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

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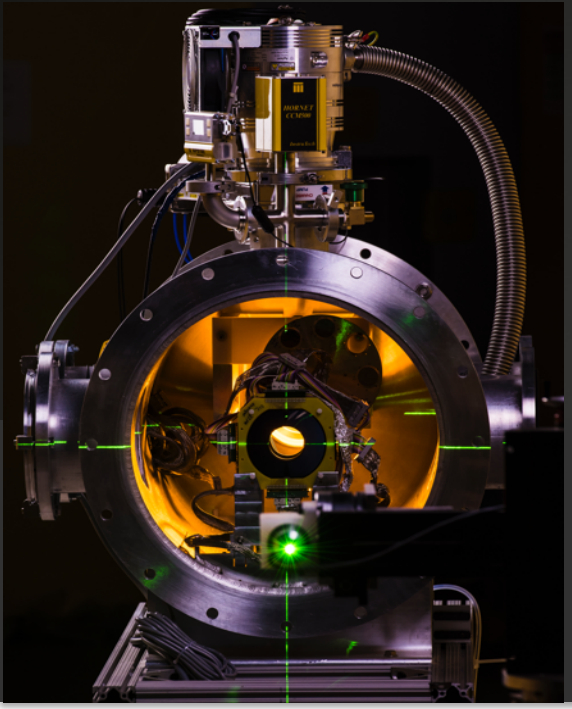

New Evaluation on Angular Distributions and Energy Spectra for Neutron-induced Charged particle Measurements

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postdocs , guest scientists

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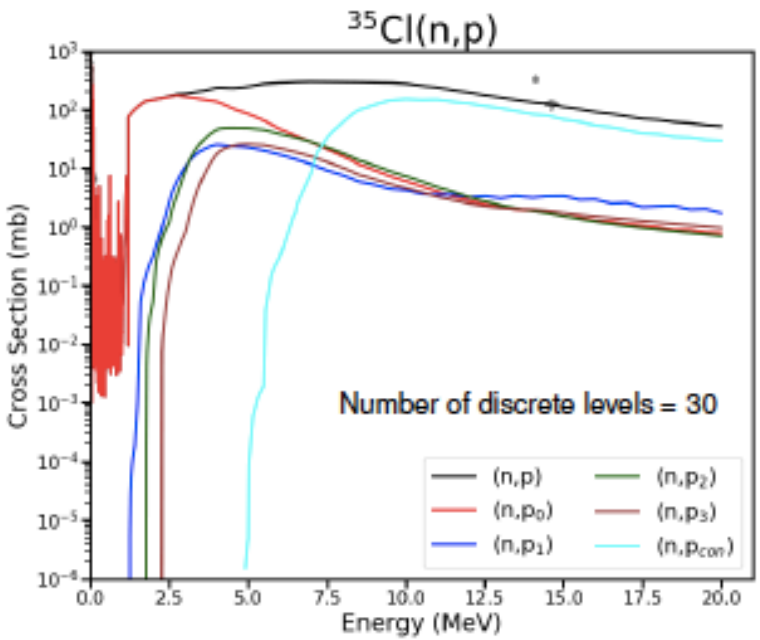
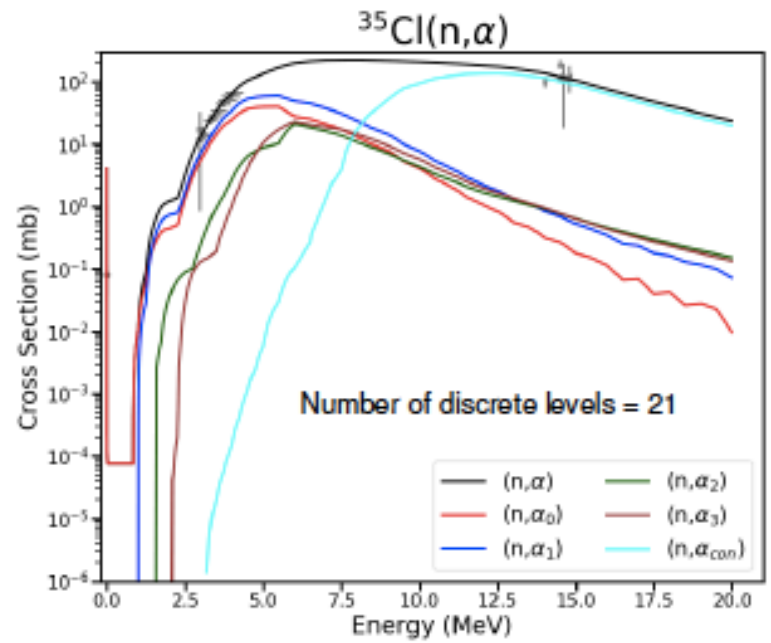
NNSA National Nuclear Security Administration

- Total cross section of neutron induced-charged particles is divided into productions of discrete levels and contiuum 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.



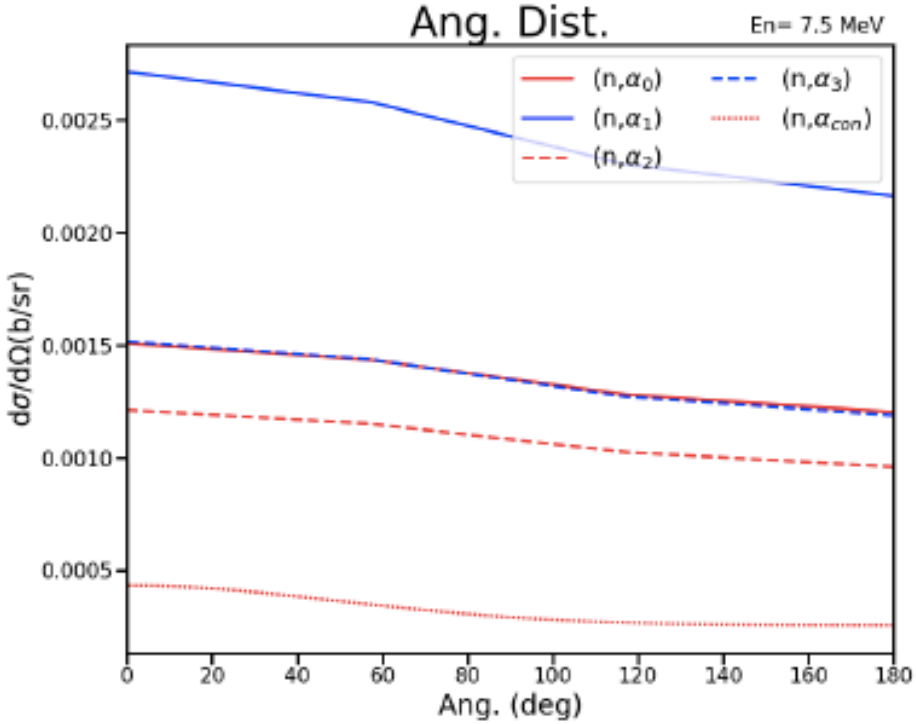


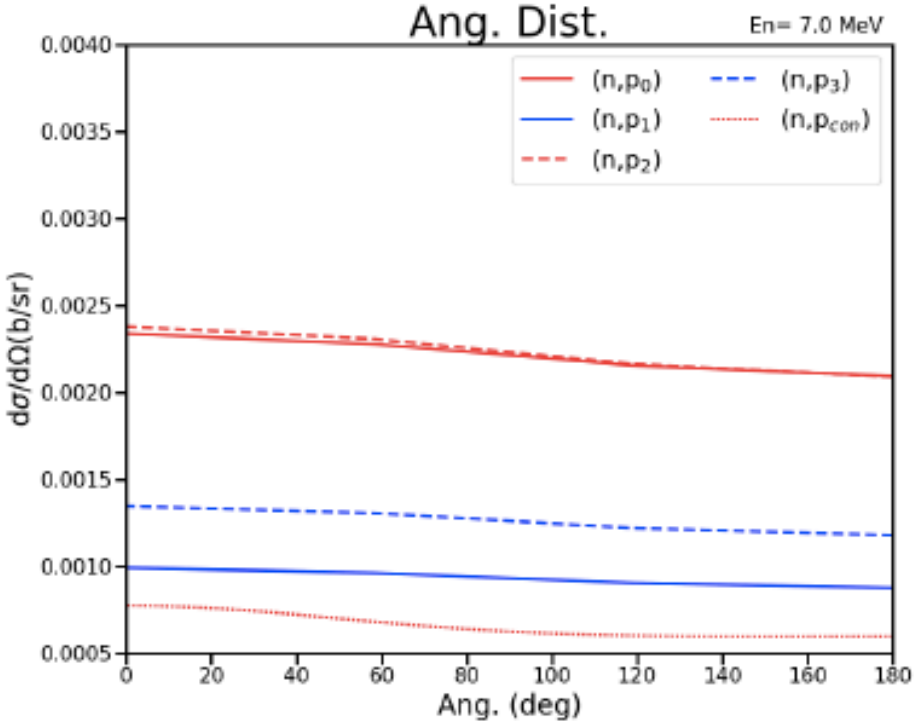
(n,p) & (n,α) cross sections on ^{35}Cl in ENDF/B-VIII.0

