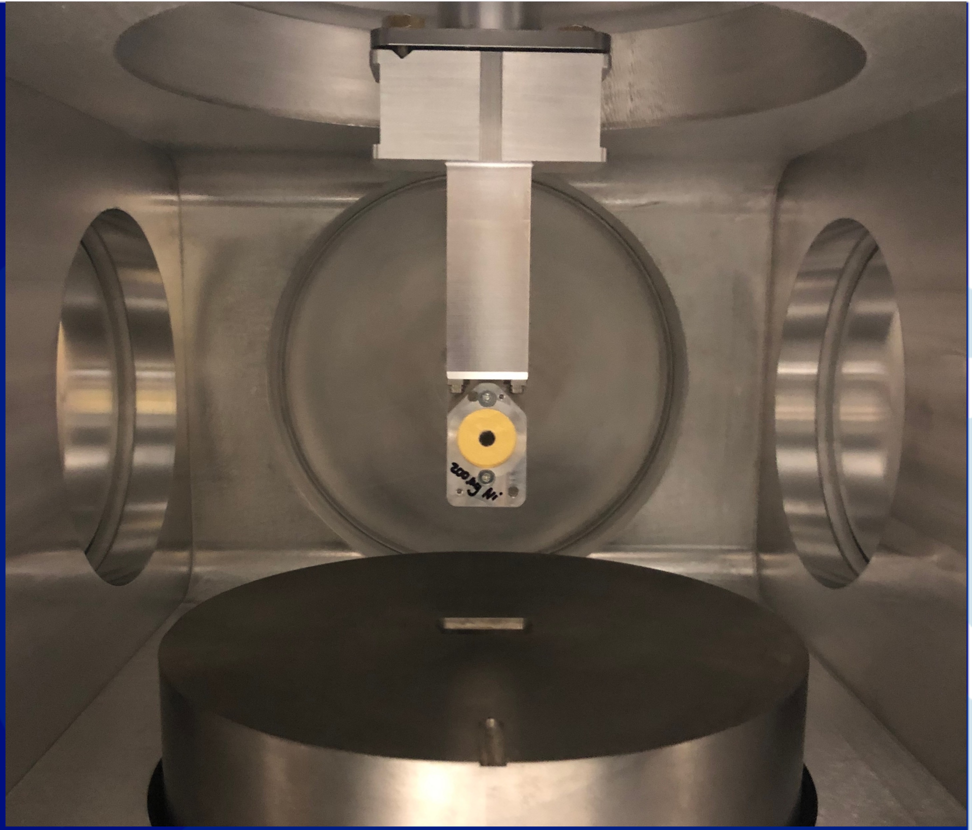
LA-UR-23-30116

Los Alamos NATIONAL LABORATORY

Experimentally determined ^{56}Ni(n,p) cross section and its impact on nu-p process



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North Carolina State Univ.: C. Frohlich

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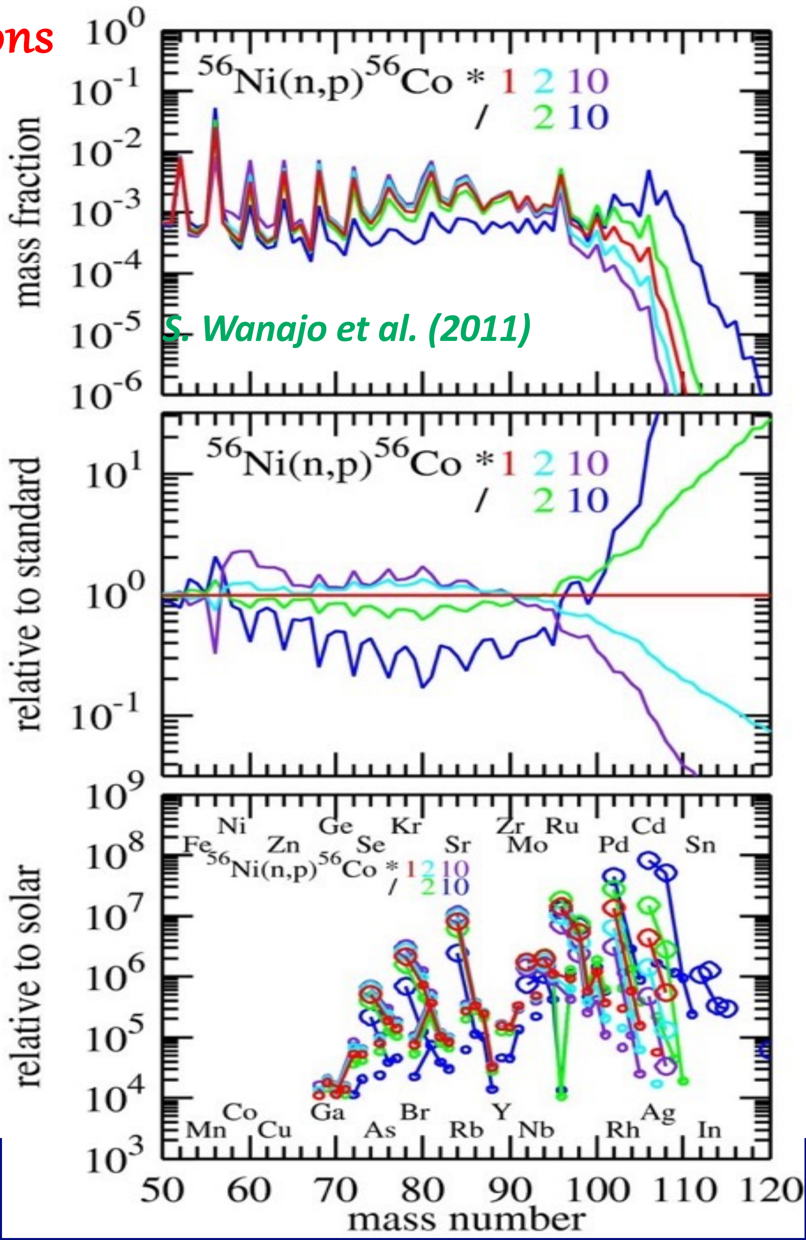
Nuclei in the Cosmos XVII 2023

September 17-22, 2023

Confirming the importance of νp process via ^{56}Ni(n,p) reaction measurement

Neutrino-driven winds in core-collapse supernovae can produce additional neutrons through anti-neutrino capture on protons; $\overline{\nu}_e + p \rightarrow n + e^+$

- With additional neutron flux, (n,p) cross sections on proton-rich nuclei are usually larger by orders of magnitude than that of proton captures, overcoming the waiting points in the rapid proton capture process
- ^{56}Ni is the most abundant seed nucleus, so any small neutron reaction such as (n,p) would make the most impact on yielding a final abundance during νp process. Until now, this direct measurement was impossible, due to the limited access to radioactive targets and unavailable neutrons' energy and flux
- A time-reversed reaction of ^{56}Co(p,n)^{56}Ni using a radioactive ^{56}Co beam at Facility for Rare Isotope Beams (FRIB) is being pursued; led by G. Perdikakis from CMU.



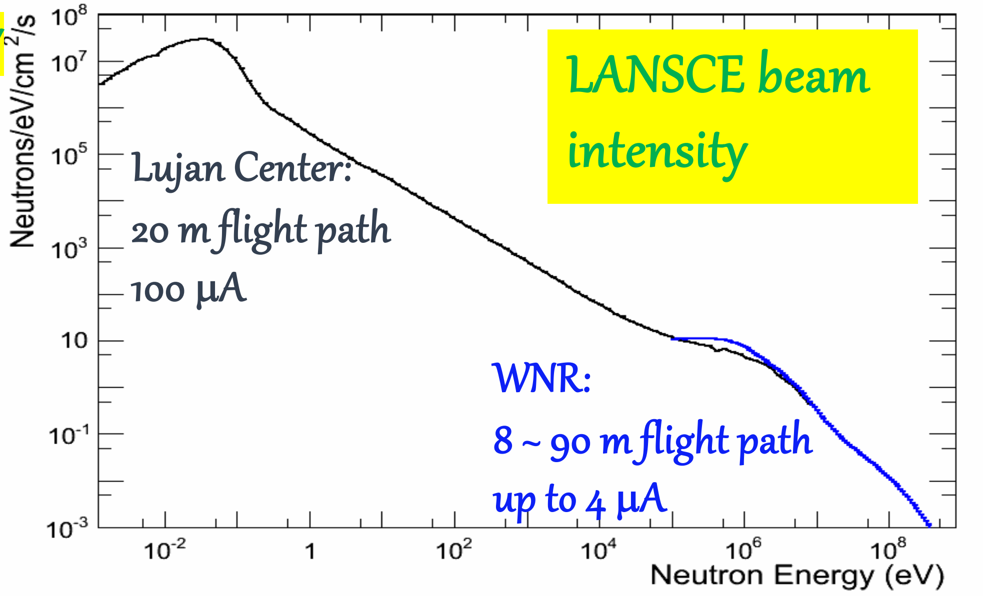
LANSCE is a multidisciplinary accelerator complex serving multiple missions

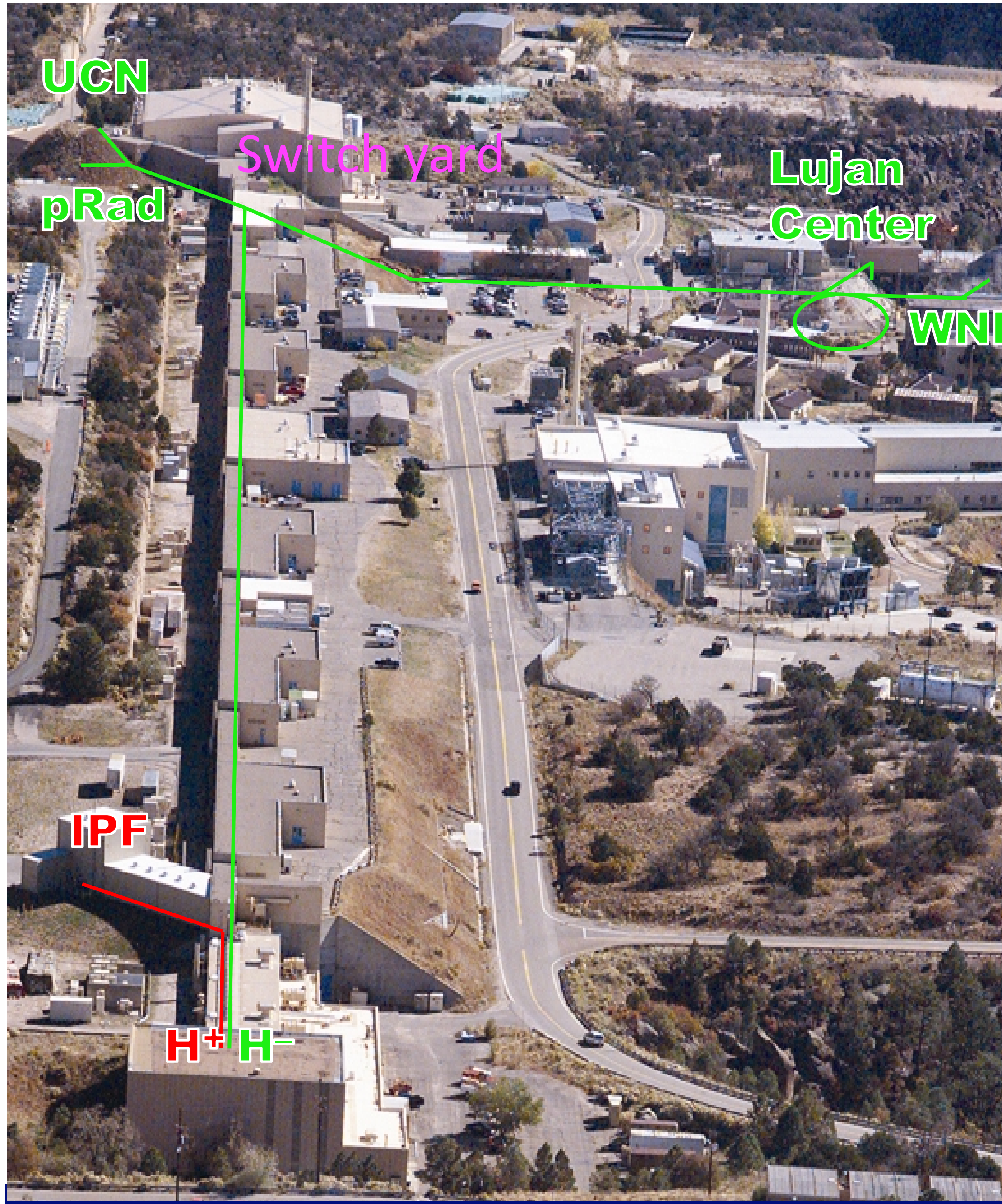
Uniquely capable of accelerating 800 MeV of H^- and 100 MeV of H^+ simultaneously, with 120 pulses per second shared among 5 facilities

