

New Evaluation on Angular Distributions and Energy Spectra for Neutron-induced Charged particle Measurements

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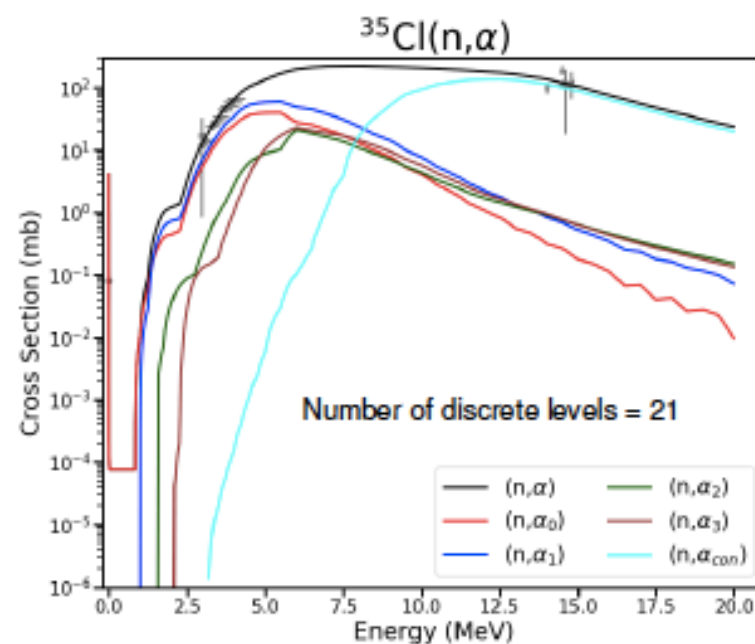
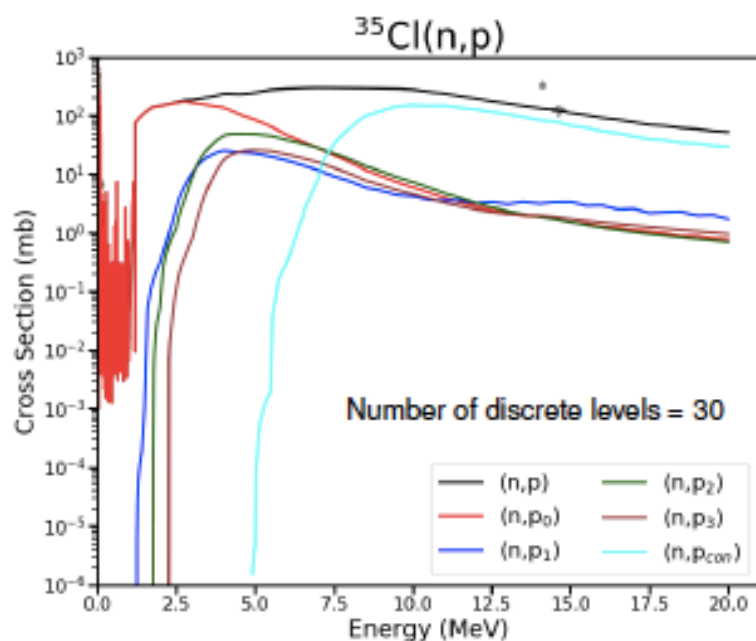
Physics Division (P-27): H.Y. Lee, L. Zavoroka, S. Kuvin, A. Georgiadou

postdocs , guest scientists

- Total cross section of neutron induced-charged particles is divided into productions of discrete levels and continuum state,

$$(n, x_{tot}) = \sum_{i=0}^N (n, x_i) + (n, x_{cont}),$$

where x is particles like n, p, α and so on, N is number of discrete levels used.

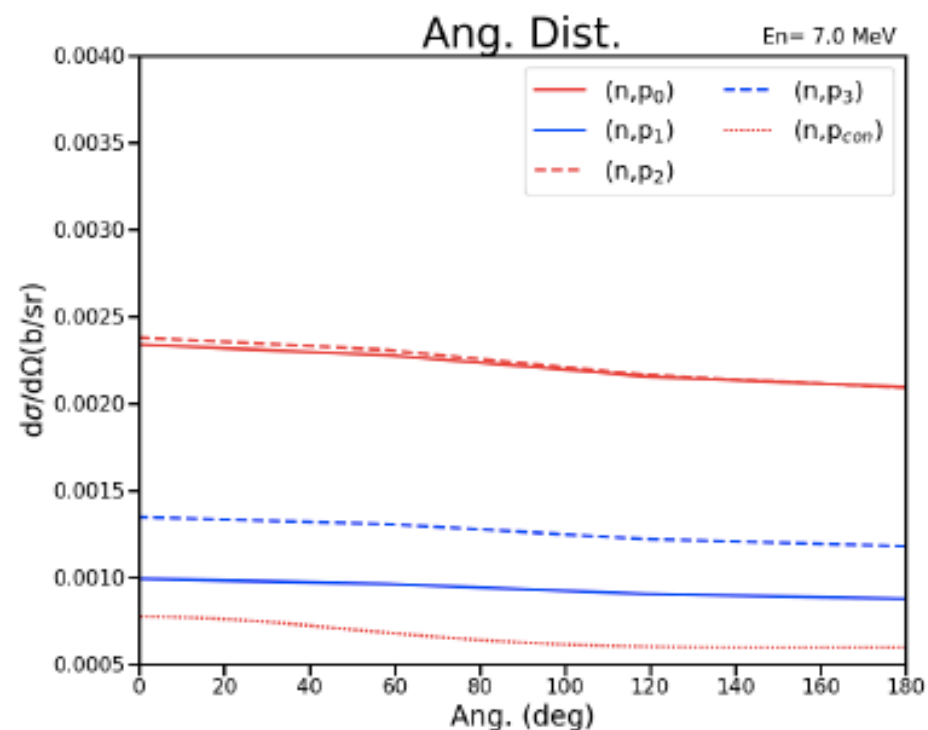
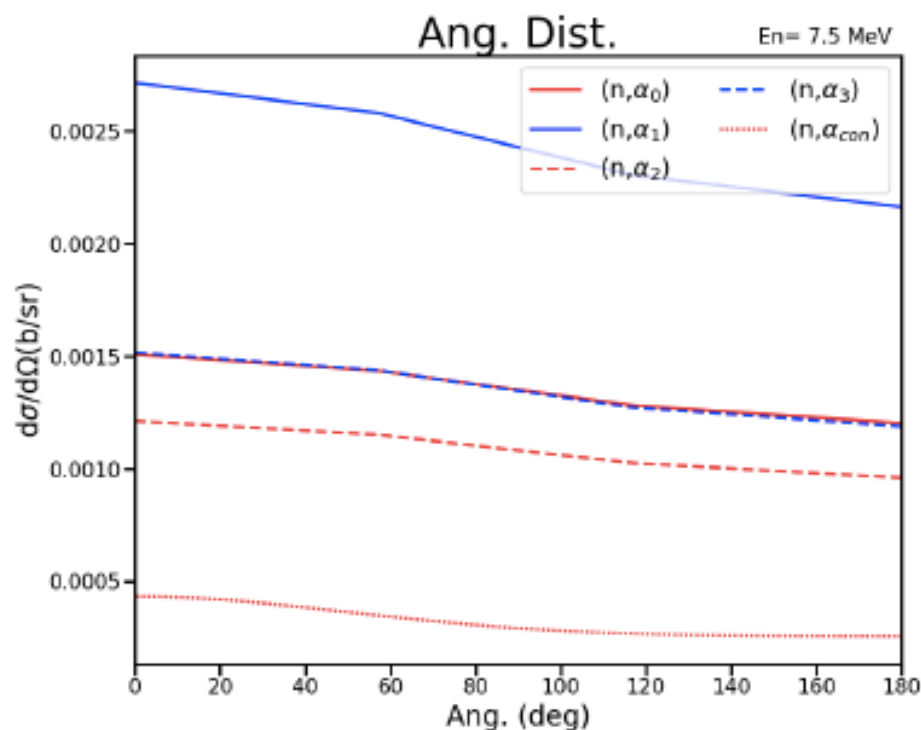


