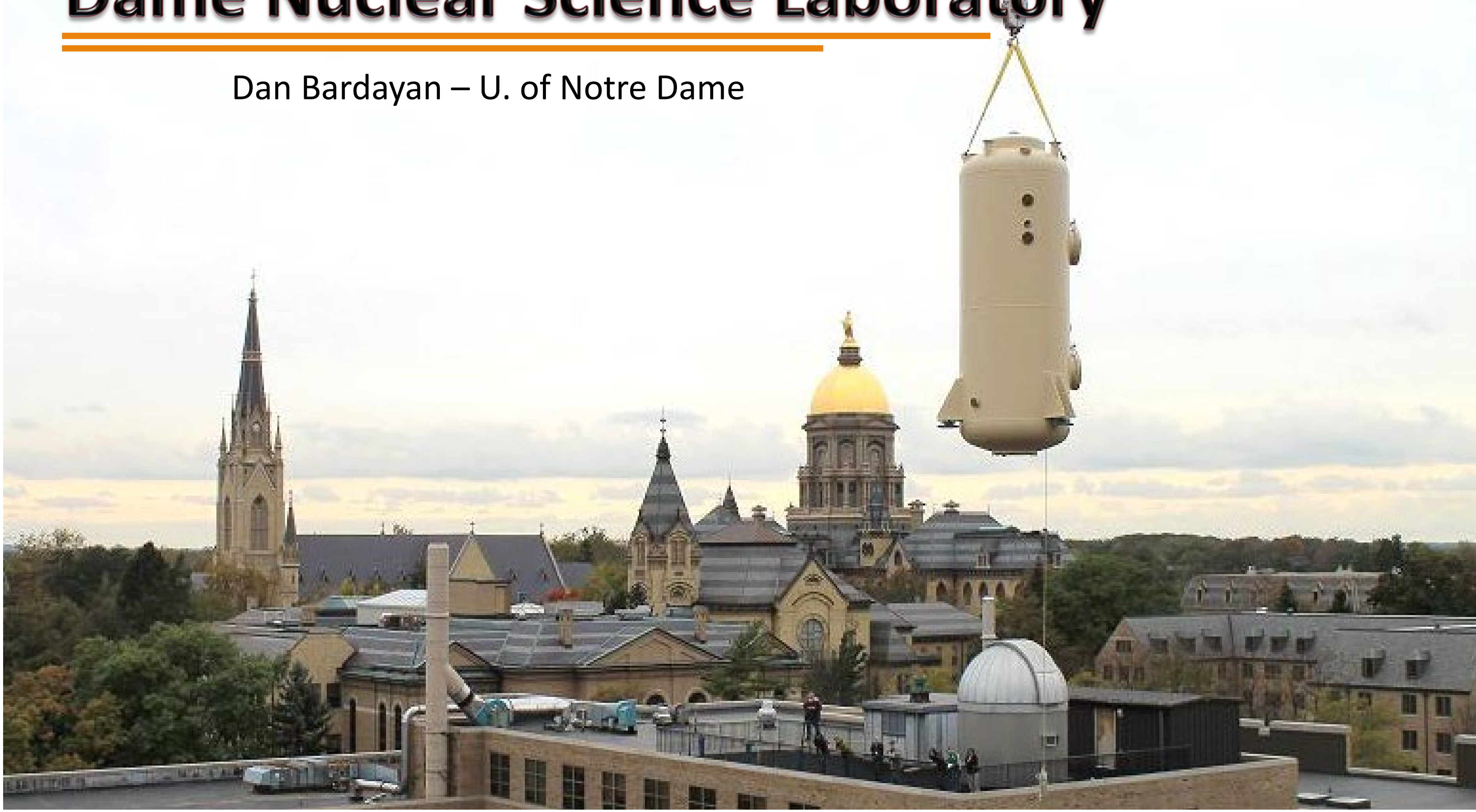
Nuclear Astrophysics at the Notre Dame Nuclear Science Laboratory

Dan Bardayan – U. of Notre Dame



NSL 80th Anniversary Celebrated April 2018

T & R faculty involved in variety of research

The number of nuclear physics teaching and research (T&R) faculty has grown significantly from five in 2010 to ten in 2023.