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

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

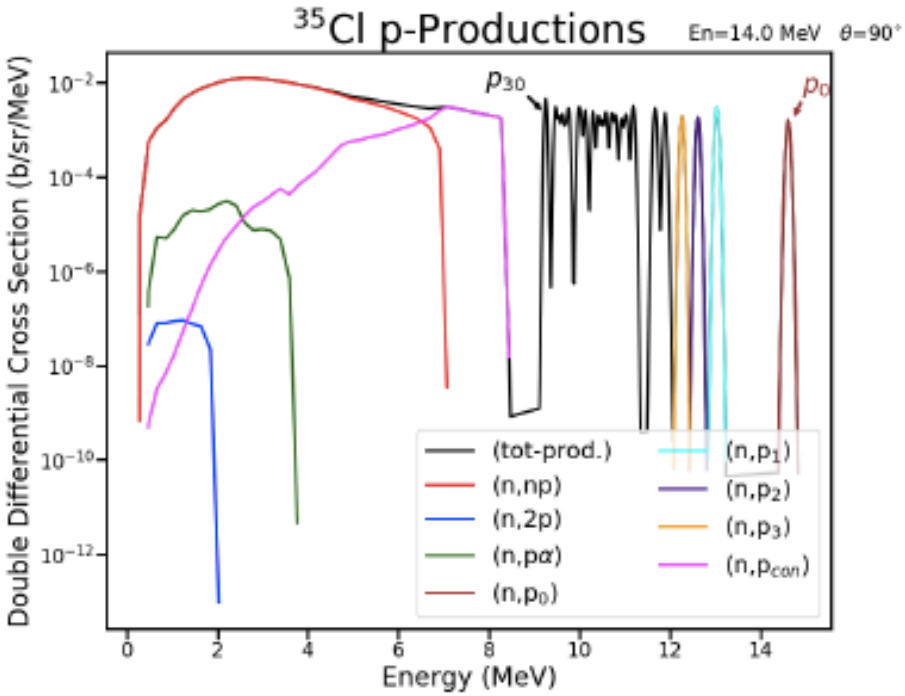
(LAB system)

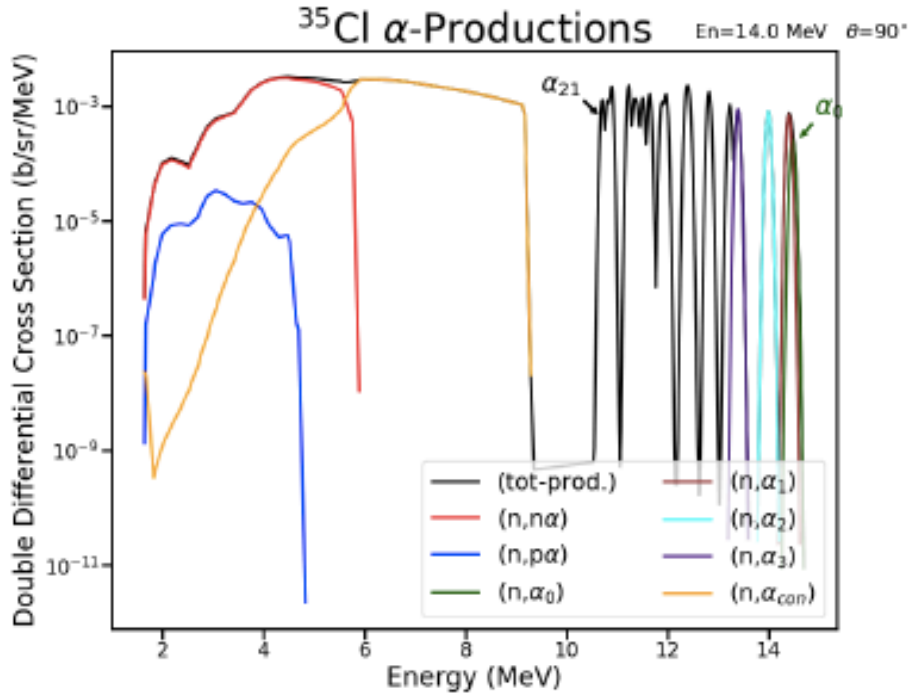




Energy spectra of (n,p) and (n,α) reactions

Double differential crosss sections of emitted particles





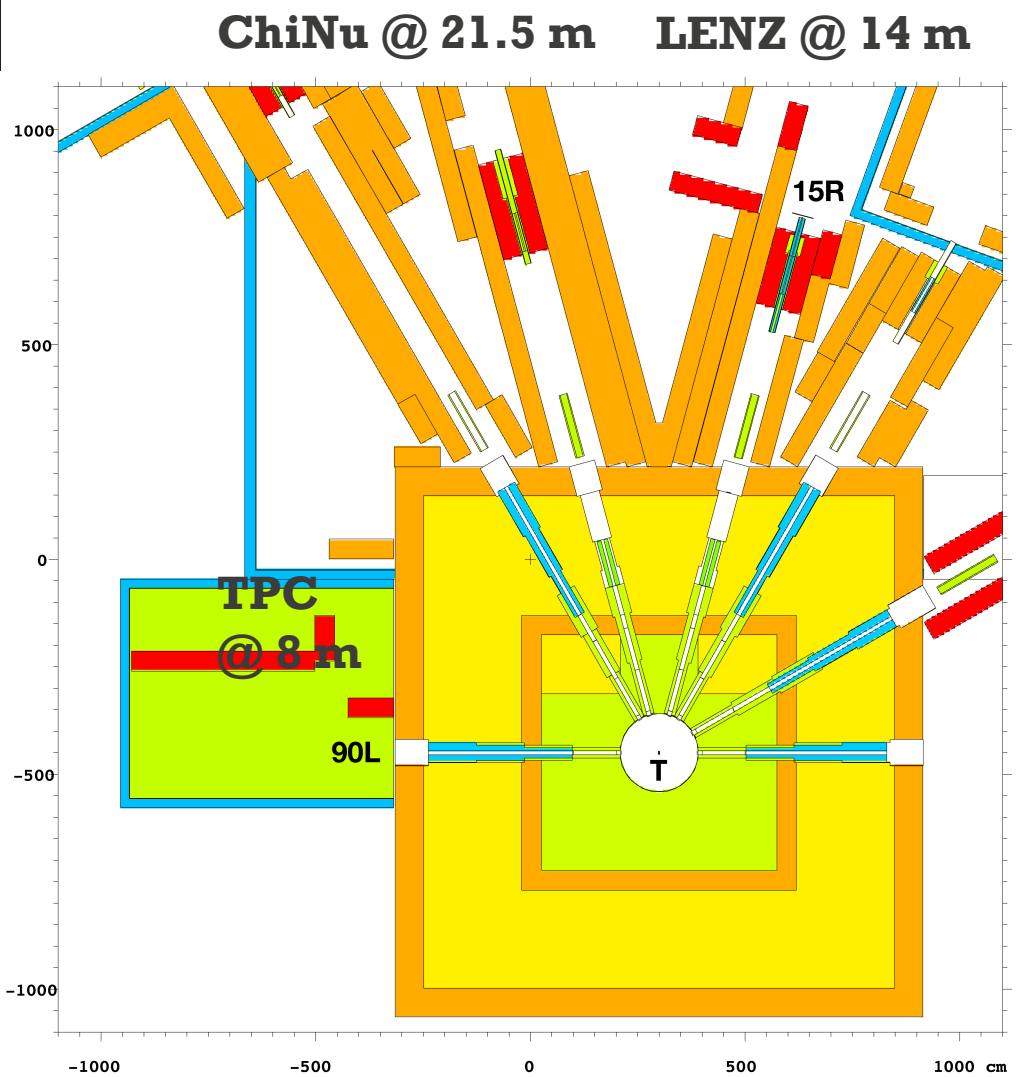
Status of evaluations for emitted charged particles in ENDF/B-VIII.0

