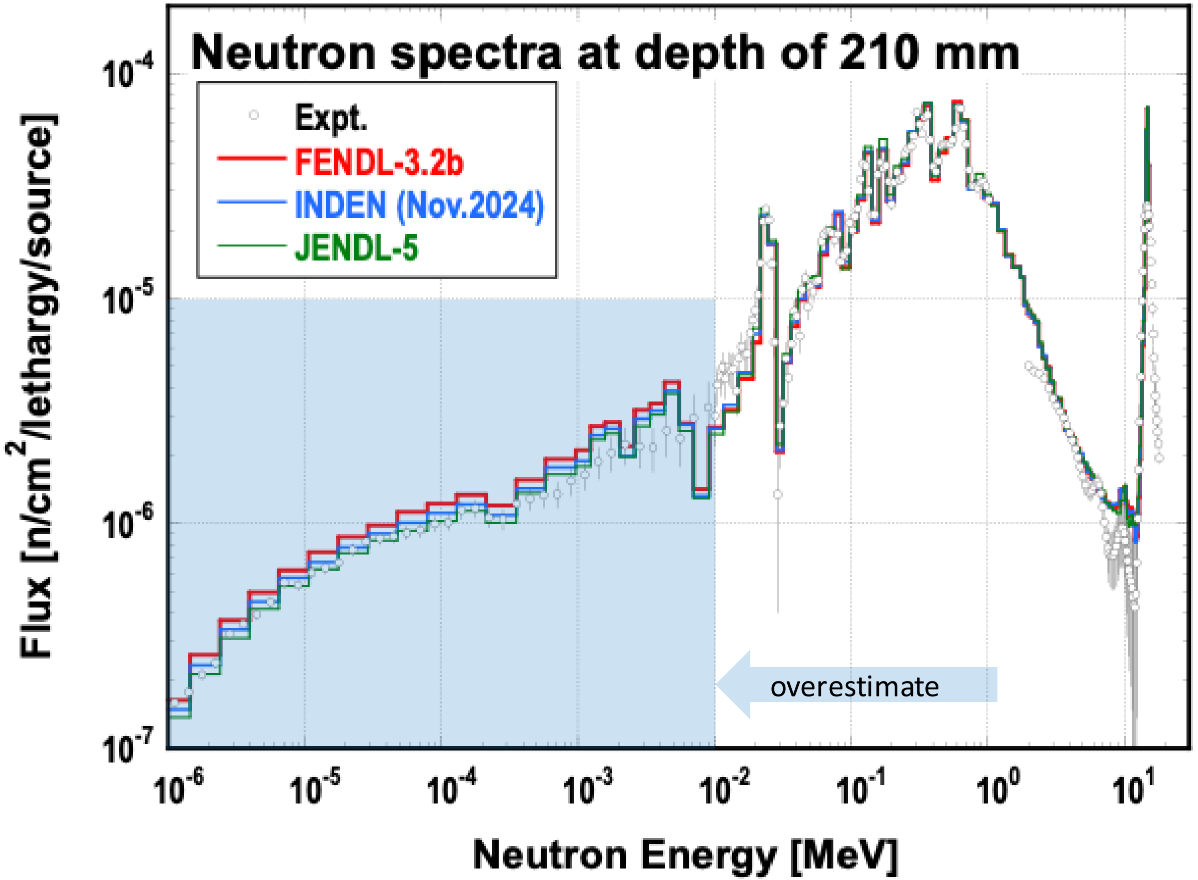
all plots of Calc./Expt. provided by these energy bins

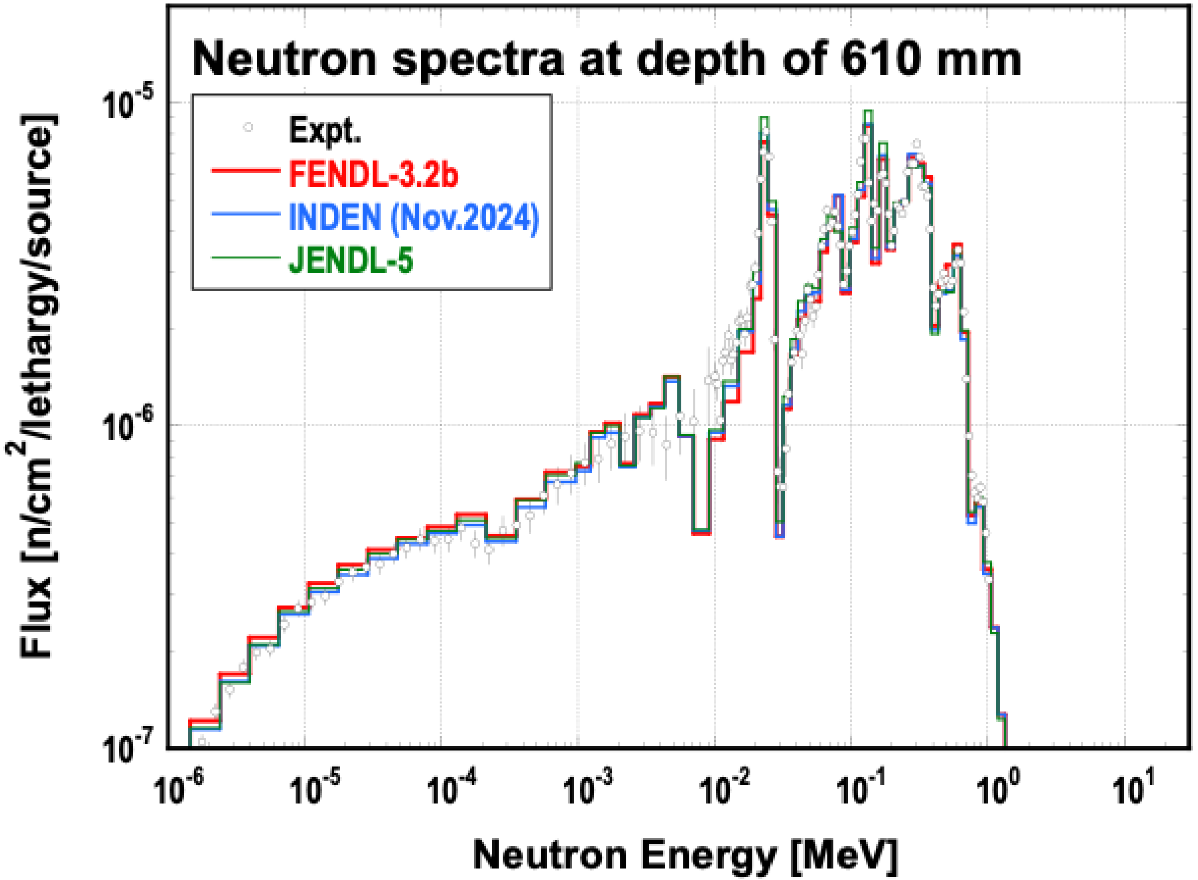
- over 10 MeV
- 0.1 – 1 MeV
- 10 – 100 keV
- 1 – 10 keV
- 0.1 – 1 keV
- 10 – 100 eV



Details of the experiment:
[ref] F. Maekawa et al., JAERI-Data/Code 98-021 (1998).

