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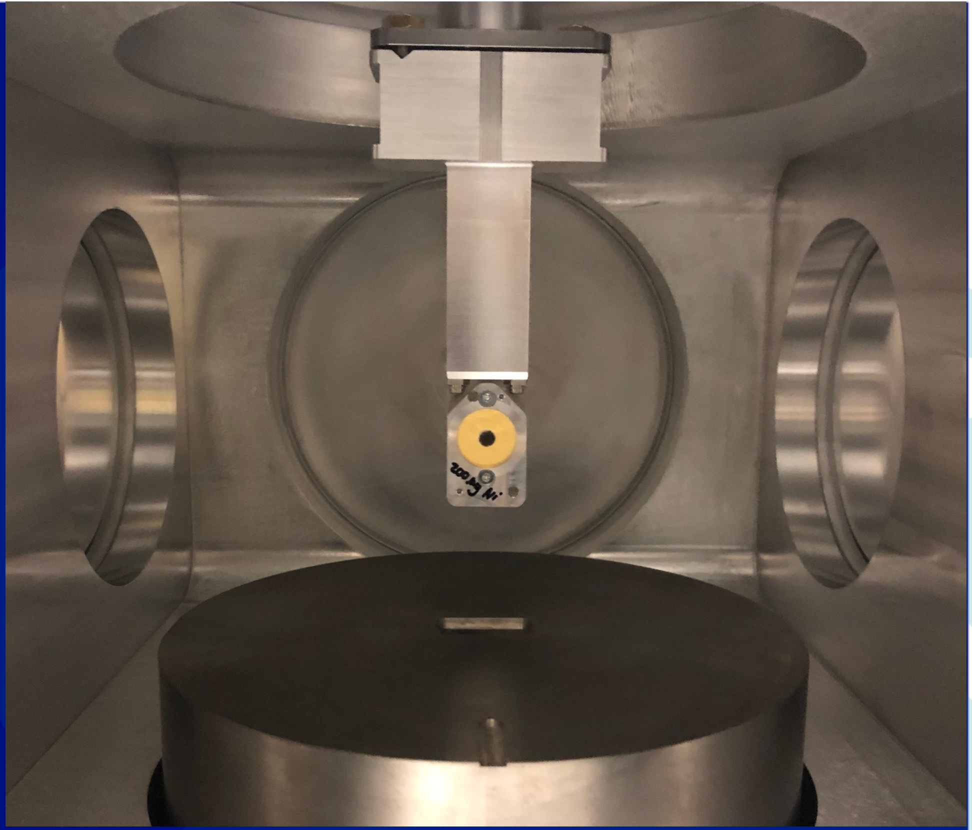


Updates on experimental reaction studies on radioactive nuclei including astrophysical impacts and solenoidal development at LANSCE

Hye Young Lee

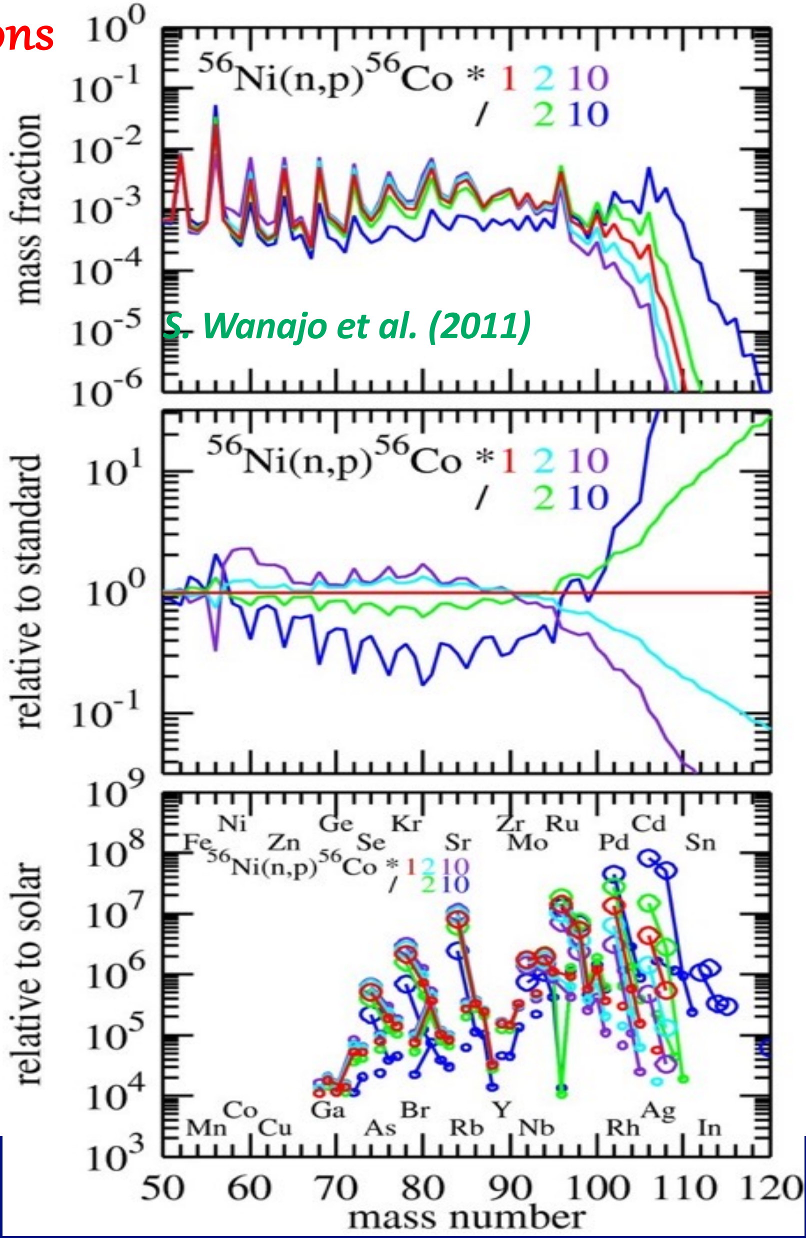
Physics Division, Los alamos National Laboratory

*Compound Nuclear Reactions and Related Topics (CNR*24)*

July 8-12, 2024

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; $\overline{\nu}_e + p \rightarrow n + e^+$



S. Wanajo et al. (2011)

- 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)

