Study of ^{59}Ni(n,p)^{59}Co and ^{59}Ni(n,α)^{56}Fe

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Los Alamos National Laboratory

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11/18/2021

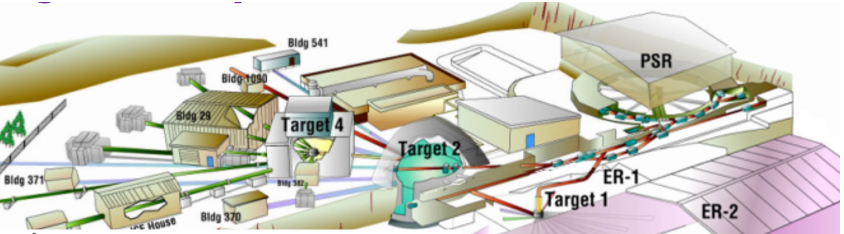
LA-UR-21-32061

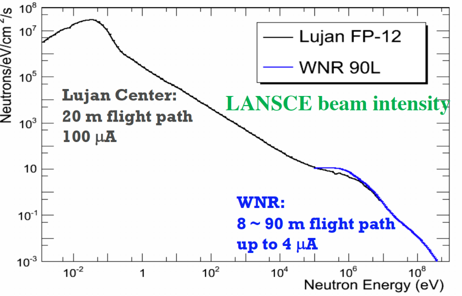
Outline

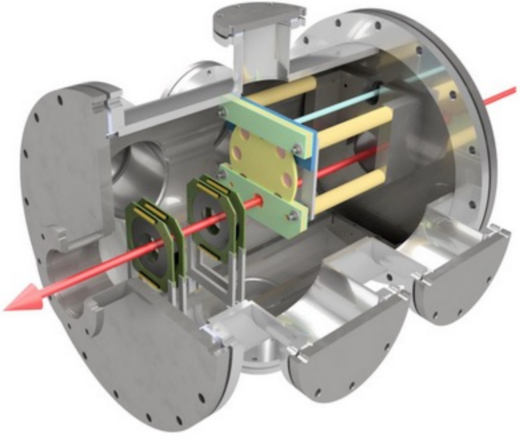
- Neutron induced charged particle measurements with LENZ at LANSCE
- Efforts to include improved outgoing charged particle spectra to ENDF/B-VIII.0 for our simulations of the LENZ experimental setup.
- Study of ^{59}Ni(n,p)^{59}Co and ^{59}Ni(n,α)^{56}Fe with a ^{59}Ni target
  - Comparison to a surrogate ratio measurement
  - 59Ni is a significant background component to our measurement of ^{56}Ni(n,p)
- Summary/outlook

LENZ: The Low Energy (n,z) experimental station

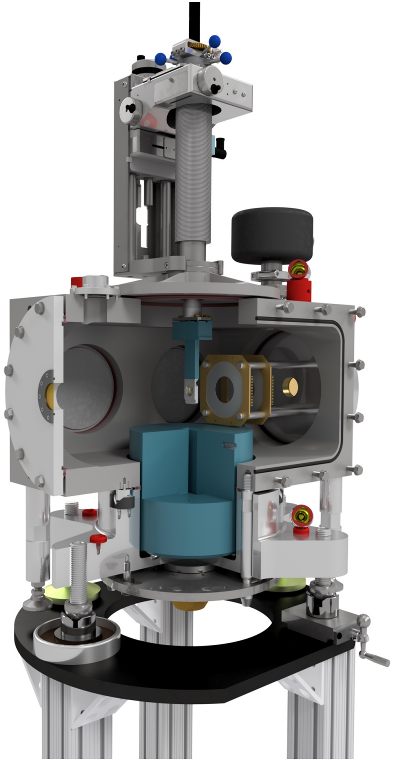
- Detect outgoing charged particles using double-sided silicon strip detectors in a compact setup close to the target sample.







Schematic diagram of the LENZ instrument, composed of two sets of dE DSSD detector telescopes at forward angles, and a target wheel in the middle of the instrument. Red arrow shows the neutron beam direction.



hotLENZ rendering by B. DiGiovine

- WNR Facility at LANSCE: fast neutrons with a broad energy spectrum ~100s of keV to ~100s of MeV