Result of neutron spectra





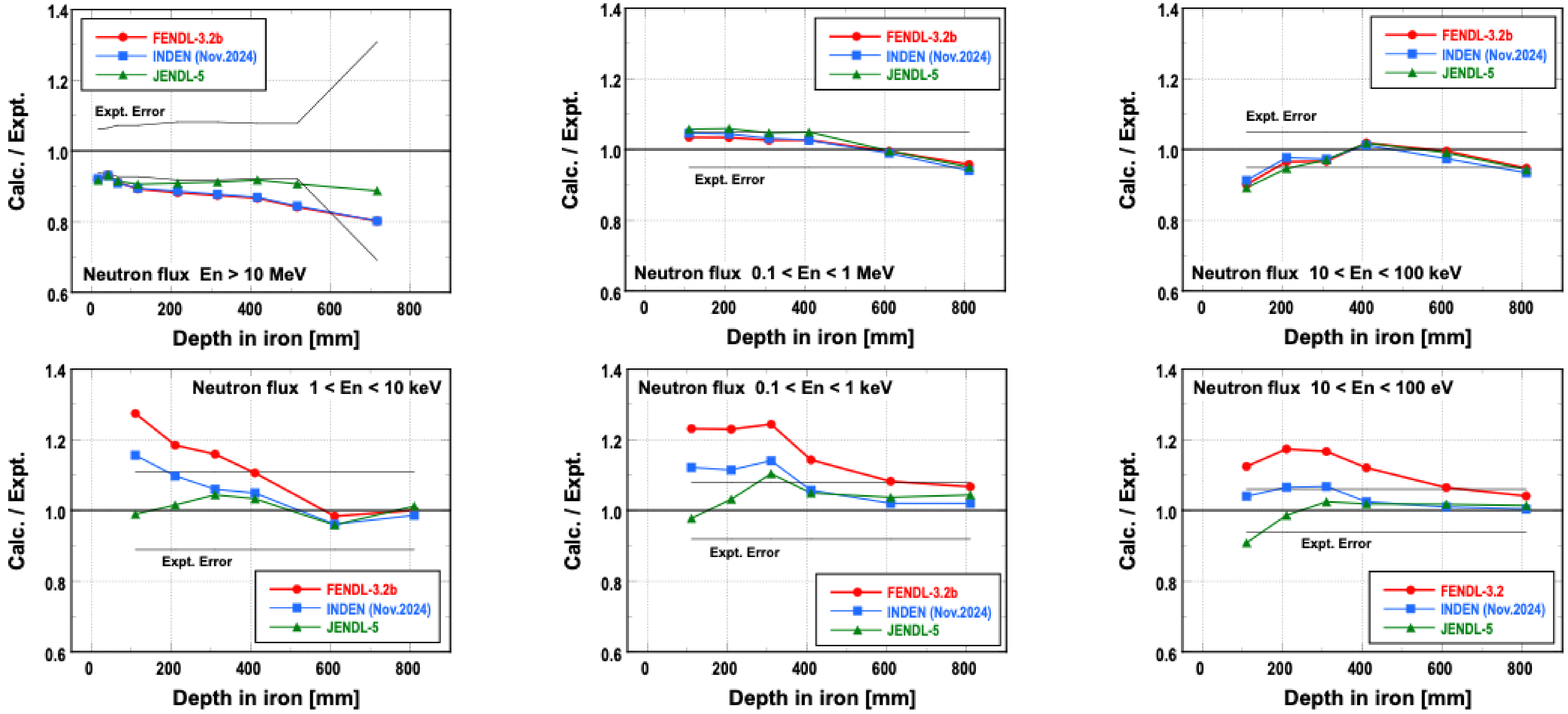
- **Swallower depth:**

INDEN is better than FENDL-3.2b, though both overestimate the measured neutron under 10 keV.

- **Deeper depth:**

Mostly FENDL-3.2b and INDEN show a good agreement with the measured data.

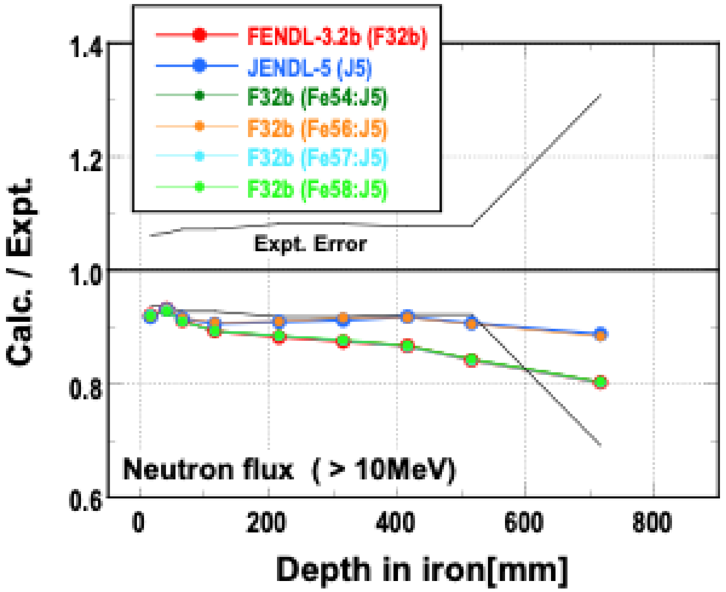
Results of Neutron flux (Calc./Expt.)

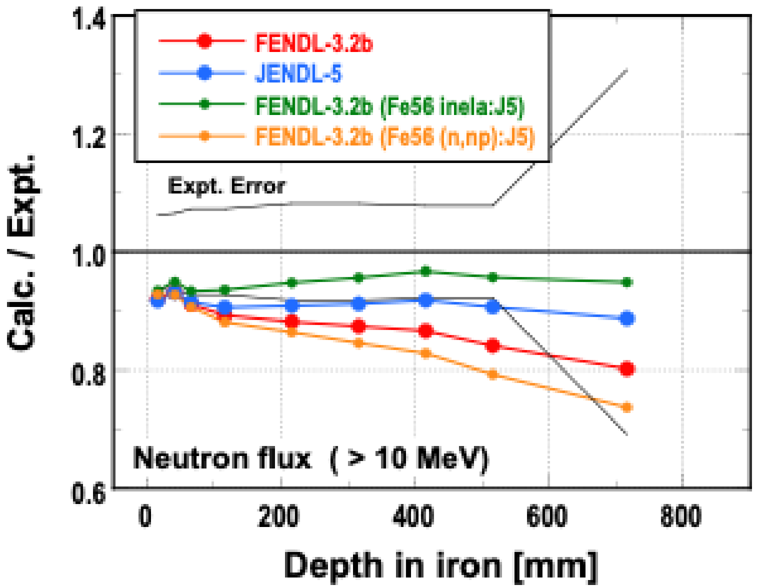


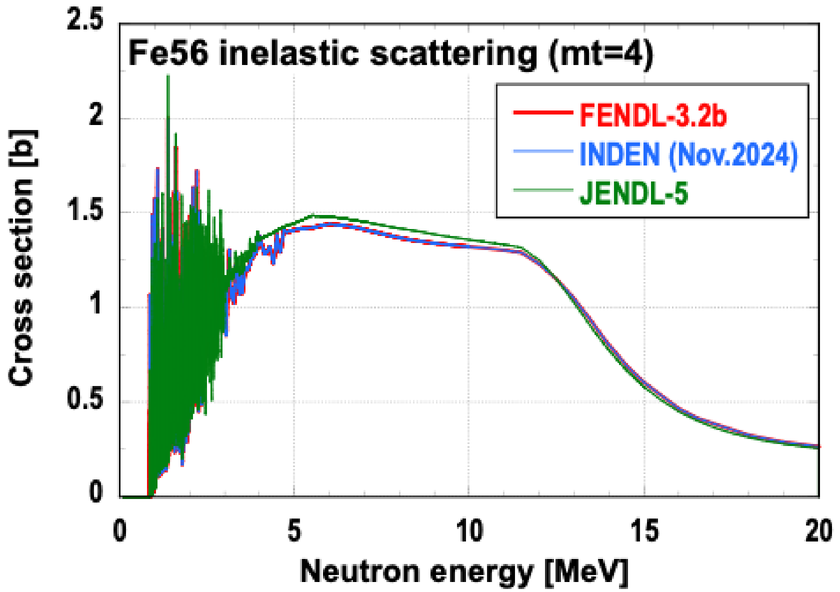
- **JENDL-5 is the best for any energy region.**
- **The INDEN recommended version (Nov.2024) is better than FENDL-3.2b (INDEN-1.0)**