(n,p) & (n, α) cross sections on ^{35}Cl in ENDF/B-VIII.0

Angular distributions of (n,p) and (n, α) reactions

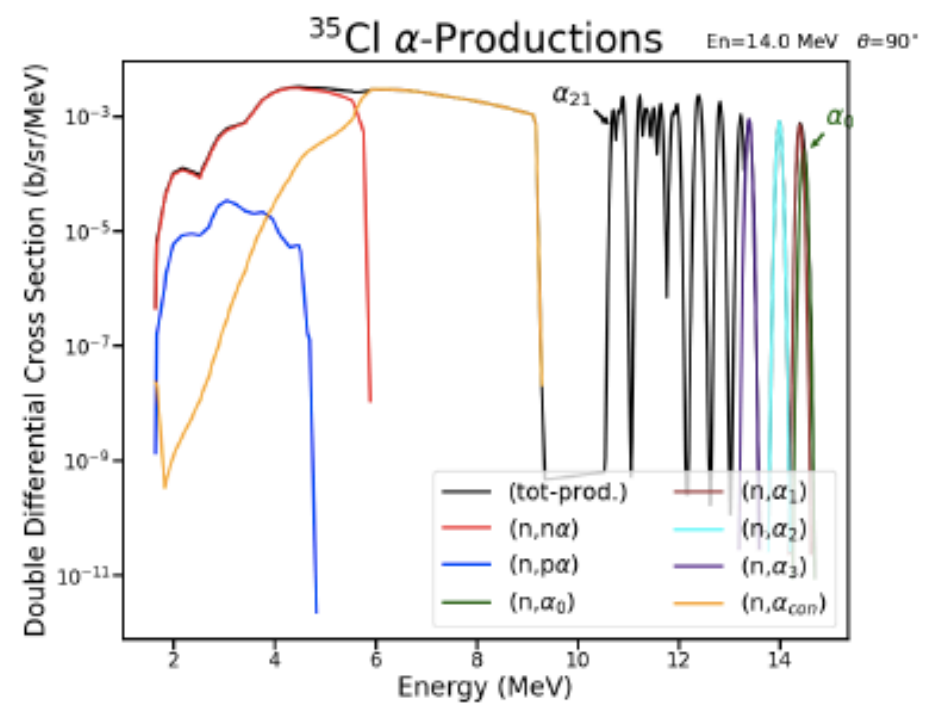
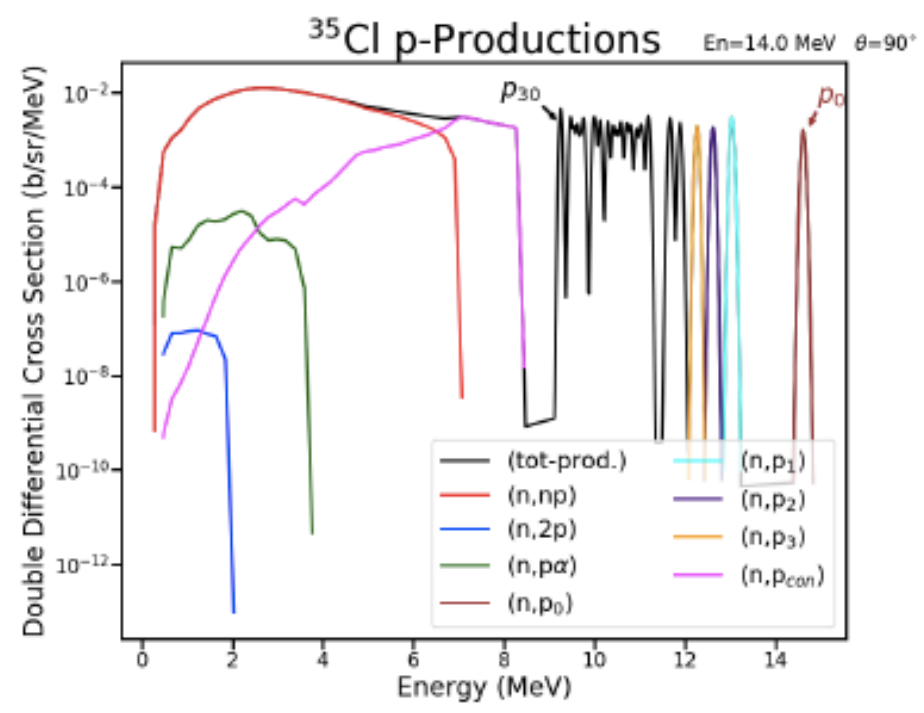
Angular distributions of discrete levels for (n,p) and (n, α) reactions on ^{35}Cl

(LAB system)



Energy spectra of (n,p) and (n, α) reactions

Double differential cross sections of emitted particles



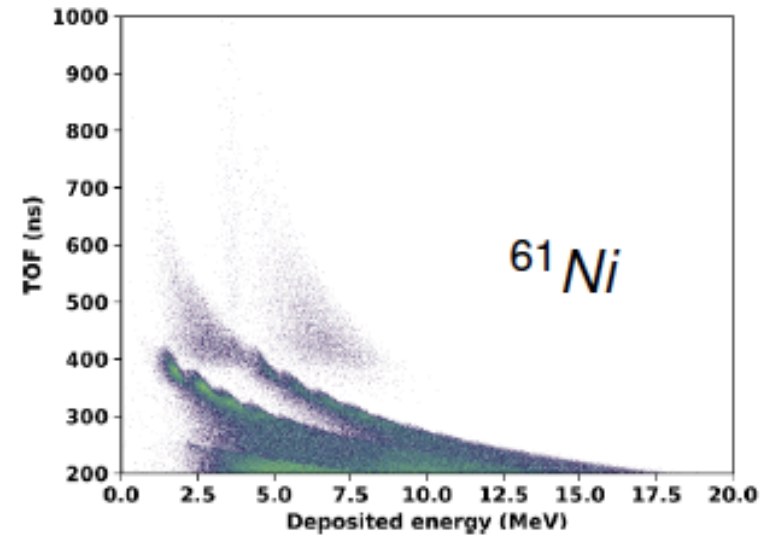
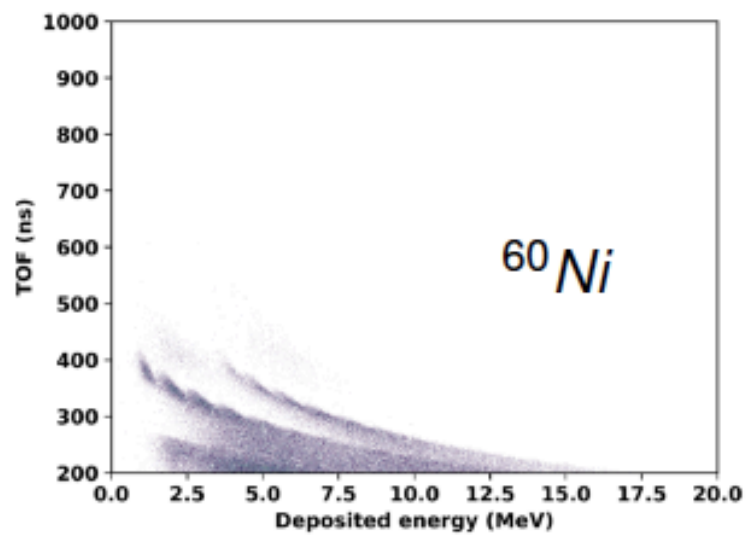
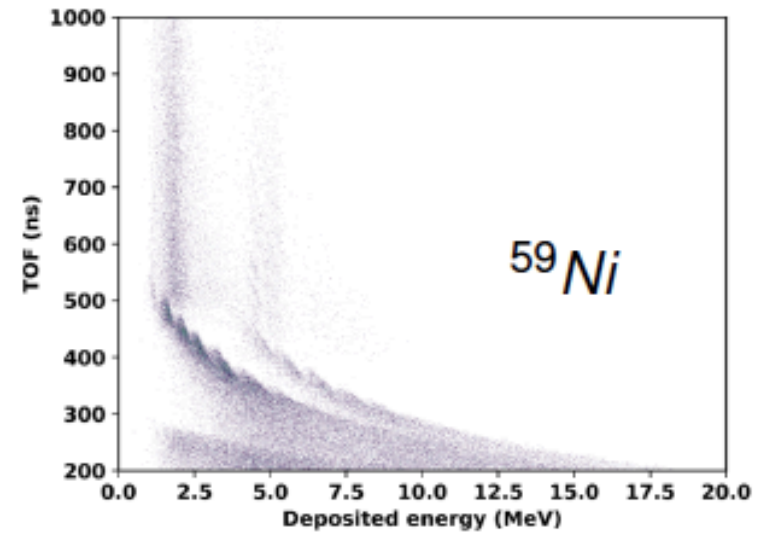
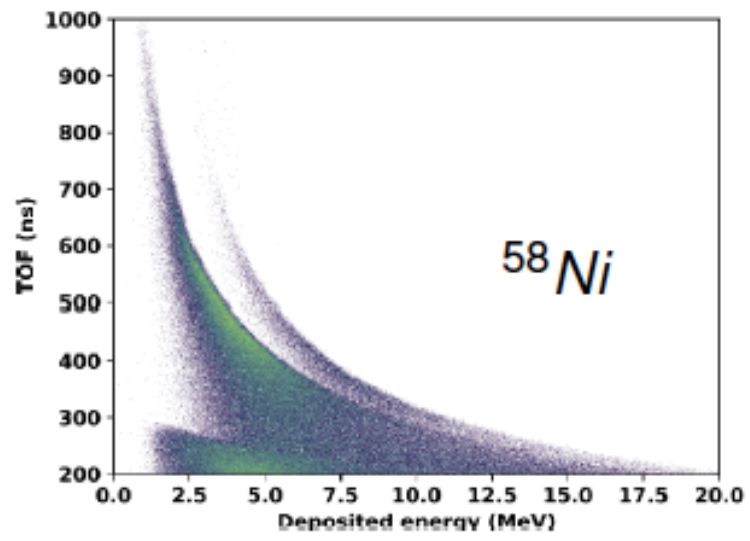
Status of evaluations for emitted charged particles in ENDF/B-VIII.0