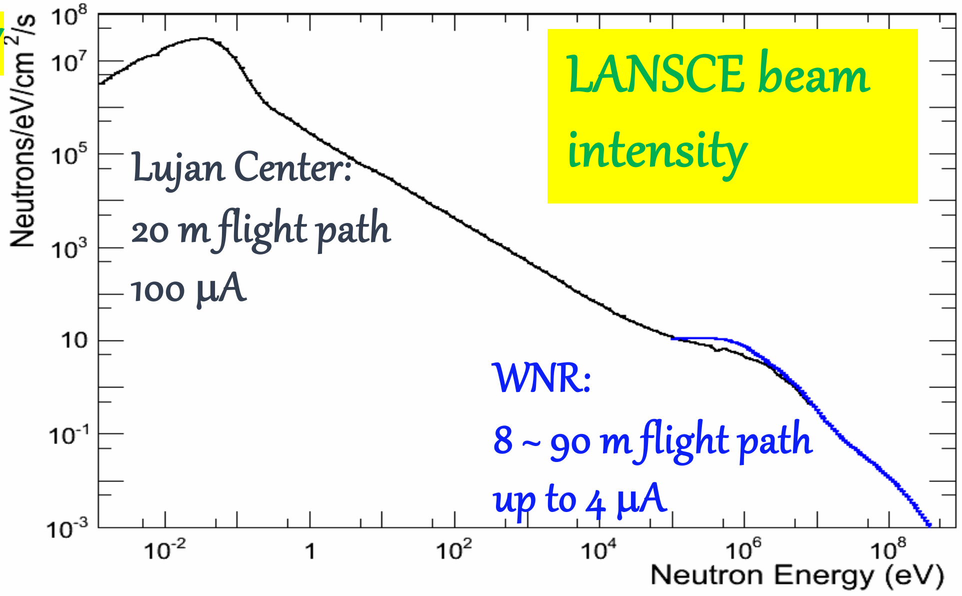
LANSCE beam energy

Lujan Center

-thermal ~ 100 keV

WNR

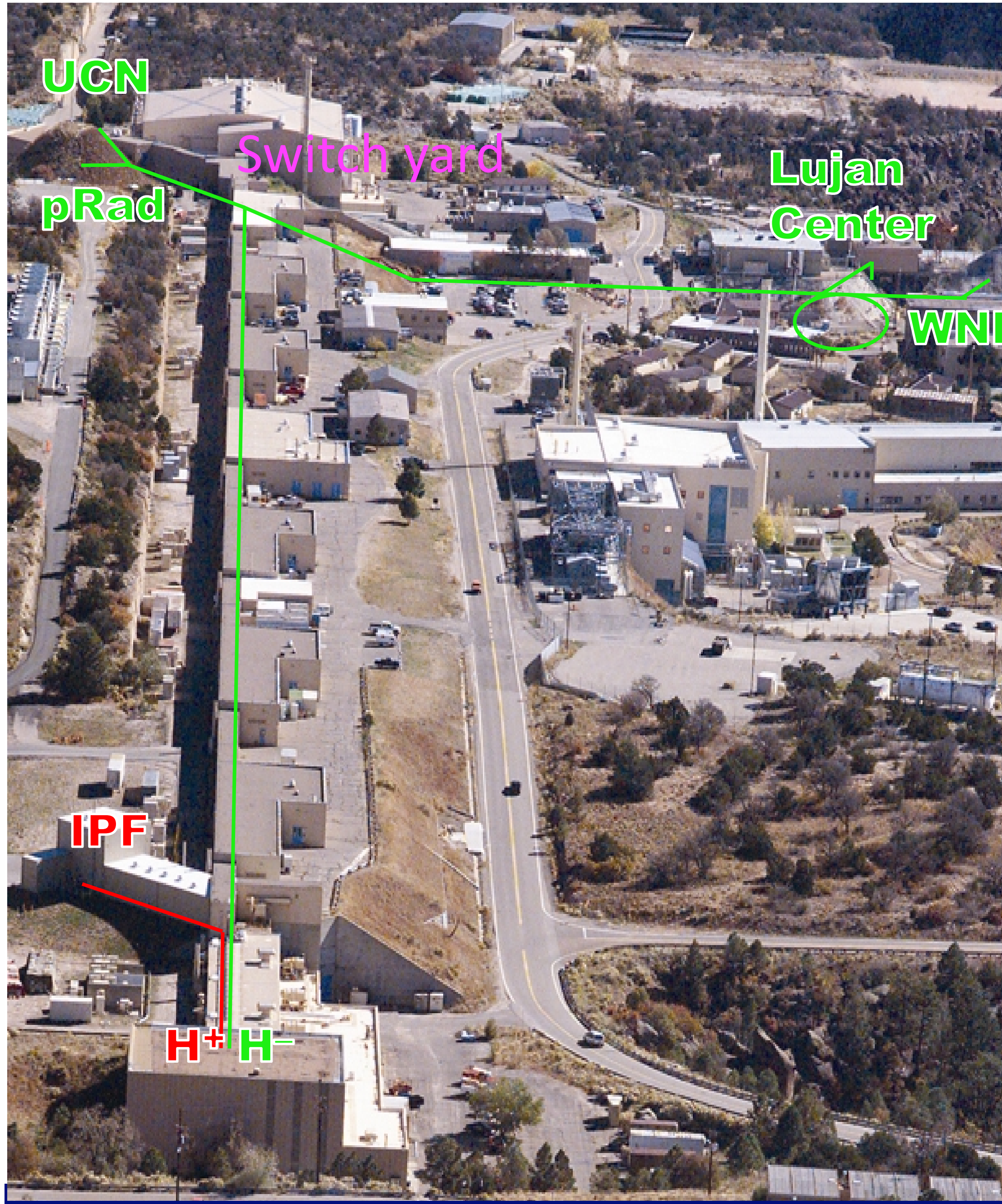
-100 keV ~ 600 MeV



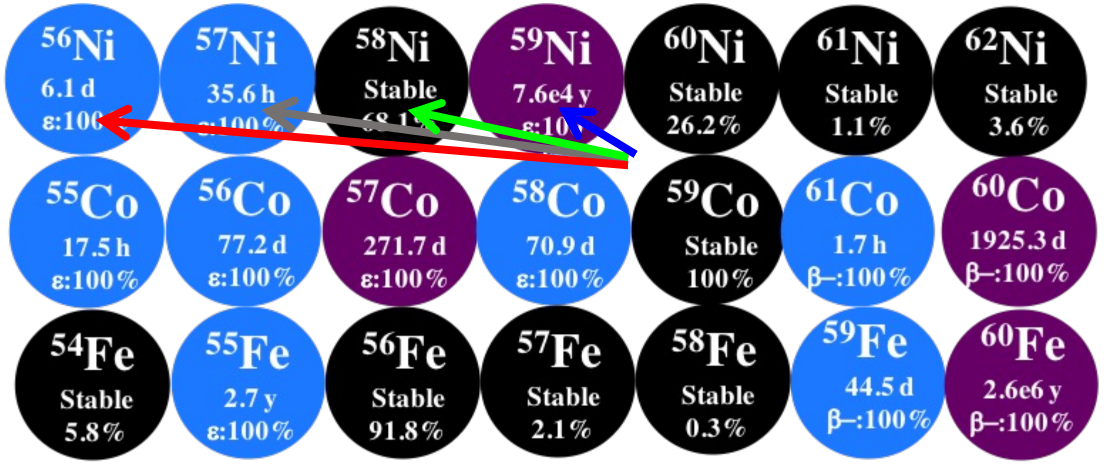
LANSCE beam intensity

Lujan Center:
20 m flight path
100 µA

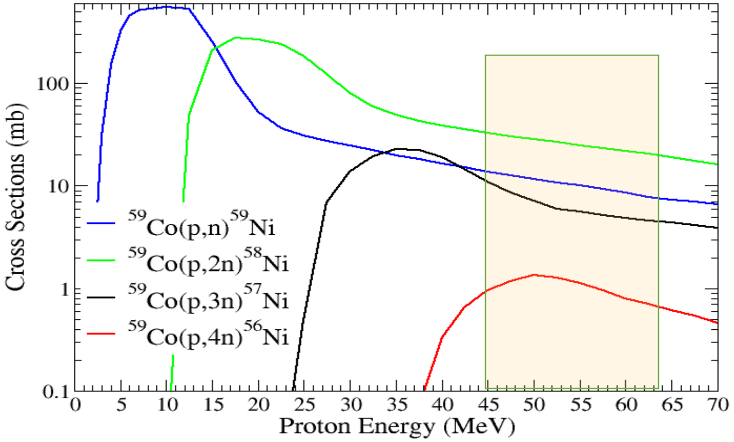
WNR:
8 ~ 90 m flight path
up to 4 µA

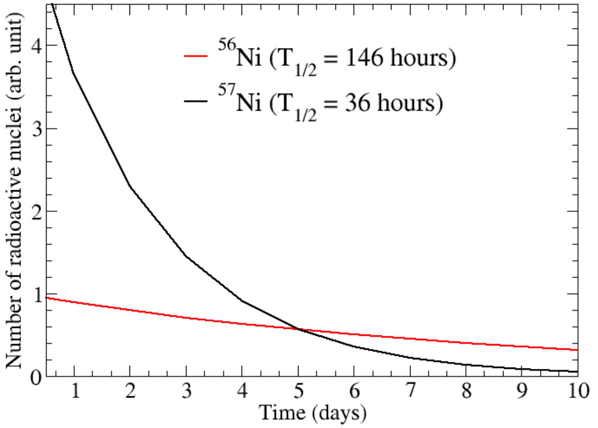


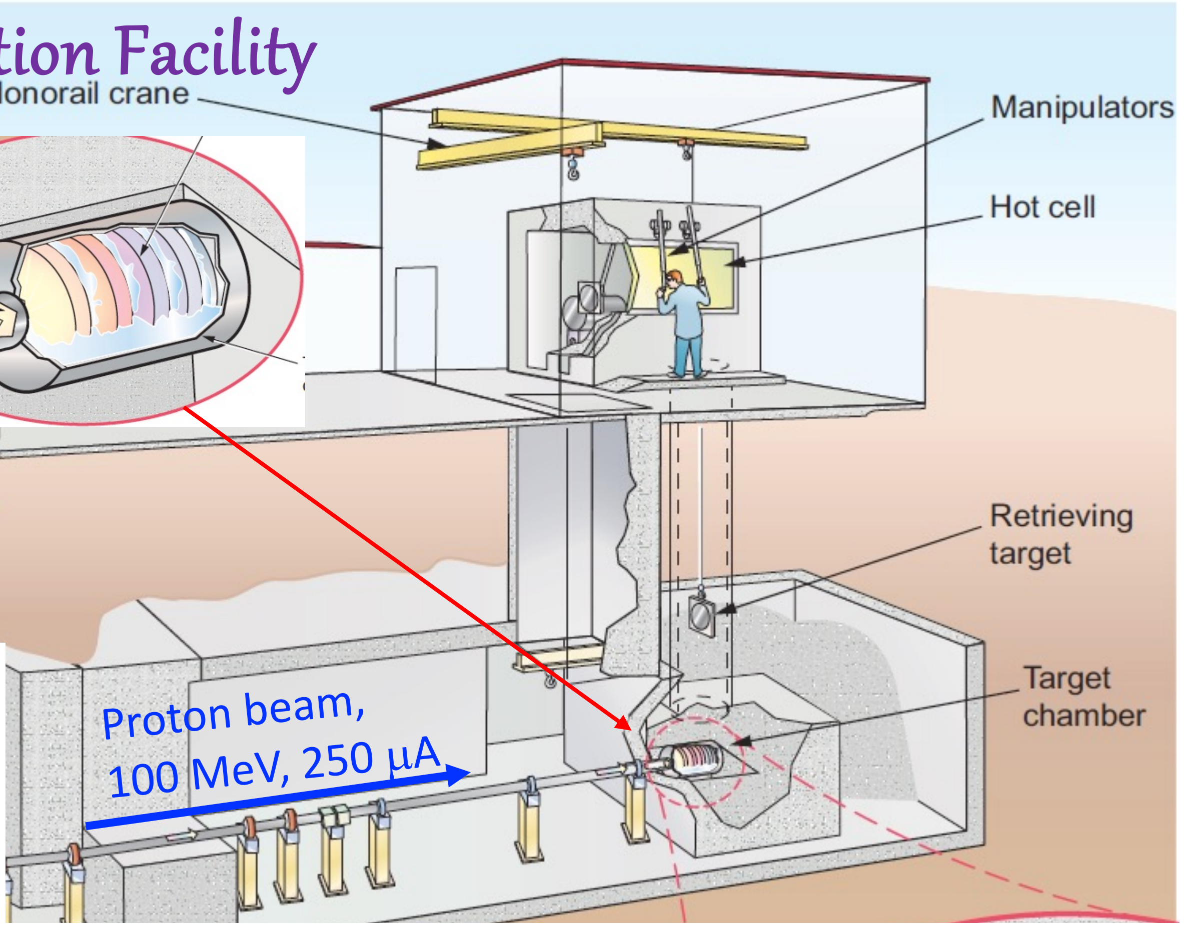
^{56}Ni Isotope Production at LANL-Isotope Production Facility



Ni isotope production cross sections



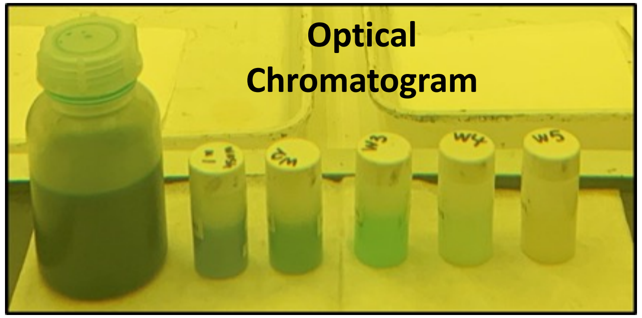




Proton beam, 100 MeV, 250 μA

-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:

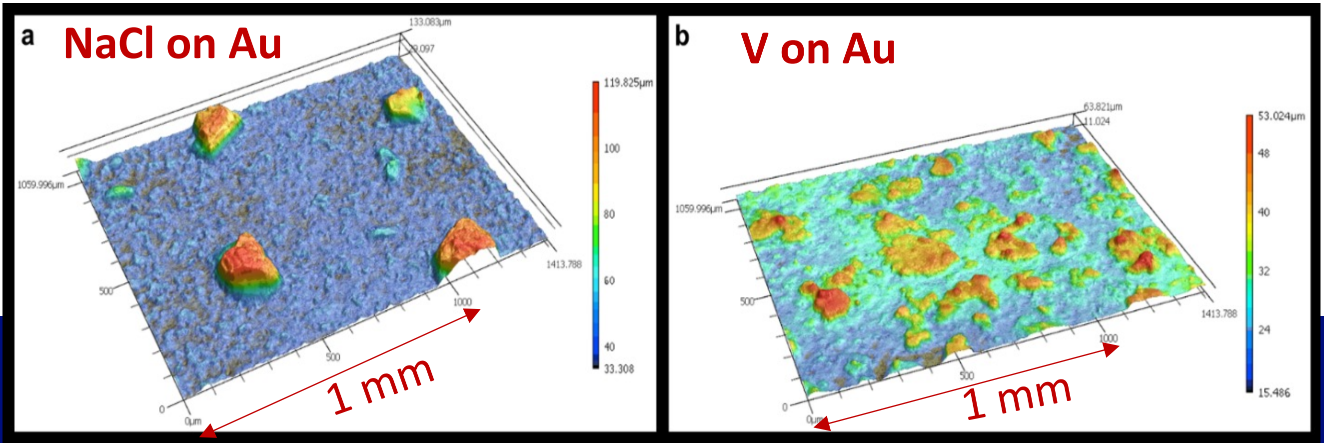
 a. Inductive coupled plasma-Optical emission spectroscopy (ICP-OES),

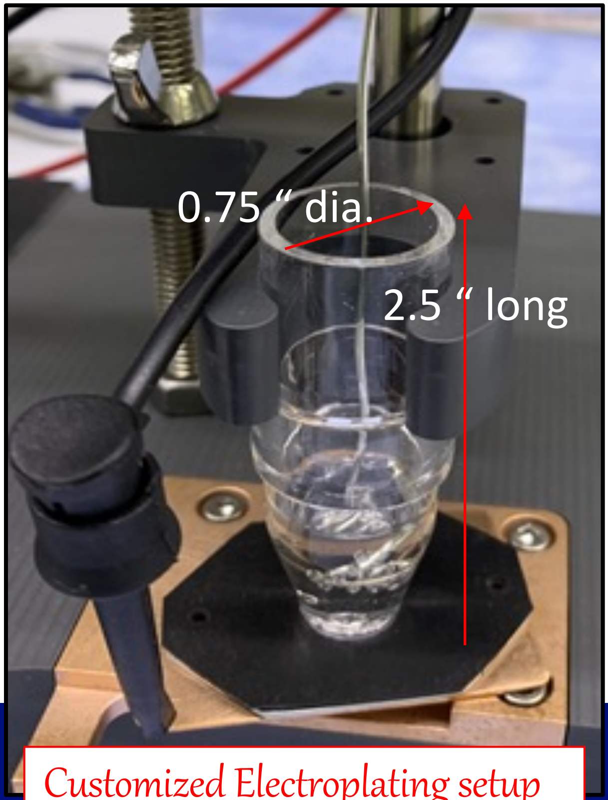
 b. SEM, SEM-EDS, c. X-ray Absorption Spectroscopy (XAS)

 - Radiometric techniques:

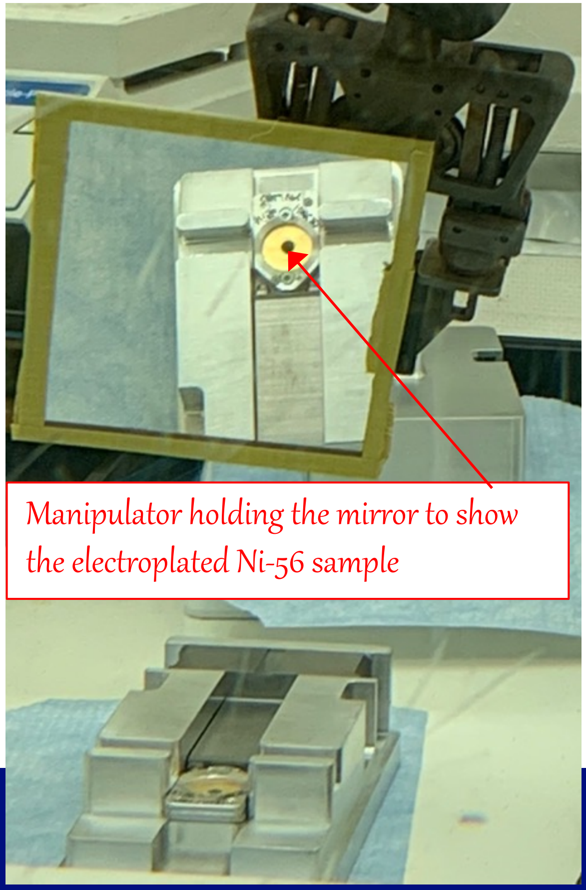
 a. liquid scintillator counting (LSC) for Ni-63, b. x-ray spectroscopy for Ni-59, c. gamma spectroscopy for Ni-56 & Ni-57

Optical 3D images





Customized Electroplating setup



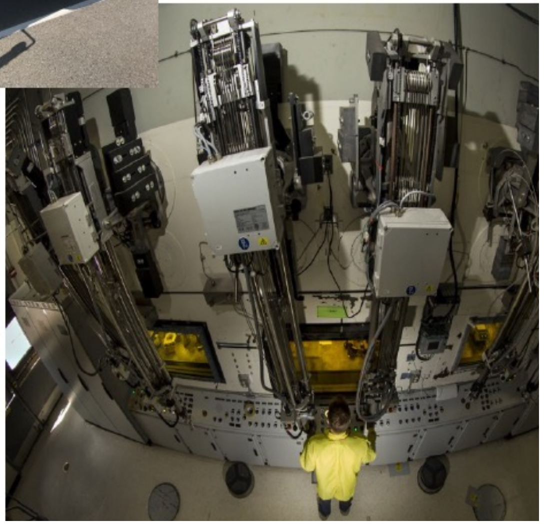
Manipulator holding the mirror to show the electroplated Ni-56 sample

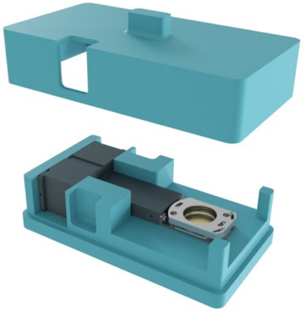
Isotope Production Facility at LANSCE produces "short-lived" radionuclides. Chemical separation and thin-target fabrication is performed at Hot Cell facility in TA48.