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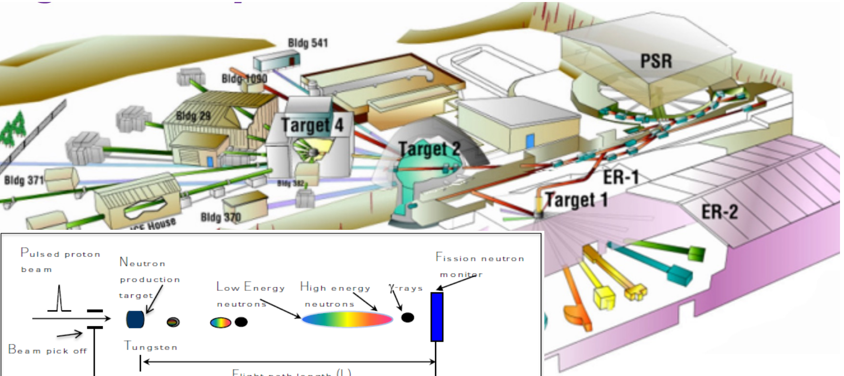
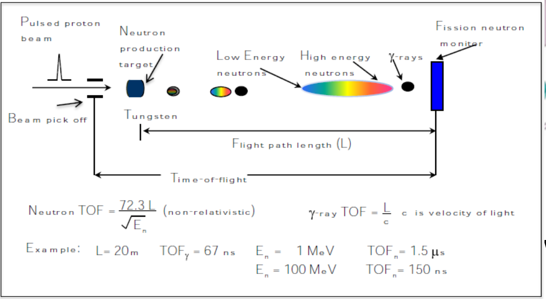
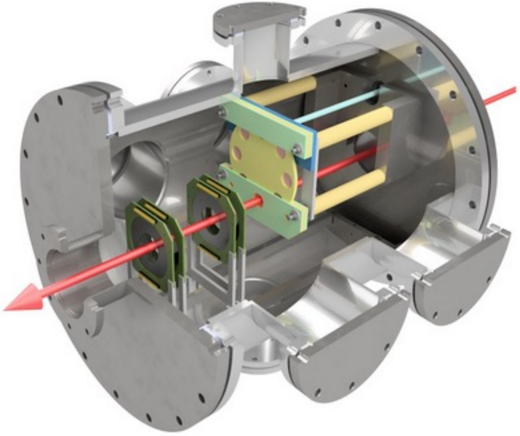




WNR Facility at LANSCE: fast neutrons with a broad energy spectrum ~100s of keV to ~100s of MeV



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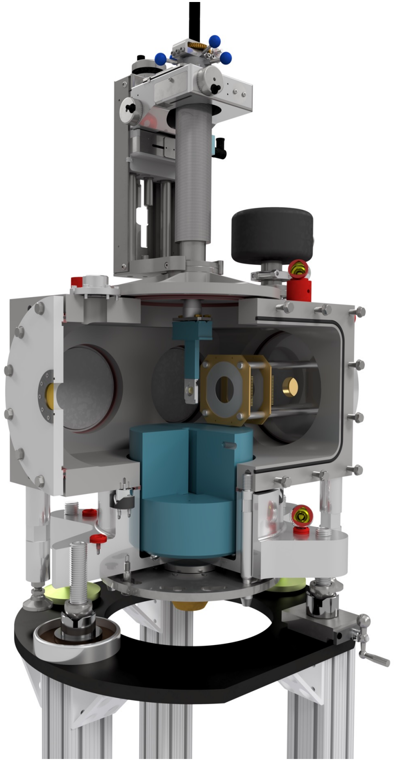

hotLENZ rendering by B. DiGiovine

Nuclear data needs for neutron-induced charged-particle reactions (n,z)

- Damage due to hydrogen and helium production in structural materials like Fe, Cr, Ni, etc.
  - Manuscript on $^{54}Fe(n,z)/^{56}Fe(n,z)$ to be submitted for publication.
  - Measurements of $^{58}Ni(n,z)/^{60}Ni(n,z)$ with LENZ are under analysis (D. Votaw)
- Precision measurements of key reactions like $^{6}Li(n,t)^{4}He$, $^{10}B(n,a)^{7}Li$, $^{12}C(n,a)^{9}Be$, $^{16}O(n,a)^{13}C$, etc.
  - Reactions on carbon studied using a diamond detector as an active carbon target, published in PRC.
  - Differential cross section measurements on $^{16}O(n,a)^{13}C$ to be submitted for publication.
- Informing the design of next-gen reactions (e.g. fast spectrum molten salt reactors) where reactions like $^{35}Cl(n,p)^{35}S$ can play a significant role as a neutron poison and produces ^{35}S($T_{1/2}$ ~ 75 days) that can complicate the path to certification for designs that incorporate chloride salts.
  - Study of $^{35}Cl(n,p)^{35}S$ with LENZ published in PRC. Results presented at previous meetings
- Constraining the νp-process for nuclear astrophysics by studying (n,p) reactions on proton-rich unstable nuclei (radioactive targets). e.g. $^{56}Ni(n,p)^{56}Co$ (^{56}Ni $T_{1/2}$ ~ 6 days)
  - Data analysis underway for the study of $^{56}Ni(n,p)$ with hotLENZ.
- Radiochemistry diagnostics for quantifying performance of nuclear fuel burning.

LENZ: Low Energy (n,z) collaboration/experimental setup developed to pin down these types of reactions that are ubiquitous in nature. Measure double differential cross sections with respect to energy and angle with an emphasis on incident neutron energies between 100 keV and 20 MeV.