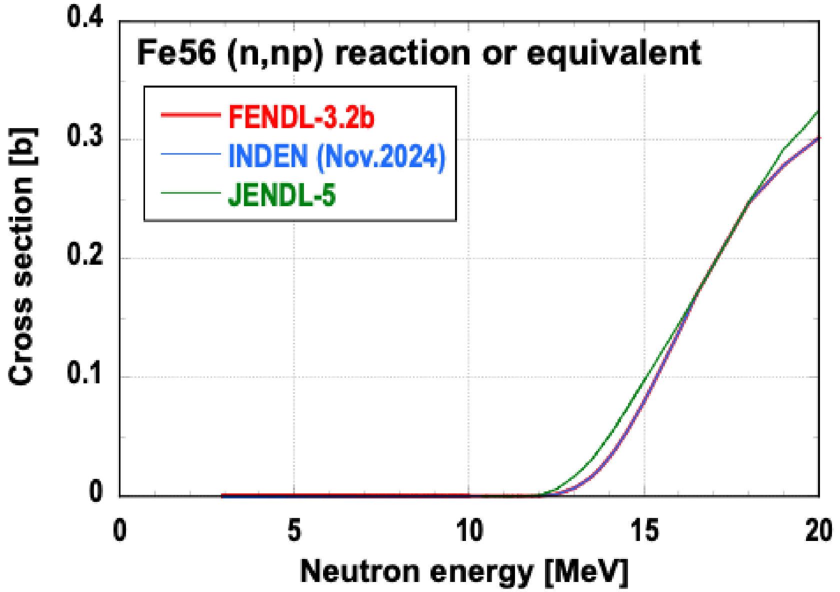
Reasons of underestimation above 10 MeV

- **INDEN (Nov.2024) and FENDL-3.2b have the same (n,2n), (n,np)… data in ^{56}Fe sensitive to higher energy neutrons.**
- **We compare the reaction data between FENDL-3.2b and JENDL-5.**







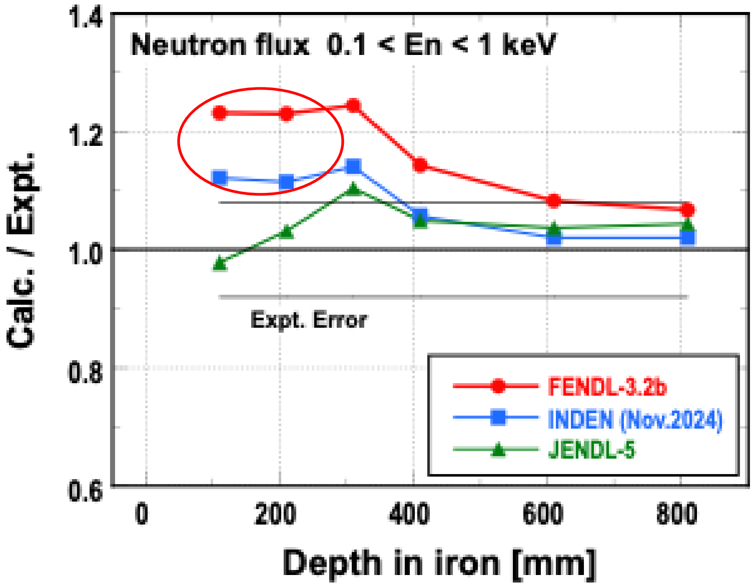


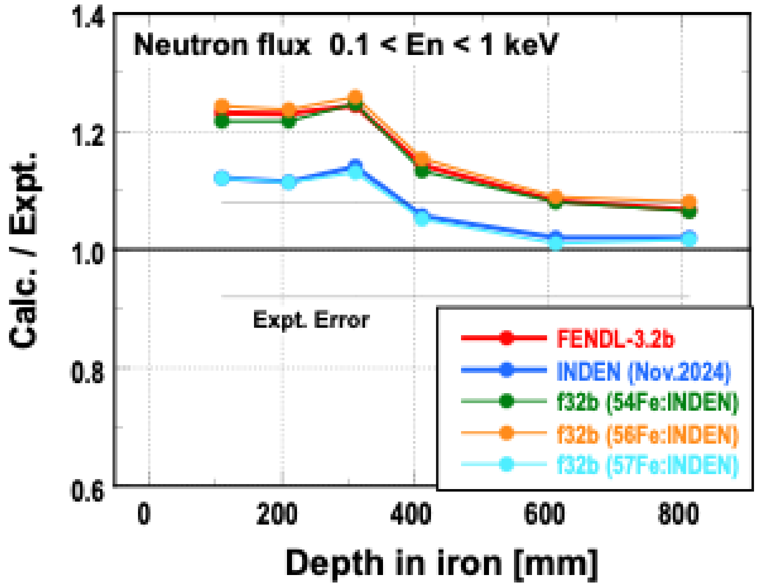
- FENDL-3.2b and INDEN underestimate the measured neutron flux above 10 MeV.
- JENDL-5 shows the better agreement with the measured ones.

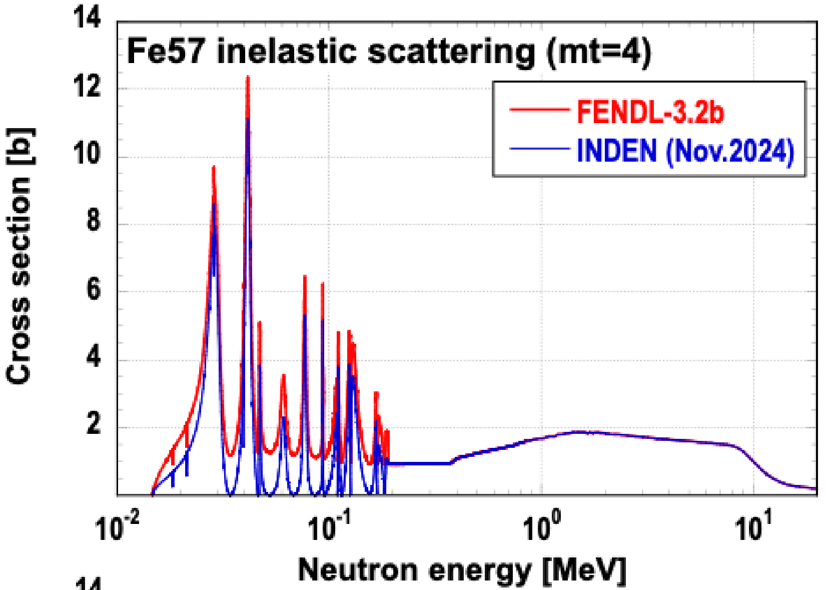
➢ **The inelastic scattering and (n,np) reaction data of ^{56}Fe cause the difference between INDEN and JENDL-5.**

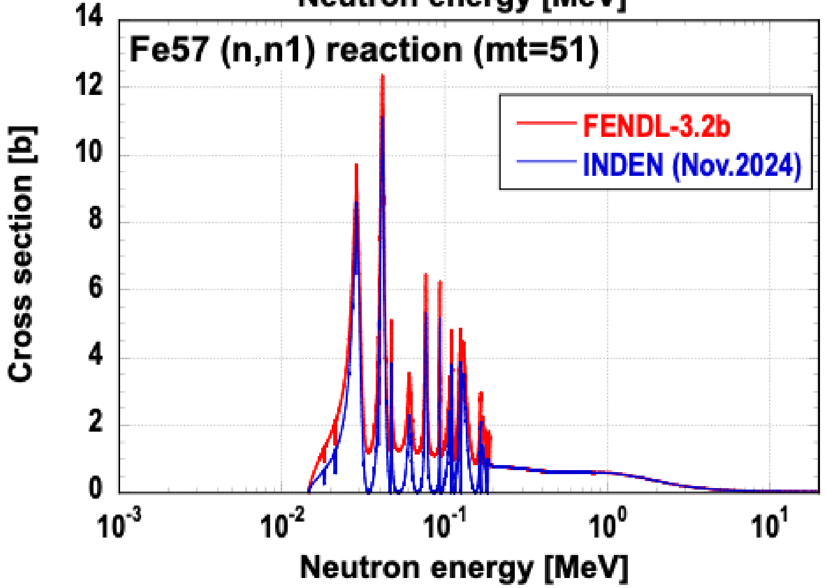
Reactions to make differences on neutron flux below 10 keV

The result of 1 keV <En < 10 keV shows the similar tendency.