- Status of evaluations on (n,x) reactions in ENDF/B-VIII.0 (x=p,d,t, α) (total: 557 nuclei)

Particle	A	B	C	D
proton (p)	189	265	9	94
alpha (α)	163	273	25	96
deuteron (d)	18	246	4	289
triton(t)	14	227	3	313

- $(n,x_{tot}) = (n,x_{level}) + (n,x_{cont})$, level: g.s, 1st excited level, 2nd excited level, . . .
- A: (n,x_{level}) and (n,x_{cont})
- B: (n,x_{tot}) only
- C: (n,x_{level}) or (n,x_{cont})
- D: no data

MCNP Simulation for Ni isotopes in ENDF/B-VIII.0

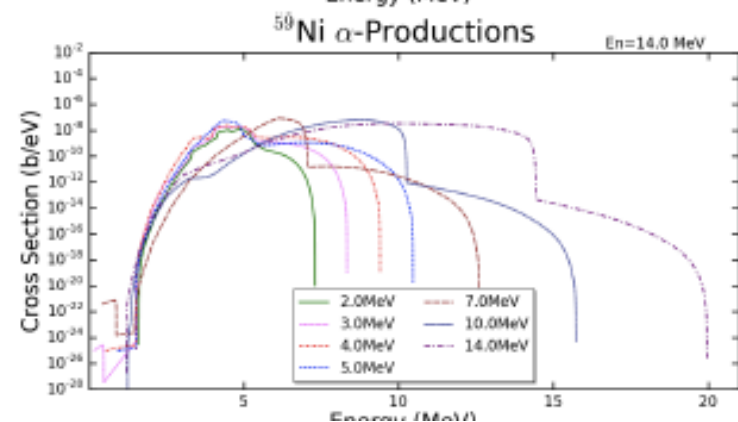
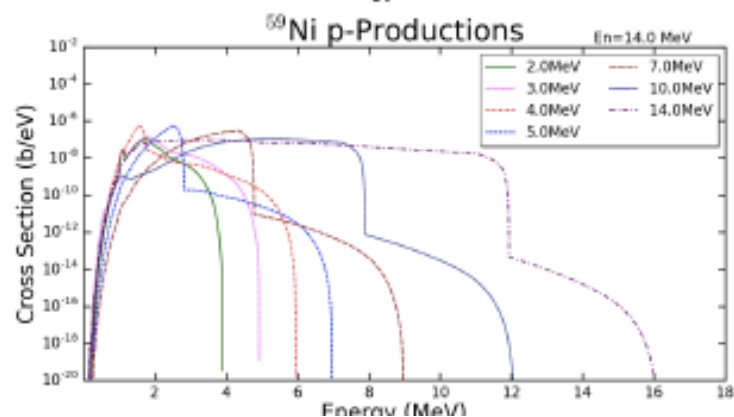
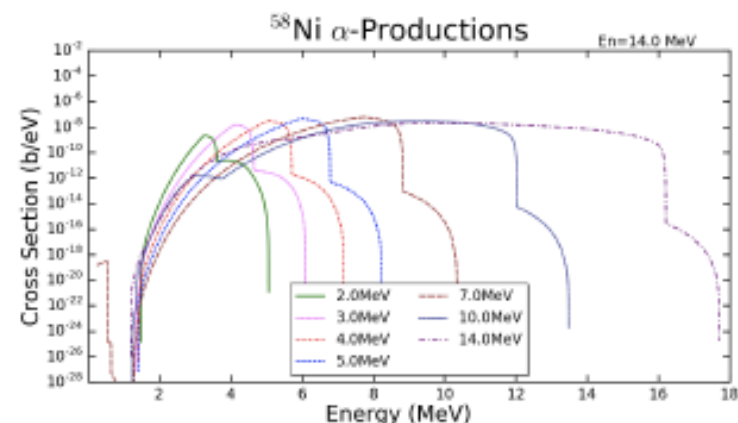
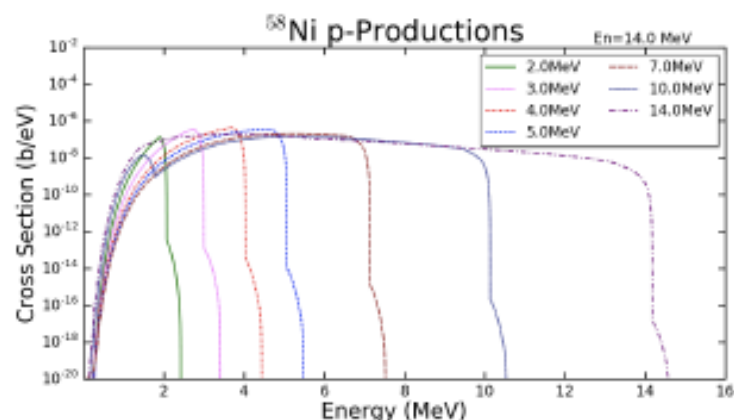


Status of (n,p) & (n, α) reaction cross sections in ENDF/B-VIII.0

No data for discrete levels of (n,p) & (n, α) cross sections

=> No angular distributions for discrete levels

Energy spectra shifted to low energy region



Angular distribution of Hauser-Feshbach formalism in CoH₃

Blatt-Biedenharn Formalism:

$$\left(\frac{d\sigma}{d\Omega}\right)_{ab} = \sum_L B_L P_L(\cos\theta_b),$$

where the Legendre coefficient,

$$\begin{aligned} B_L &= \frac{1}{4k_a^2} \frac{(-)^{I_B - I_A + s_b - s_a}}{(2s_a + 1)(2I_A + 1)} \\ &\times \sum_J (2J + 1)^2 \frac{1}{N_J} \sum_{l_a j_a} \sum_{l_b j_b} W_{ab} \\ &\times \{X_{l_a j_a} X_{l_b j_b} + Y_{l_a j_a, l_b j_b}\}, \end{aligned}$$

is explicitly calculated.

cf.

$$\begin{aligned} B_L^{HF} &= \frac{1}{4k_a^2} \frac{(-)^{I_B - I_A + s_b - s_a}}{(2s_a + 1)(2I_A + 1)} \\ &\times \sum_J (2J + 1)^2 \frac{1}{N_J} \\ &\times \sum_{l_a j_a} \sum_{l_b j_b} X_{l_a j_a} X_{l_b j_b}. \end{aligned}$$

Many codes employ B_L^{HF} multiplied by width fluctuation.