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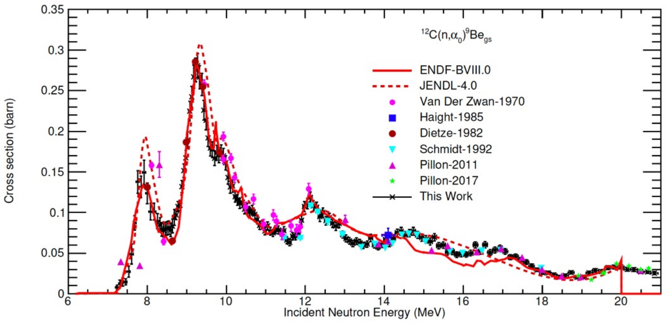

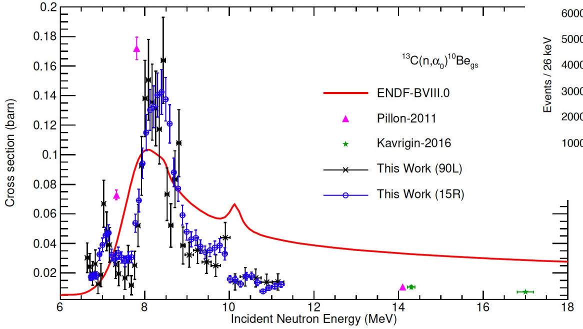

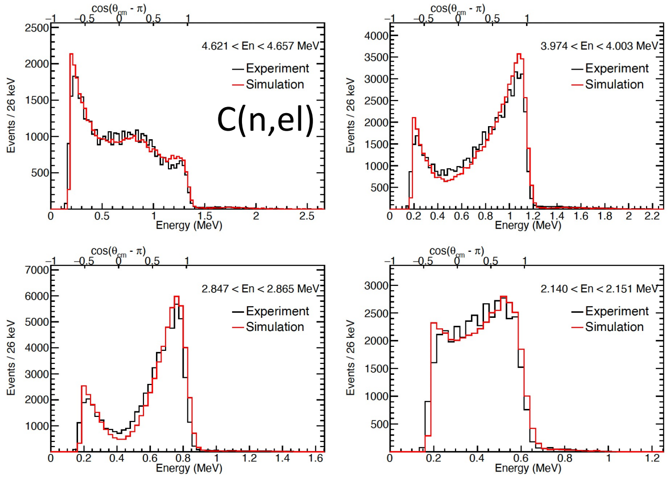

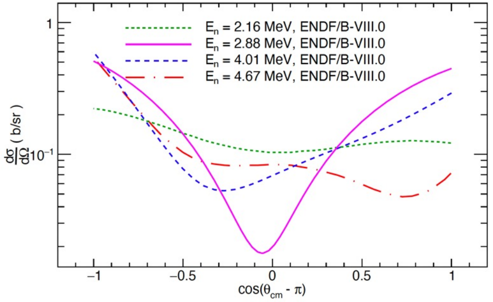

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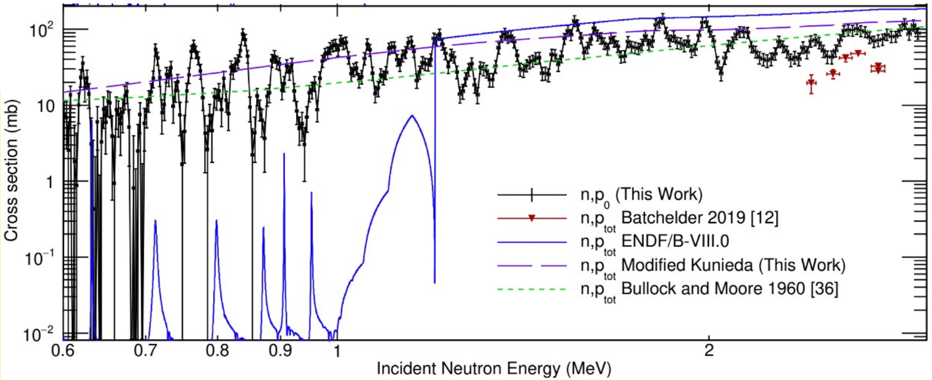
Kuvin *et al.* Phys. Rev. C **104**, 014603, 2021

Nuclear data needs for neutron-induced charged-particle reactions (n,z)

- Overall trend of the energy averaged cross section fairly well reproduced by statistical calculations aside from the fluctuations.
- ENDF/B-VIII.0 slightly overestimates the cross section above 1.25 MeV and significantly underestimates it below 1.25 MeV



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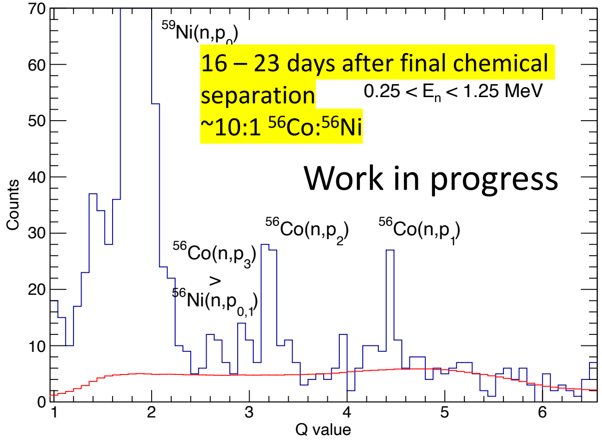
Nuclear data needs for neutron-induced charged-particle reactions (n,z)

- Measurement of $^{56}Co(n,p)^{56}Fe$ in the latter days of the experiment provides clean signature of the ^{56}Ni content at the beginning of the experiment and background characterization.

- $^{59}Ni(n,p)$ peak provides evidence of IPF produced nickel.