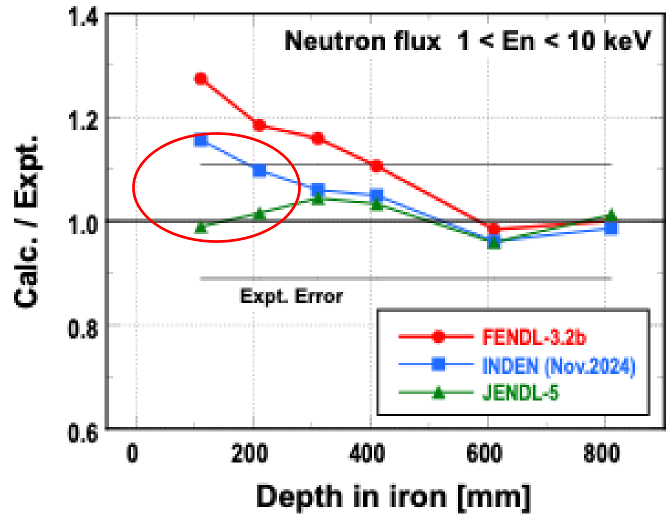






- We confirm clear different tendency on neutron flux below 10 keV between FENDL-3.2b and INDEN.
- The calculated neutron flux using FENDL-3.2b overestimates the measured one than that using INDEN (Nov.2024) data.
- The reason of the difference is coming from ^{57}Fe data, inelastic scattering data with residual in discrete excited level in particular.

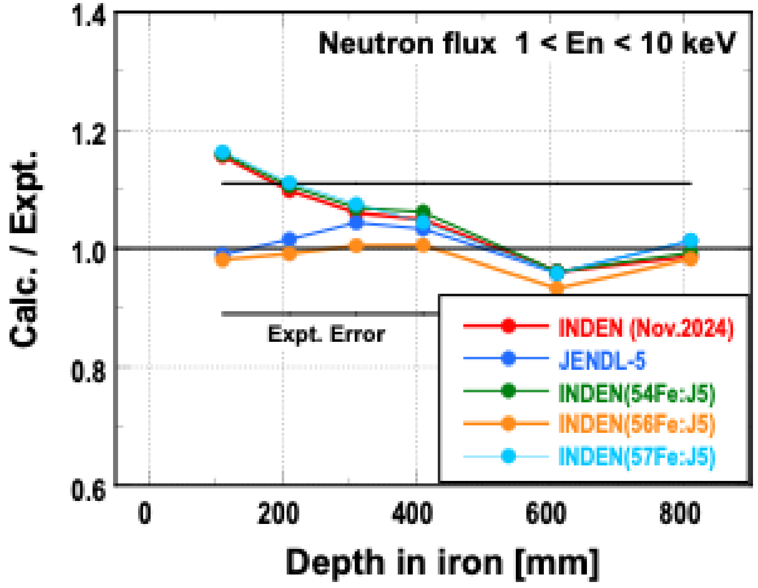
Reactions to make differences on neutron flux below 10 keV (cont.)



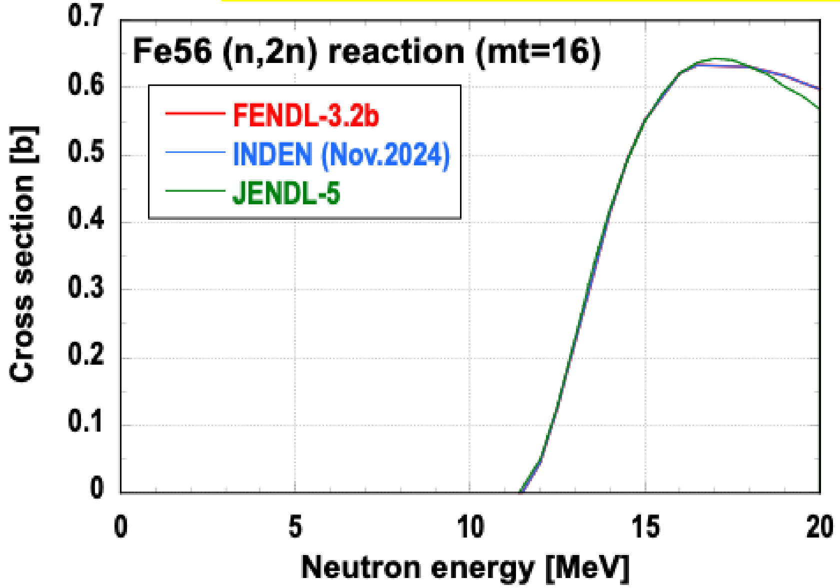
Small difference between INDEN and JENDL-5 might come from ^{56}Fe data, in particular,

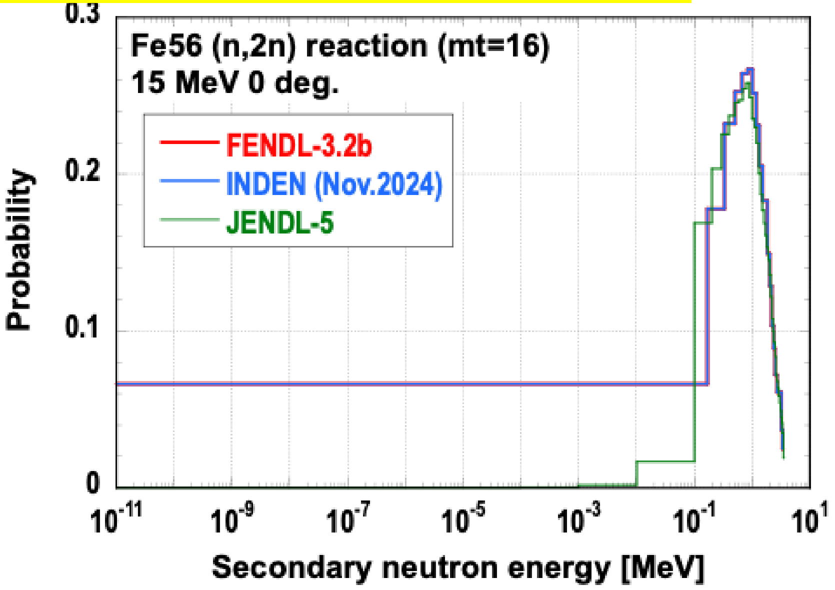
- secondary neutron spectra of (n,2n) reaction in ^{56}Fe
- Inelastic scattering data in ^{56}Fe

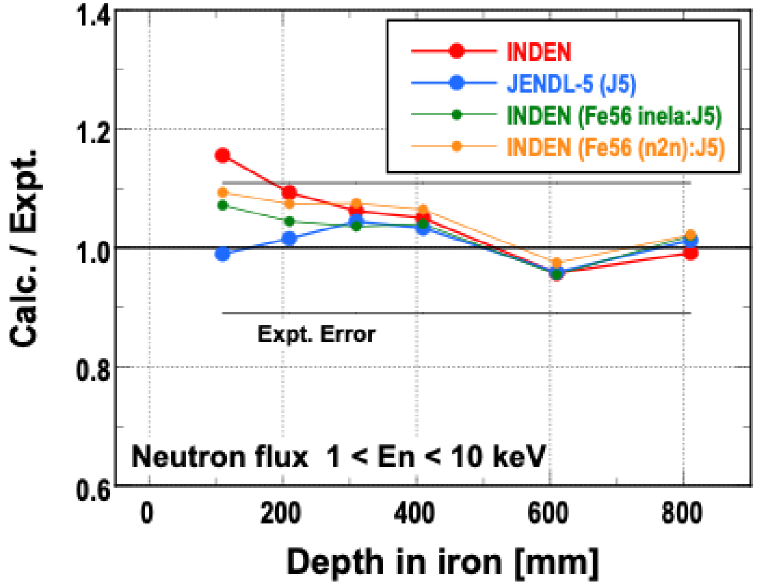
(see the cross-section plot in P.15)



Note that ^{56}Fe data of INDEN and FENDL-3.2b are almost the same.