1. Isotope Production Facility (DOE-Office of Science)
2. Proton Radiography (NNSA)
3. Ultra-Cold Neutron Source (DOE-Office of Science)
4. Lujan Center (NNSA)
5. Weapons Neutron Research (WNR) Facility (NNSA)

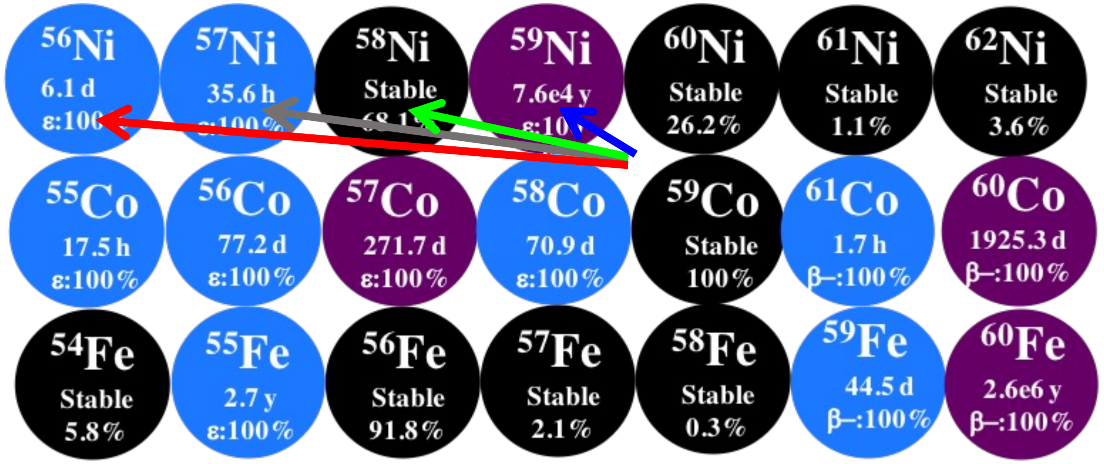
LANSCE beam energy

Lujan Center
-thermal ~ 100 keV
WNR
-100 keV ~ 600 MeV

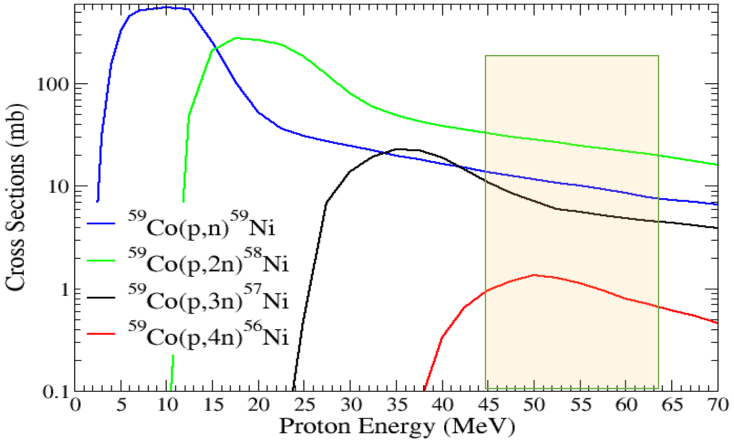


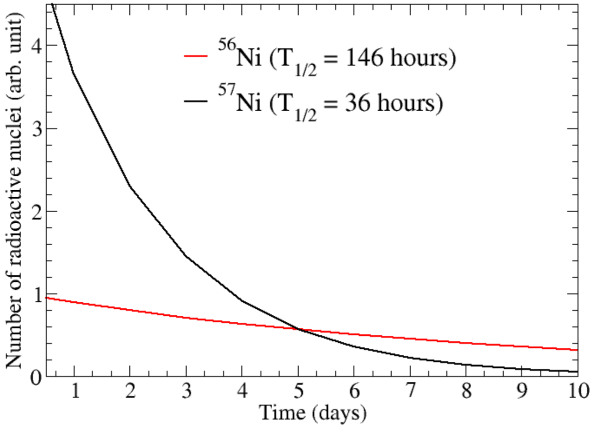


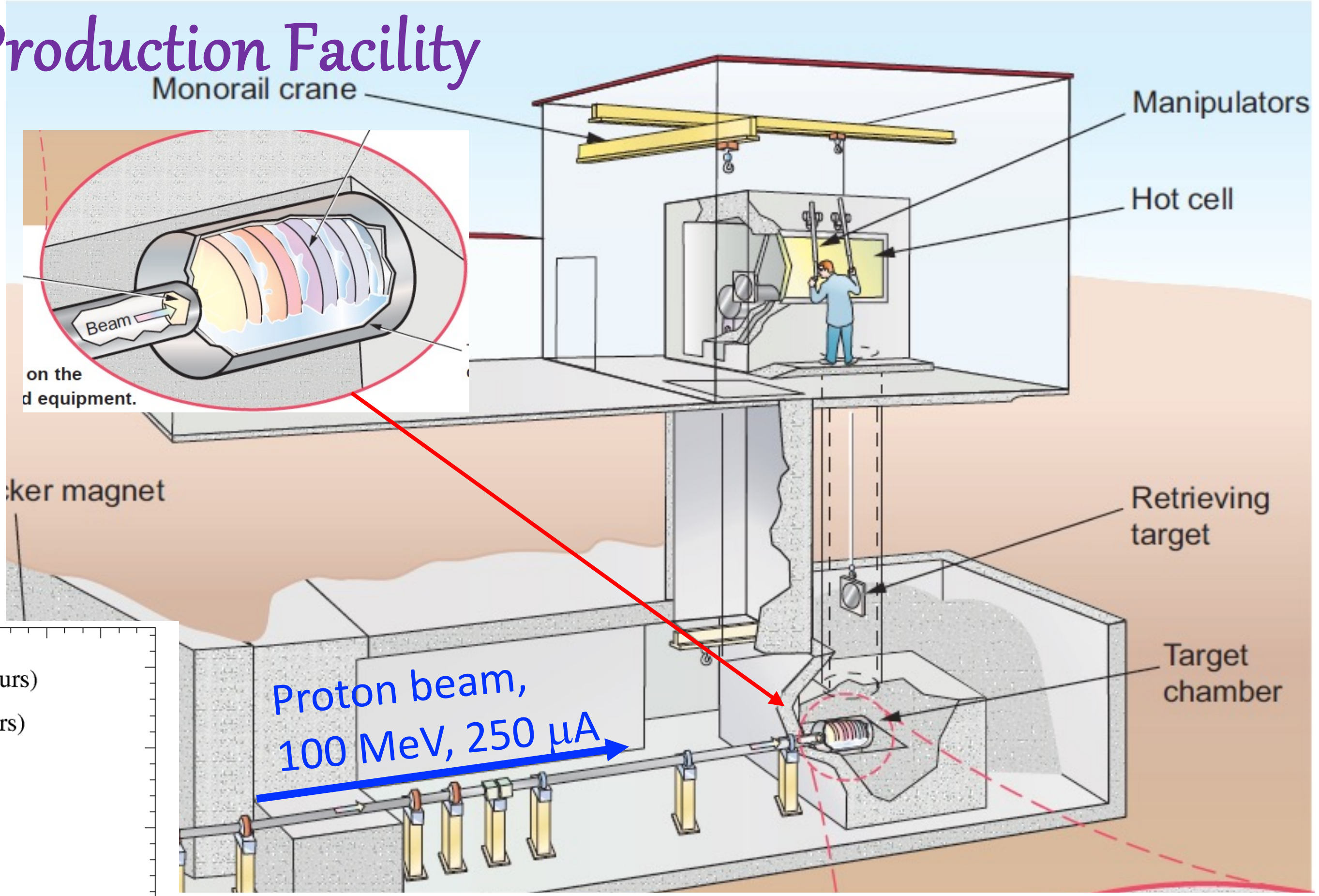
^{56}Ni Isotope Production at LANL-Isotope Production Facility



Ni isotope production cross sections

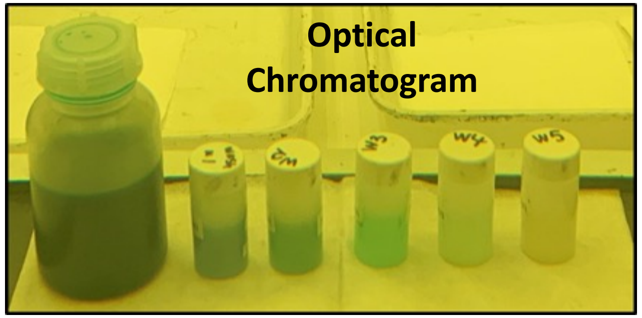






-At LANL, the first ^{56}Ni isotope was produced via ^{59}Co(p, 4n) at IPF, a reaction sample was fabricated after chemical separation at the Hotcell facility, and the ^{56}Ni(n,p) reaction was performed at LANSCE/WNR; -Produced ^{56,57,58,59}Ni isotopes by irradiating Co foils with proton energies at 92 MeV, 44-46 MeV, and 22-31 MeV, in order to validate the radionuclide production yields and chemical separation efficiencies at IPF