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

Hot Cell Facility

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

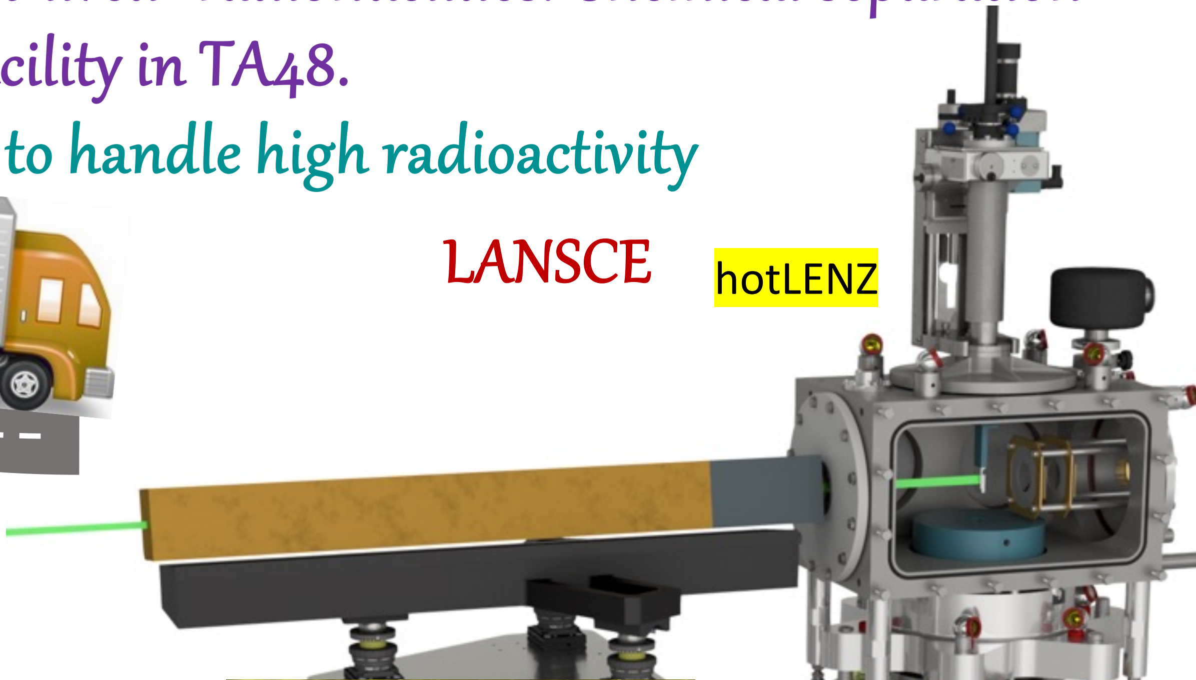




Sample housing for sturdy mounting during transport

LANSCE

hotLENZ



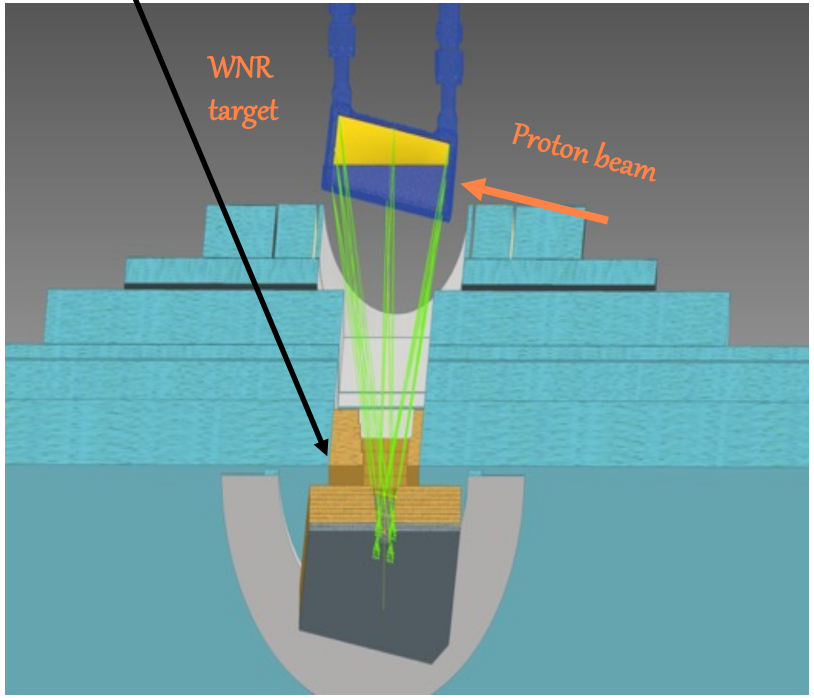
IPF Hot Cell

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

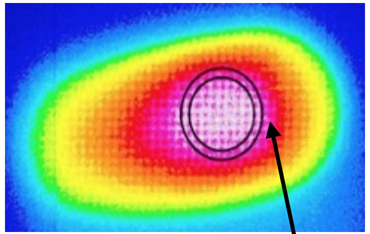
Lee

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

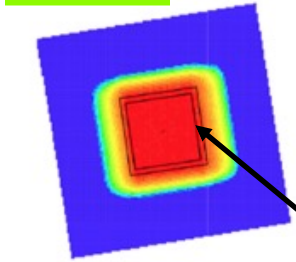
Advanced secondary collimation improved neutron flux and beam spot with immensely reduced background



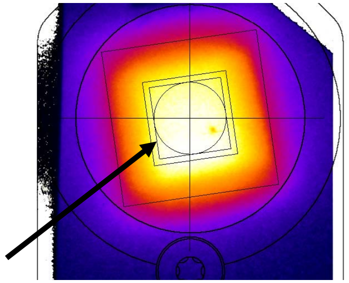
Beam image using conventional collimation



MCNP simulation using asymmetric collimation



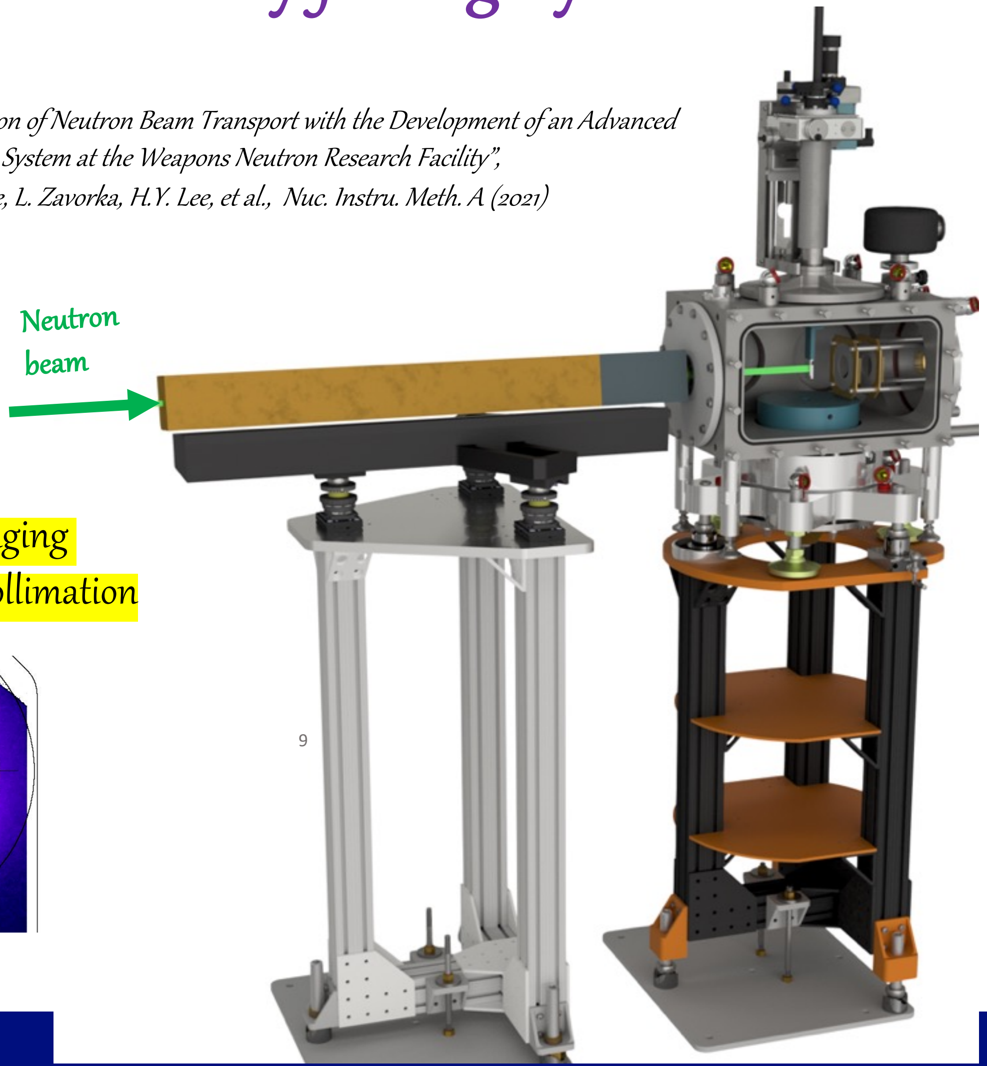
Improved Beam Imaging using asymmetric collimation



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)

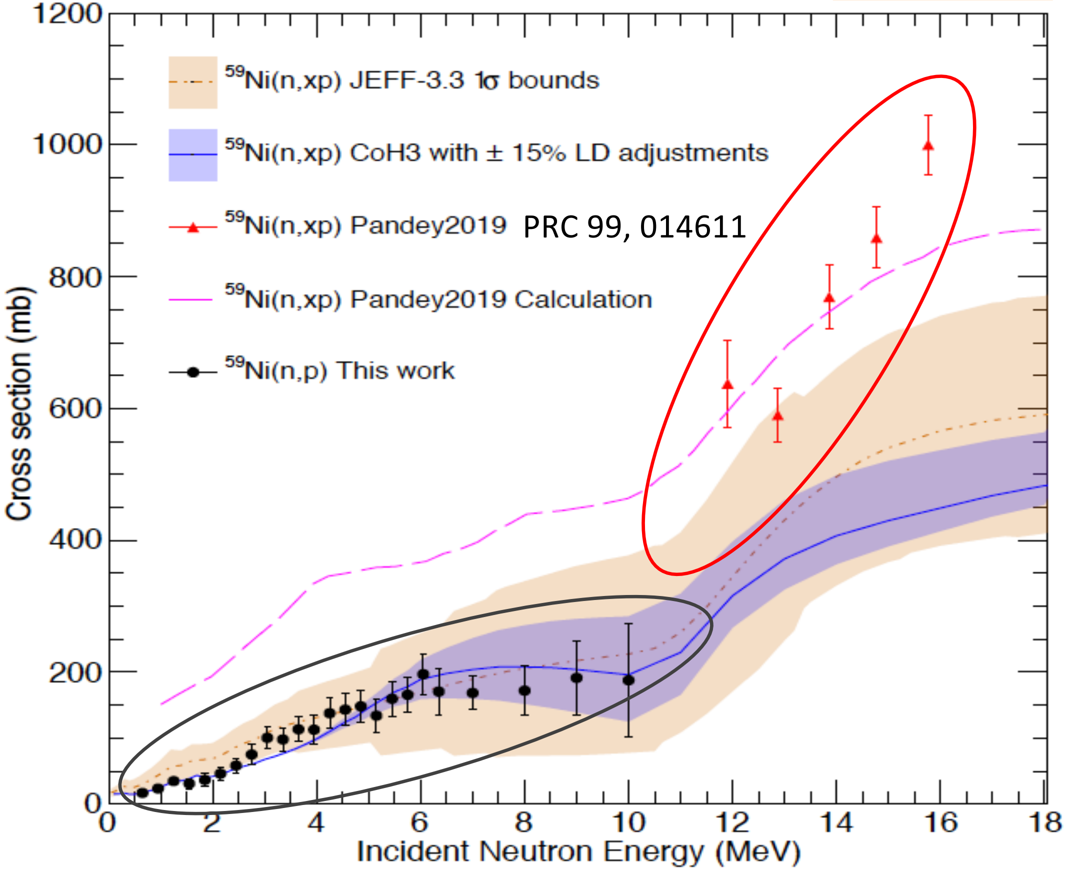


Ni-59: directly measured cross sections reveal a large discrepancy to the surrogate measurement