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QST/TIARA Fe experiment

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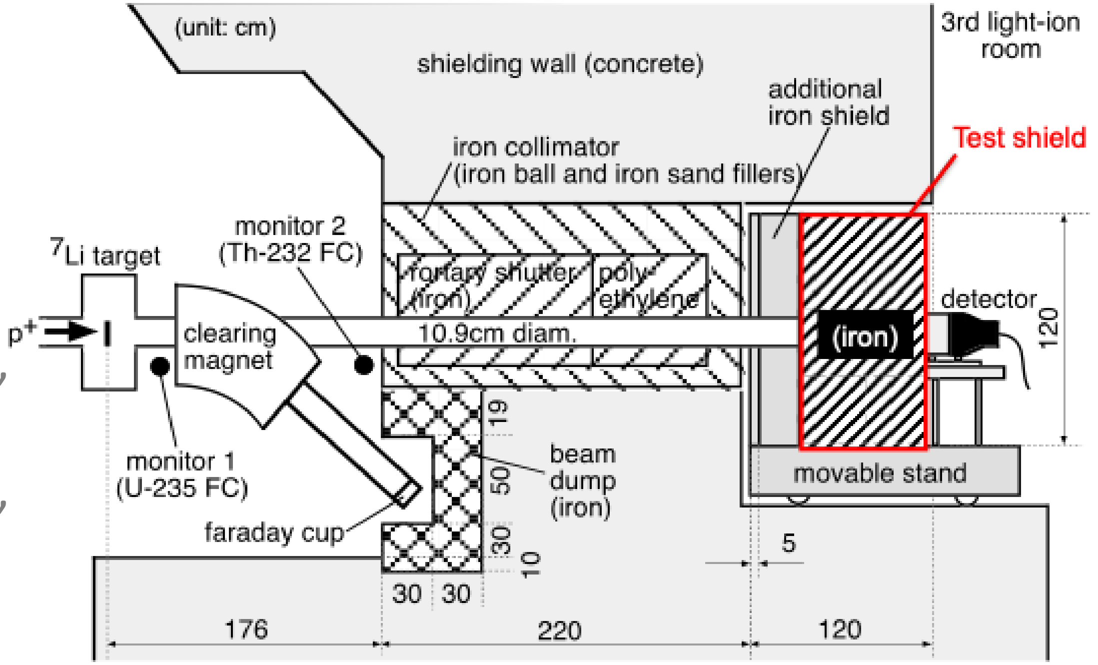
Basic information

- Experiments of Fe assembly performed by high energy neutrons over 20 MeV [ref] were conducted in this study.
- Neutron spectra measured by scintillators
  - 40 MeV neutrons: Fe test shield assemblies of 10, 20, 40, 70 and 100 cm in thickness
  - 65 MeV neutrons: Fe test shield assemblies of 20, 40, 70, 100 and 130 cm in thickness
- To show the differences intuitively, we provide Calc./Expt. plots for two energy regions
  - Continuous regions: sum up from 10 to 35 (or 60) MeV neutron fluxes
  - Peak regions: sum up from 35 (or 60) to 45 (or 70) MeV neutron fluxes

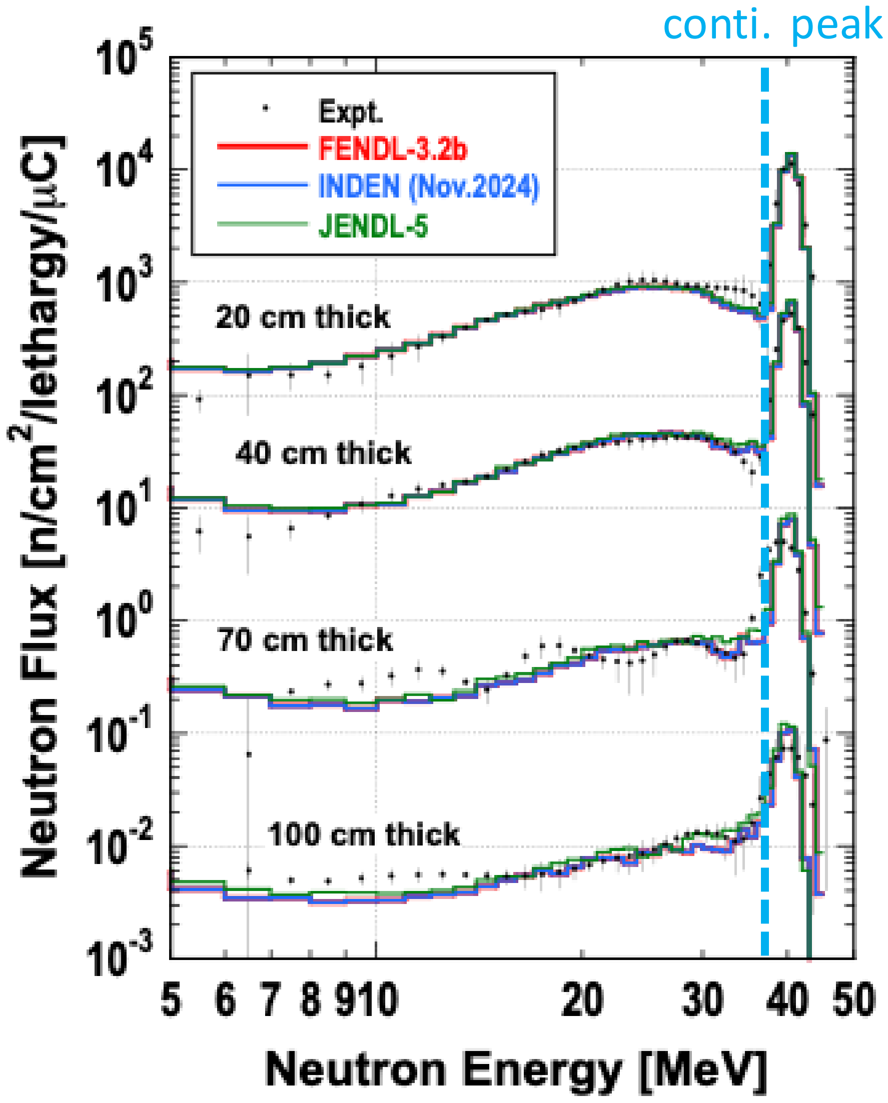


<Note>
TIARA concrete shielding experiments can be useful for O data validation study

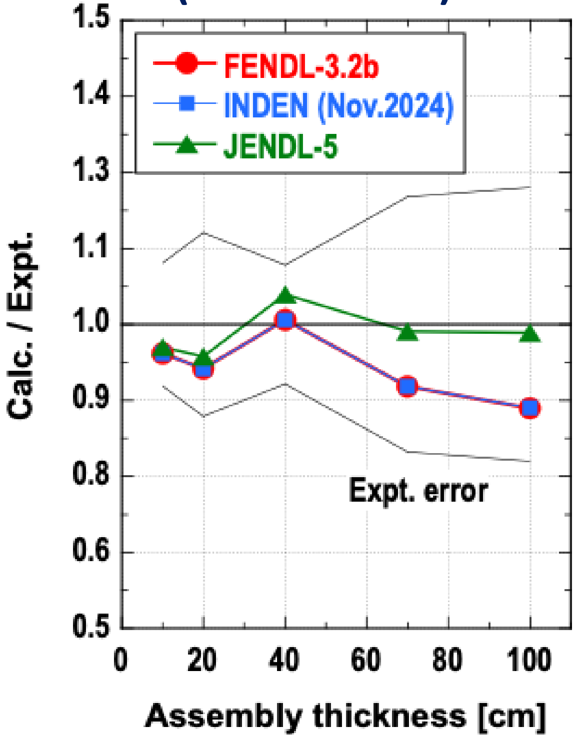
Details of the experiments:
[Ref] H. Nakashima et al., JAERI-Data/Code 96-005 (1996).