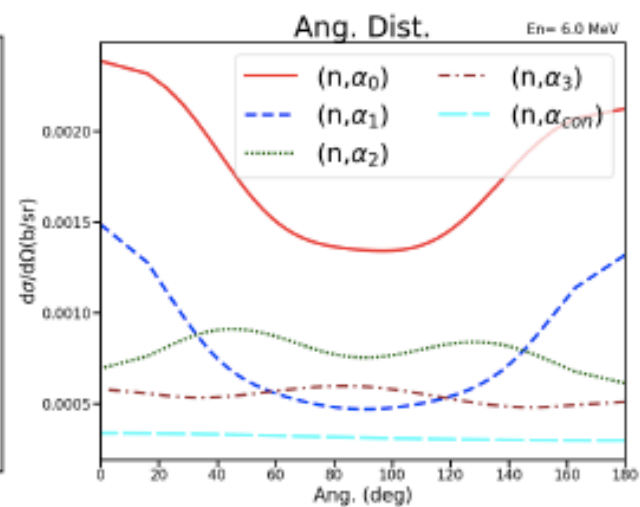
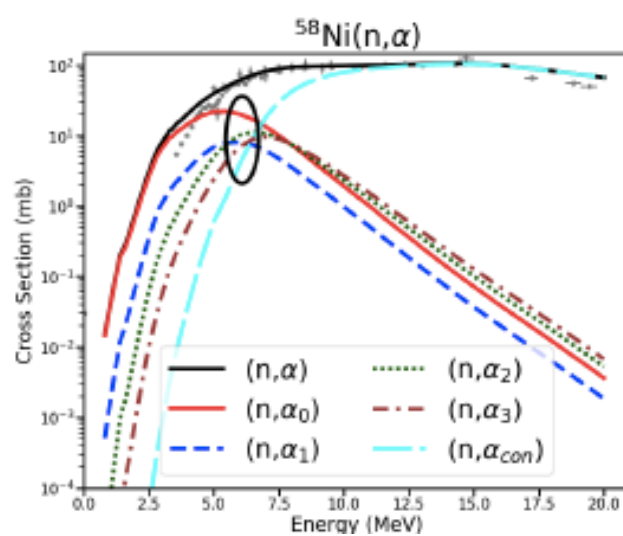
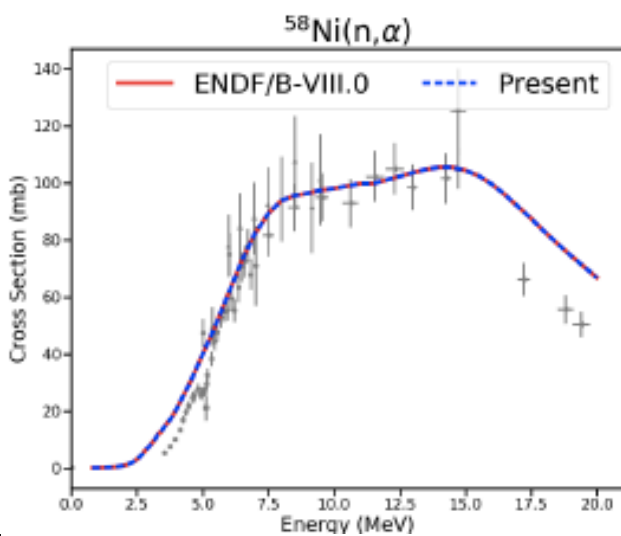
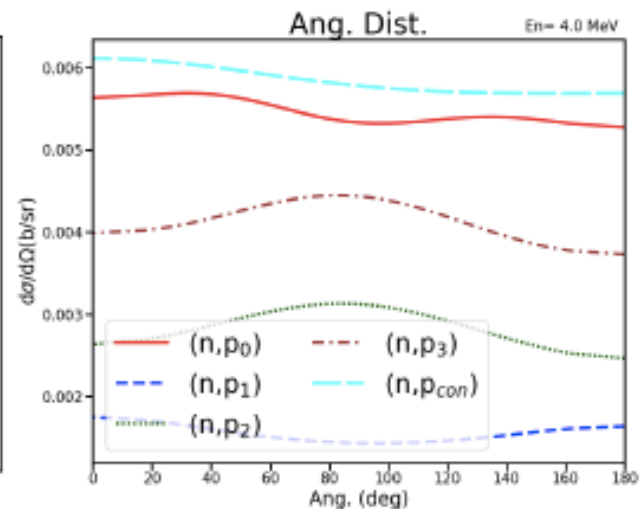
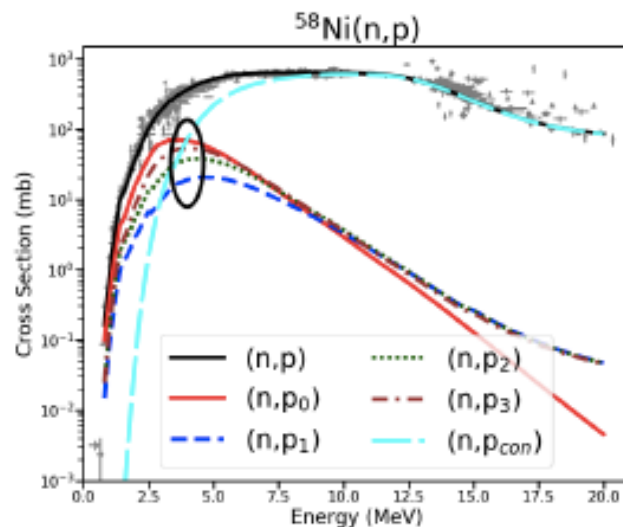
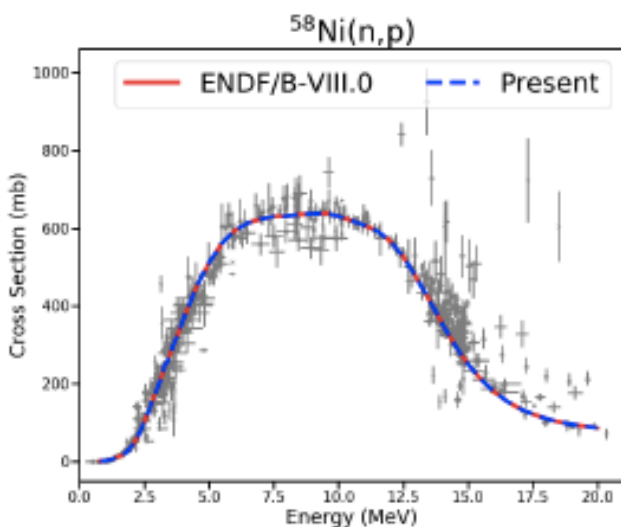
Data with various forms in ENDF/B-VIII.0

- Several cases
 - Cross sections and double differential cross sections (DDX) for total (n,p) and (n, α) without data of discrete levels
 - Cross sections for discrete levels with isotopic distributions
 - Cross sections for discrete levels but no data for continuum state
 - Implicit or explicit spectra
 - (No) Discrete γ emissions for discrete levels of (n,p) and (n, α)
- Consistent form saved in new evaluations
 - Discrete levels and continuum state are separately saved in MF3
 - Angular distributions for discrete levels are saved in MF4
 - Energy-angular distributions for continuum are saved in MF6
 - Photon transitions are saved in MF12 for their multiplicity and MF14 for probability.

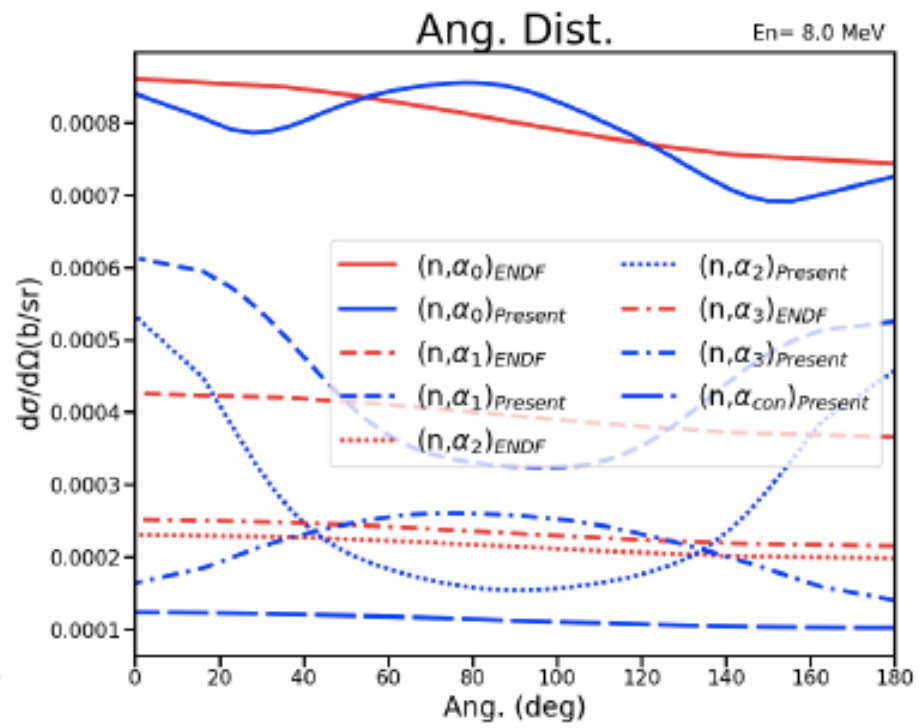
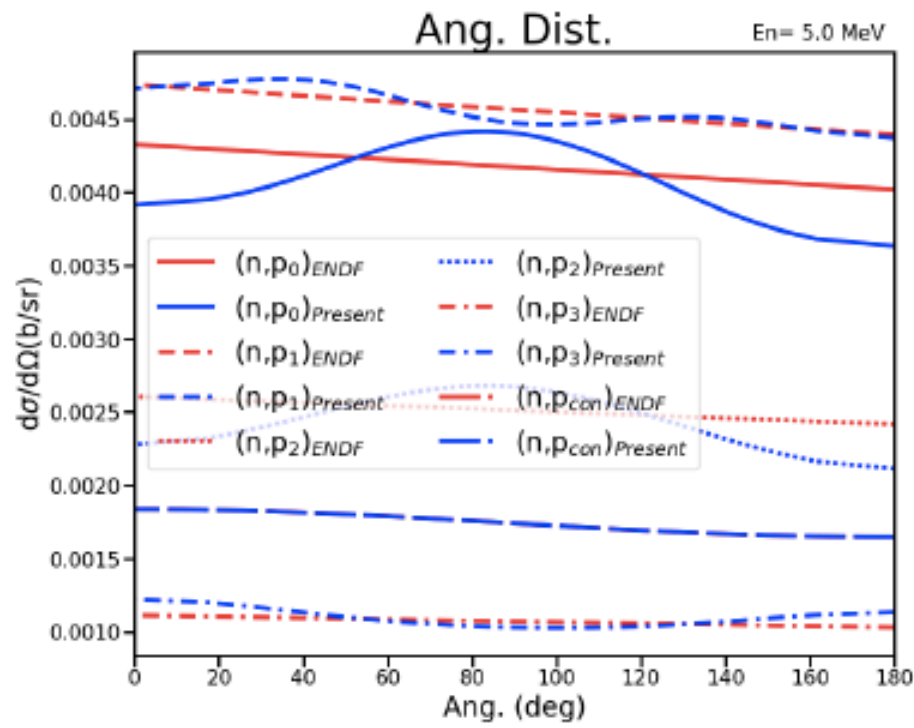
Replacing/Adding new angular distributions and energy spectra