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  - Data analysis underway for the study of $^{56}Ni(n,p)$ with hotLENZ. Measurements on stable ^{58}Ni, ^{60}Ni, long-lived radioactive ^{59}Ni, and short lived ^{56}Ni will help to provide a more complete evaluation of the nickel isotopes.

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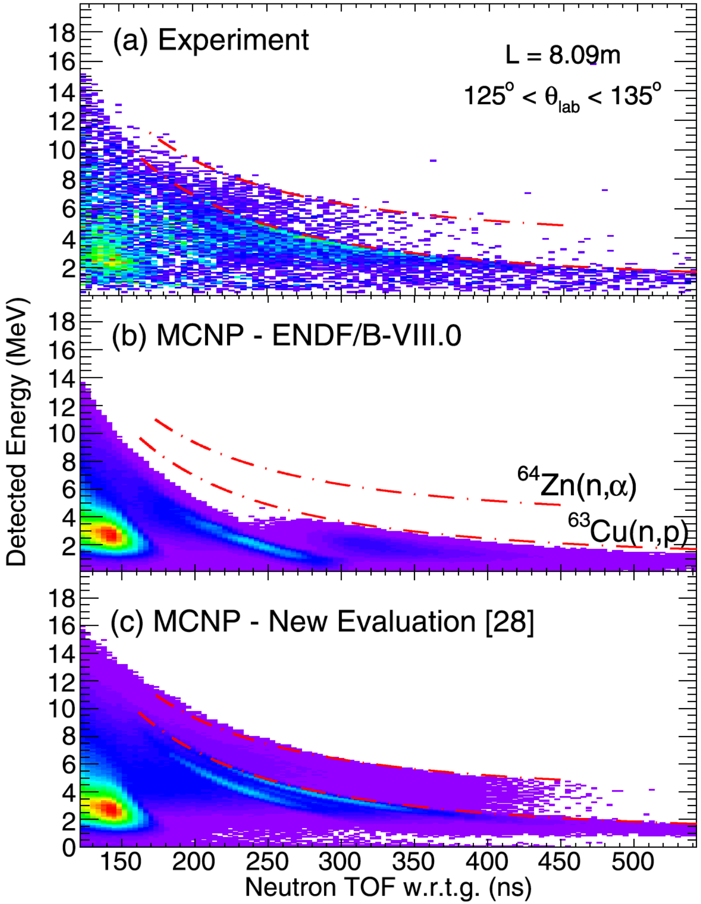
Improved evaluations of (n,p) and (n,a)

- Include missing particle production spectrum, discrete states, angular information. ENDF/B-VIII.0 total cross-sections unmodified (and partial cross-sections when available)

- Modified evaluations for (n,p) and (n,a) were performed for 62 different isotopes by Hyeong-il Kim of KAERI and incorporated into the MCNP simulation. En8lz1 : lz version 1, built on ENDF/B-VIII.0

H. I. Kim et al., Nucl. Instrum. Methods Phys. Res. A 964,163699 (2020). https://doi.org/10.1016/j.nima.2020.163699



Reactions on a brass target

Improved evaluations of (n,p) and (n,a)

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Data libraries also generated for reactions on ^{56}Ni, ^{57}Ni, ^{56}Co, ^{57}Co, etc for which no previous ENDF/B-VIII.0 evaluation existed

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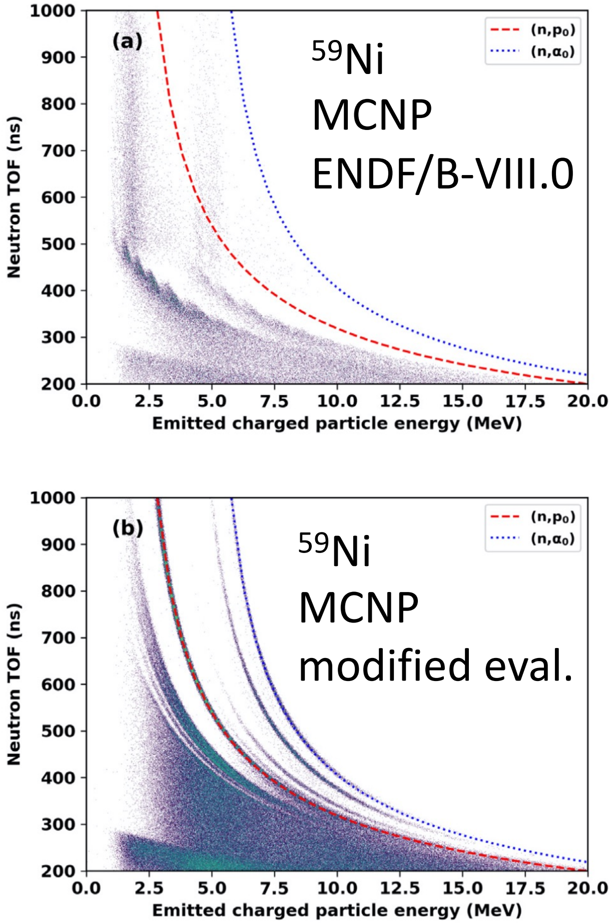