40 MeV neutron

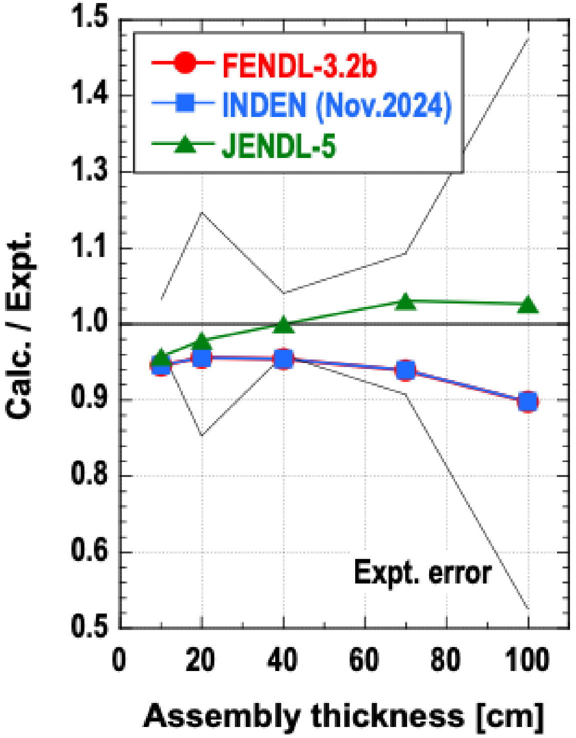
Neutron spectra



continuous region (10 – 35 MeV)

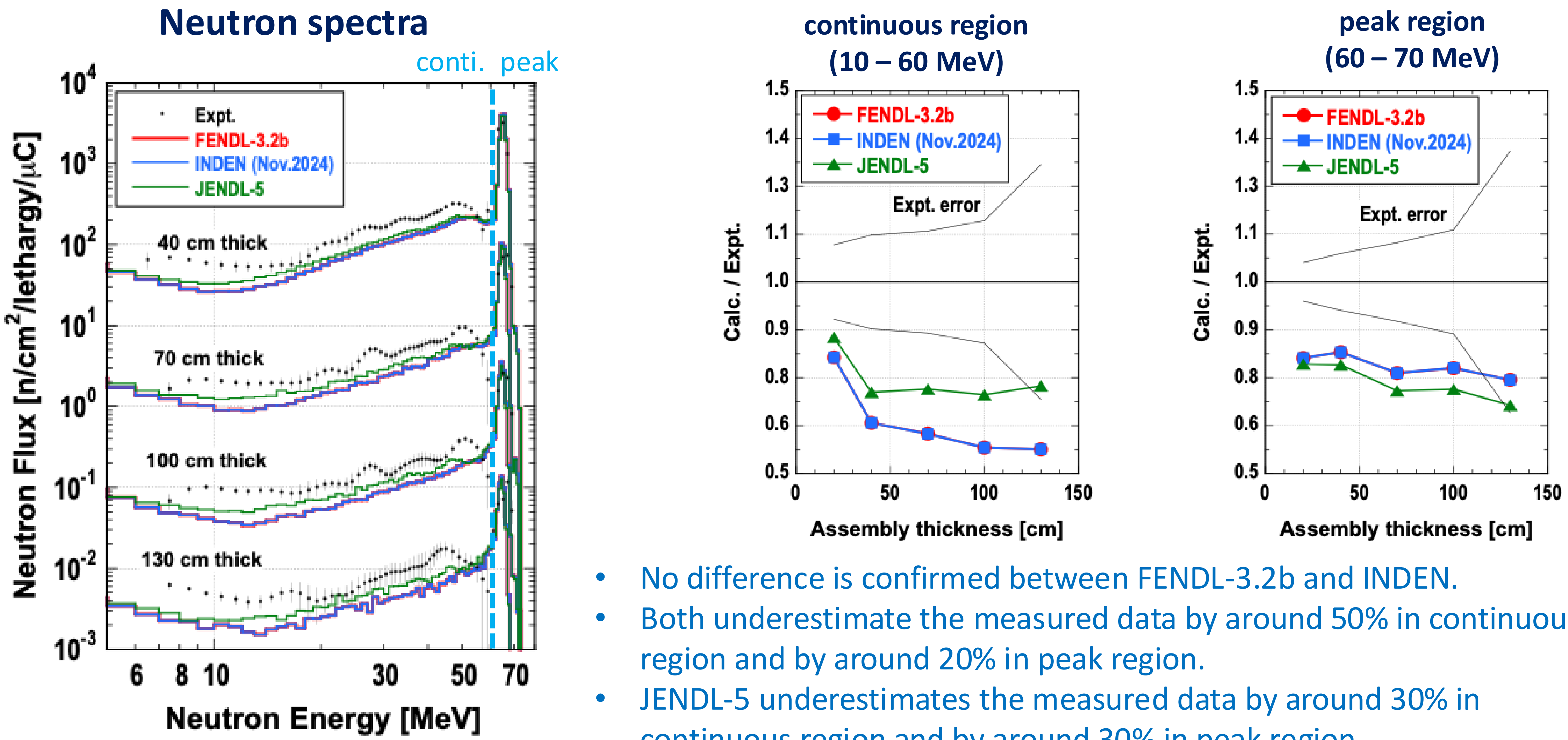


peak region (35 – 45 MeV)



- No difference is confirmed between FENDL-3.2b and INDEN.
- Both show a good agreement with the measured data in whole energy region.
- JENDL-5 shows the better agreement with the measured data in whole energy region.

65 MeV neutron

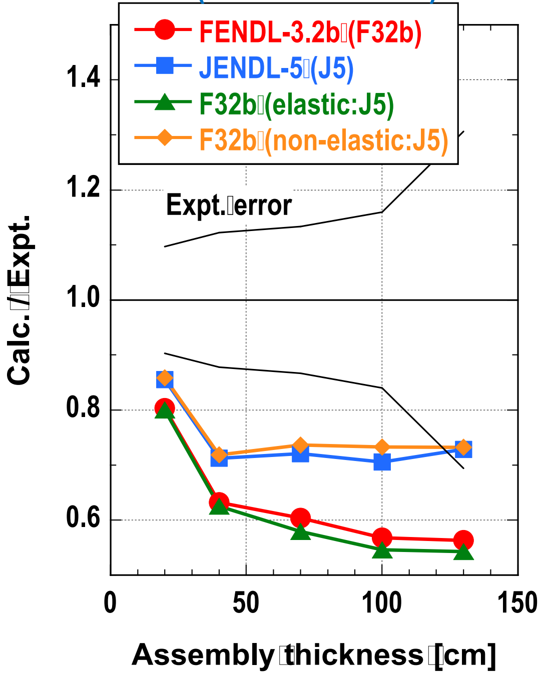


- No difference is confirmed between FENDL-3.2b and INDEN.
- Both underestimate the measured data by around 50% in continuous region and by around 20% in peak region.
- JENDL-5 underestimates the measured data by around 30% in continuous region and by around 30% in peak region.

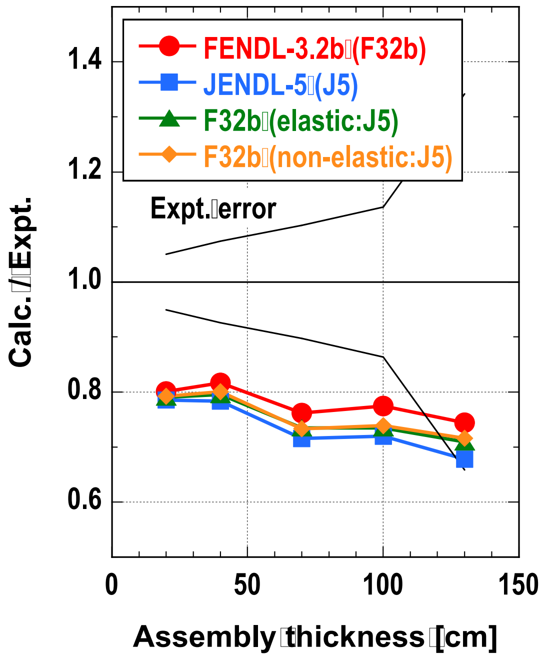
Reason of the underestimation (65 MeV neutrons)