- Summary for calculating and formatting (n,p) and (n,α) reaction cross sections
 - Adopting cross sections of ENDF/B-VIII.0 for (n,p) and (n,α) if data available, where threshold energies are recalculated using mass data by Audi2012 and FRDM2012
 - Calculated by CoH₃ for cross sections of discrete levels if no data available, where (n,p_{tot}) and (n,α_{tot}) are normalized to those of ENDF/B-VIII.0.
 - Calculated by CoH₃ for angular distributions and energy spectra of (n,p) and (n,α) reactions
 - Formatting: DeCE
 - Processing: NJOY2016
 - Simulation: MCNP-6.2

Normalization/Adding



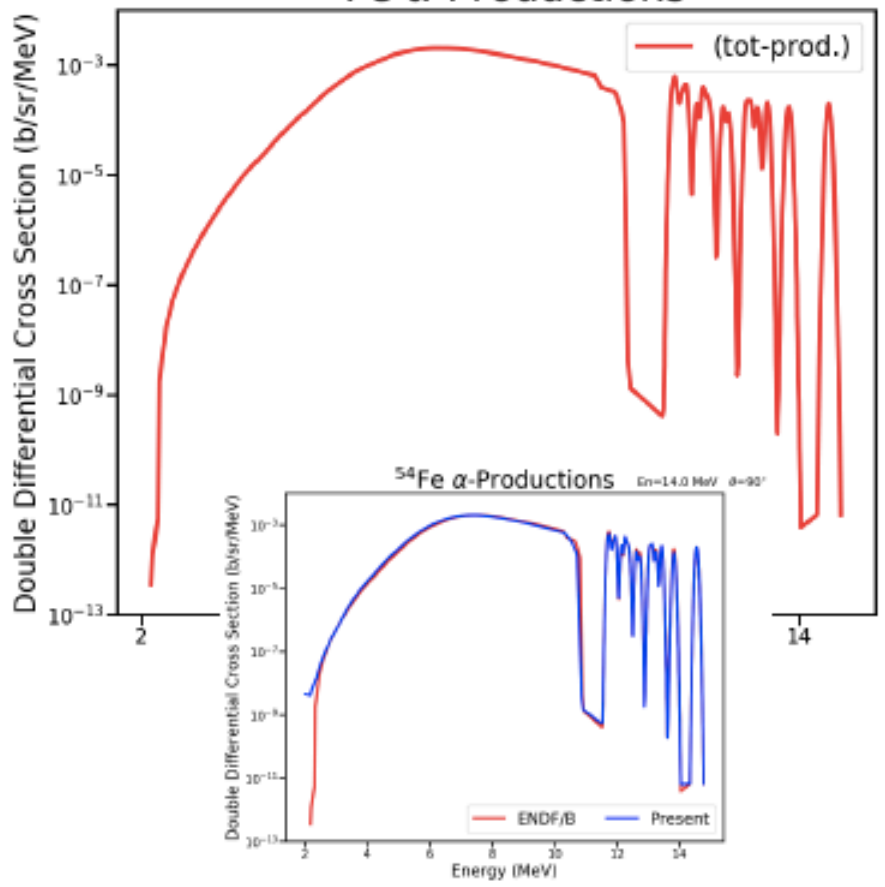
Comparison to angular distributions for ^{54}Fe