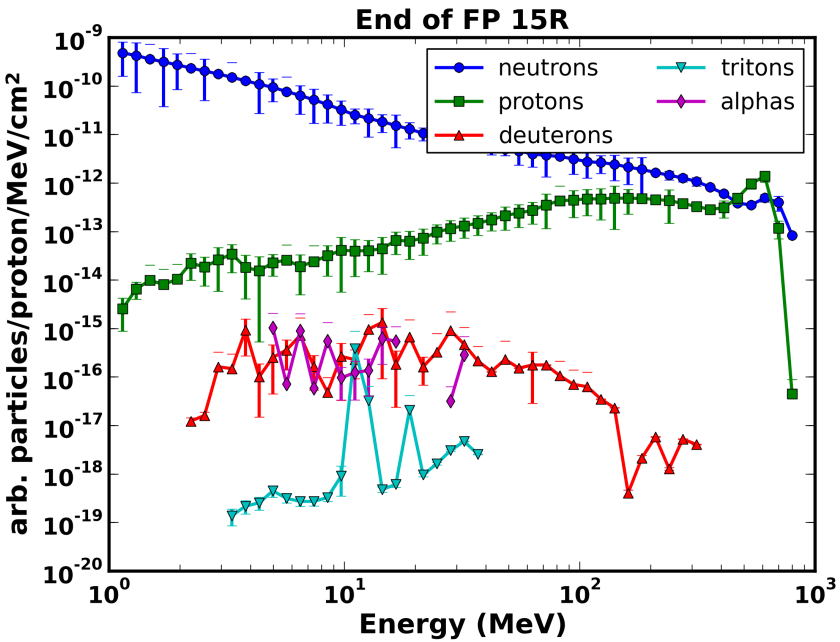
- Status of evaluations on (n,x) reactions in ENDF/B-VIII.0 (x=p,d,t,α) (total: 557 nuclei)

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

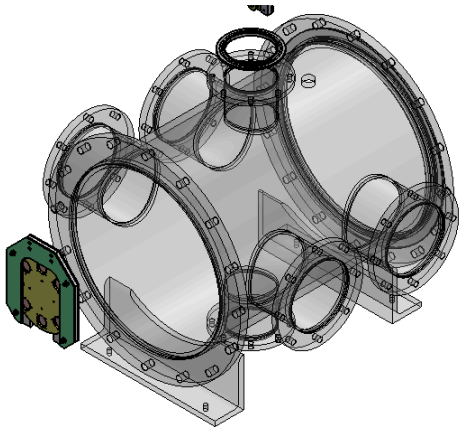
- $(n,x_{tot})=(n,x_{level})+(n,x_{cont})$, level: g.s, 1st excited level, 2nd excited level, . . .
- A: (n,x_{level}) and (n,x_{cont})
- B: (n,x_{tot}) only
- C: (n,x_{level}) or (n,x_{cont})
- D: no data