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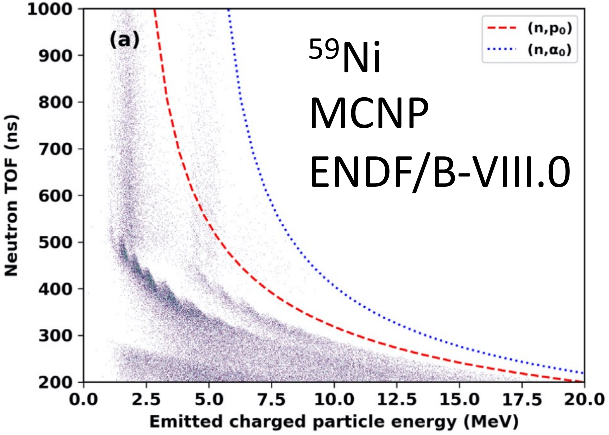

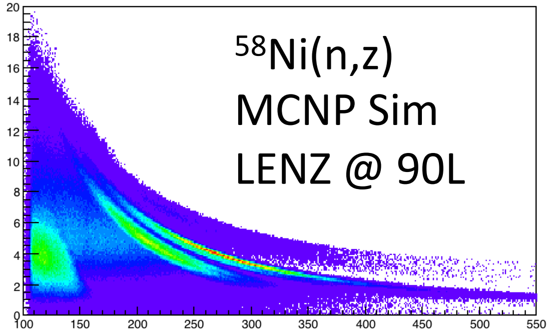

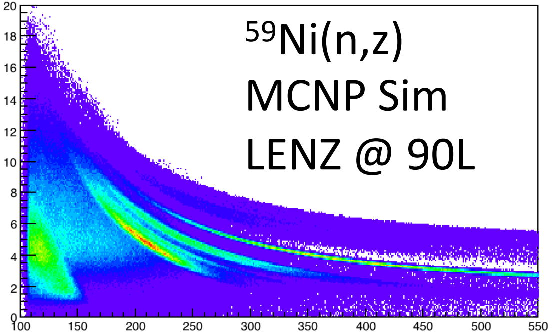

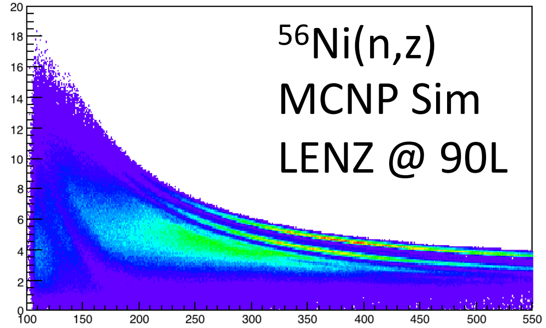

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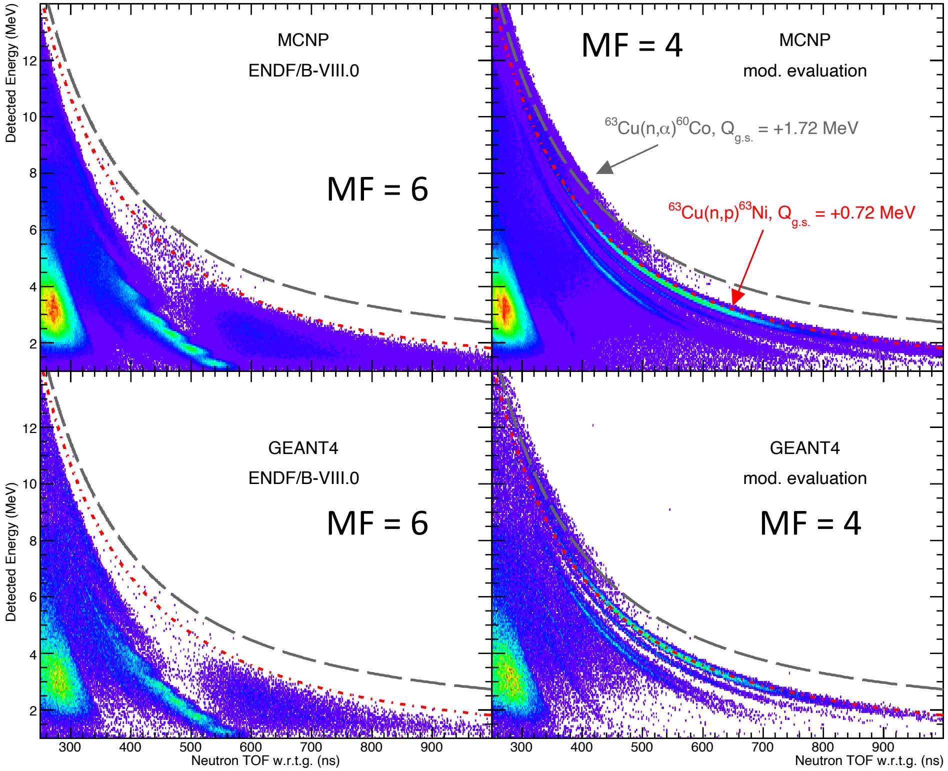
Los Alamos NATIONAL LABORATORY

Benchmarking (n,z) reactions between GEANT4 and MCNP

- Simulation of $^{63}Cu(n,z)$ shows good agreement between MCNP and GEANT4 when ENDF/B-VIII.0 is used. However, the spectra is not realistic and does not reproduce the expected outgoing charged particle energies from experiment. This library includes total cross sections and DDX information (MF=6)