Ni/Co separation and target fabrication



- Improved Ni recovery from 40 % (initial) to 90 % (final)
- Uncertainty: 5-10 % for sample solution amount uncertainty inside hot cell operation ~ 1% for sample counting uncertainty
- Established reliable sample characterization methods for this project:

 - Analytical techniques:

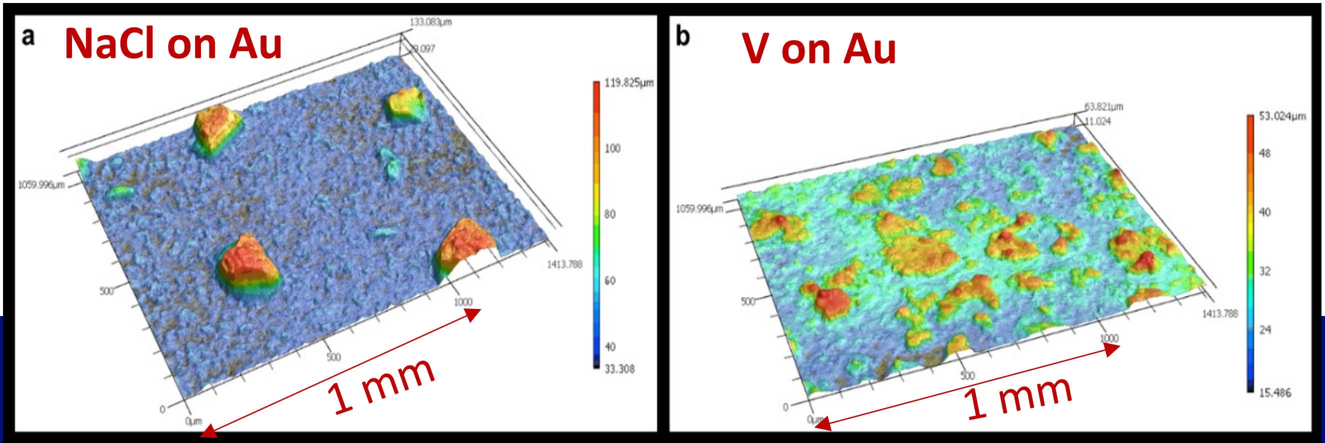
  a. Inductive coupled plasma-Optical emission spectroscopy (ICP-OES),

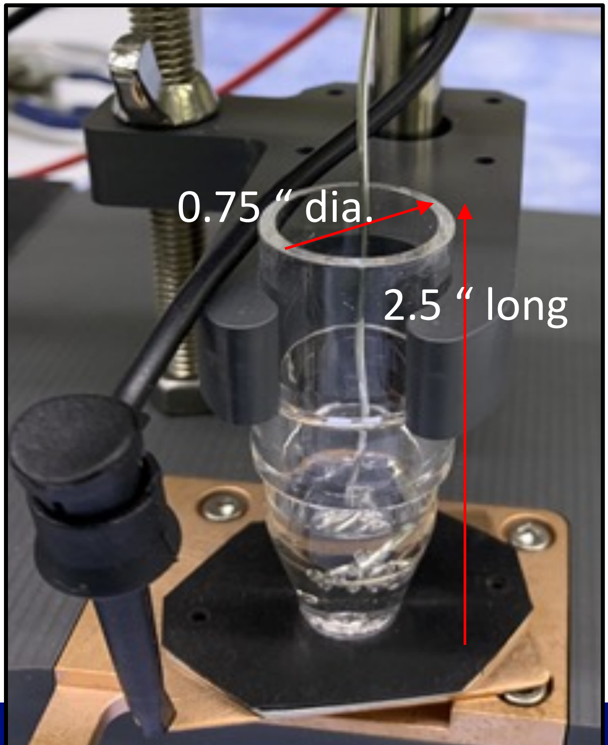
  b. SEM, SEM-EDS, c. X-ray Absorption Spectroscopy (XAS)

 - Radiometric techniques:

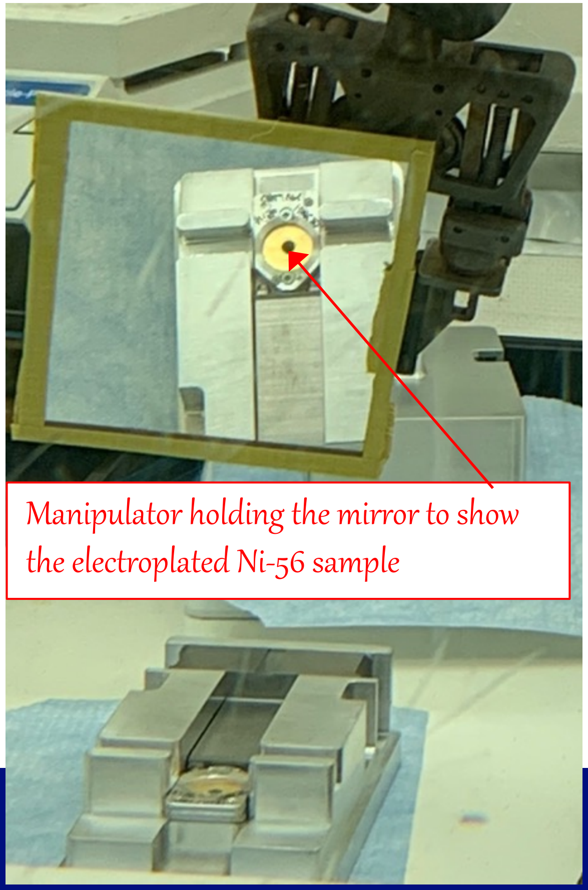
  a. liquid scintillator counting (LSC) for Ni-63, b. x-ray spectroscopy for Ni-59, c. gamma spectroscopy for Ni-56 & Ni-57

Optical 3D images





Customized Electroplating setup



Manipulator holding the mirror to show the electroplated Ni-56 sample

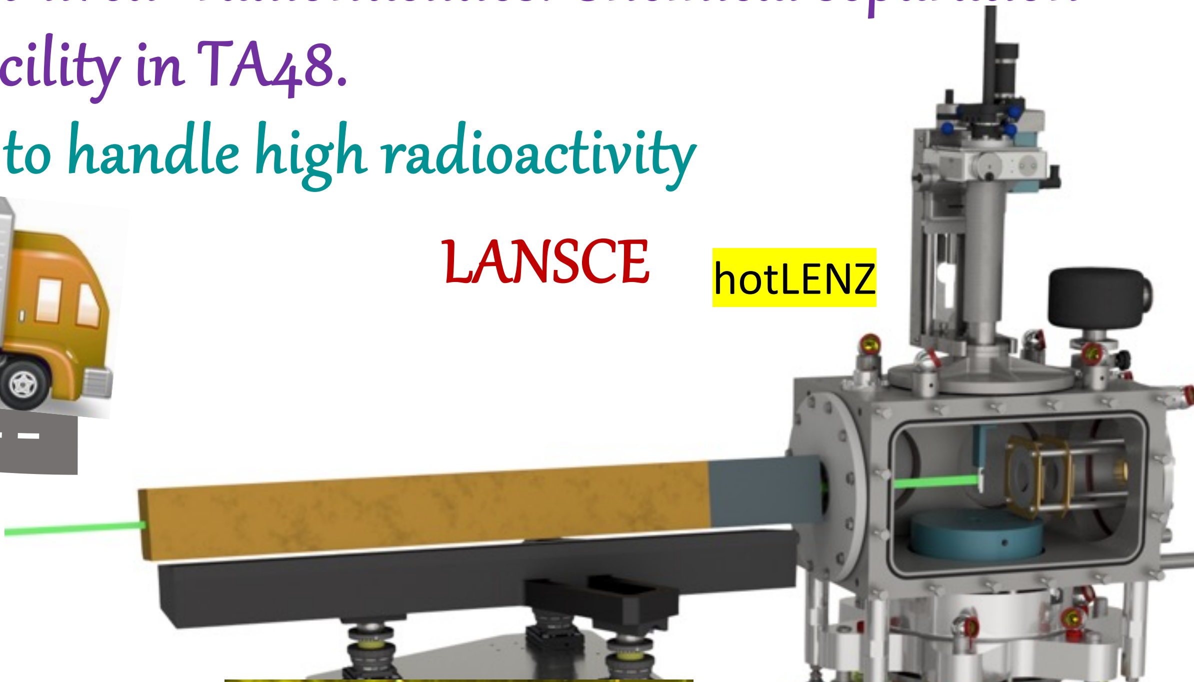
Isotope Production Facility at LANSCE produces "short-lived" radionuclides. Chemical separation and thin-target fabrication is performed at Hot Cell facility in TA48.

Great collaborator is the manipulator inside Hot Cells to handle high radioactivity

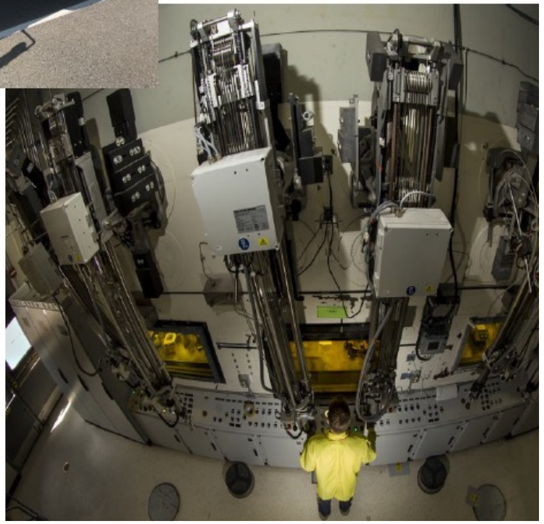
TA48

LANSCE

hotLENZ



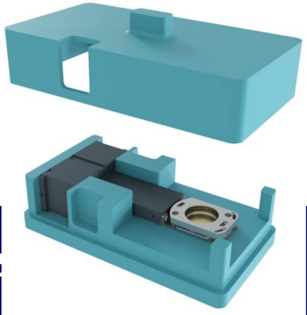
Hot Cell Facility



Picking up ^{56}Ni sample to prepare for packaging

IPF Hot Cell

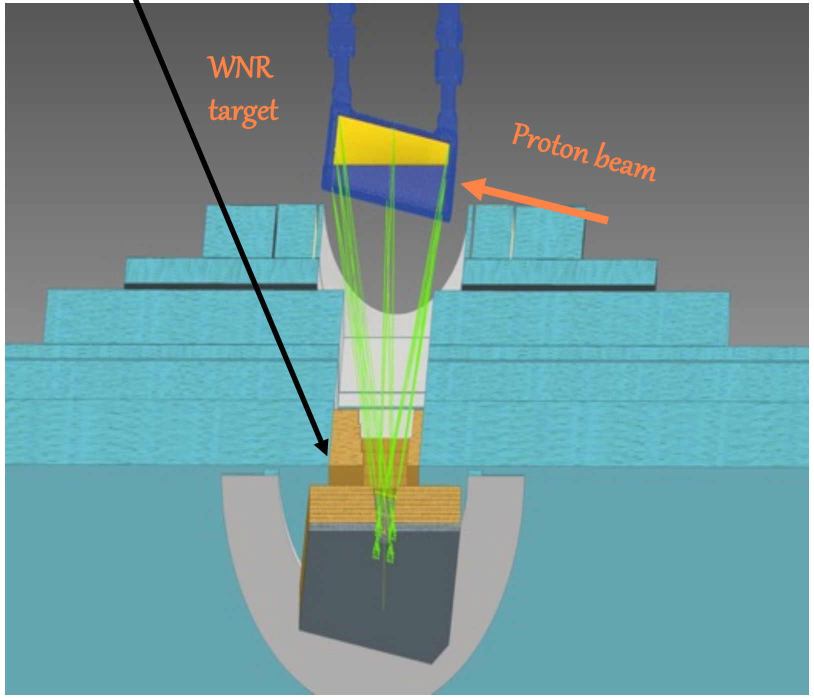
Inserting the ^{56}Ni plug into the instrument cask