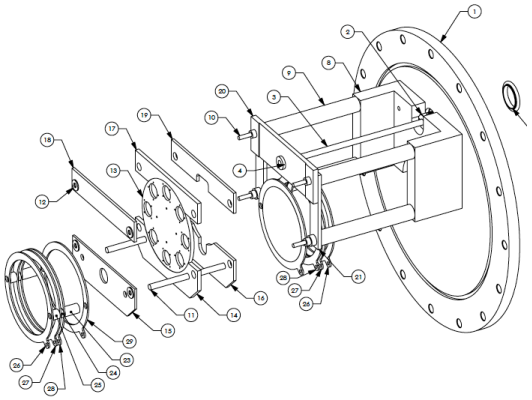
WNR spallation neutron production

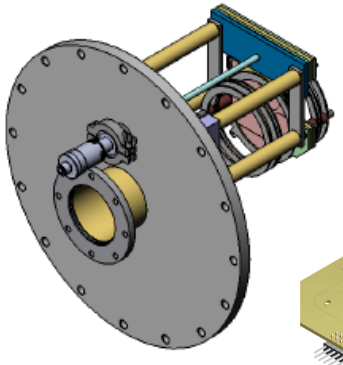


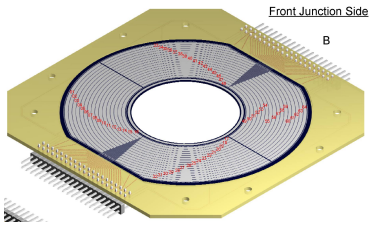


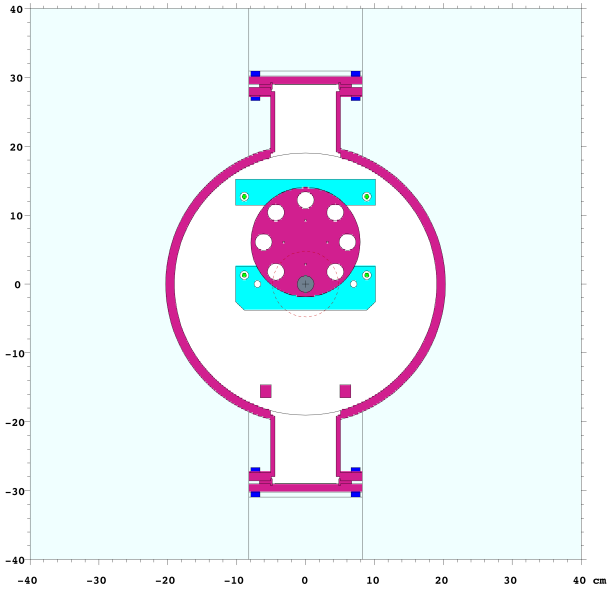
LENZ geometry modeling using MCNP 6.2

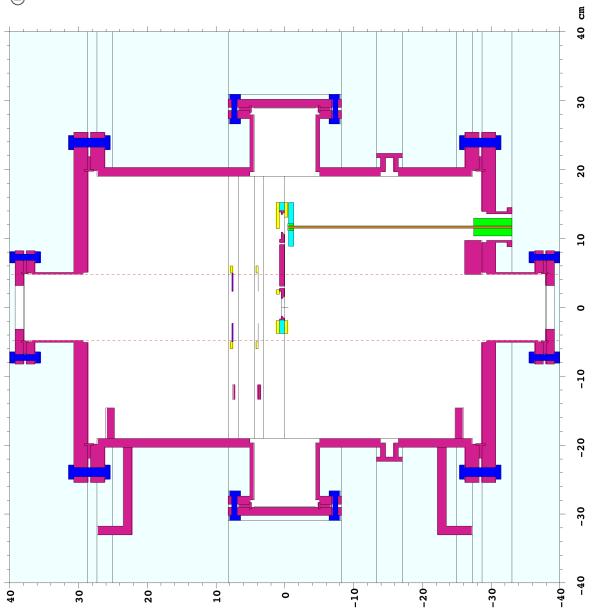


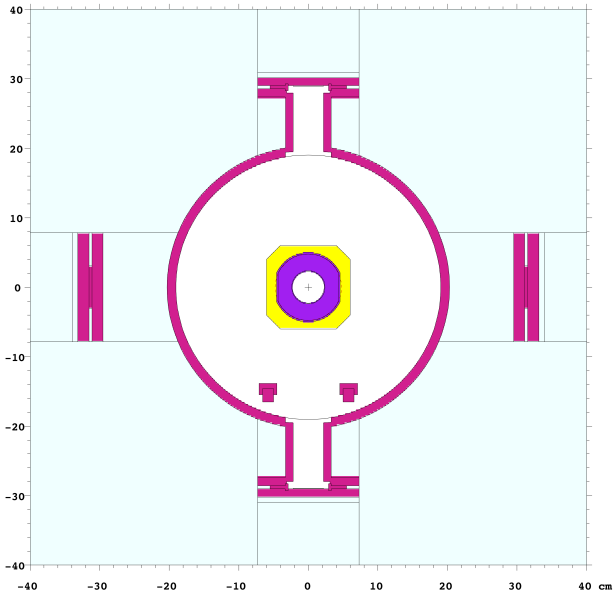




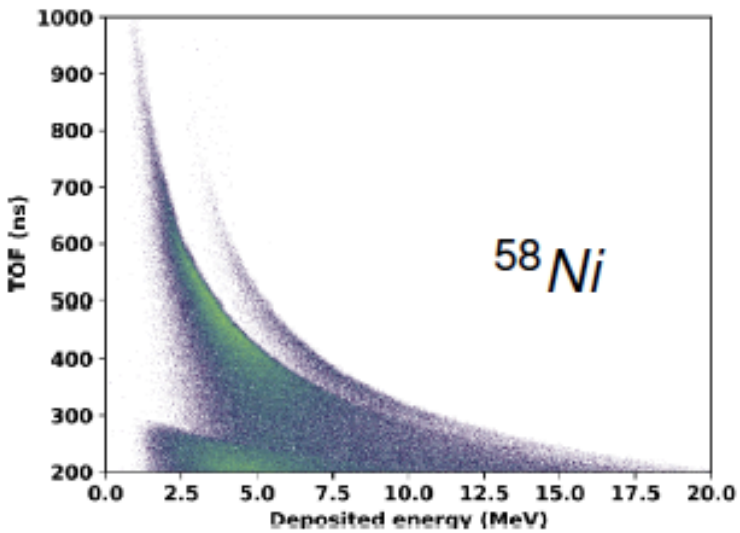


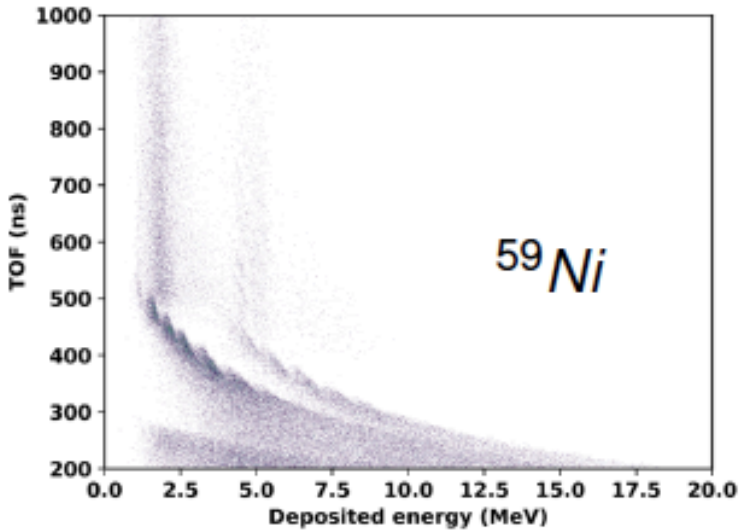


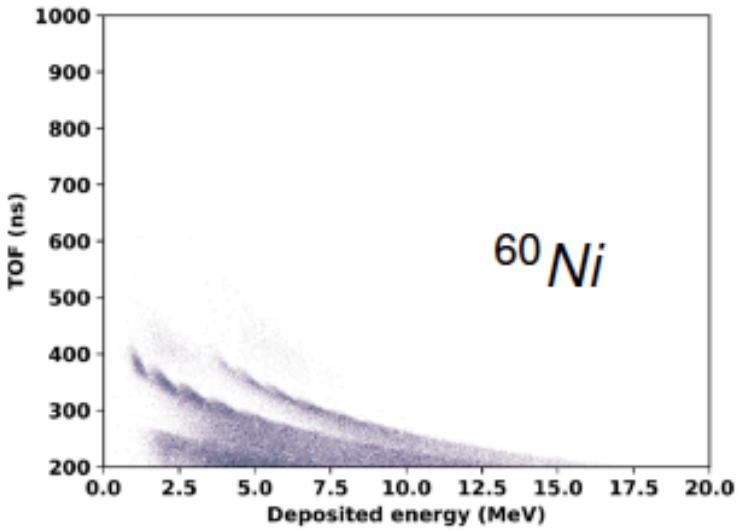


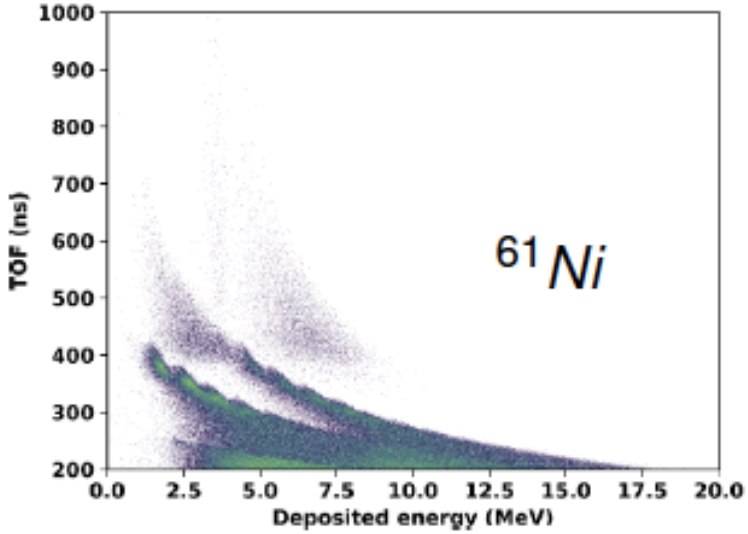


MCNP Simulation for Ni isotopes in ENDF/B-VIII.0







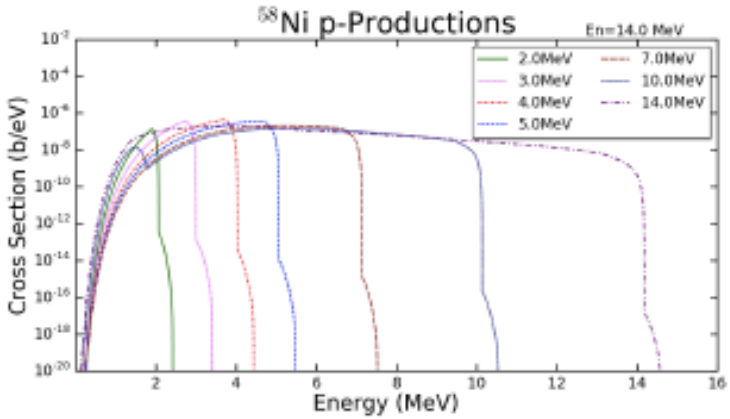


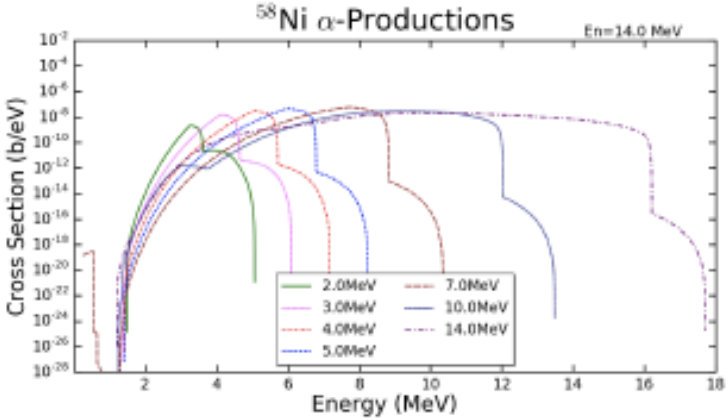
Status of (n,p) & (n,α) reaction cross sections in ENDF/B-VIII.0

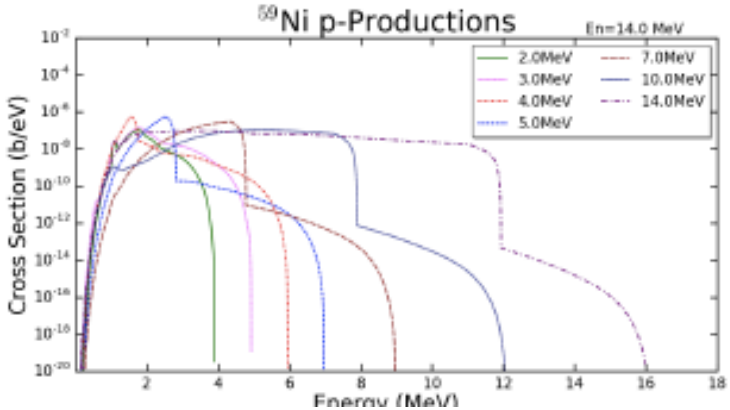
No data for discrete levels of (n,p) & (n,α) cross sections

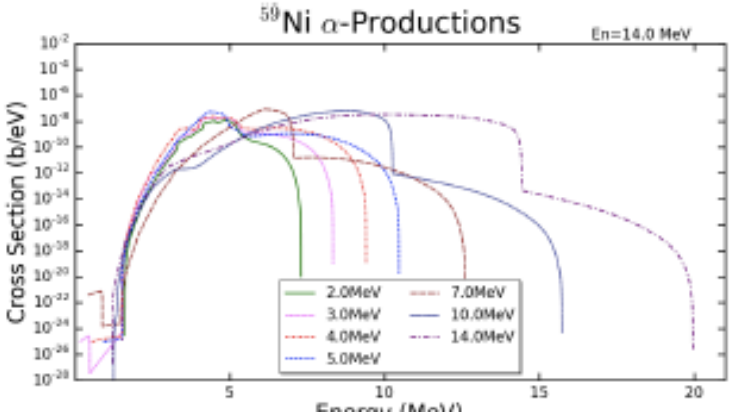
=> No angular distributions for discrete levels

Energy spectra shifted to low energy region









Angular distribution of Hauser-Feshbach formalism in CoH_3

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.