- 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

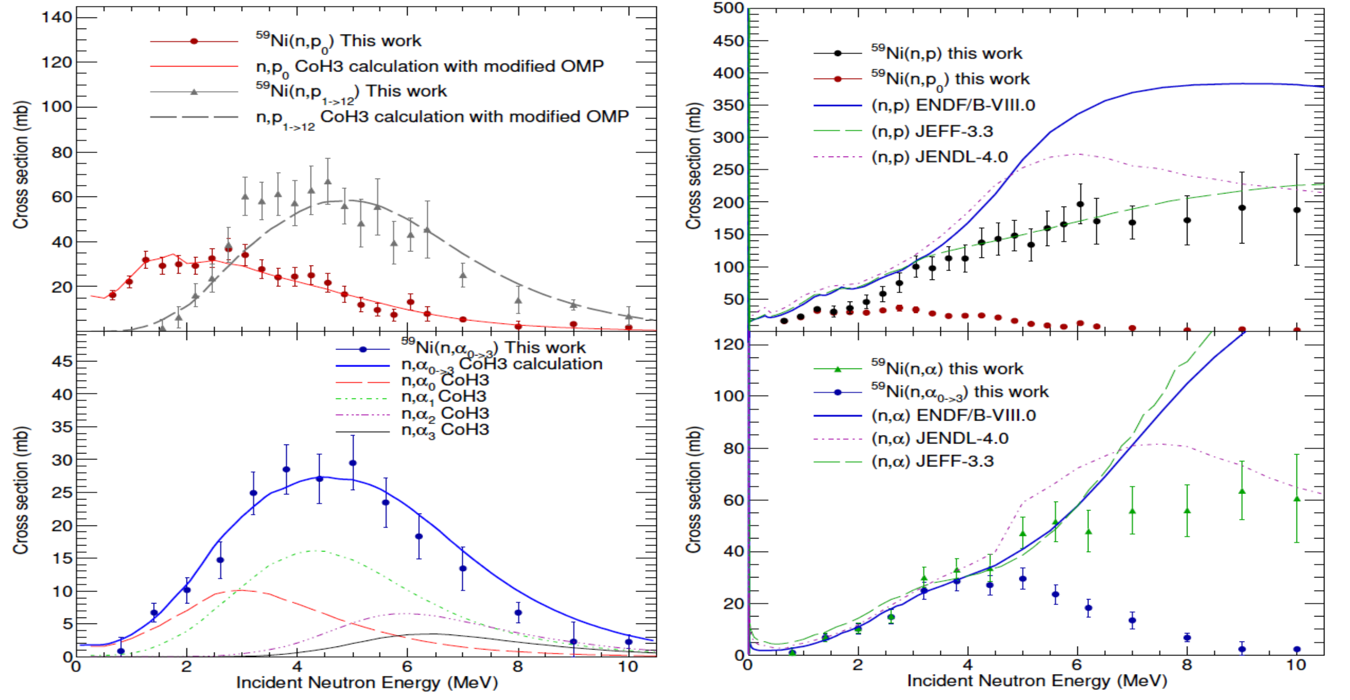
Direct experimental measurements of cross sections for unstable long-lived radionuclide (^{59}Ni) are not possible as it does not occur in naturally available Ni isotopes.

Pandey 2019



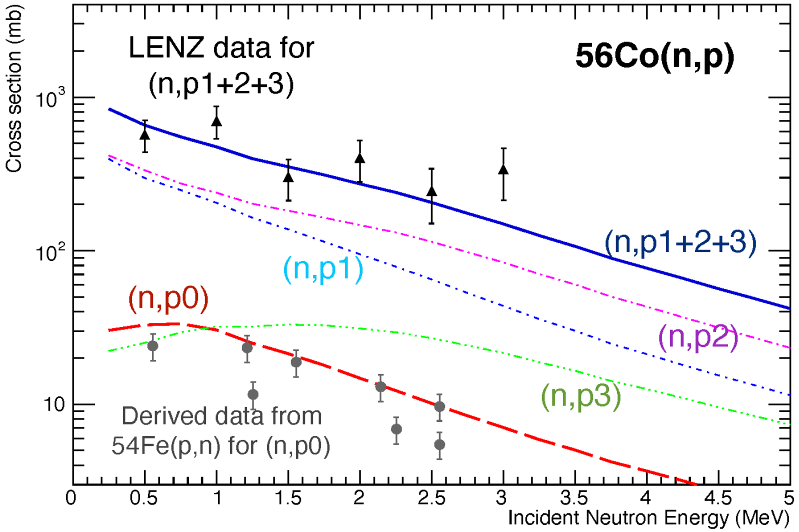
PRC 99, 014611

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

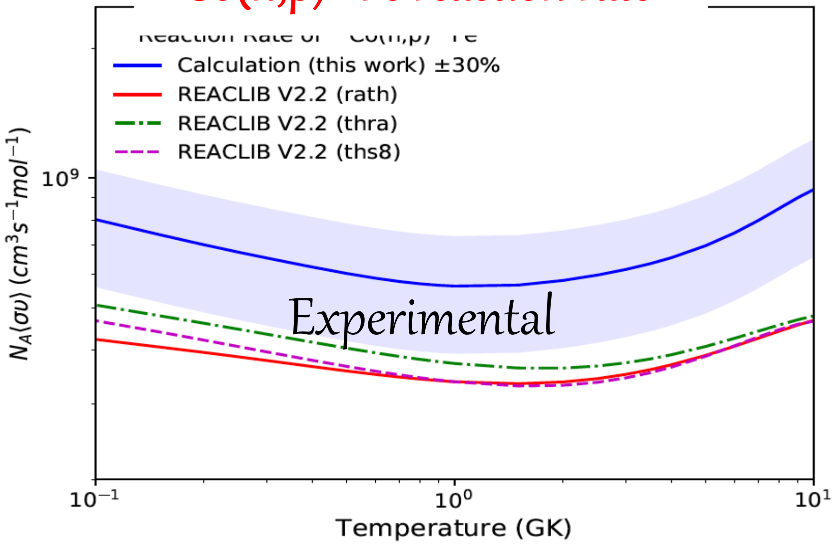


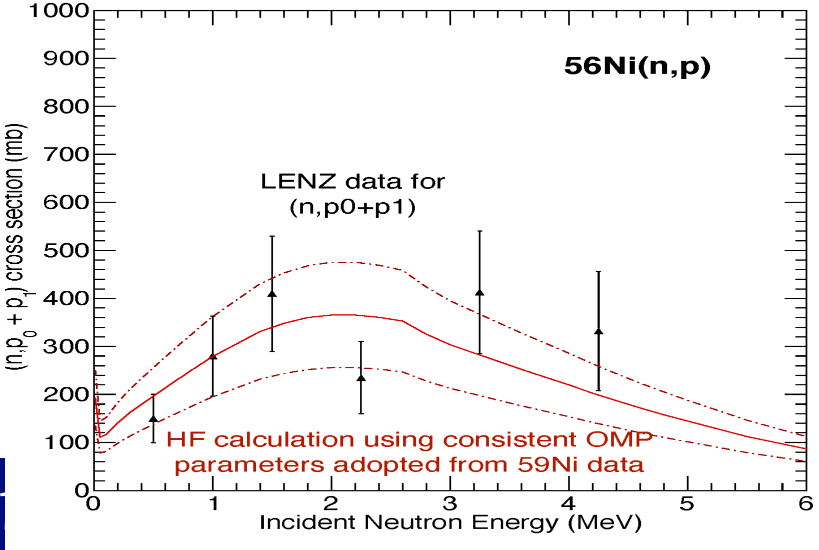
First directly measured (n,p) cross sections on ^{56}Co and ^{56}Ni ($T_{1/2}$=6 days, produced at IPF)