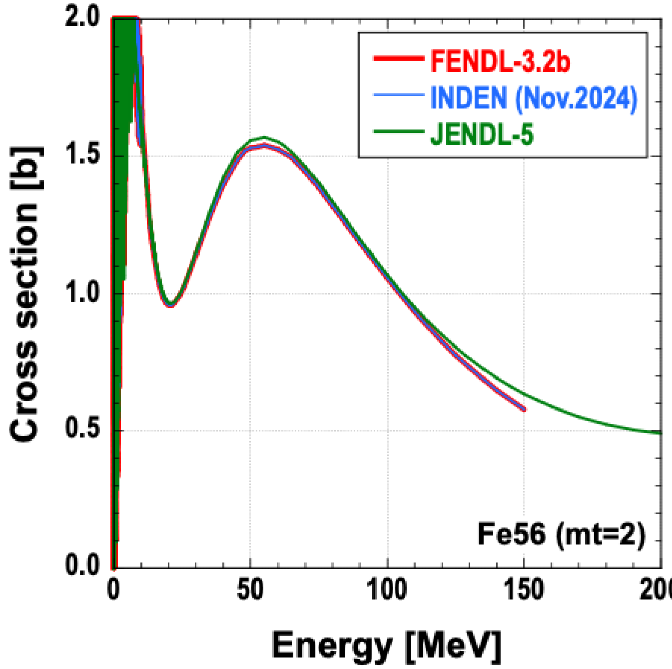
(1) Which iron isotope data cause underestimation?
→ Replacing iron isotope data one by one shows that ^{56}Fe causes the underestimation.
(2) Which reaction data in ^{56}Fe cause underestimation?
→ Replacing non-elastic (mt=5 or equiv.) scattering data shows the effect.

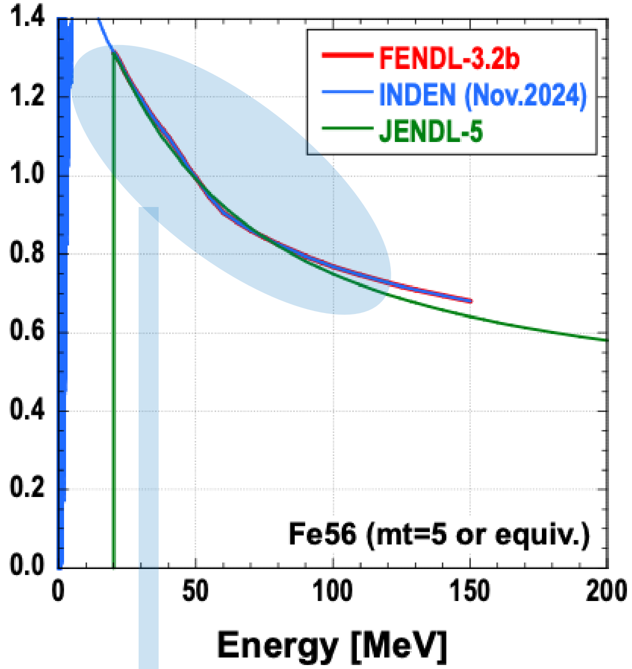
continuous region
(10 – 60 MeV)

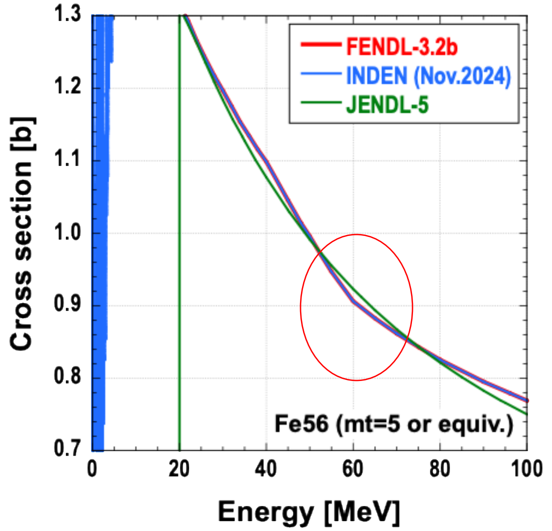


peak region
(60 – 70 MeV)









Cross-section and energy-angular distribution of mt=5 (equiv.) in ^{56}Fe of INDEN and FENDL-3.2b should be re-evaluated.

Short remarks on Fe data

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- INDEN Fe data
  - underestimated the measured neutron fluxes above 10 MeV.

- Some reaction data should be re-evaluated in ^{56}Fe;
  - Inelastic scattering data
  - (n,2n) reaction data
  - (n,np) reaction data
  - Non-elastic scattering data

- Neutron fluxes below 10 keV calculated using INDEN Fe showed better agreement with measured ones than those using FENDL-3.2b due to the discrete excited level of inelastic scattering data in ^{57}Fe.

Summary

- We performed INDEN benchmark tests using FNS Cu and Fe experiments and TIARA Fe experiments for further INDEN improvement.
- Remarks on INDEN Cu and Fe data as follow:

Copper (Cu) – FNS/Cu exp.	Iron (Fe) – FNS/Fe and TIARA/Fe exp.
• For neutrons above 10 MeV, the reaction rates calculated using INDEN showed the good agreement with the measured ones. • INDEN underestimated the measured reaction rate of ^{115}In(n,n')^{115m}In more than FENDL-3.2b. • For lower energy neutrons, the reaction rates calculated using INDEN underestimated the measured ones like those using other nuclear data libraries.	• For neutrons above 10 MeV, the neutron fluxes calculated using INDEN underestimated the measured ones. • The underestimation tendency was drastically large with higher energy neutrons, 65 MeV. • Inelastic scattering, (n,2n), (n,np) reactions, non-elastic scattering data in ^{56}Fe should be re-checked. • Inelastic scattering data in ^{57}Fe of INDEN is better than that of FENDL-3.2b.

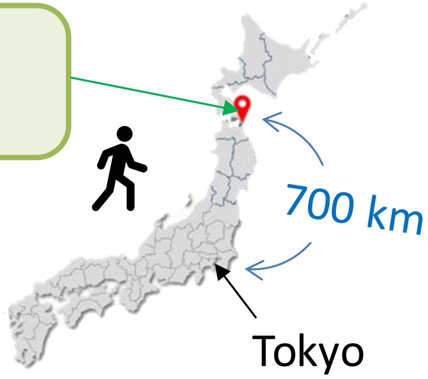
- Mostly the current recommended version files of INDEN are better than those of FENDL-3.2b. But JENDL-5 is the best for Fe data.