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

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

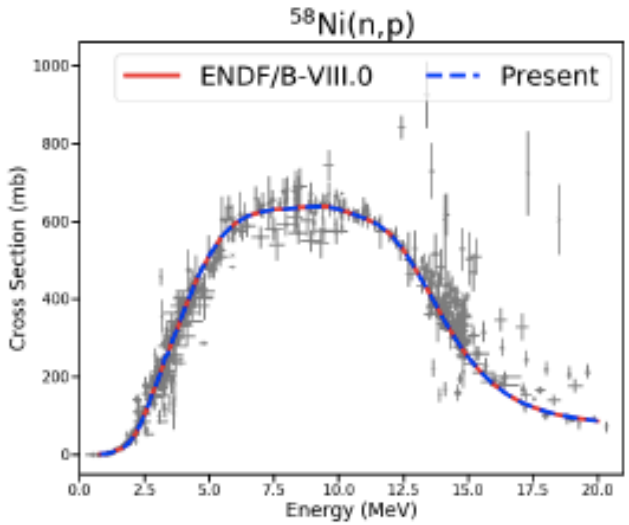
Data with various forms in ENDF/B-VIII.0

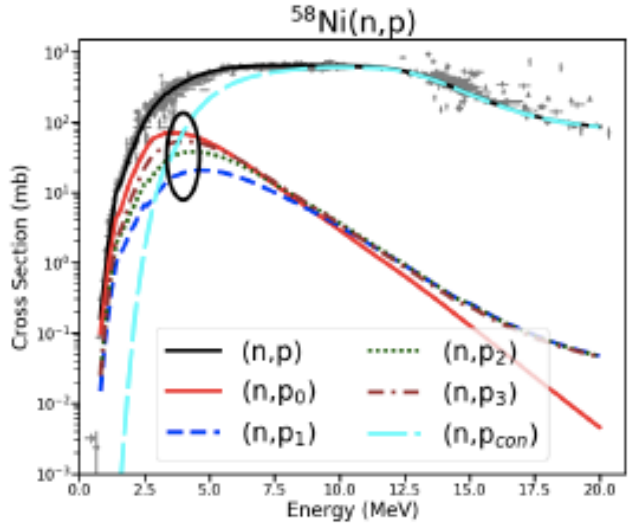
- Several cases
  - Cross sections and double differential cross sections (DDX) for total (n,p) and (n,α) without data of discrete levels
  - Cross sections for discrete levels with isotopic distributions
  - Cross sections for discrete levels but no data for continuum state
  - Implicit or explicit 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 distribtuions for discrete levels are saved in MF4
  - Energy-angular distribtuions for continuum are saved in MF6
  - Photon trasitions are saved in MF12 for their multiplicity and MF14 for probability.

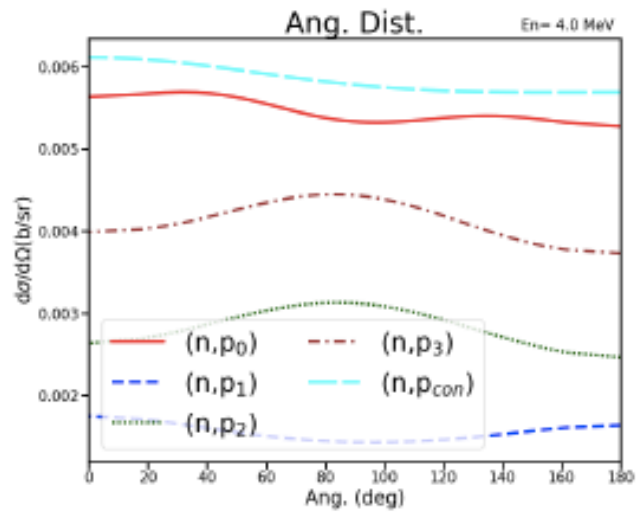
Replacing/Adding new angular distributions and energy spectra

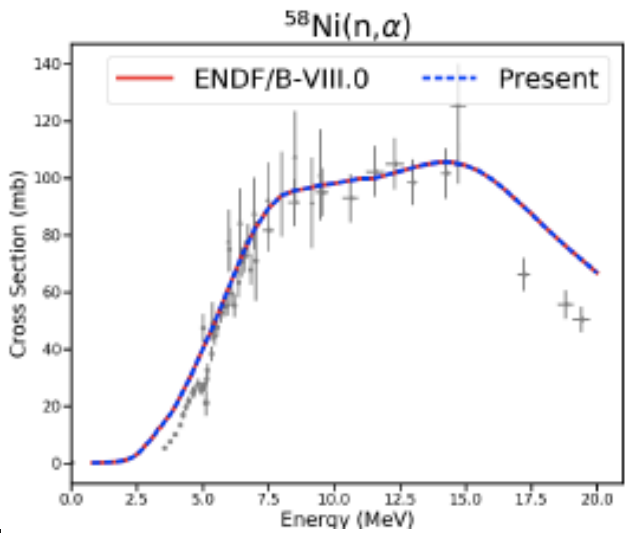
- Summary for calculating and formatting (n,p) and (n,α) reaction cross sections
  - Adopting cross sections of ENDF/B-VIII.0 for (n,p) and (n,α) if data available, where threshold energies are recalculated using mass data by Audi2012 and FRDM2012
  - Calculated by CoH_3 for cross sections of discrete levels if no data available, where (n,p_{tot}) and (n,α_{tot}) are normalized to those of ENDF/B-VIII.0.
  - Calculated by CoH_3 for angular distributions and energy spectra of (n,p) and (n,α) reactions
  - Formatting: DeCE
  - Processing: NJOY2016
  - Simulation: MCNP-6.2