Implicit/Explicit Spectra

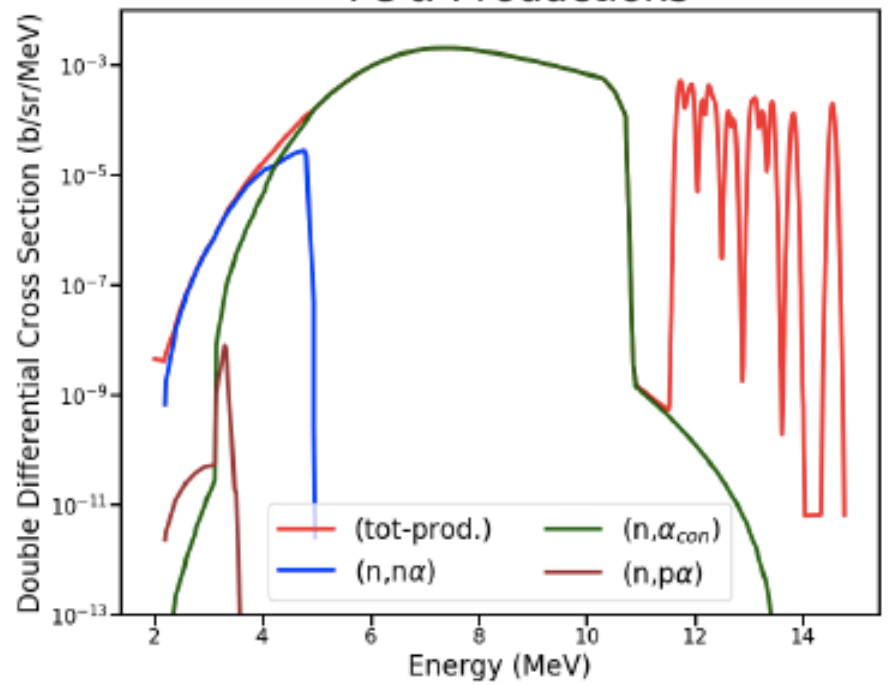
ENDF/B-VIII.0

^{54}Fe α -Productions $E_n=14.0$ MeV $\theta=90^\circ$



new evaluation

^{54}Fe α -Productions $E_n=14.0$ MeV $\theta=90^\circ$

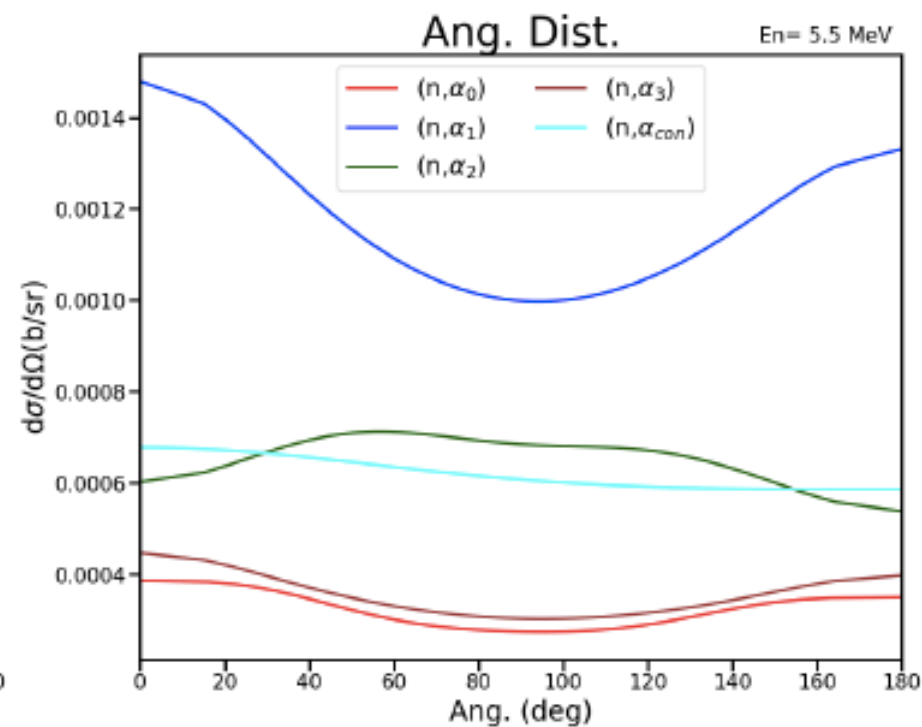
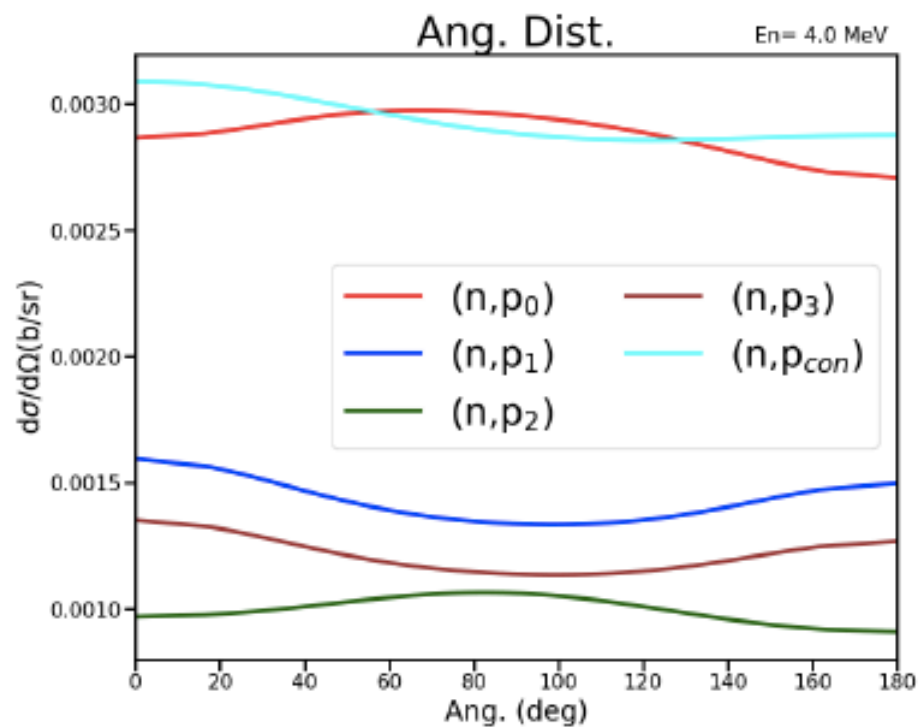


Newly updated Nuclei

Numbers of discrete levels in the residual nuclei included to calculate (n,p) and (n, α) reaction cross sections. The numbers in parenthesis present the number of discrete levels given in ENDF/B-VIII.0, where '0' stands for no partial cross section given in the evaluation.

Target	p	α	Target	p	α	Target	p	α
²⁷ Al	20 (20)	20 (20)	⁵⁰ Cr	10 (0)	10 (0)	⁶⁴ Zn	10 (0)	10 (0)
²⁸ Si	14 (14)	16 (16)	⁵¹ Cr	10 (0)	10 (0)	⁶⁵ Zn	10 (0)	10 (0)
²⁹ Si	16 (16)	20 (20)	⁵² Cr	10 (0)	10 (0)	⁶⁶ Zn	10 (0)	10 (0)
³⁰ Si	6 (6)	12 (12)	⁵³ Cr	10 (0)	10 (0)	⁶⁷ Zn	10 (0)	10 (0)
³¹ Si	1 (1)	15 (15)	⁵⁴ Cr	10 (0)	10 (0)	⁶⁸ Zn	8 (0)	10 (0)
³² Si	1 (1)	1 (1)	⁵⁴ Fe	34 (34)	24 (24)	⁶⁹ Zn	17 (17)	18 (18)
³⁵ Cl	30 (30)	21 (21)	⁵⁶ Fe	10 (10)	19 (19)	⁷⁰ Zn	1 (0)	1 (0)
³⁶ Cl	16 (16)	32 (32)	⁵⁷ Fe	18 (18)	39 (39)	⁷³ As	10 (0)	10 (0)
³⁷ Cl	10 (0)	6 (6)	⁵⁸ Fe	17 (17)	10 (10)	⁷⁴ As	10 (0)	10 (0)
³⁹ K	10 (0)	10 (0)	⁵⁸ Ni	10 (0)	10 (0)	⁹⁰ Zr	12 (12)	9 (9)
⁴⁰ K	10 (0)	10 (0)	⁵⁹ Ni	10 (0)	10 (0)	⁹¹ Zr	6 (6)	40 (40)
⁴¹ K	10 (0)	10 (0)	⁶⁰ Ni	10 (0)	10 (0)	⁹² Zr	1 (1)	40 (40)
⁴⁶ Ti	10 (0)	10 (0)	⁶¹ Ni	10 (0)	10 (0)	⁹³ Zr	17 (17)	27 (27)
⁴⁷ Ti	10 (0)	10 (0)	⁶² Ni	10 (0)	10 (0)	⁹⁴ Zr	10 (10)	40 (40)
⁴⁸ Ti	10 (0)	10 (0)	⁶³ Ni	26 (26)	28 (28)	⁹⁵ Zr	16 (16)	9 (9)
⁴⁹ Ti	10 (0)	10 (0)	⁶⁴ Ni	10 (0)	1 (0)	⁹⁶ Zr	3 (3)	10 (10)
⁵⁰ Ti	9 (0)	10 (0)	⁵⁸ Co	40 (40)	40 (40)	¹⁰⁷ Ag	10 (0)	10 (0)
⁴⁹ V	40 (40)	40 (40)	⁵⁹ Co	10 (0)	10 (0)	¹⁰⁹ Ag	31 (31)	2 (2)
⁵⁰ V	10 (0)	10 (0)	⁶³ Cu	10 (0)	10 (0)	¹⁸⁰ Ta	10 (0)	10 (0)
⁵¹ V	10 (0)	10 (0)	⁶⁴ Cu	40 (40)	40 (40)	¹⁸¹ Ta	10 (0)	10 (0)
			⁶⁵ Cu	10 (0)	10 (0)	¹⁹⁷ Au	10 (0)	10 (0)

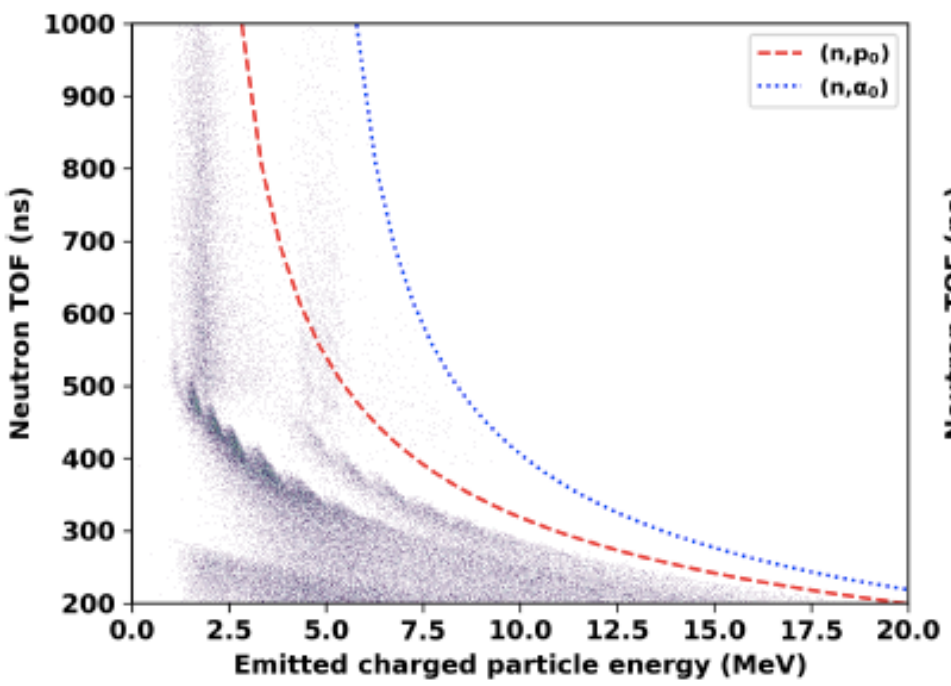
Angular distribution for (n,p) and (n, α) on ^{59}Ni