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

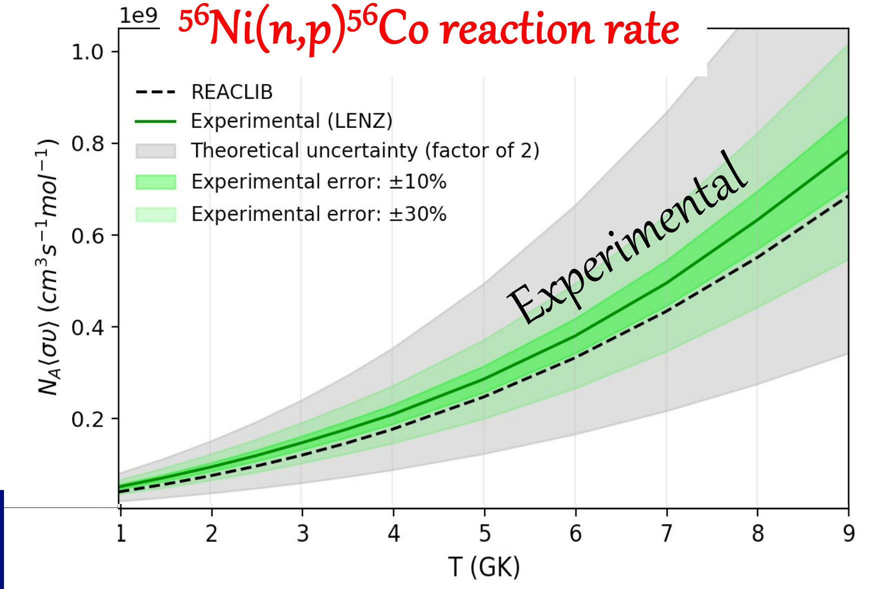


^{56}Co(n,p)^{56}Fe reaction rate



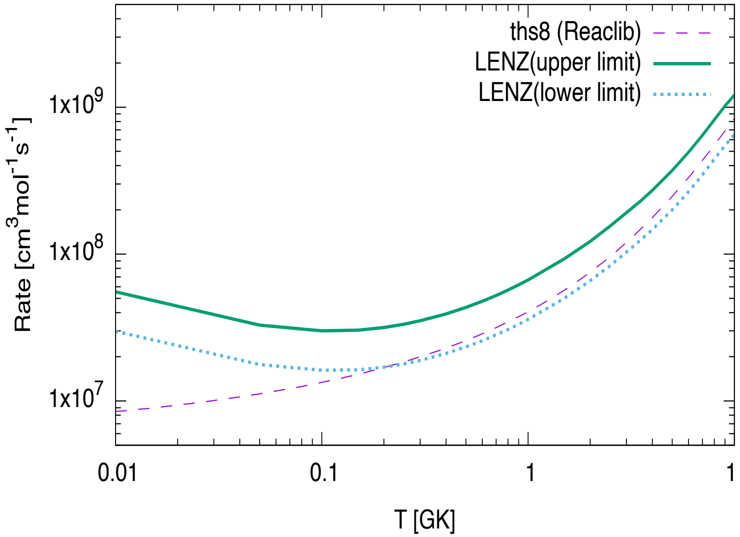


^{56}Ni(n,p)^{56}Co reaction rate



Hydrodynamics calculations for nu-p process synthesis

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

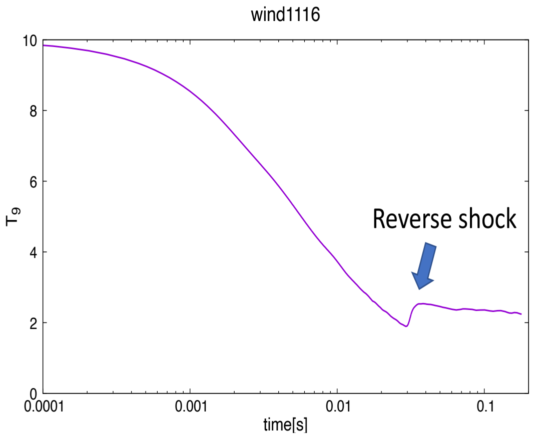


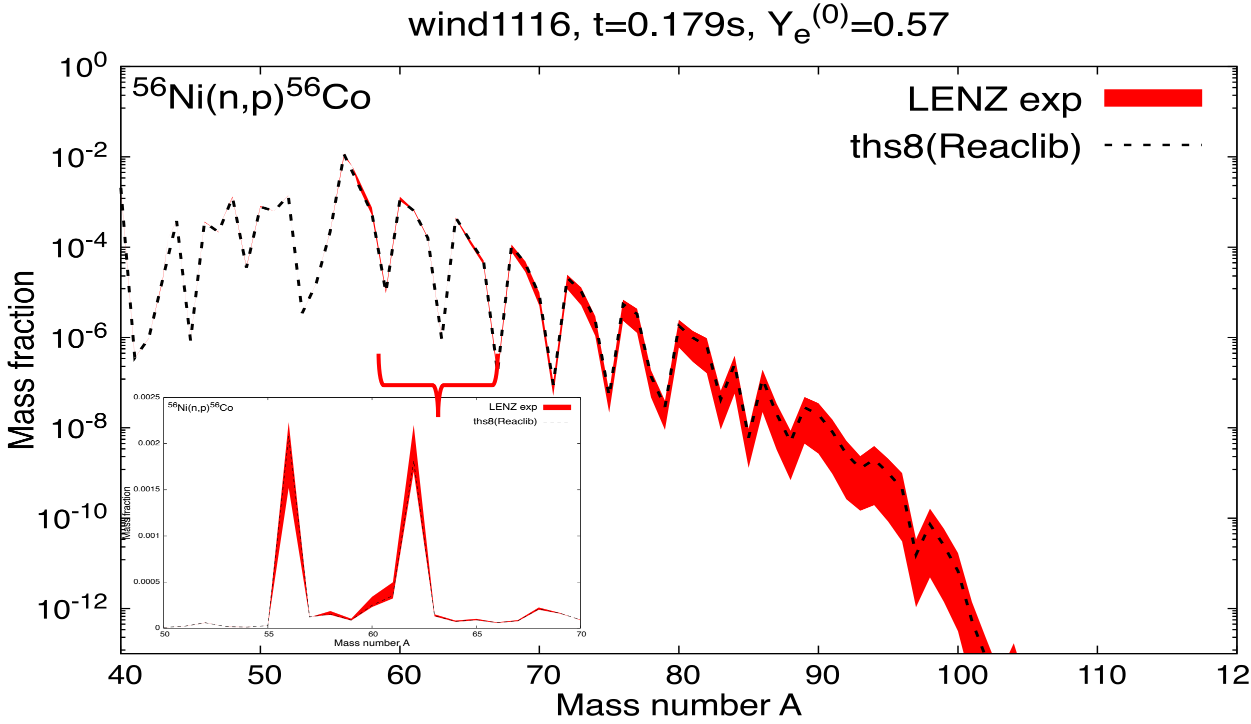
Hydrodynamical parameters

4.0s, 25 M$_{sun}$, Sasaki2022

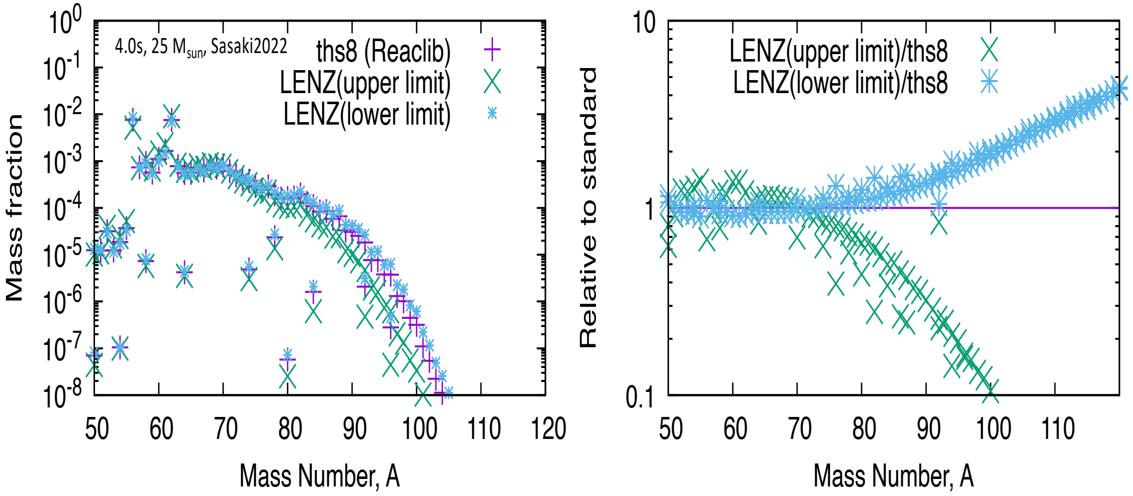
PNS Radius [km]	PNS Mass[$M_\odot$]	Y_e	τ_{dyn}[ms]	S[$k_B$nuc^{-1}]	$\dot{M}$[M$_\odot s^{-1}$]
12.6	1.75	0.578	86.2	138	2.04×10^{-6}

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





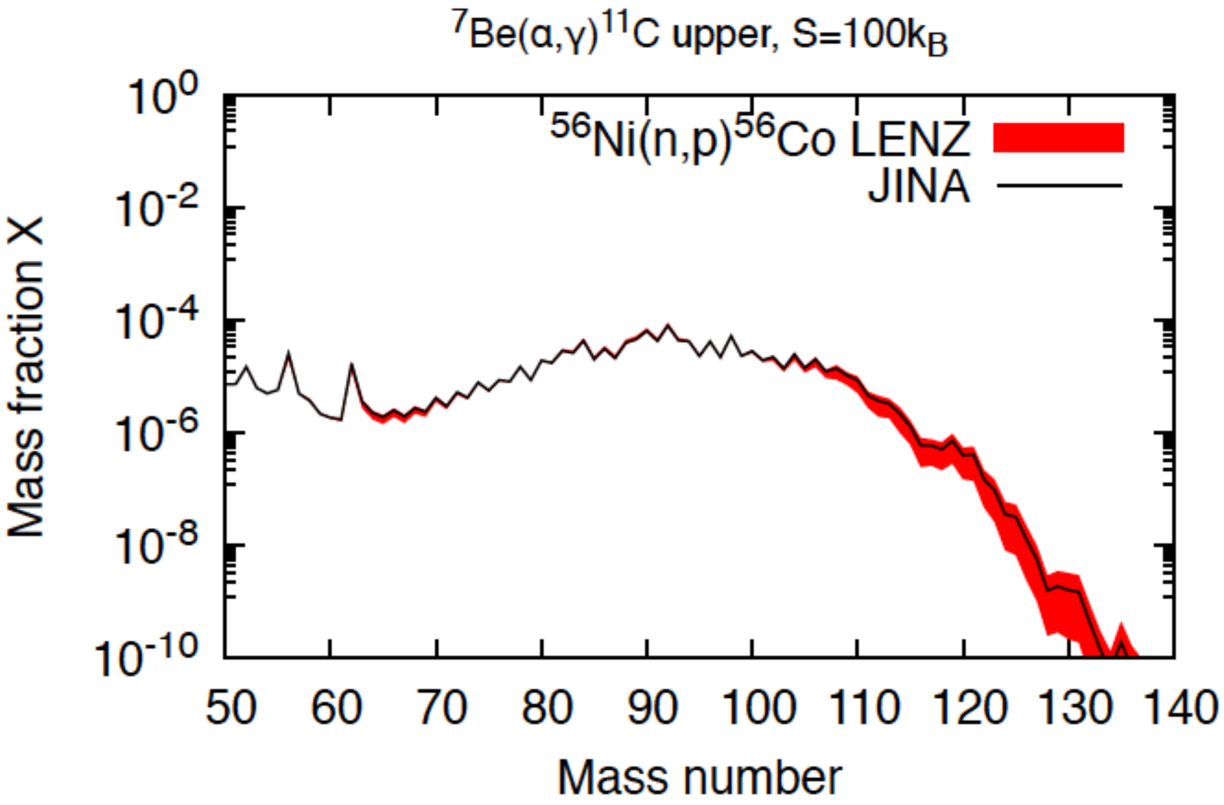
Mass fractions after beta decays

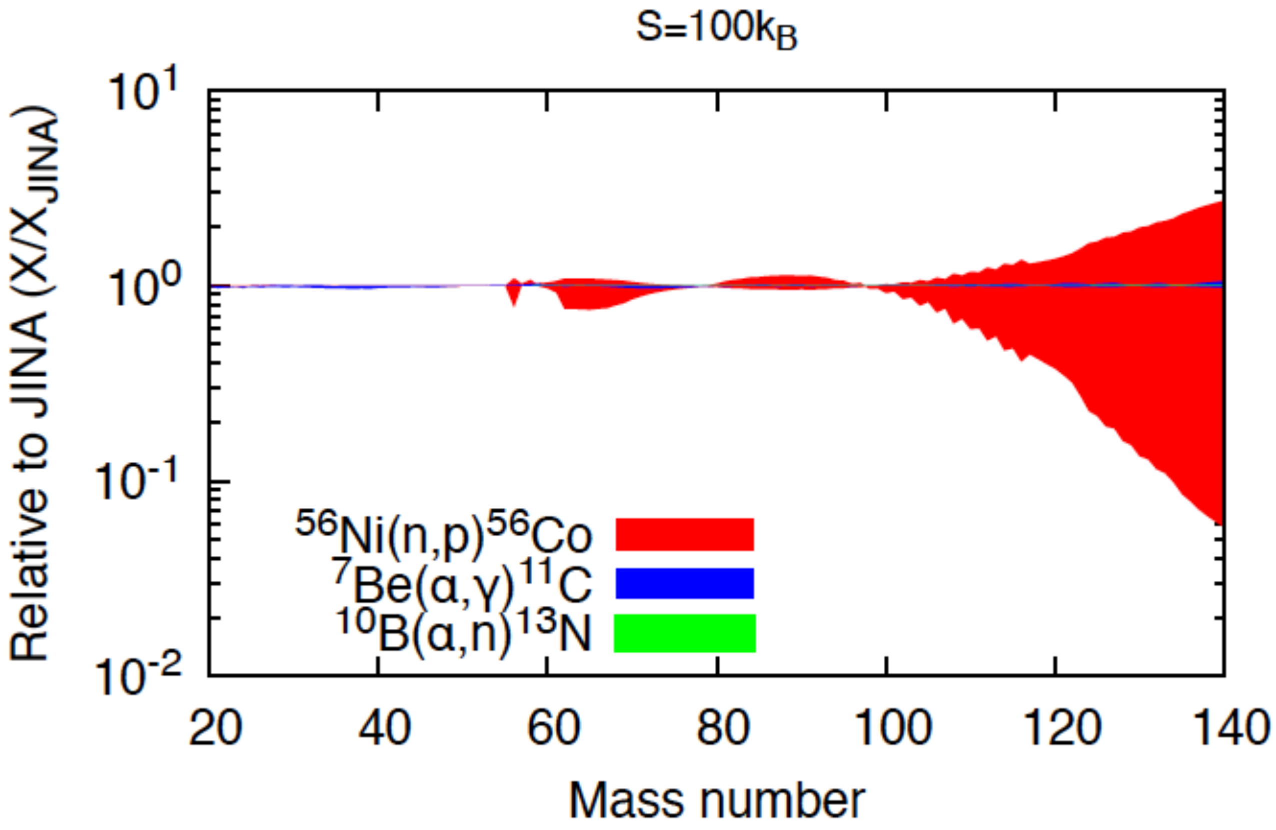


The nu-p process (T9 = 1.5 – 3) does not terminate due to the reverse shock, while considering two neutrino reactions:

$$\boxed{\begin{aligned} \nu_e + n &\rightarrow e^- + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n \end{aligned}}$$

Sensitivity of nu-p process nucleosynthesis from experimental uncertainties





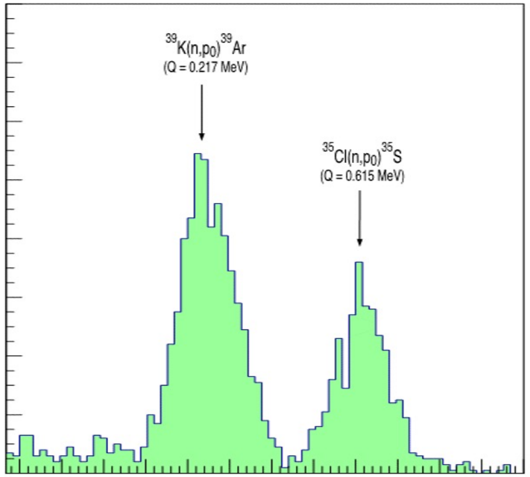
Currently the most sensitivity comes from the ^{56}Ni(n,p) reaction rate (with 30% uncertainty) as shown in red, in particular to produce the mass number, A > 100.