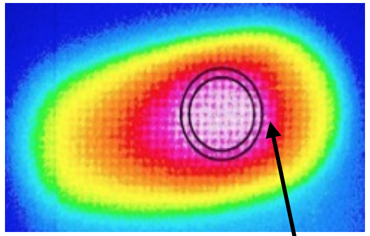
Sample housing for sturdy mounting during transport

Advanced (asymmetric-ratio) secondary collimation at WNR was optimized using Monte Carlo N-Particle (MCNP) code and Laser Tracker for ideal neutron flux, beam spot, and background, in order to increase the reaction signal sensitivity for highly radioactive sample

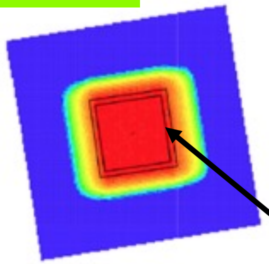
Advanced secondary collimation improved neutron flux and beam spot with immensely reduced background



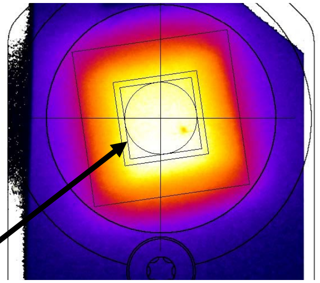
Beam image using conventional collimation



MCNP simulation using asymmetric collimation

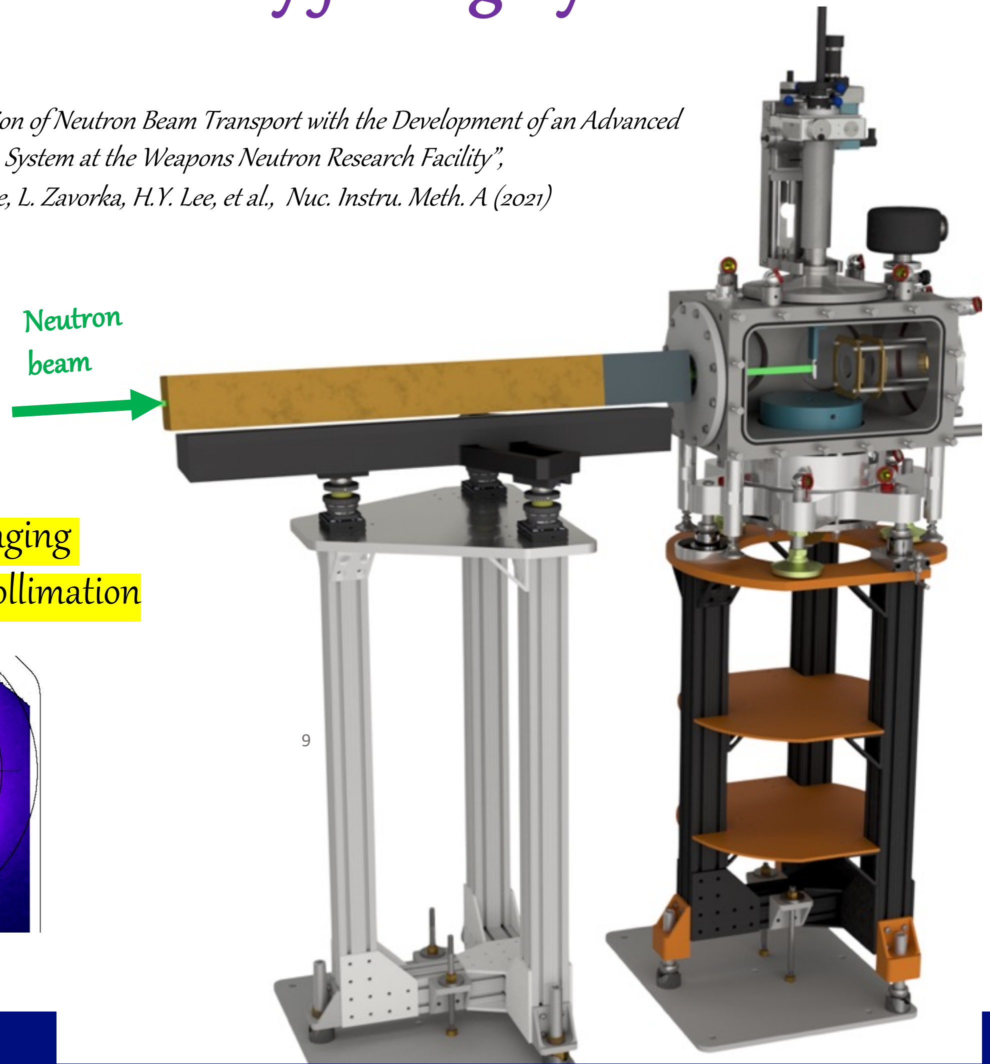


Improved Beam Imaging using asymmetric collimation



6 mm
col

"Optimization of Neutron Beam Transport with the Development of an Advanced Collimation System at the Weapons Neutron Research Facility",
B. DiGiovine, L. Zavorka, H.Y. Lee, et al., Nuc. Instru. Meth. A (2021)

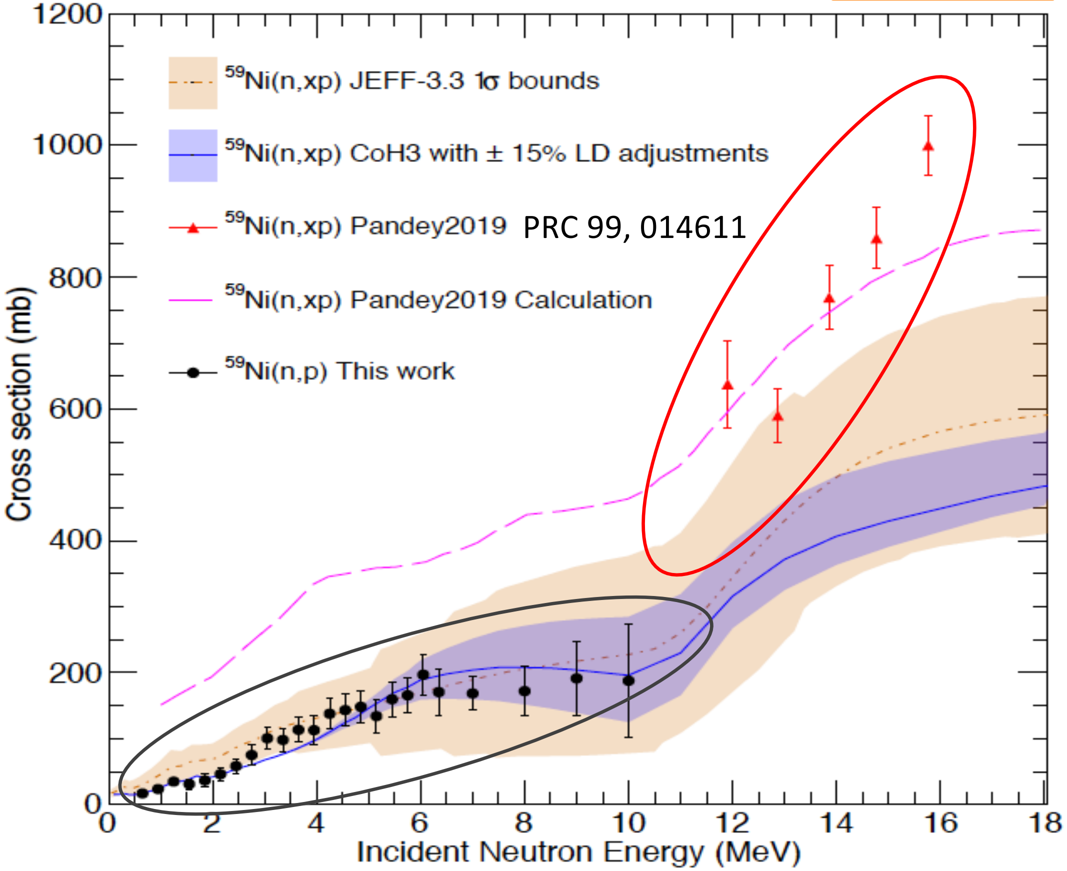


Ni-59: directly measured cross sections reveal a large discrepancy to the surrogate measurement

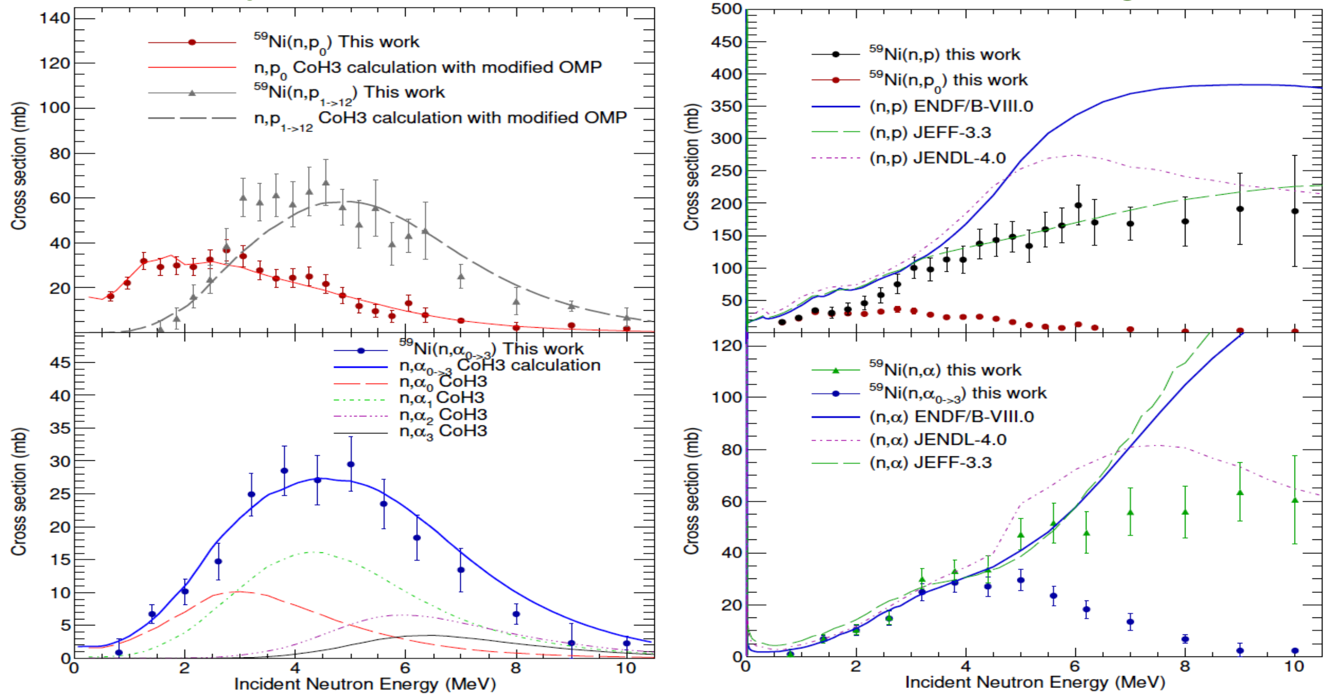
- Theoretical extrapolation to lower energies was based on **the surrogate measurement (red circle)** at the limited, high energy range and showed a large discrepancy ***(up to a factor of 4 overestimate),*** when compared with directly measured LANSCE data (black circle)
- Direct measurements on radioactive isotopes should be made, when feasible