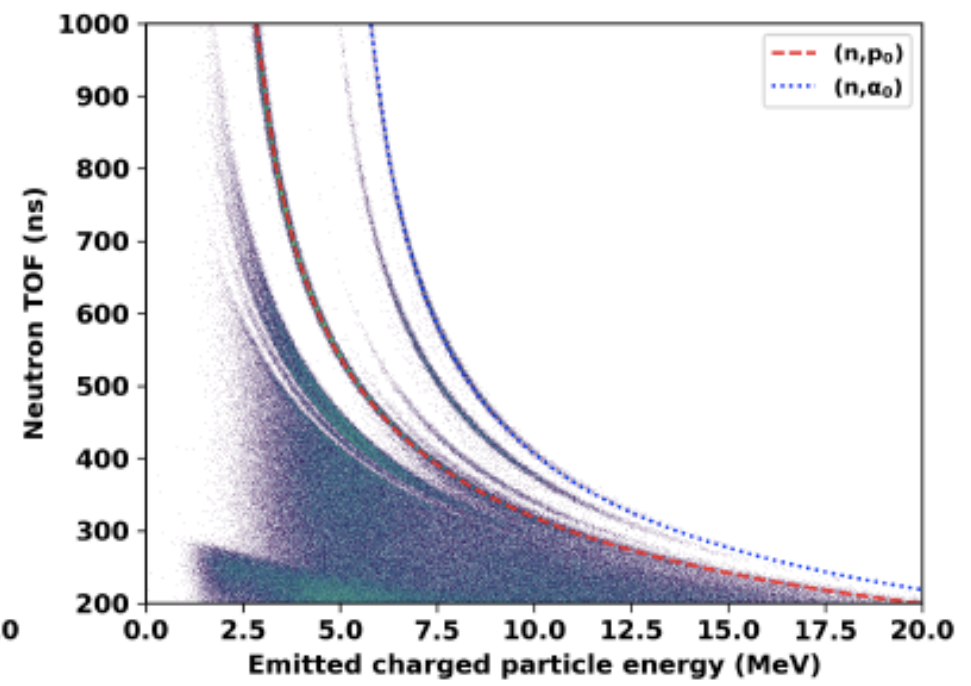
No data for Angular distributions in ENDF/B-VIII.0

MCNP Simulations for ^{59}Ni

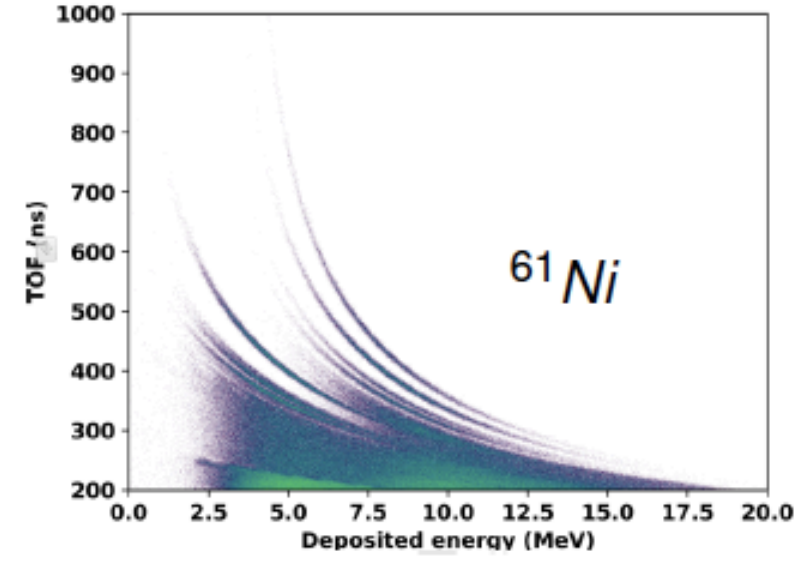
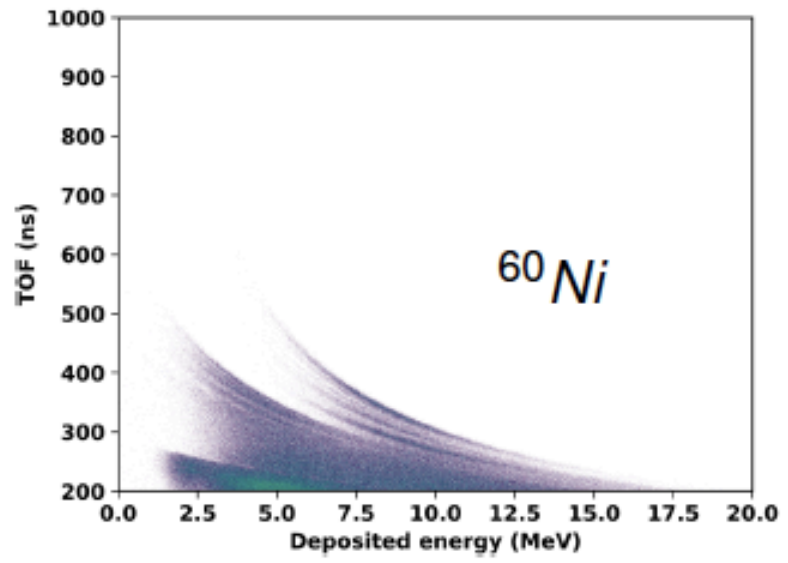
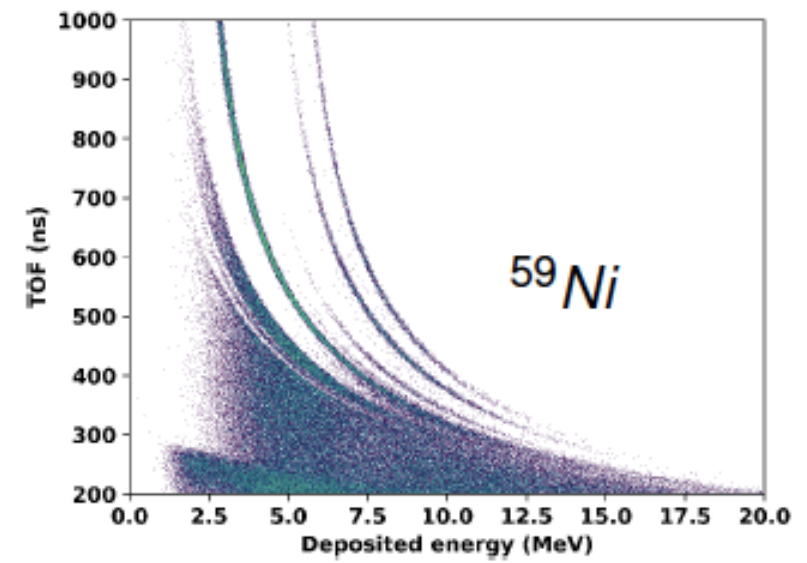
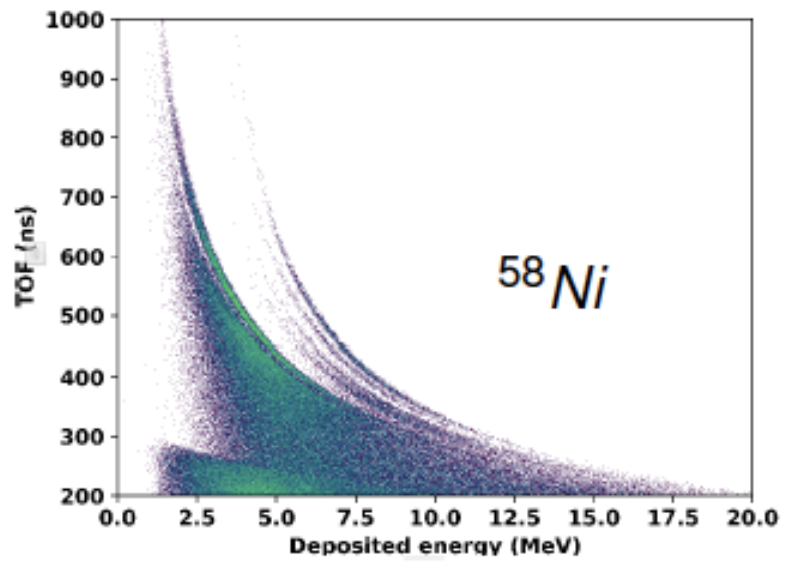
ENDF/B-VIII.0