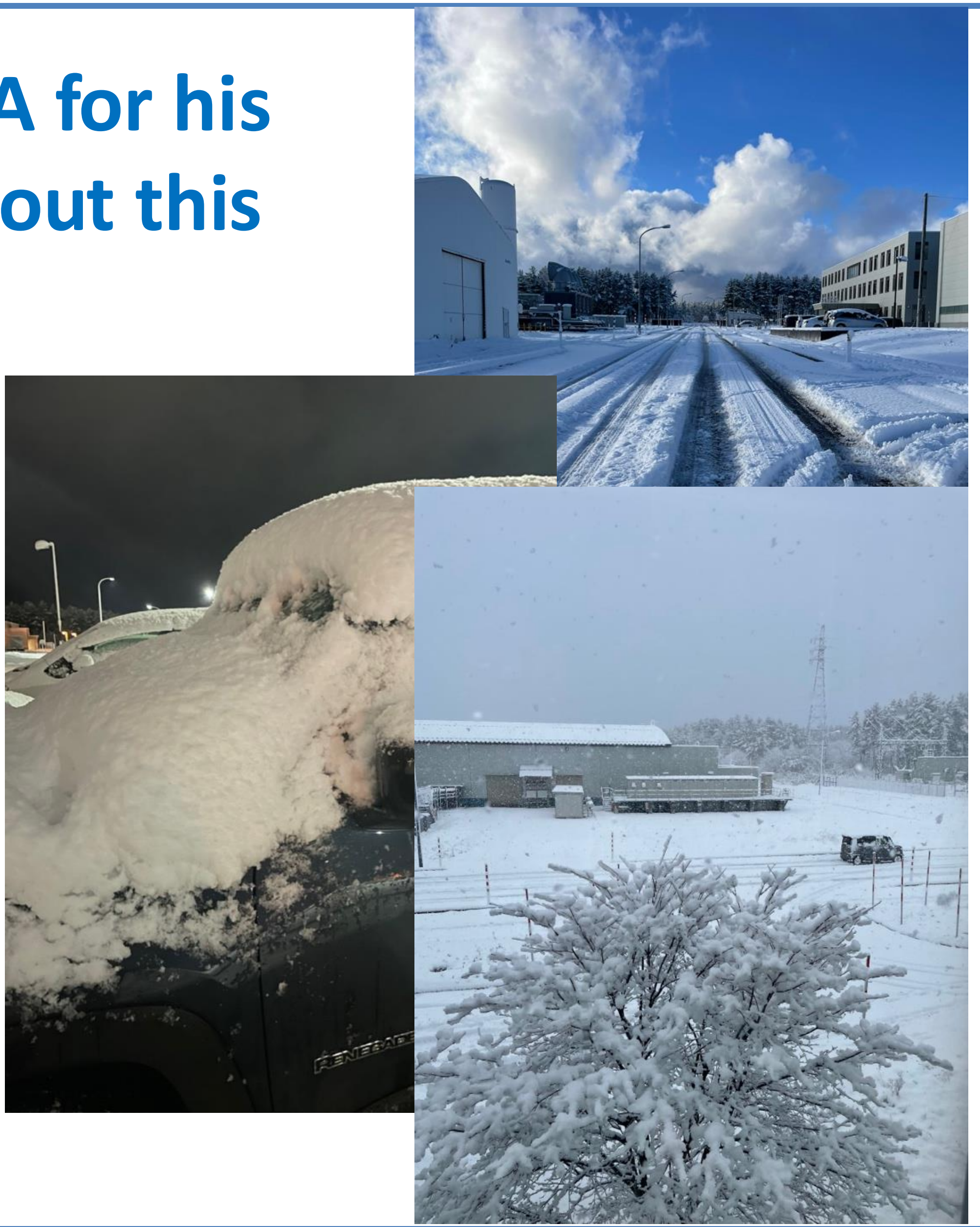
Acknowledgement and…

I gratefully acknowledge Dr. Konno of JAEA for his invaluable guidance and support through out this study.

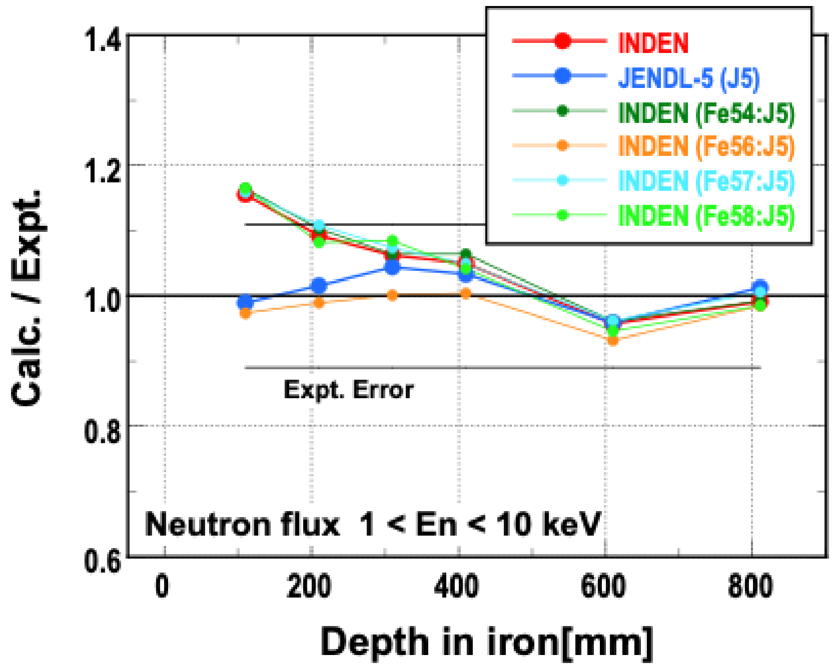
Also thank you for your attention.

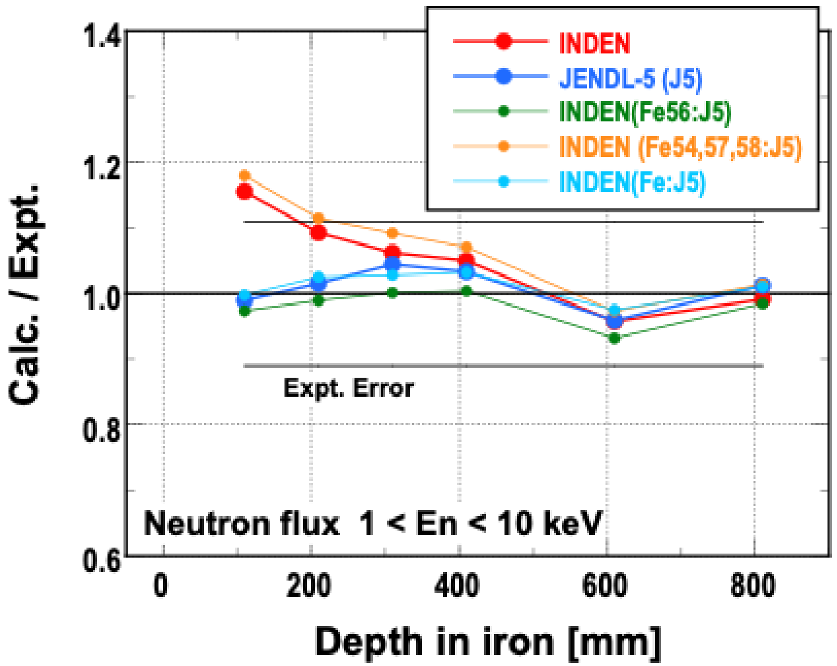
QST in Rokkasho, Aomori, Japan

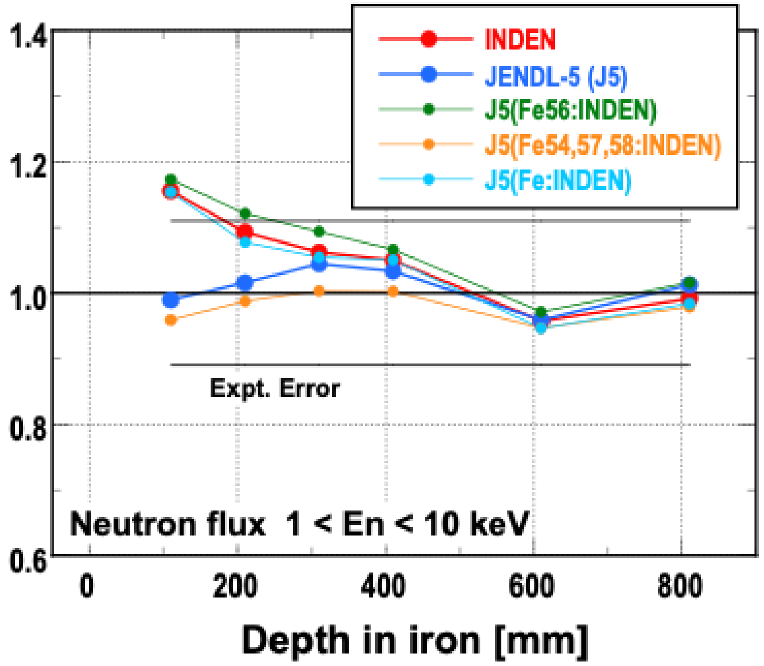




INDEN vs JENDL-5 (Fe) in details







As shown in P.17, we confirmed that ^{56}Fe data made the different tendency between INDEN and JENDL-5.
But, replacing ^{56}Fe data only does not show the same result as JENDL-5.

- Each effect of ^{54}Fe, ^{57}Fe and ^{58}Fe data is very minor because of their natural abundance are not so high (<10%).
- However, the summed effect of ^{54}Fe, ^{57}Fe and ^{58}Fe data is conspicuous.