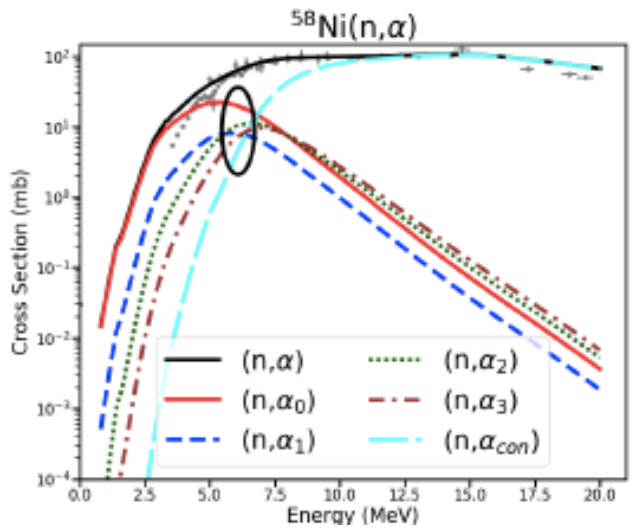
Normalization/Adding

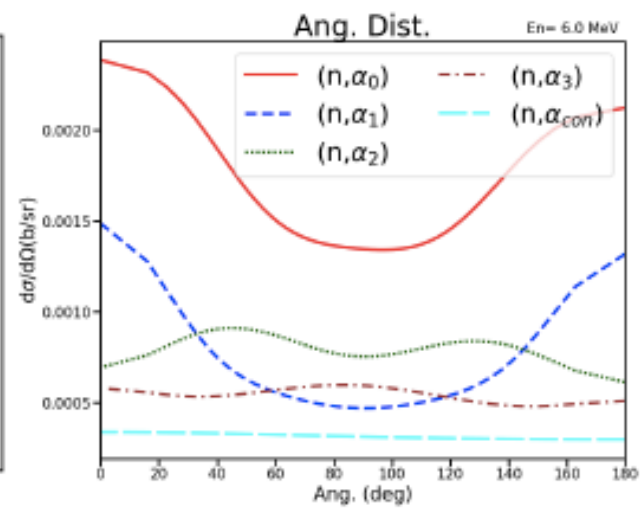




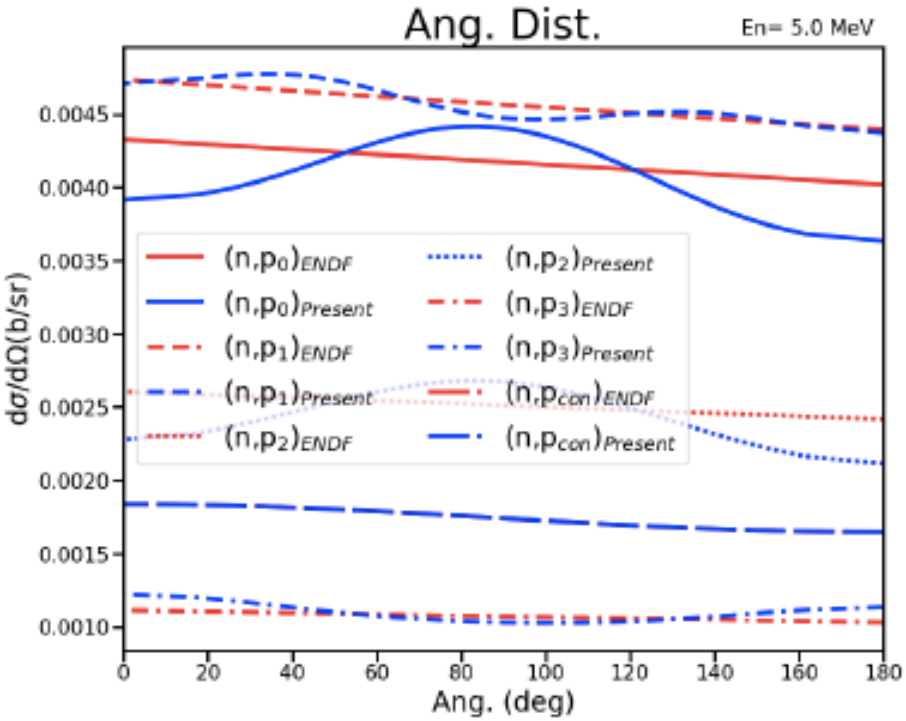


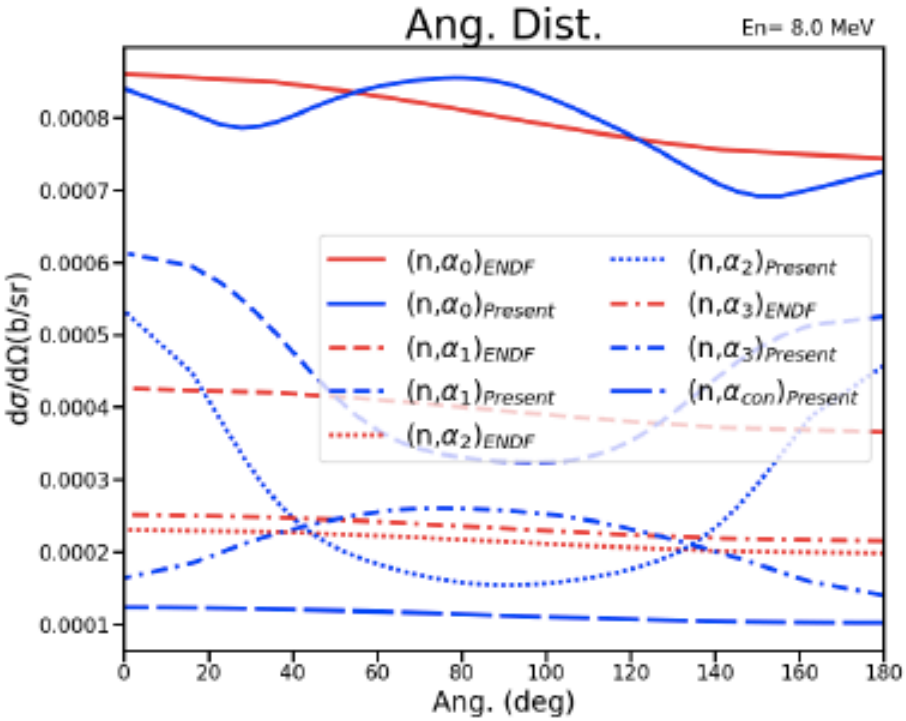






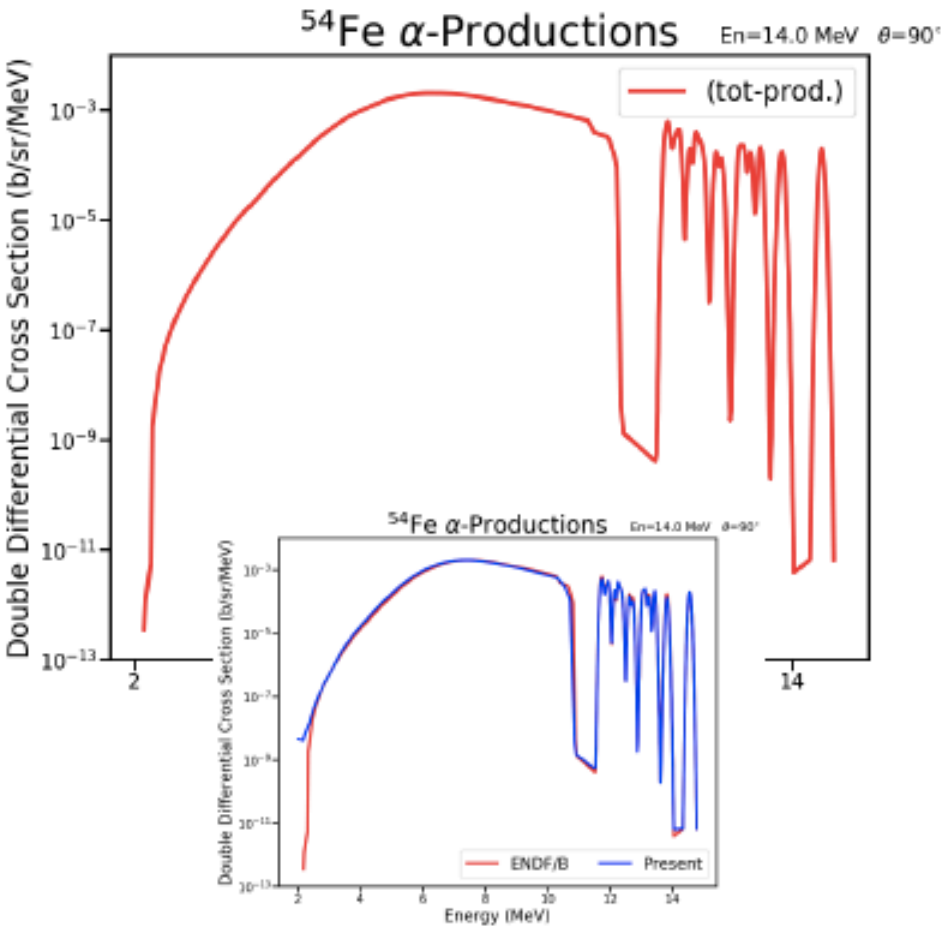
Comparison to angular distributions for ^{54}Fe