Direct experimental measurements of cross sections for unstable long-lived radionuclide (^{59}Ni) are not possible as it does not occur in naturally available Ni isotopes.

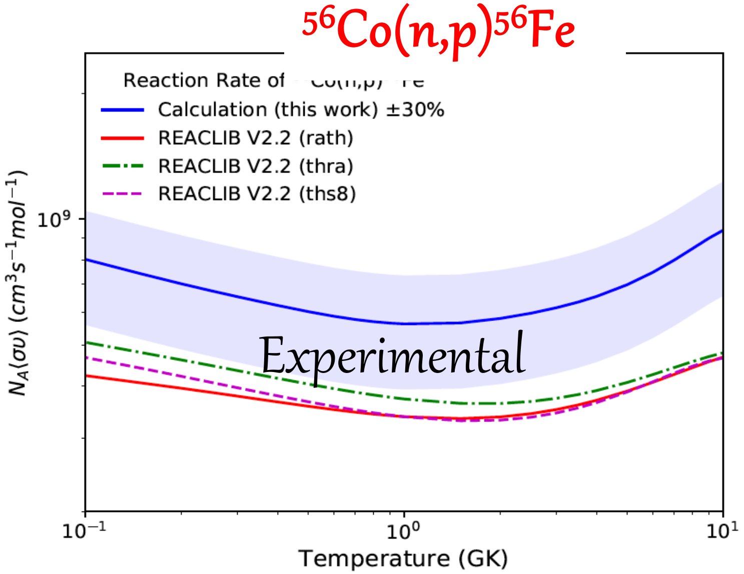
Pandey 2019



Double differential cross sections at a broad neutron energy range provide additional information as theoretical constraints in reaction modeling



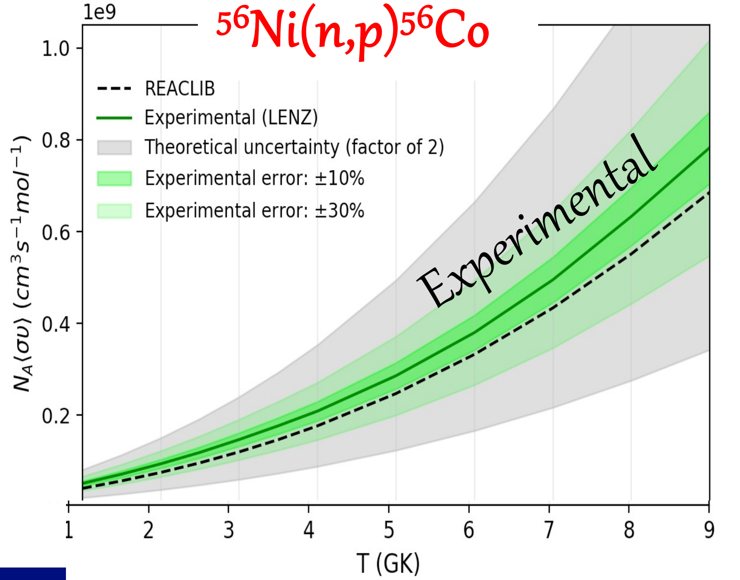
First directly measured (n,p) cross sections on ^{56}Co and ^{56}Ni ($T_{1/2}$=6 days, produced at IPF)

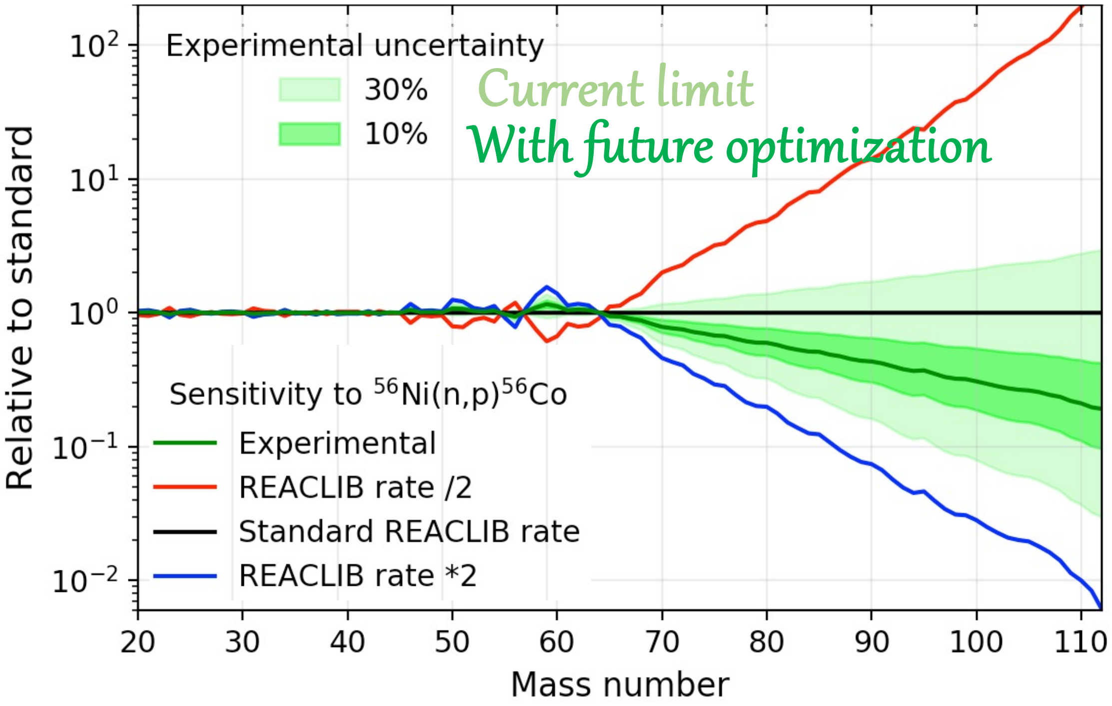


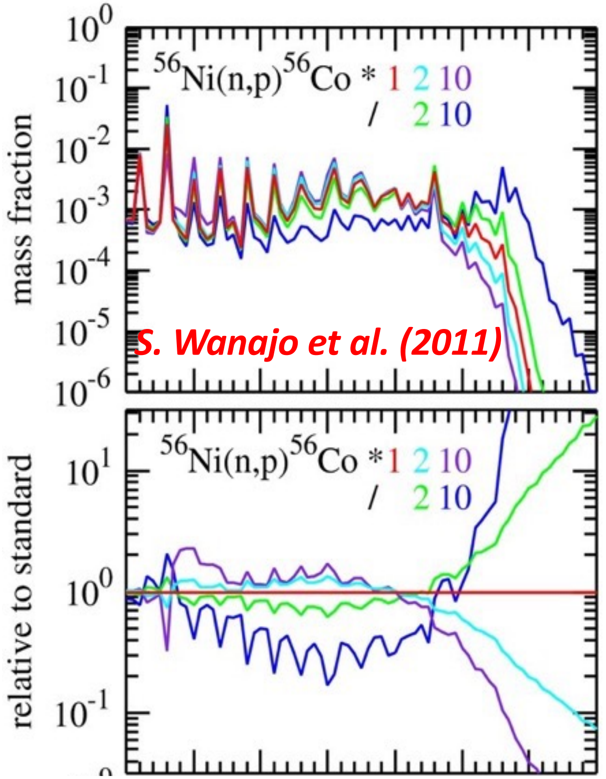
- Experimental reaction rates data are compared with statistical calculation & REACLIB
- Total uncertainties from the current measurement are ~30 %

Using the measured rate, the elemental abundances during νp-process are better understood by constraining nuclear input uncertainty and investigating further astrophysical parameters

^{56}Ni is the most abundant seed nucleus, so any small neutron reaction such as (n,p) would make the most impact on yielding a final abundance during νp process.