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

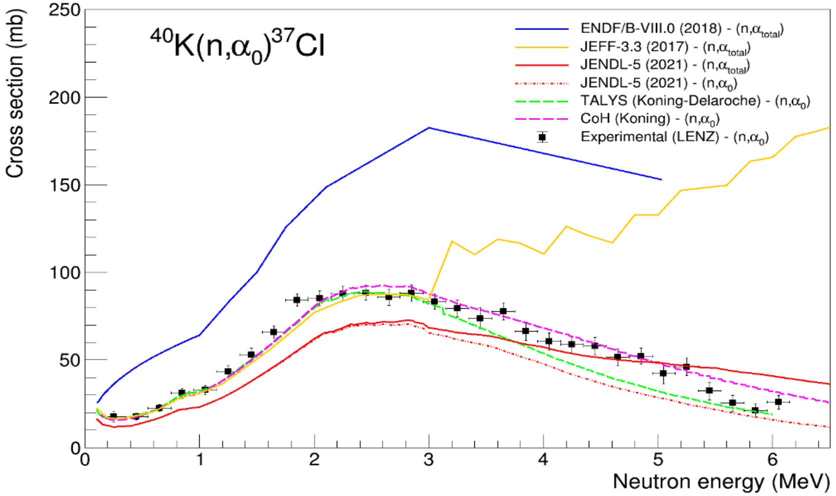
Ratios of partial cross sections of ^{39}K(n,p_0) and ^{35}Cl(n,p_0) reactions in the enriched and natural KCl targets confirm the atomic percentages between Cl and K of the enriched targets

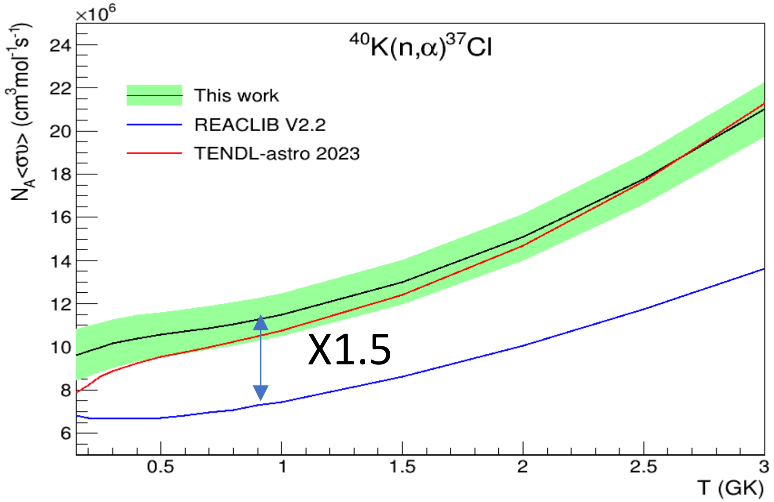


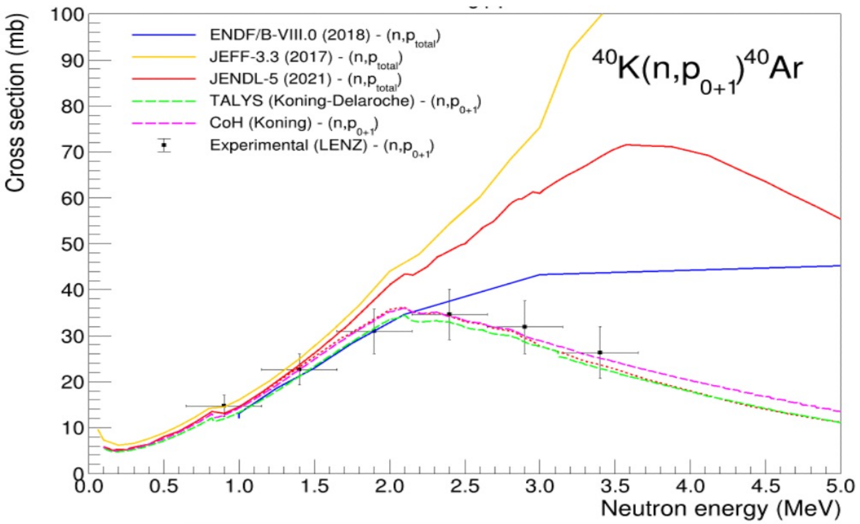
Reconstructed Q-values for (n,p) reactions of ^{39}K(n,p_0) (Q = 0.217 MeV) and 35Cl(n,p_0) (Q = 0.615 MeV)

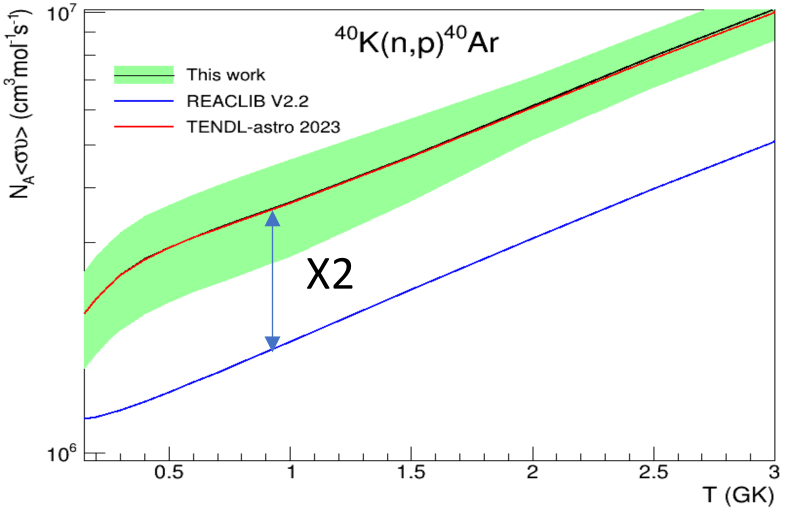
"Electrospraying Deposition and Characterizations of Potassium Chloride targets for Nuclear Science Measurements", S. Dede, S. D. Essenmacher, et al., Nucl. Instr. Meth. A (2023)

LANSCE cross sections and experimentally determined reaction rates





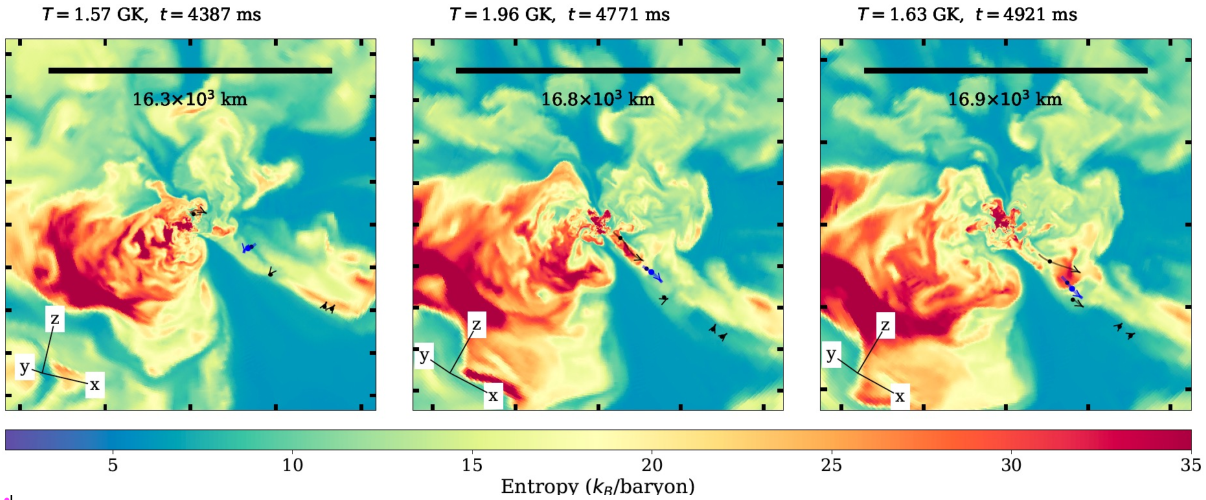




Directly measured (n,p) and (n,α) cross sections on ^{44}Ti ($T_{1/2}$= 59.1 y)

Led by S. Kuvin & H. Jayatissa

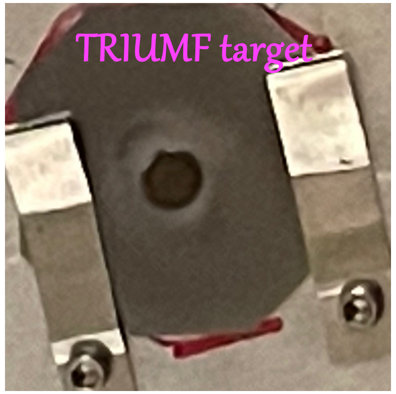
- For the interest of gamma-ray astronomy and nucleosynthesis in supernovae, as destruction mechanism for ^{44}Ti
- total 42 μCi of ^{44}Ti (4X10^{15}, 0.30 mg) was produced via ^{45}Sc(p,2n) at TRIUMF in 1999
  (natural Ti was 660 times more than that of ^{44}Ti)
- Thin film ^{44}TiO$_2$ was fabricated using electroplating technique with 96% deposition yield and 85% recovery of 44Ti in the chemical separation

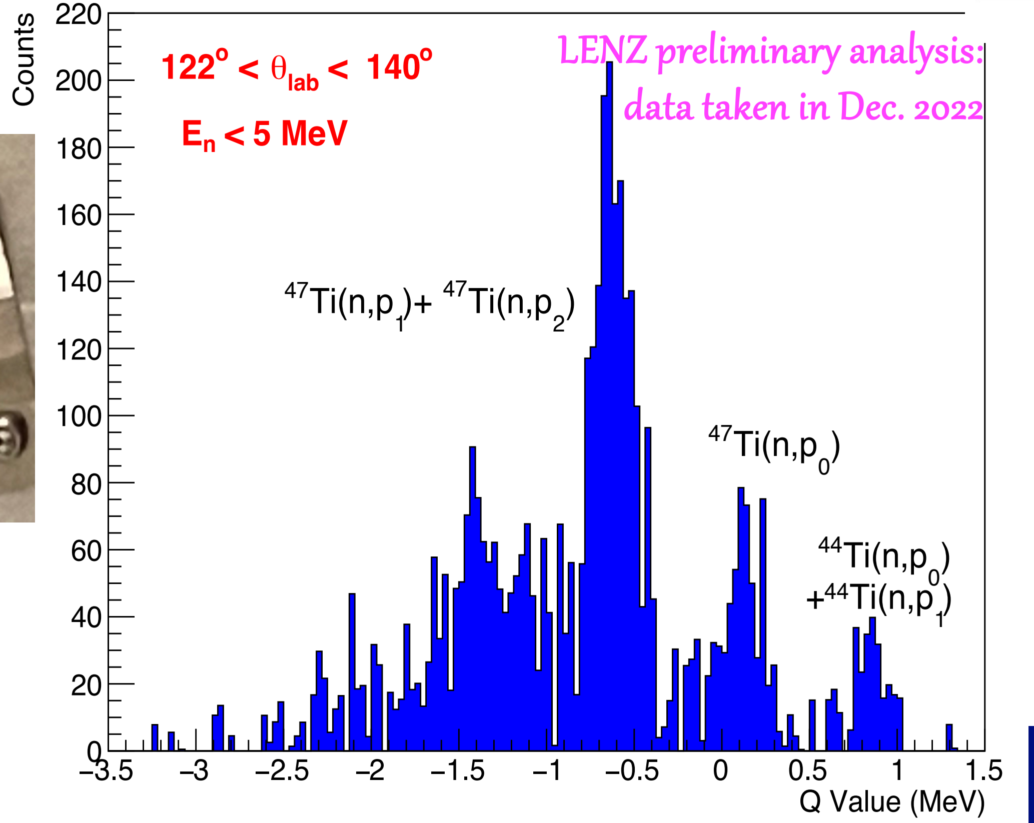

T = 1.57 GK, t = 4387 ms

T = 1.96 GK, t = 4771 ms

T = 1.63 GK, t = 4921 ms

Time series of 2D slices of the entropy in the 3D SN model. One particle that very efficiently produces ^{44}Ti is highlighted in blue


TRIUMF target


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

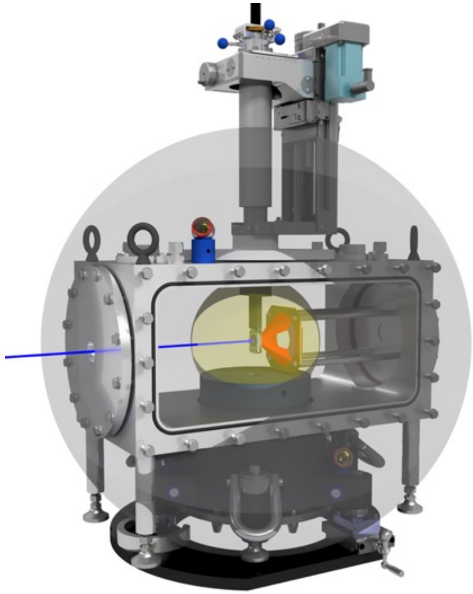
New Ti samples were fabricated for 2023 run cycle