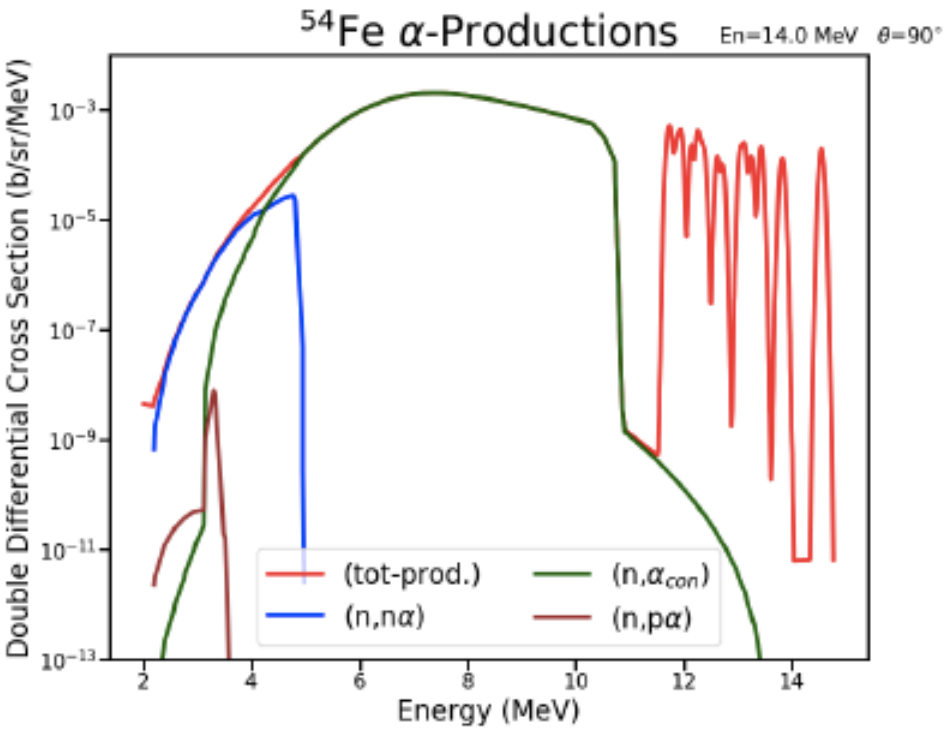


Implicit/Explicit Spectra

ENDF/B-VIII.0



new evaluation

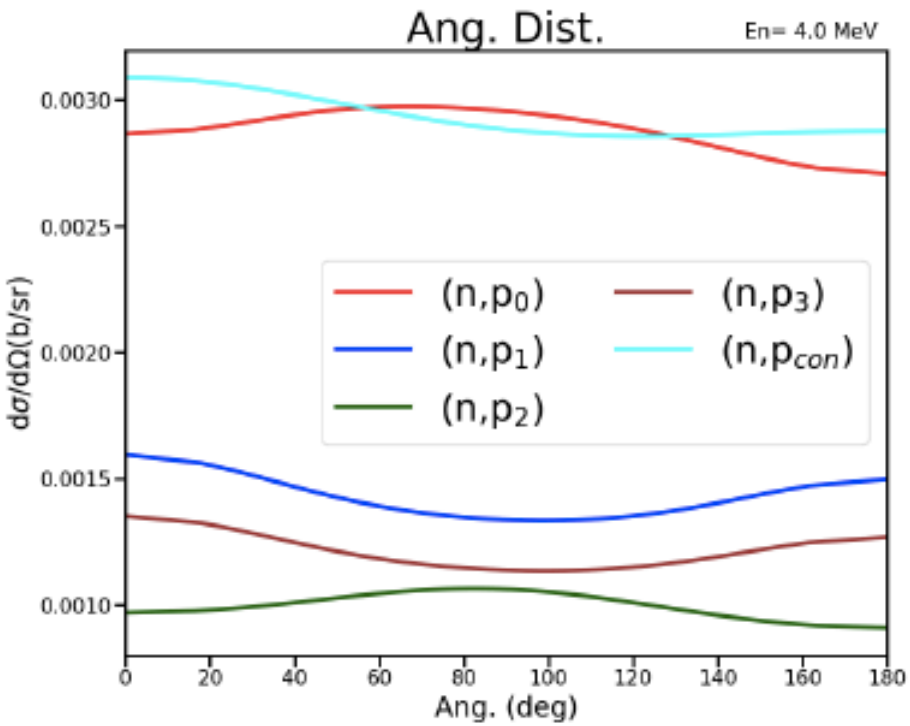


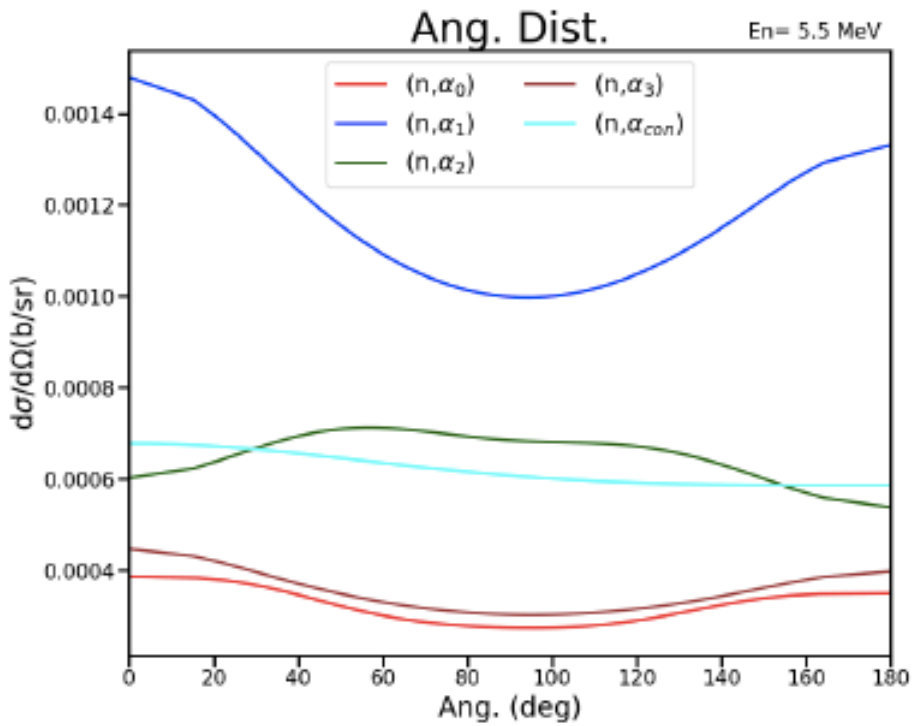
Newly updated Nuclei

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 partical 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

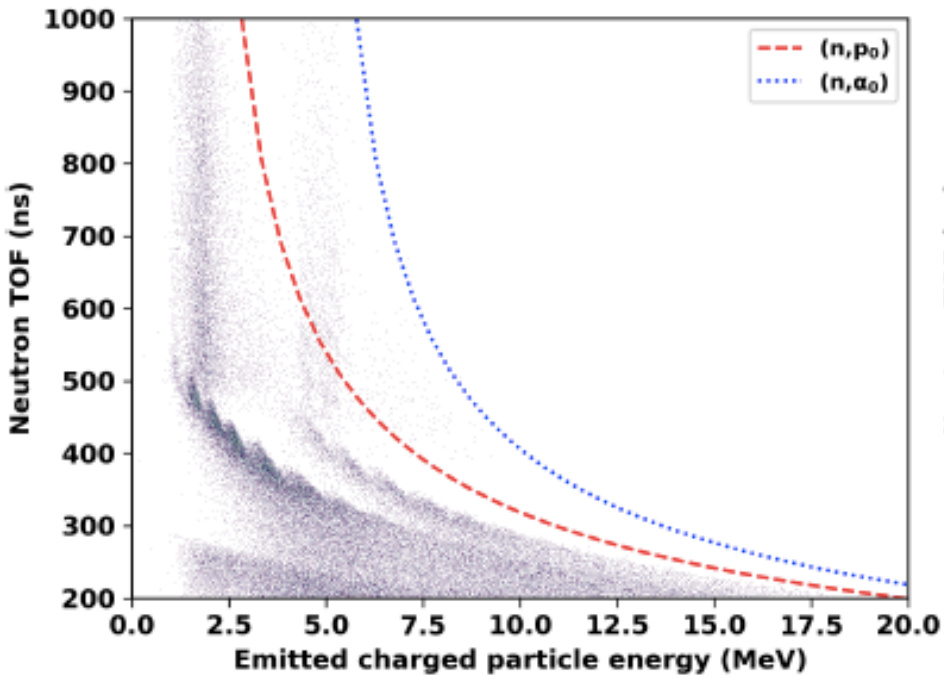




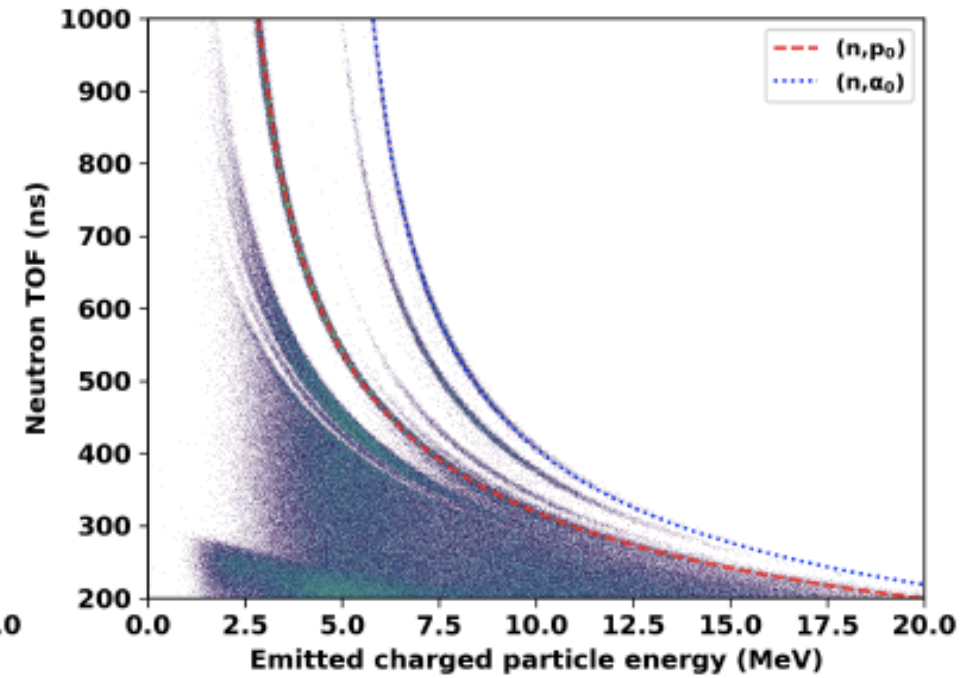
No data for Angular distributions in ENDF/B-VIII.0