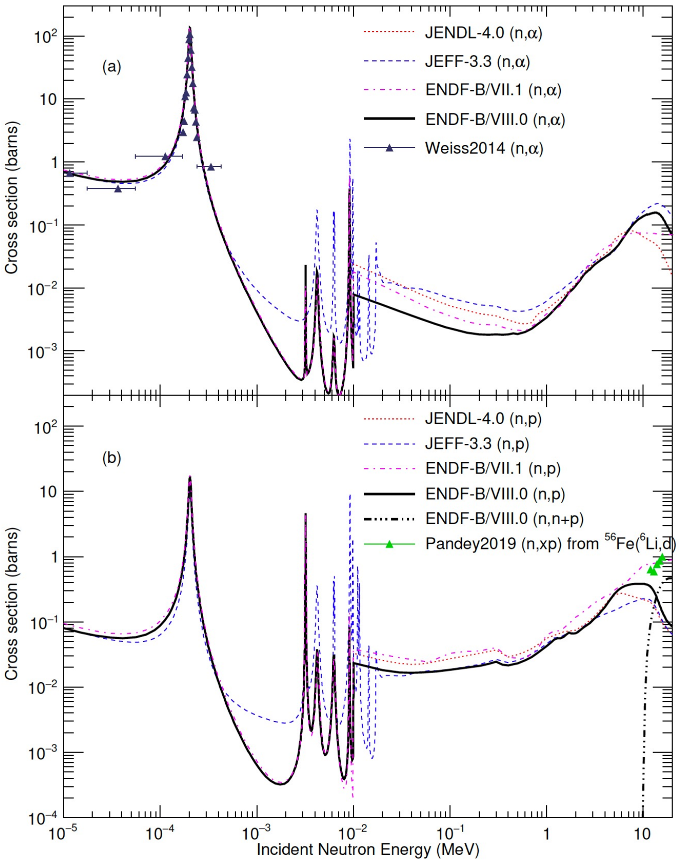
- However, when using the modified data library as an input, which includes partial cross sections to discrete states and angular distributions (MF=4), GEANT4 and MCNP are only in agreement after making modifications to the GEANT4 source code.

- GEANT4 simulation was developed in collaboration with CMU and recent development has been led by P. Tsintari. A manuscript is expected to be submitted soon.

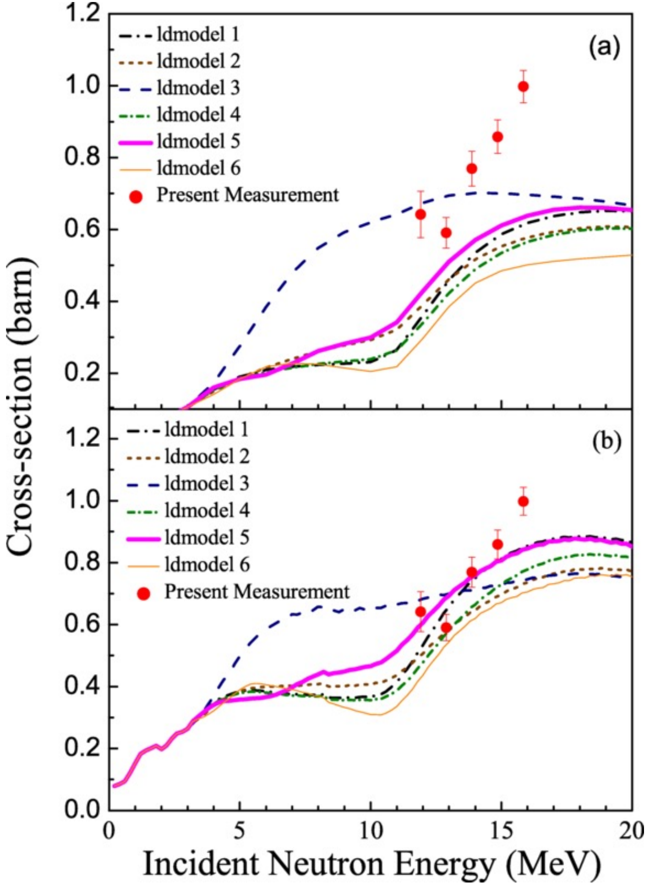


^{59}Ni(n,p)^{59}Co and ^{59}Ni(n, α)^{56}Fe

- ^{59}Ni is a long-lived ($T_{1/2}$ ~ 100,000 years) unstable isotope of nickel that is bookended between the stable A=58 and A=60 isotopes.
- Can build up to a non-negligible portion of the total nickel content in reactors from neutron capture on ^{58}Ni at thermal energies and from ^{60}Ni(n,2n) at fast neutron energies in fusion reactors.
- No prior experimental data on ^{59}Ni(n,p) or ^{59}Ni(n,a) at fast neutron energies above 20 keV, except for (n,xp) cross sections derived through a surrogate ratio method (SRM) above 10 MeV.
- Measured with LENZ during the 2019 (~1 ug of ^{59}Ni) and 2020 (~100 ug ^{59}Ni) run-cycles.
- JEFF-3.3 includes the most recent evaluation of ^{59}Ni from thermal to fast neutron energies.
- New data allows for a sensitive test of calculations that use global input parameters and/or to benchmark indirect methods like SRM.