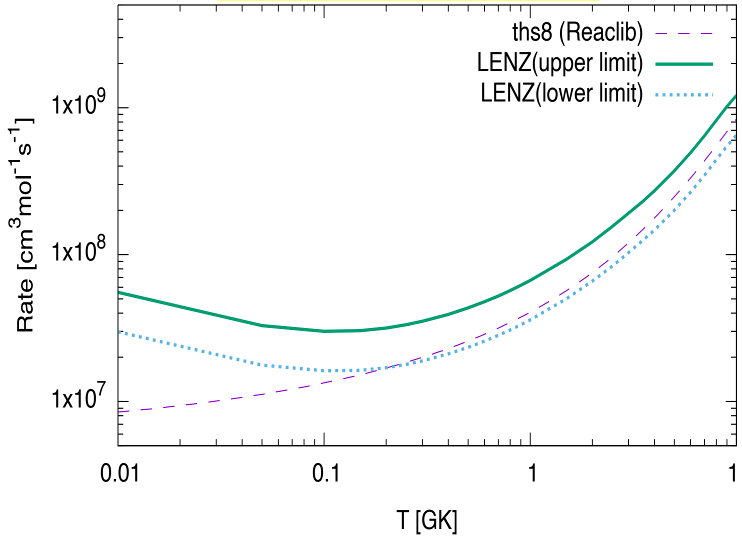






Hydrodynamics calculations for nu-p process synthesis

^{56}Ni(n,p) reaction rate



Hydrodynamical parameters

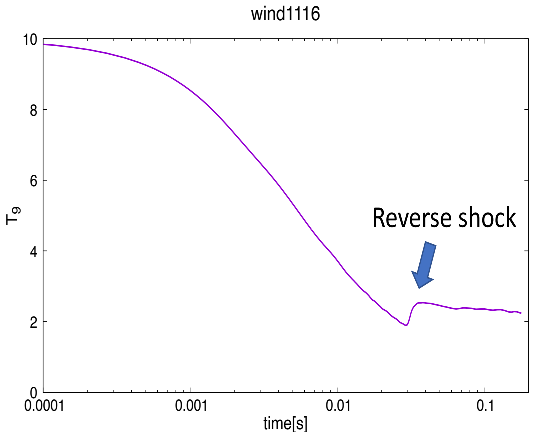
4.0s, 25 M_{sun}, Sasaki2022

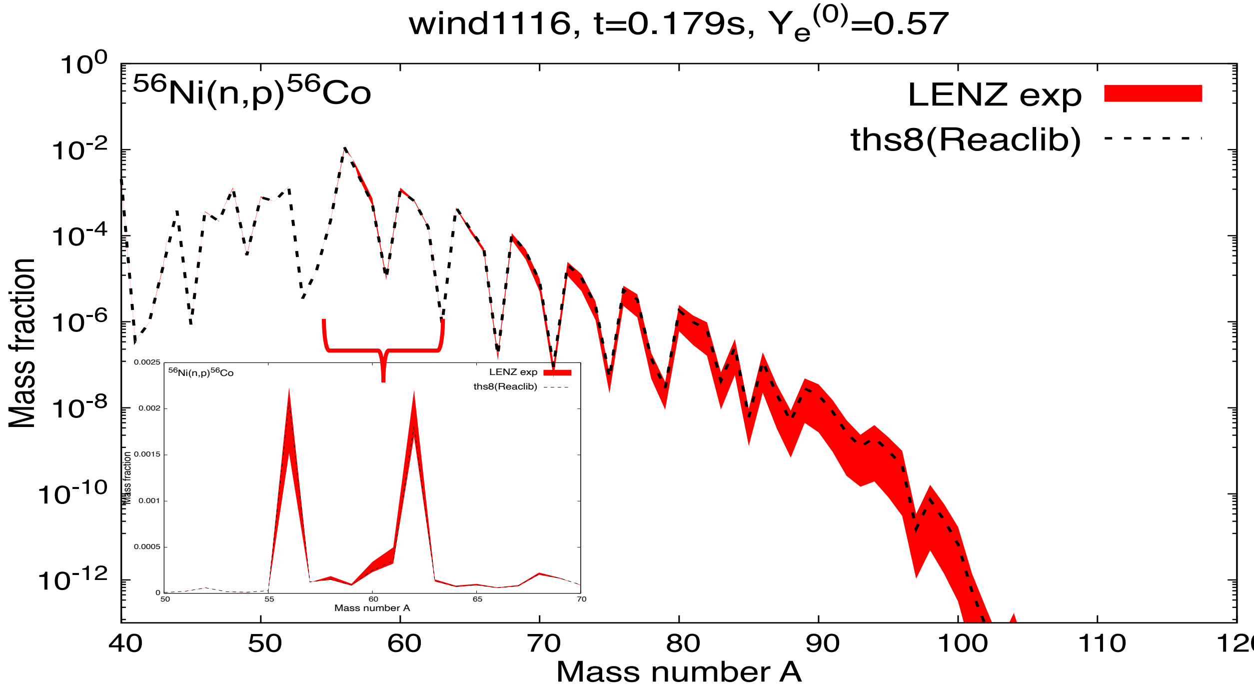
PNS Radius [km]	PNS Mass[$M_\odot$]	Y_e	τ_{dyn}[ms]	S[$k_B$nuc^{-1}]	$\dot{M}$[$M_\odot s^{-1}$]
12.6	1.75	0.578	86.2	138	2.04×10^{-6}

Wanajo (2011)

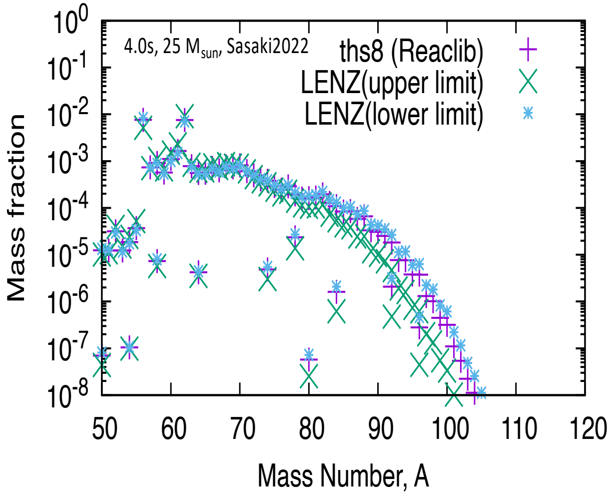
M_{ns} ($M_\odot$)	log L_ν (erg s^{-1})	r_{wt} (100 km)	$Y_{e,9}$[a]	$\dot{M}$ (10^{-4} $M_\odot$)	S (k_B)	τ_1[b] (ms)	τ_2[c] (ms)	$T_{wt,9}$[d]	$Y_{e,3}$[e]	Y_p/Y_h[f]	$n_{\bar{\nu}_e}$	Δ_n	log f_{max}[g]	nuc(f_{max})[h]	nuc(A_{max})[i]	Fig.
1.4	52.0	3.00	0.600	2.70	57.0	17.5	245	2.19	0.550	124	0.0834	10.3	7.16	^{96}Ru	^{106}Cd	All

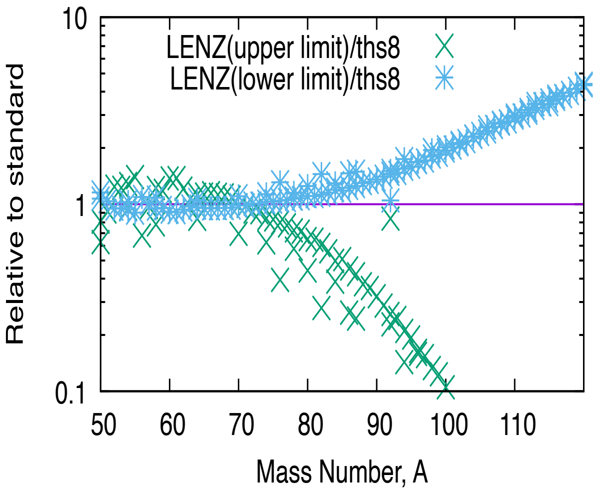
Wind termination study: temp profile and electron fraction Ye=0.570





Mass fractions after beta decays



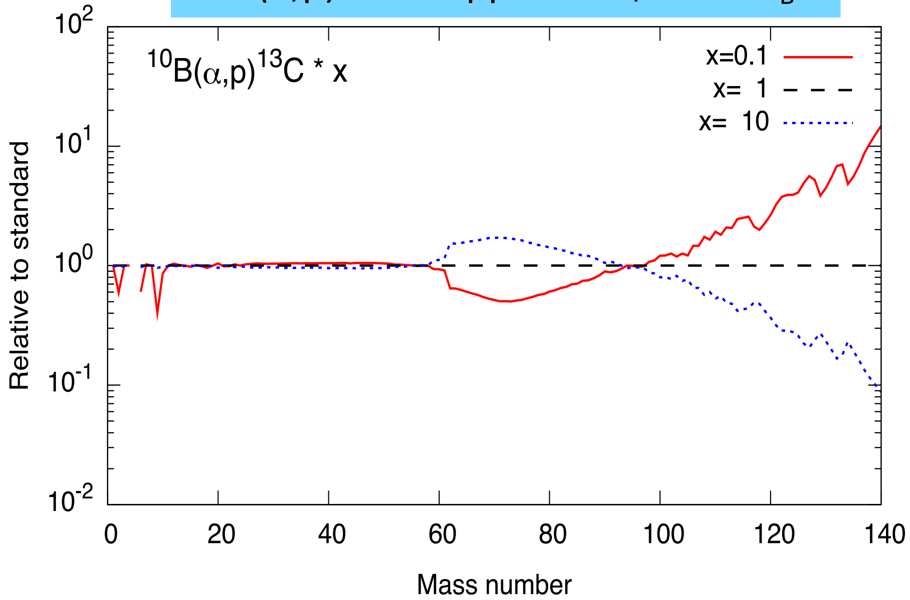


The nu-p process (T_9 = 1.5 – 3) does not terminate due to the reverse shock, while considering two neutrino reactions:

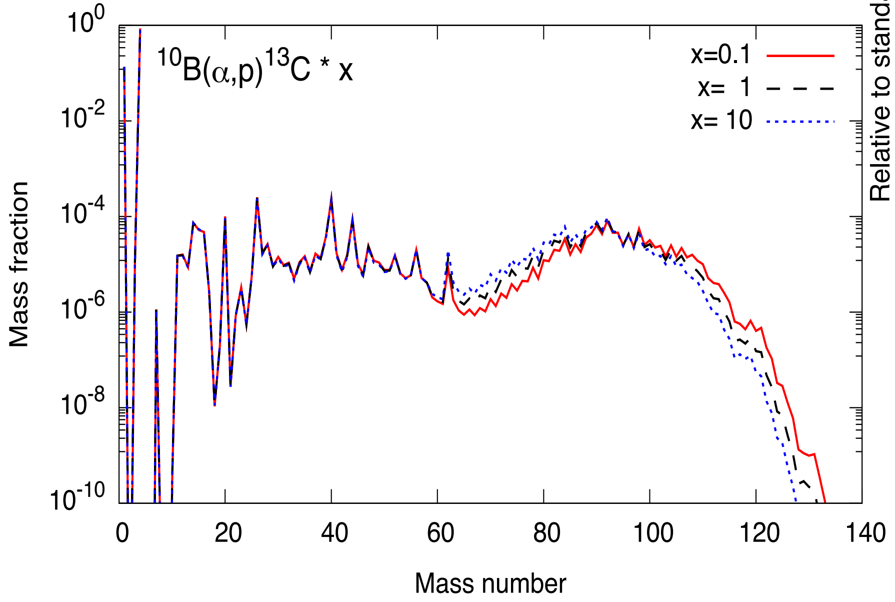
$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Sensitivity study of $^{10}B(\alpha,p)^{13}C$ rate while fixing $^{56}Ni(n,p)$ rate to LANL experimental rate upper and lower limits