New Al samples are planned for 2024 run cycle

Sean Kuvin's LANL LDRD Early Career Research Award in 2023-2025

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

Conventional (n,Z) studies



Optimized

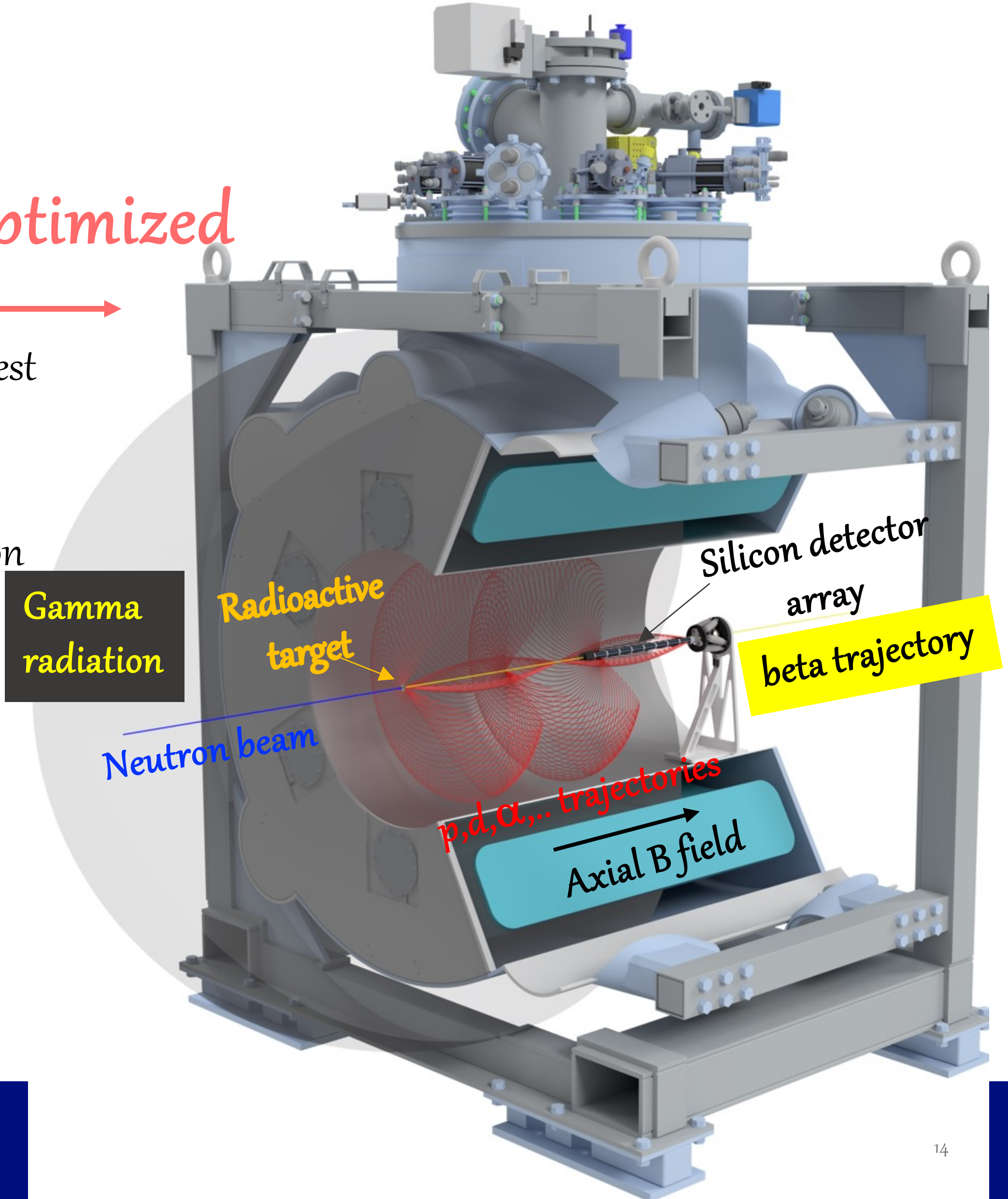
- Reduced radiation damage to detectors to achieve best experimental resolutions
- Solid angle coverage ~ 2π
- Different charged particles are identified by cyclotron period

Blue line: LANSCE neutron beam

Yellow sphere: intrinsic beta decays

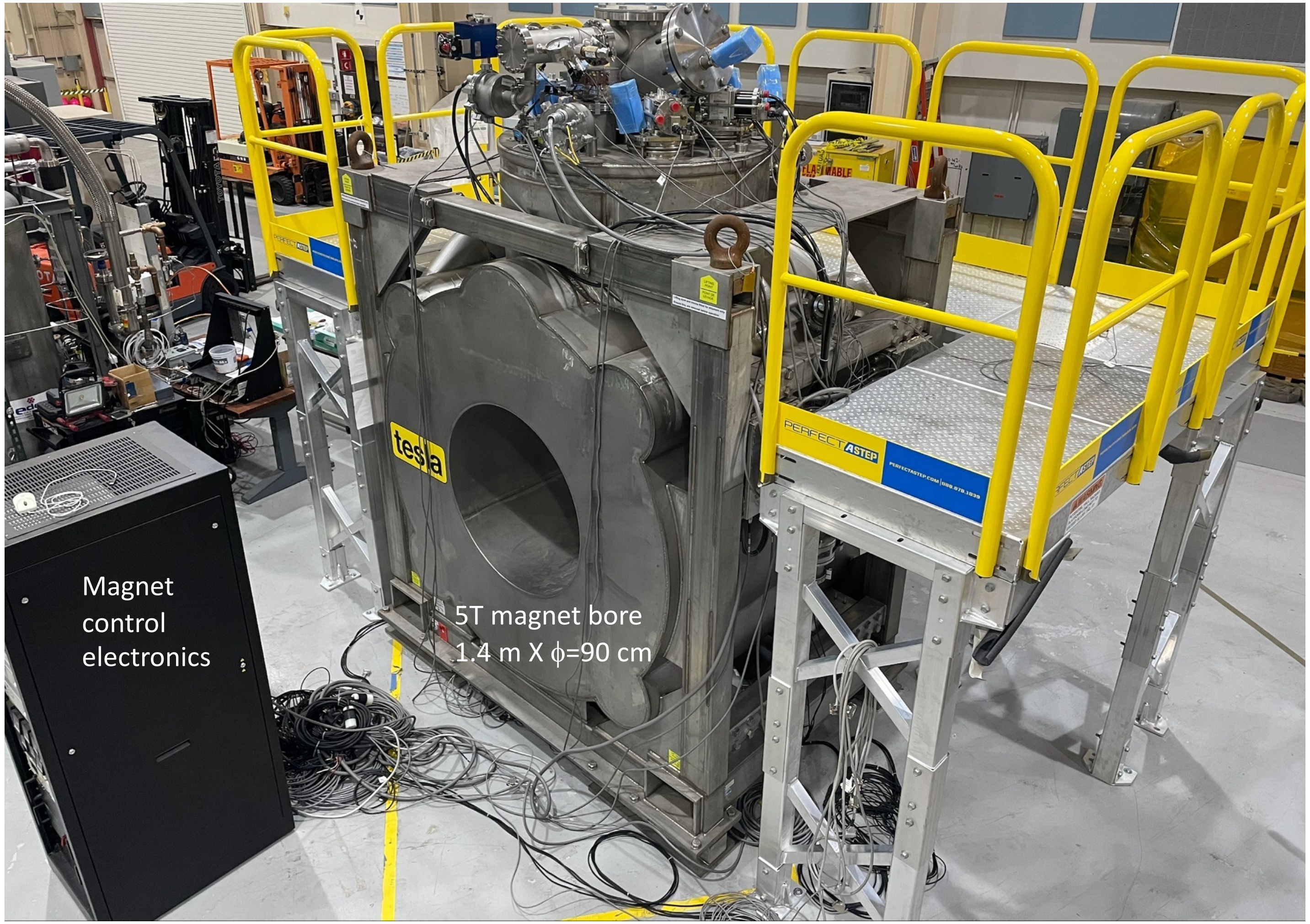
Gray sphere: intrinsic gamma decays

Red envelop: solid angle coverage for reaction charged particles



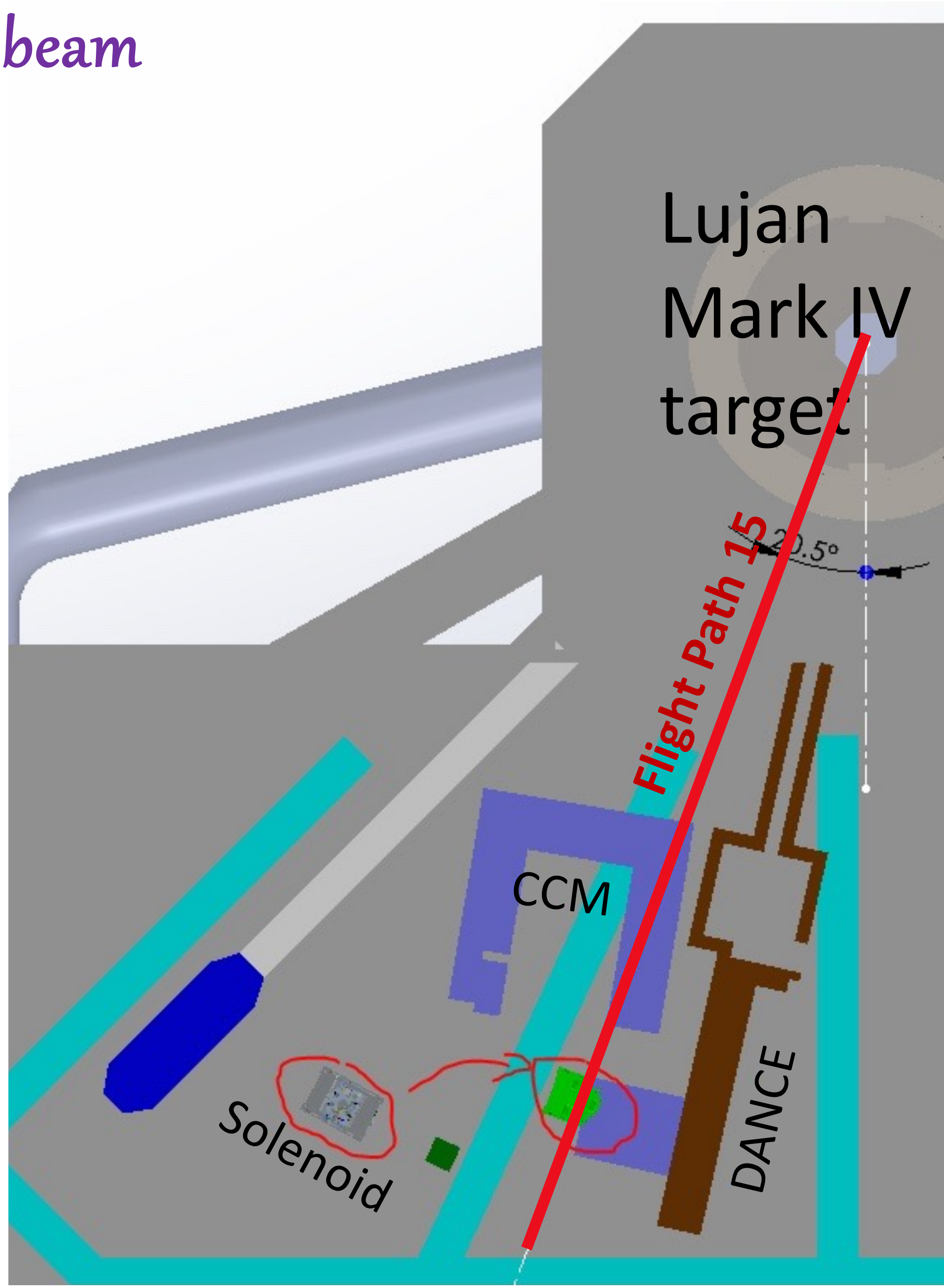
5T superconducting solenoid installation at Lujan: In-beam measurements planned at a new Flight Path 15