Surrogate ratio measurement of ^{59}Ni(n,xp)

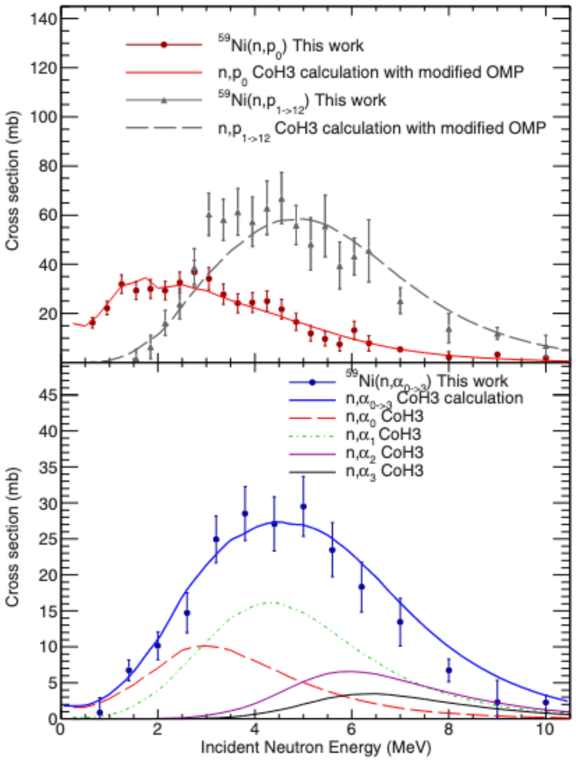


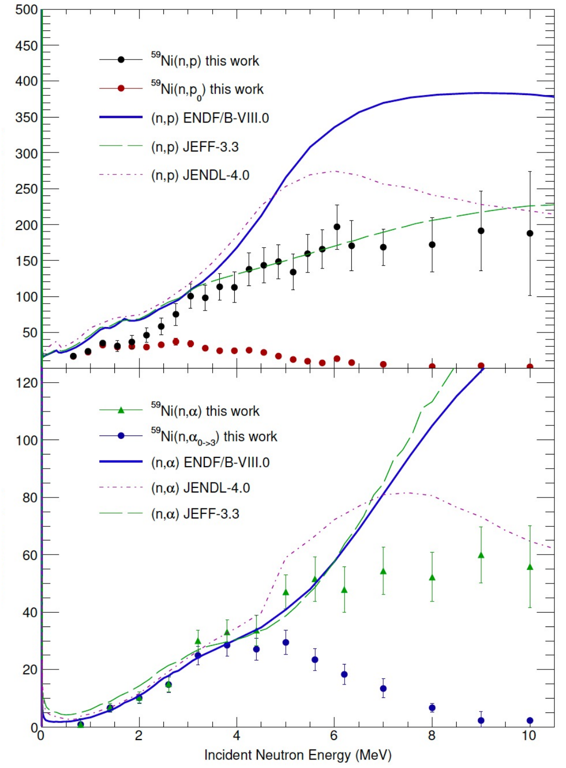
- Prior to this work, the only available ^{59}Ni(n,xp) cross section information at fast neutron energies was derived from a surrogate ratio method.
- The scale and trend of their data was inconsistent with statistical calculations using default parameters and with ENDF, JEFF, and JENDL for which they conclude that new evaluations are necessary.
- Modifications to the optical potentials used in the statistical calculations are proposed to reproduce the scale of their experimental data.

From Pandey et al. https://doi.org/10.1103/PhysRevC.99.014611

New data on 59Ni(n,p) and 59Ni(n,a) at fast neutron energies

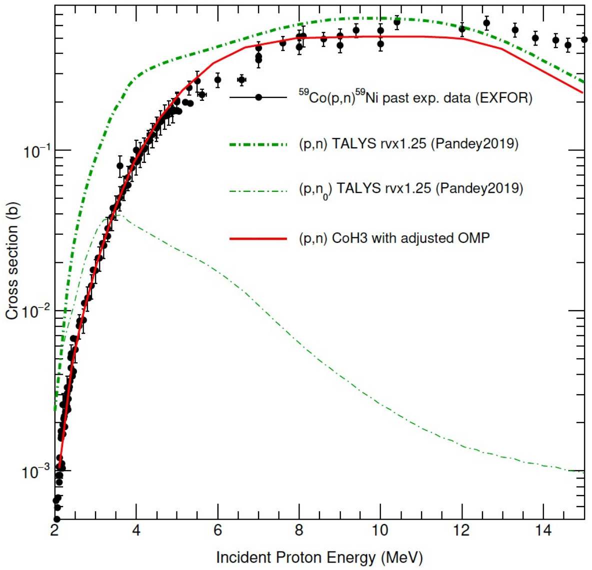
- Statistical Hauser-Feschbach calculations performed using the code CoH3 and with TALYS.
- For (n,p) below 3 MeV, the experimental cross section is approximately 30% lower than the available evaluations and from the calculations using default parameters. In contrast to the adjustment of r_v by 1.25 by Pandey, we obtain better agreement with our data by more modest scaling adjustments of 0.9, 0.95 and 0.95 for the a_w, r_w, r_v proton OMP.