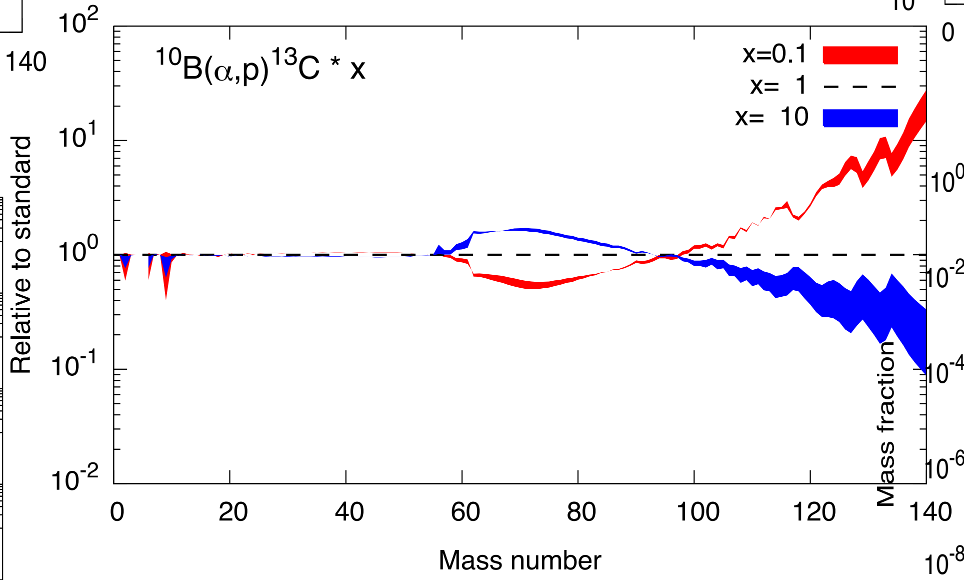
^{56}Ni(n,p) LENZ upper limit, S=100k$_B$



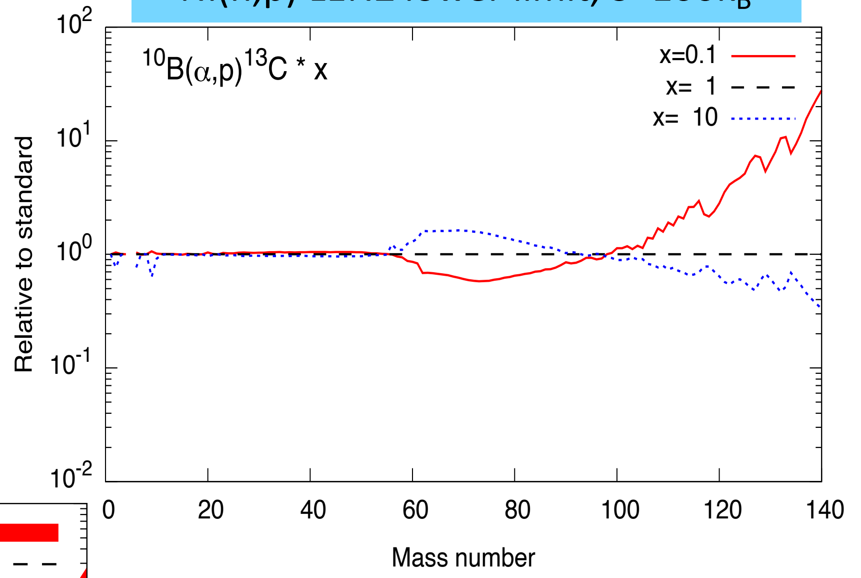
^{56}Ni(n,p)^{56}Co LENZ upper limit, S=100k$_B$



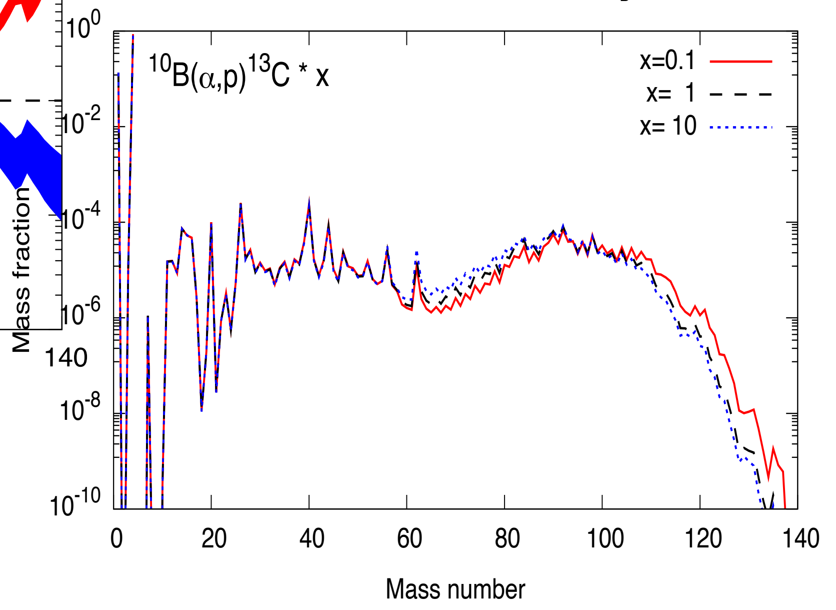
^{56}Ni(n,p)^{56}Co LENZ, S=100k$_B$



^{56}Ni(n,p) LENZ lower limit, S=100k$_B$



^{56}Ni(n,p)^{56}Co LENZ lower limit, S=100k$_B$

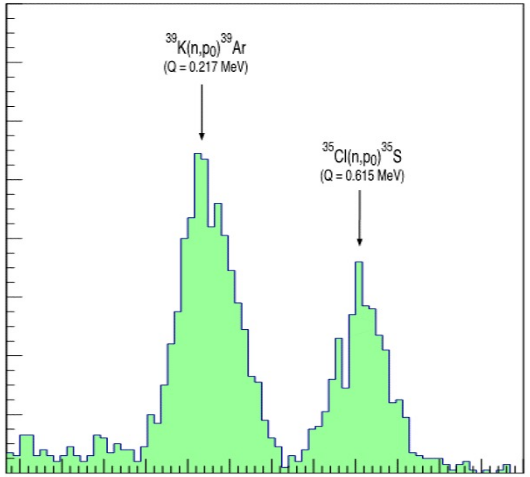


Directly measured (n,p) and (n,α) cross sections on ^{40}K ($T_{1/2}$= 1.3 Gy)

Led by P. Gastis

- For the interest of radiometric dating and radiogenic heating of exoplanets as destruction mechanism for ^{40}K
- total 13.8 mg of ^{40}KCl material was procured from Isoflex (97 % chemical enrichment, 12.8% isotopic enrichment)
- Thin film was fabricated using electrospray deposition technique by S. Dede and K. Manukyan at U. of Notre Dame

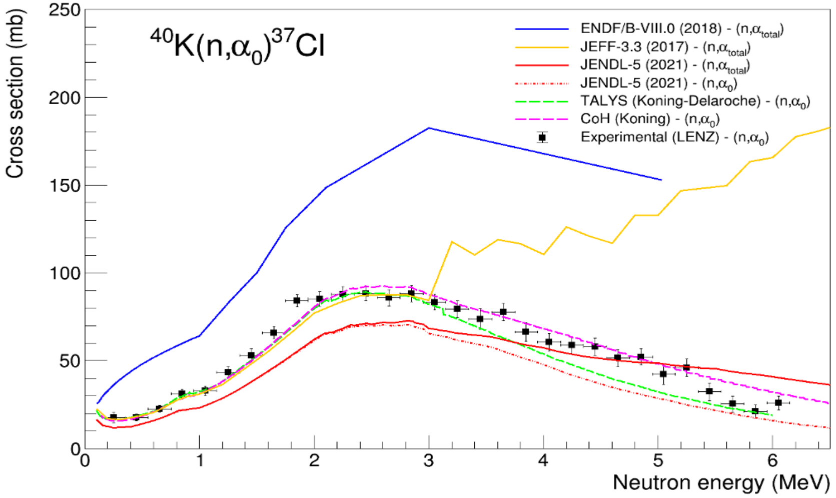
Ratios of partial cross sections of ^{39}K(n,p$_o$) and ^{35}Cl(n,p$_o$) reactions in the enriched and natural KCl targets confirm the atomic percentages between Cl and K of the enriched targets

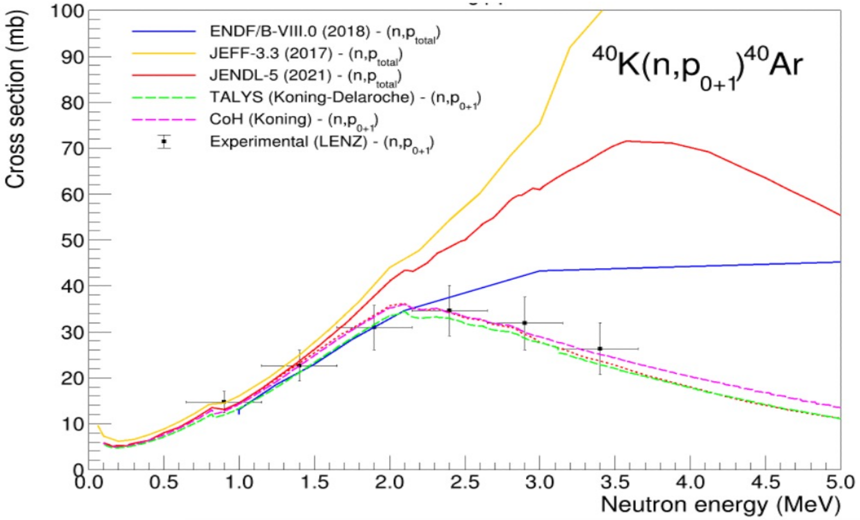


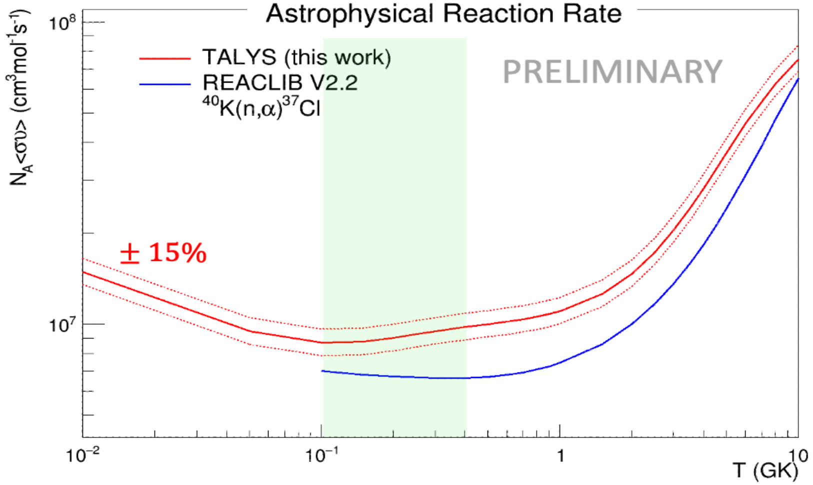
Reconstructed Q-values for (n,p) reactions of ^{39}K(n,p$_o$) (Q = 0.217 MeV) and 35Cl(n,p$_o$) (Q = 0.615 MeV)