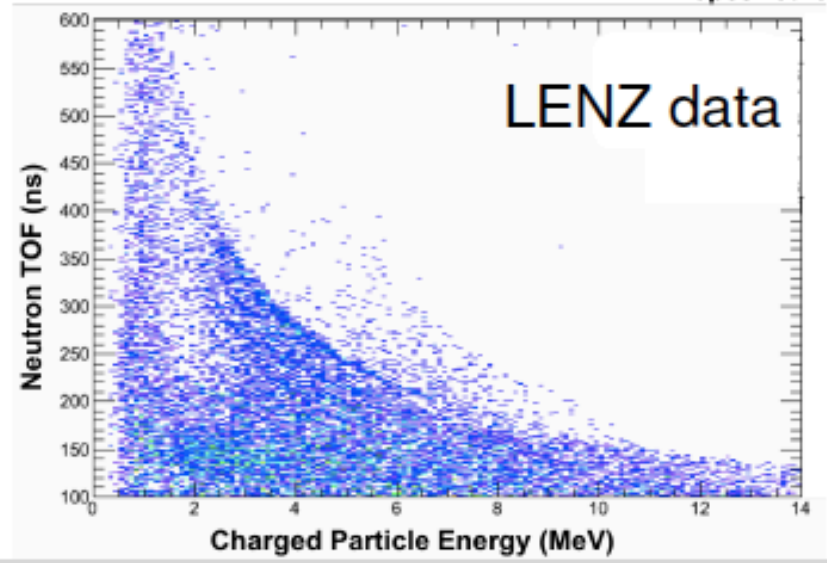
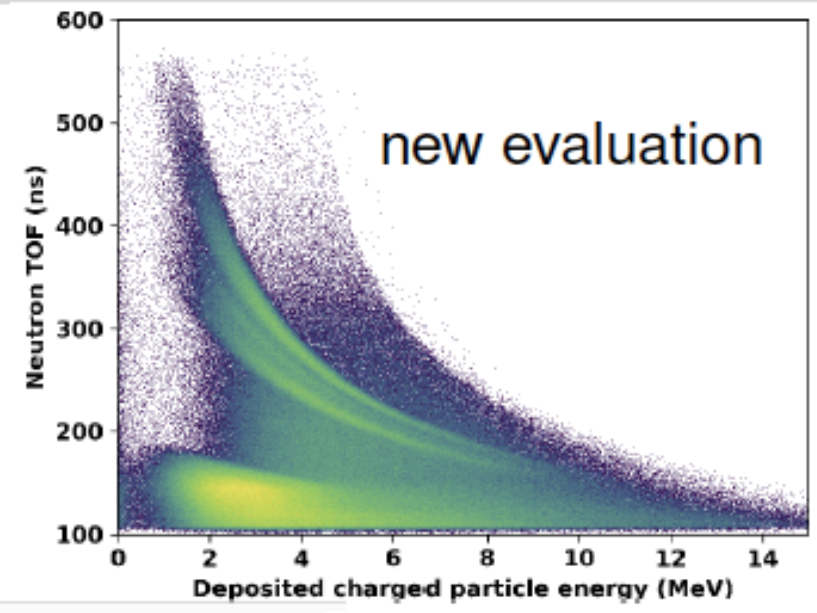
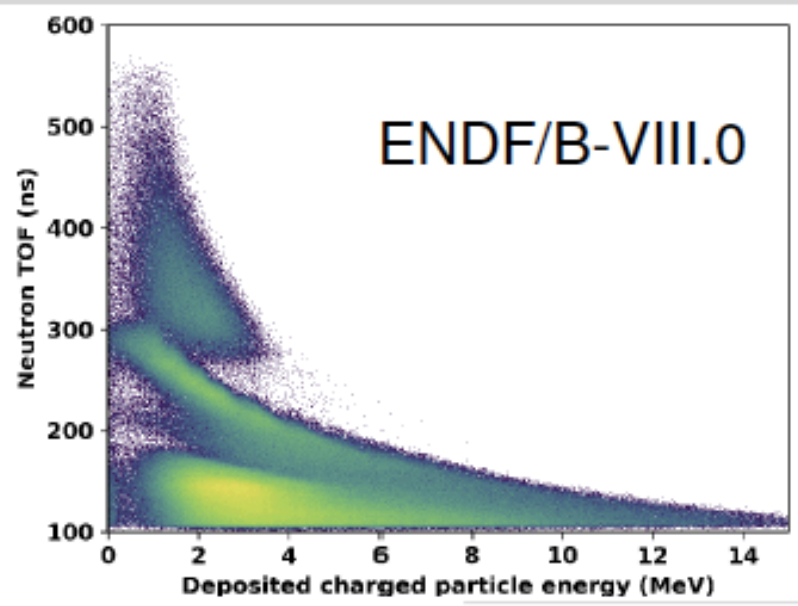
new evaluation



MCNP Simulation for Ni isotopes in new evaluations

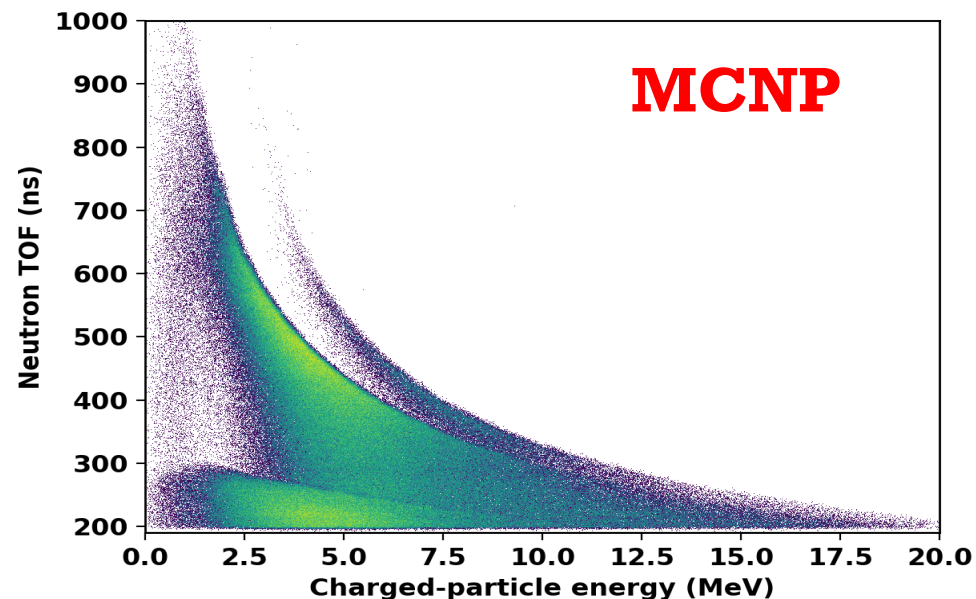
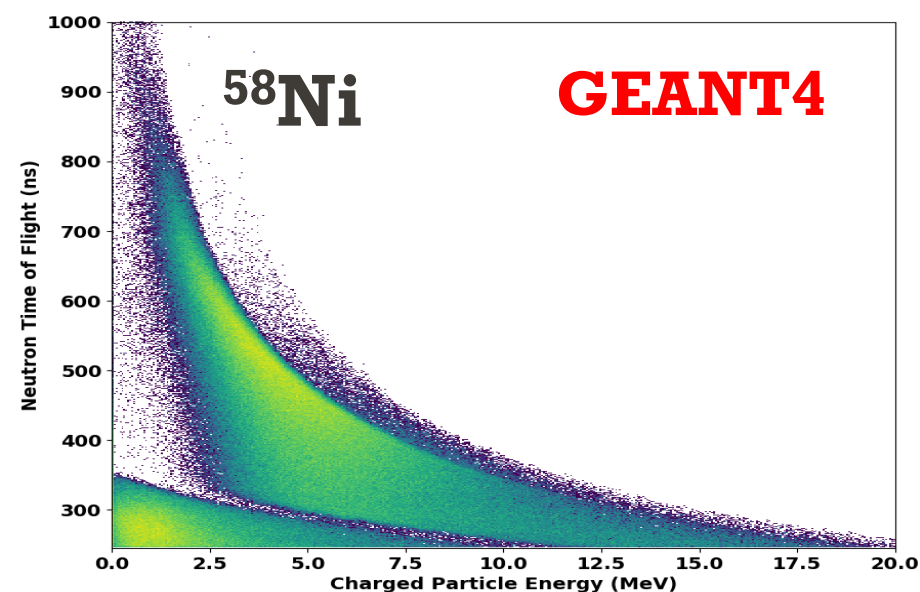


Comparison with experimental data (Brass target: 65 % ^{nat}Cu + 35 % ^{nat}Zn)



Comparison between MCNP and GEANT4 using ENDF 8

- GEANT4-LENZ simulation is developed to compare with MCNP results, using the same library
- GEANT4 has the processed G4NDL library files from the CIEMAT effort (refer to INDC(NDS)-0758) for each new ENDF formatted evaluations
- Collaboration with Central Michigan Univ., G. Perdikakis and P. Tsintari



New Evaluation on Angular Distributions and Energy Spectra for Neutron-Induced Charged-Particle Measurements

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*Submitted to Nucl.
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Summary and Outlook

- Energy-angular distributions for neutron induced-charged particles 62 nuclei have been calculated by Hauser-Feshbach model code, CoH₃.
- The measured data by the LENZ chamber for ⁵⁴Fe is at the last stage for analysis and will be compared to newly calculated angular distributions soon.
- It would be suggested to incorporate newly updated angular distributions and energy spectra of neutron-induced charged particle reactions into next ENDF/B version.