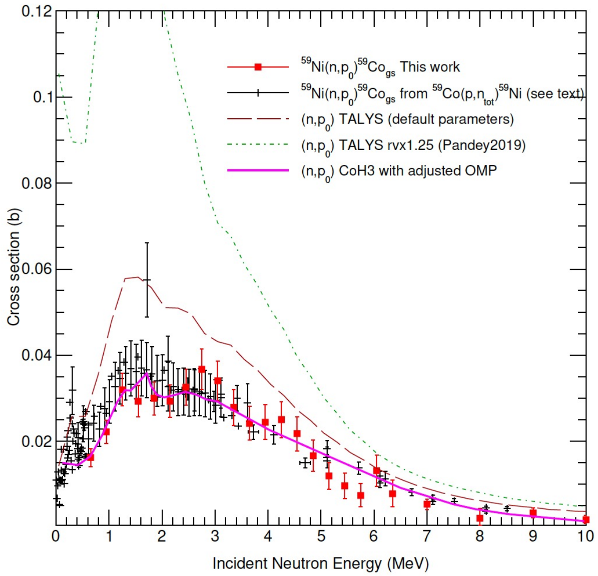




Comparison between $^{59}Ni(n,p)^{59}Co$ and $^{59}Co(p,n)^{59}Ni$

The prescribed adjustment (scaling the volume radius term by 1.25) to the default optical model parameters in TALYS by Pandey *et al.* also performs worse compared to the default parameters when reproducing the $^{59}Co(p,n)$ data. It results in a factor 4-5 difference between our direct measurement data and the calculation for $^{59}Ni(n,p_0)$ at ~2 MeV.



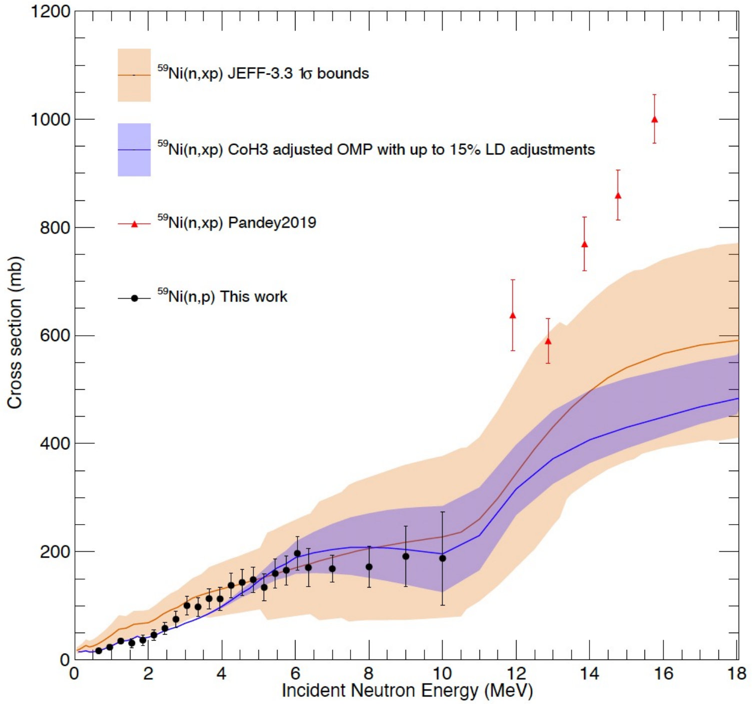


In contrast, we obtain better agreement better agreement between the (p,n) data and our experimental (n,p) data with the more modest adjustments to the proton OMP.

For (n,p_0) (right), the magenta curve is from the CoH calculation using the same optical model parameters as the red curve for $^{59}Co(p,n)$ case (left). The black data points (right) are derived from the $^{59}Co(p,n)$ data from exfor by using the statistical model calculation to get the expected ratio of (p,n_0) to (p,n) and then using detailed balance theorem to go from (p,n_0) to (n,p_0)

Study of ^{59}Ni(n,p)

- Going from the upper to lower bounds of the 1σ band from JEFF-3.3 represents a range of nearly a factor of 5 and is inconsistent with the cross sections derived from the surrogate work.
- Our direct measurement is in fairly good agreement with the central value of JEFF-3.3 above E_n = 3 MeV but requires a slight adjustment below 3 MeV.
- Raises questions about the reliability of that particular application of the SRM.
- Direct measurements on radioactive isotopes should be made, when feasible.



Summary/Outlook

- Study of ^{59}Ni(n,p) via a direct measurement with a radioactive nickel target demonstrated the importance of making direct measurements, when feasible (manuscript written, to be submitted to PRC).
- Analysis of ^{56}Ni(n,p) data is in progress.
- In addition, recent measurements on ^{58}Ni and ^{60}Ni (analysis led by D. Votaw) with LENZ will help provide a more complete evaluation of the nickel isotopes when combined with the radioisotope data.
- In anticipation of some of the nuclear data needs for (n,z) reactions on unstable nuclei, we have begun planning the development of a solenoidal spectrometer for (n,z) studies at LANSCE that will have significantly improved sensitivity over a more “traditional approach” to charged particle detection.