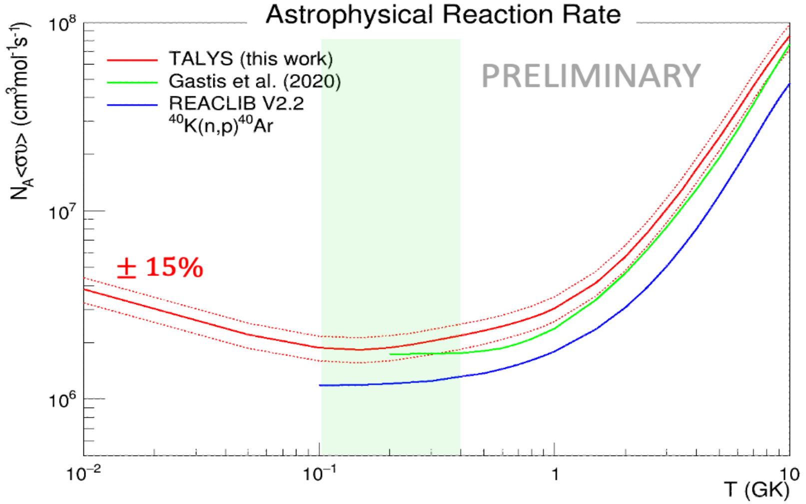
"Electrospraying Deposition and Characterizations of Potassium Chloride targets for Nuclear Science Measurements", S. Dede, S. D. Essenmacher, et al., Nucl. Instr. Meth. A (2023)

LANSCE cross sections and experimentally determined reaction rates







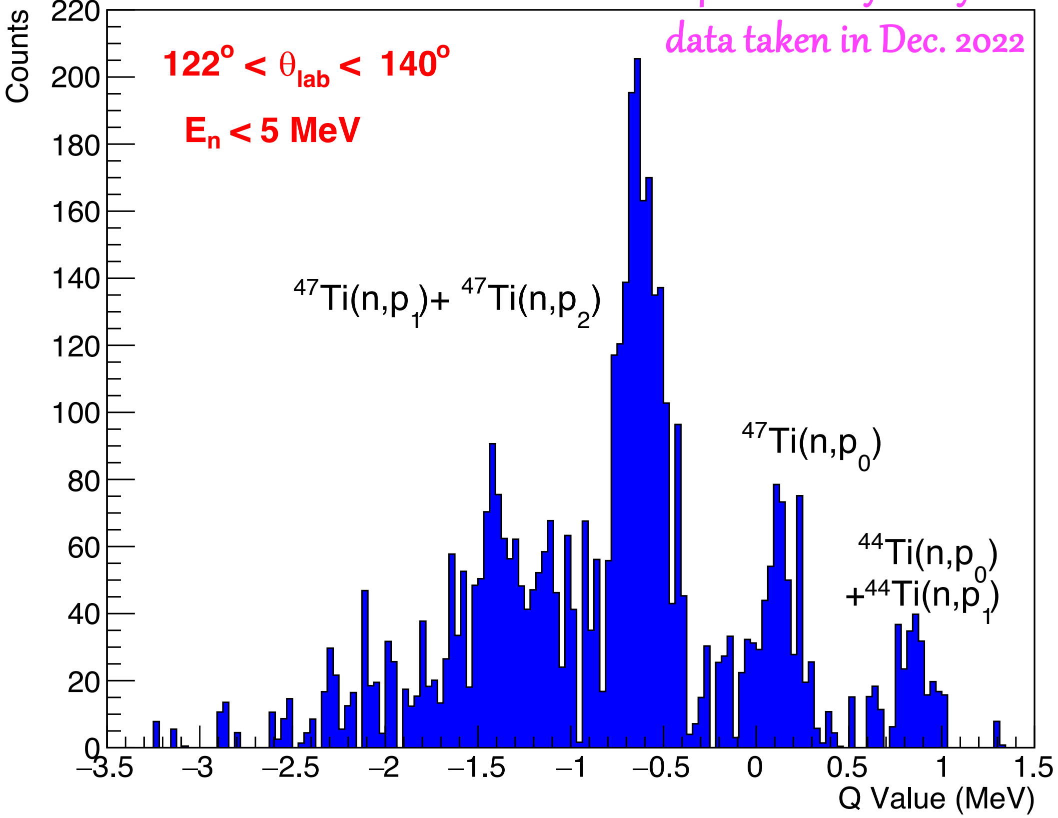


Directly measured (n,p) and (n,α) cross sections on ^{44}Ti ($T_{1/2}$= 59.1 y)

Led by S. Kuvin & H. Jayatissa

- For the interest of gamma-ray astronomy and nucleosynthesis in supernovae, as destruction mechanism for ^{44}Ti
- total 42 μCi of ^{44}Ti ($4X10^{15}$, 0.30 mg) was produced via $^{45}Sc(p,2n)$ at TRIUMF in 1999
  (natural Ti was 660 times more than that of ^{44}Ti)
- Thin film $^{44}TiO_2$ was fabricated using electroplating technique with 96% deposition yield and 85% recovery of 44Ti in the chemical separation

LENZ preliminary analysis:
data taken in Dec. 2022



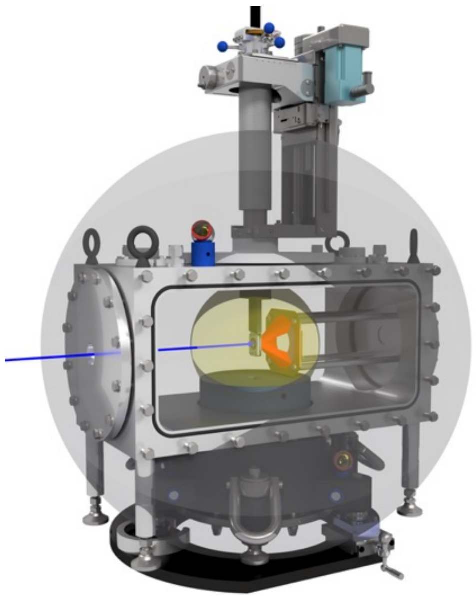
IPF produced radioactive isotopes; purchased through National Isotope Distribution Center (NIDC) at ORNL
^{44}Ti 100 μCi
^{26}Al 10 nCi

Plans to fabricate IPF samples for 2023 run cycle

Sean Kuvin's LANL LDRD Early Career Research Award in 2023-2025: *"First fast-neutron induced reaction measurements on ^{26}Al and ^{44}Ti for enhancing the interpretation of astrophysical signals"*

Future Work: Optimized solenoid spectrometer for reaction studies with radionuclides to provide *high fidelity* data for applications

Conventional (n,Z) studies



Optimized

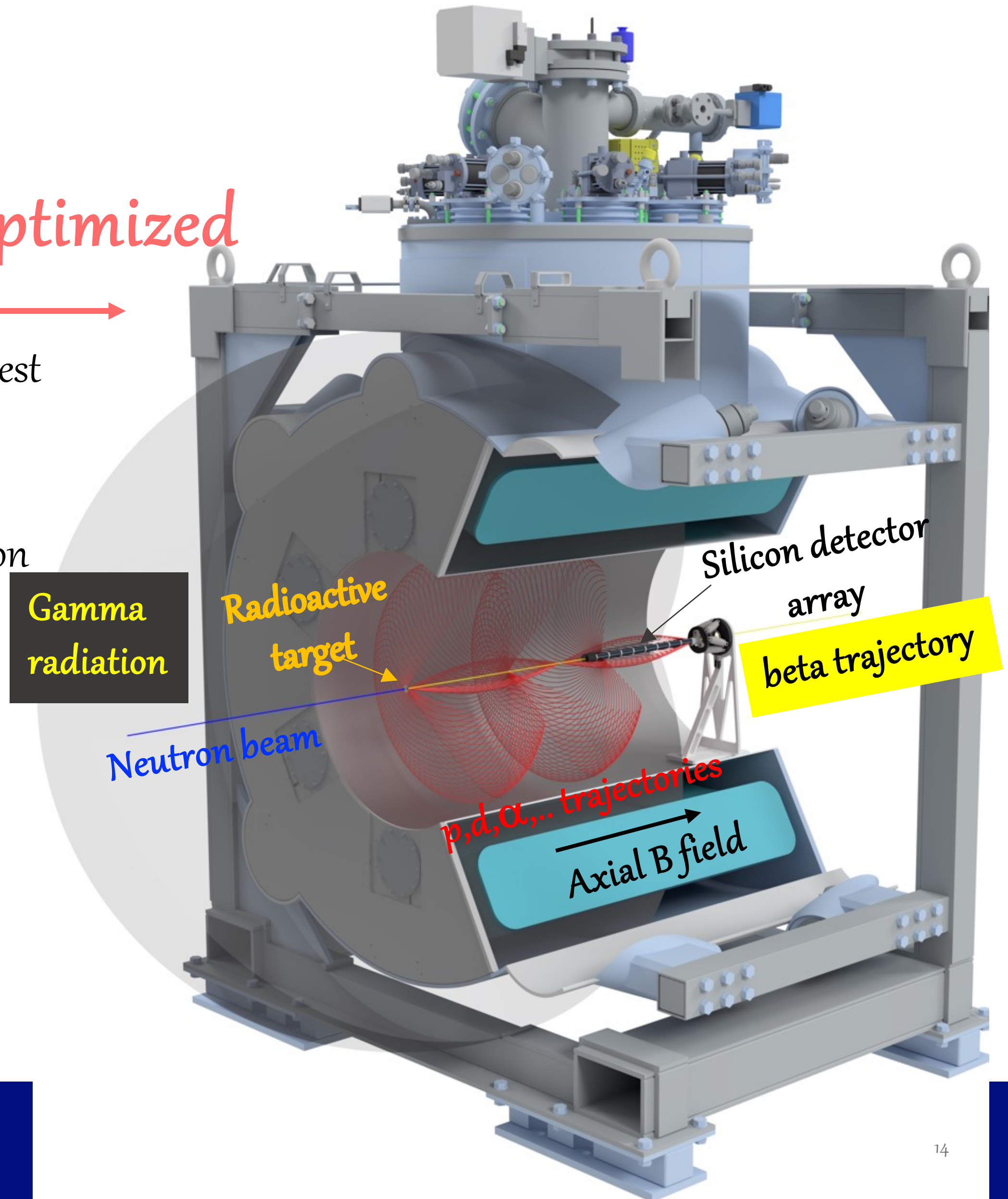
- Reduced radiation damage to detectors to achieve best experimental resolutions
- Solid angle coverage ~ 2π
- Different charged particles are identified by cyclotron period

Blue line: LANSCE neutron beam

Yellow sphere: intrinsic beta decays

Gray sphere: intrinsic gamma decays

Red envelop: solid angle coverage for reaction charged particles



Summary and Outlook

- LANSCE with Isotope Production Facility provides a unique capability to perform neutron-induced nuclear reaction studies directly over a broad energy range on "short-lived" radioactive nuclei
- Recently available (n,p), (n,α) and (n,γ) rates from LANSCE showed impacts on our understanding of different processes in nucleosynthesis, and more to come for nuclear astrophysics interests
- Direct measurements with radionuclides not only determine reaction cross sections, but also help constrain theoretical uncertainties in reaction modeling and update ENDF for missing cross sections
- With the development of the optimized solenoidal spectrometer and the neutron target facility, LANL will continue to advance radioactive reaction studies at LANSCE.

Acknowledgement

US Nuclear Data Program