MCNP Simulations for ^{59}Ni

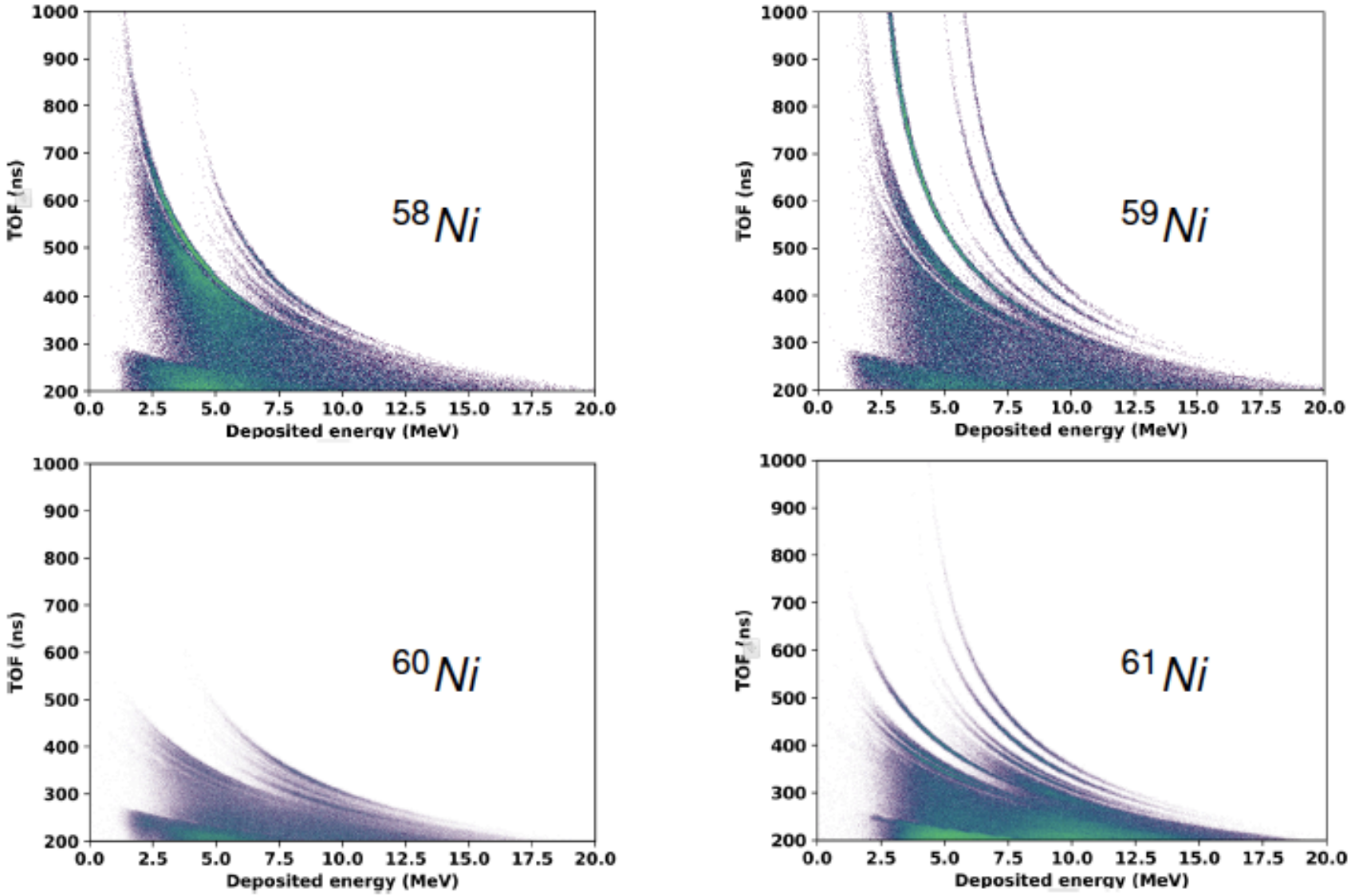
ENDF/B-VIII.0



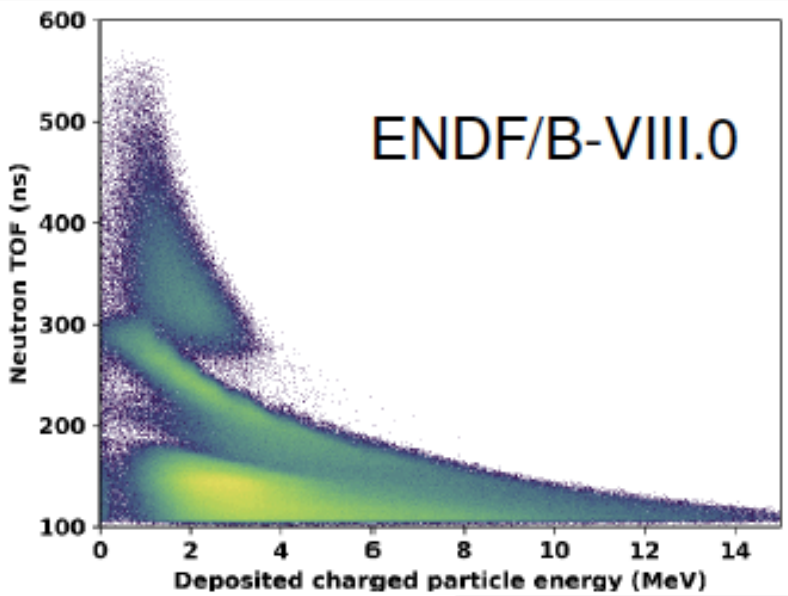
new evaluation

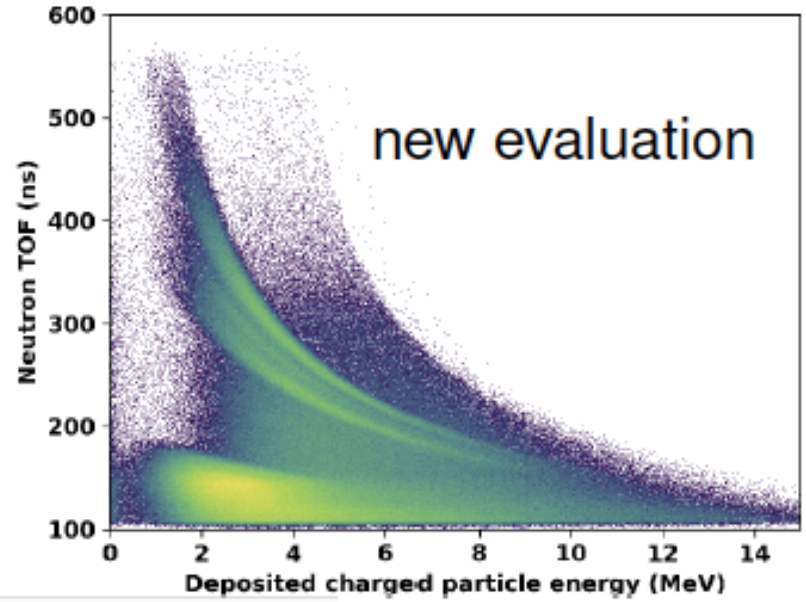


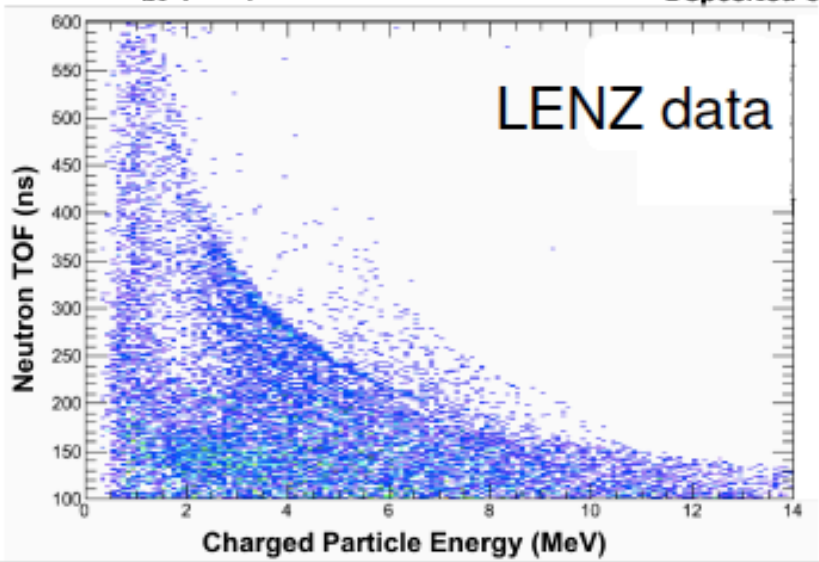
MCNP Simulation for Ni isotopes in new evaluations



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







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

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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, CoH_3.
- The measured data by the LENZ chamber for ^{54}Fe is at the last stage for analysis and will be compared to newly calcuated 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.