Magnet's 5 cold heads to be cooled by Helium compressors



Magnet control electronics

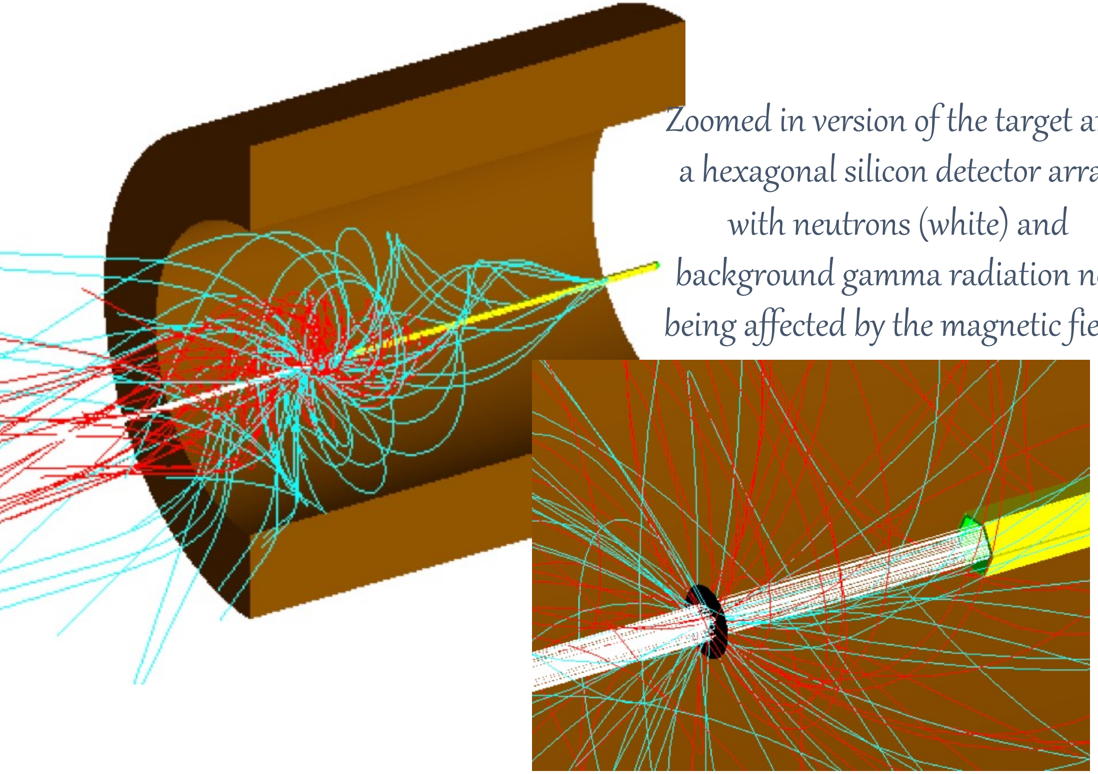
5T magnet bore 1.4 m X ϕ=90 cm



Monte Carlo simulations for optimizing detection system specifications (angular, energy, timing resolutions) to meet the required uncertainty

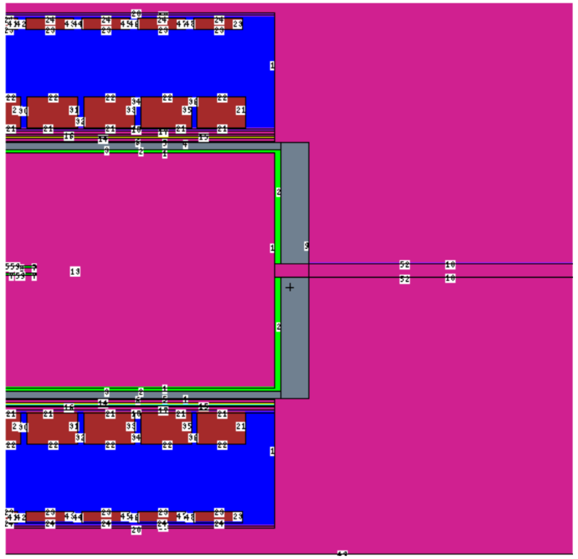
(Led by H. Jayatissa, Postdoc and D. McNeel)

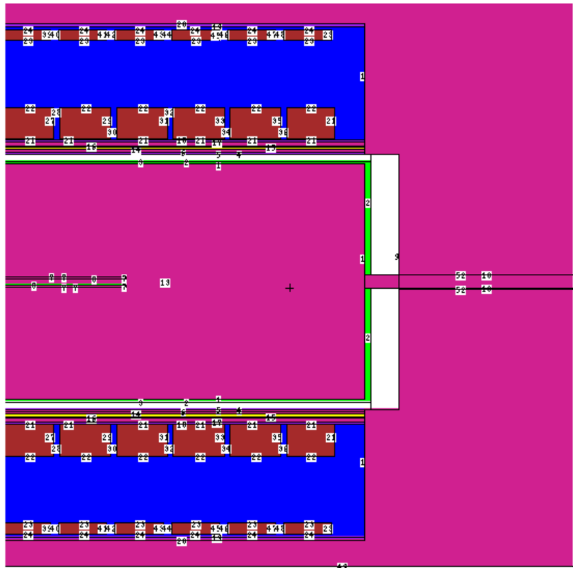
GEANT4 simulation of the ^{6}Li(n,t)α reaction for the neutron energy spectrum expected at Lujan (thermal to 0.5 MeV). The outgoing tritons (cyan) and alphas (red) are identified using a silicon detector array placed along the solenoid axis.



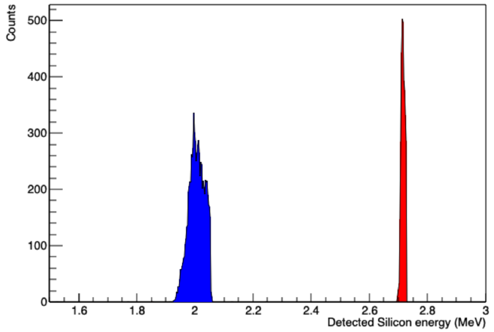
Zoomed in version of the target and a hexagonal silicon detector array with neutrons (white) and background gamma radiation not being affected by the magnetic field.

MCNP simulations for characterizing neutronics for shielding designs to reduce beam induced backgrounds to silicon detectors. Borated polyethylene shielding is tested for reducing charged particle backgrounds in silicon arrays using realistic Lujan's neutron and other particle spectra.





Detected energies of the simulated alpha (blue) and triton (red) for the ^{6}Li(n,t)α reaction for neutron energies at Lujan



Developed advanced analysis tools using AI/ML algorithm for implementation on helical spectrometer data

(Led by J. Randhawa, Postdoc)

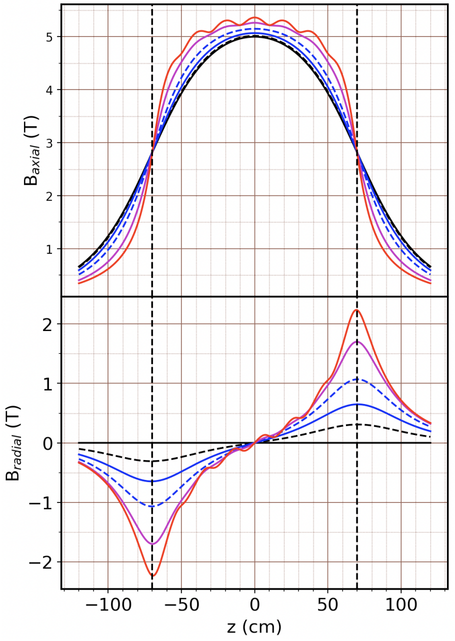
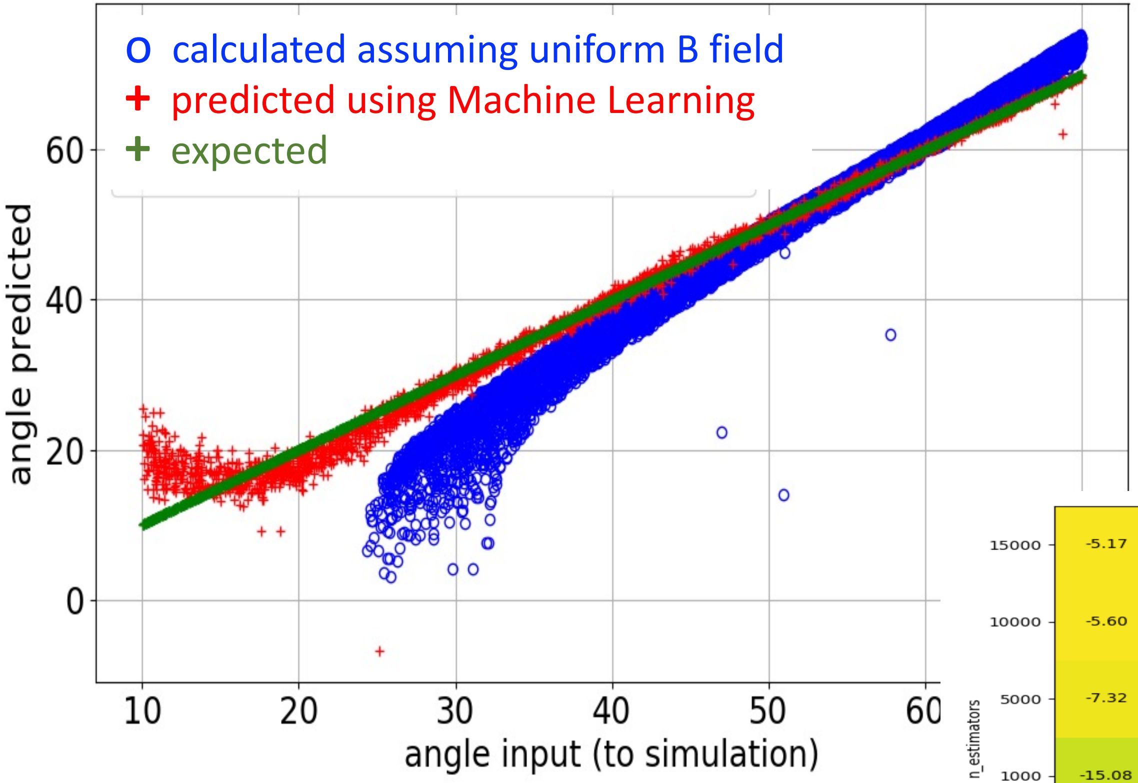
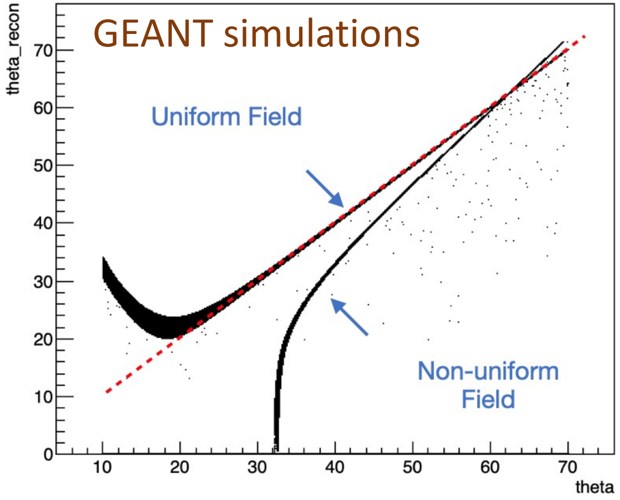


Figure 1: Field map from Tesla for a 5 T max field.

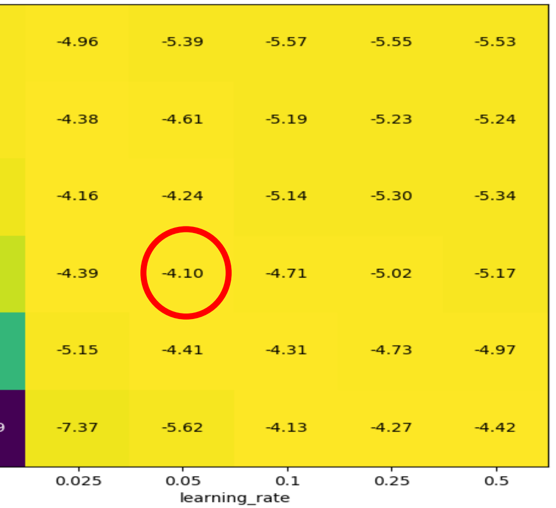
- With the current "realistic" magnetic field, it is necessary to correct non–linear behavior by incorporating Monte Carlo simulations for estimating response functions
- AI/ML tools are developed for simulated data analyses in order to
  -improve the signal to background ratios
  -enhance good signal identification
  -reduce systematic uncertainties



Detected angle vs. input angle



Machine Learning using different grid search



n_estimators \ learning_rate	0.01	0.025	0.05	0.1	0.25	0.5
15000	-5.17	-4.96	-5.39	-5.57	-5.55	-5.53
10000	-5.60	-4.38	-4.61	-5.19	-5.23	-5.24
5000	-7.32	-4.16	-4.24	-5.14	-5.30	-5.34
1000	-15.08	-4.39	-4.10	-4.71	-5.02	-5.17
500	-47.31	-5.15	-4.41	-4.31	-4.73	-4.97
50	-132.69	-7.37	-5.62	-4.13	-4.27	-4.42

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.

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