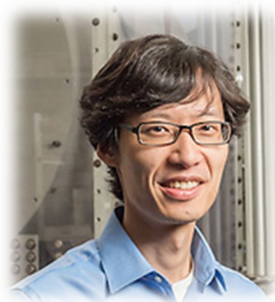
Michael Wiescher,
Nuclear Astrophysics &
Nuclear Applications

Dan Bardayan,
Nuclear Astrophysics

Ani Aprahamian
Nuclear Astrophysics &
Nuclear Structure Physics

Max Brodeur,
Nuclear Astrophysics &
Fundamental Symmetries

Manoel Couder,
Nuclear Astrophysics &
Nuclear Applications



Tan Ahn,
Nuclear Astrophysics &
Nuclear Structure

Philippe Collon,
Nuclear Astrophysics &
Nuclear Applications

Anna Simon-Robertson,
Nuclear Astrophysics &
Nuclear Reactions

Umesh Garg,
Nuclear Astrophysics &
Nuclear Structure

Graham Peaslee,
Nuclear Applications

NSL research faculty drive innovations

NSF support

James deBoer
R-matrix development

Patrick O'Malley
TriSol/St. Benedict

Wanpeng Tan
User Support

NSF support + Other

Khachatur Manukyan
Materials, Applications, & Targets

Daniel Robertson
FN upgrade, n beamline, CASPAR

Project based DOE support

Georg Berg
SECAR/HRS

Jay Laverne
Rad. Chemistry

University support

Joachim Görres
Research Support

Ed Stech
NSL Operation

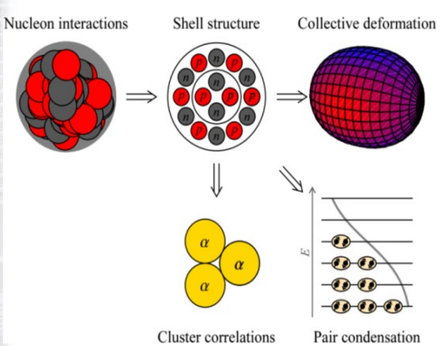
The Notre Dame Nuclear Theory Group

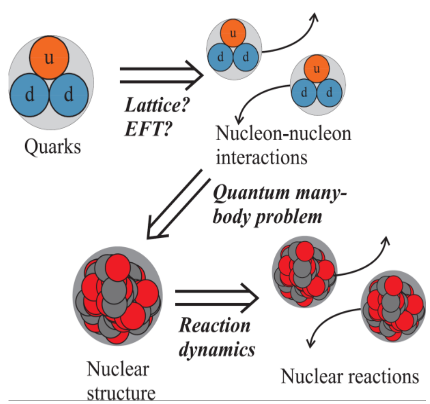
Dr. Ragnar Stroberg

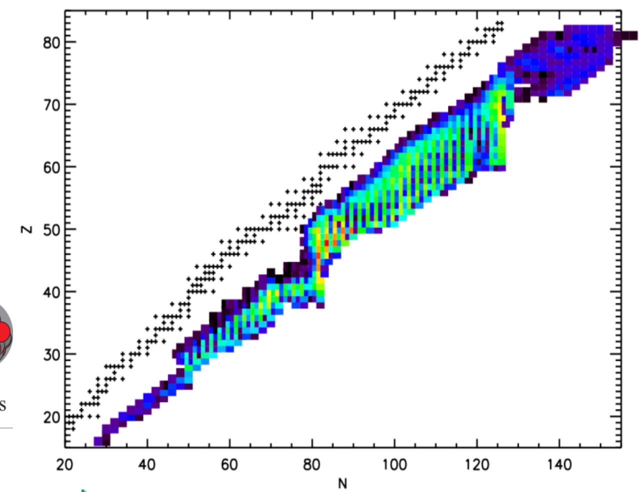
Dr. Mark Caprio

Dr. Rebecca Surman

Dr. Grant Mathews

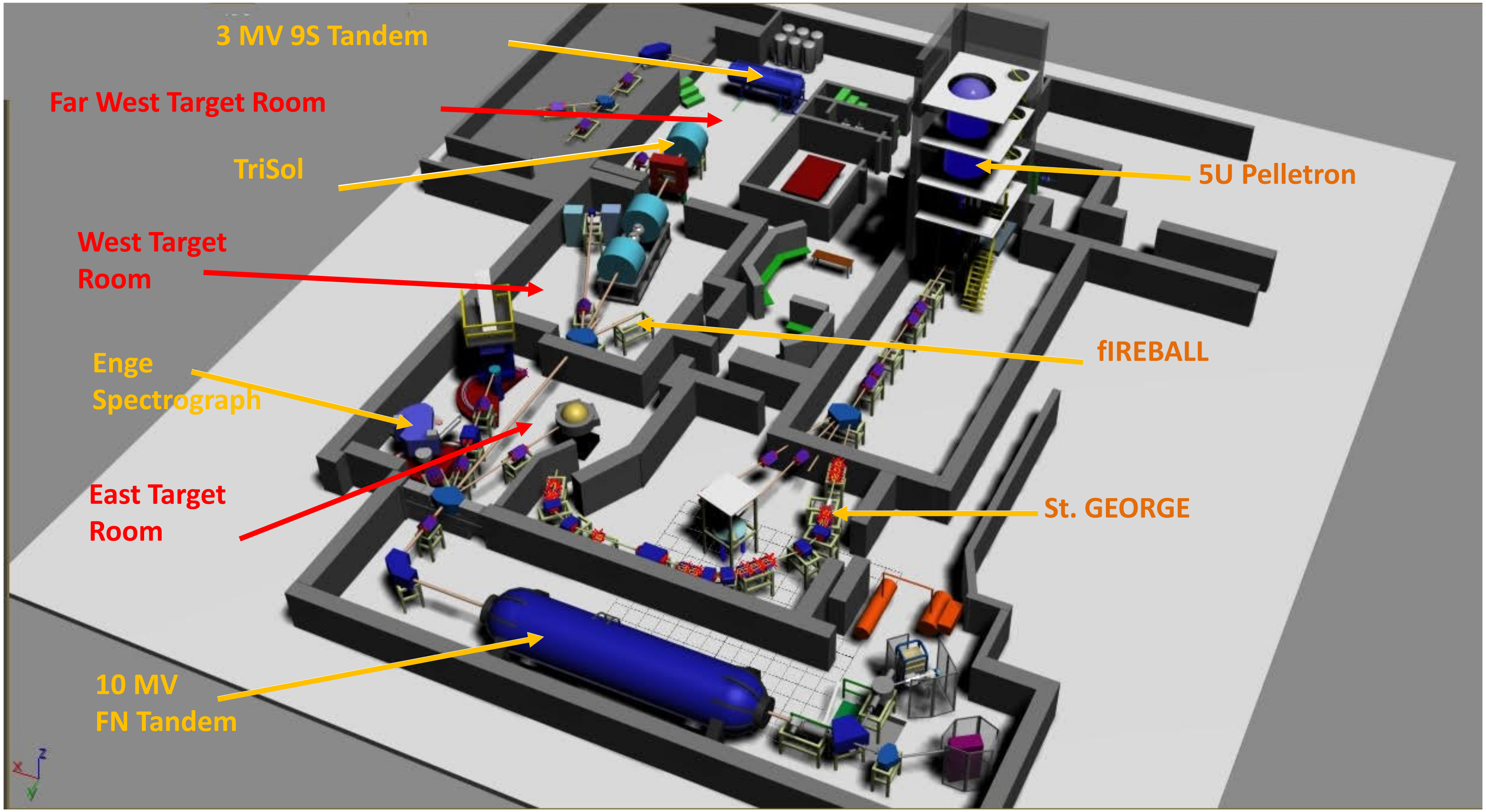






Close collaboration with the experimental group on nuclear structure and astrophysics!

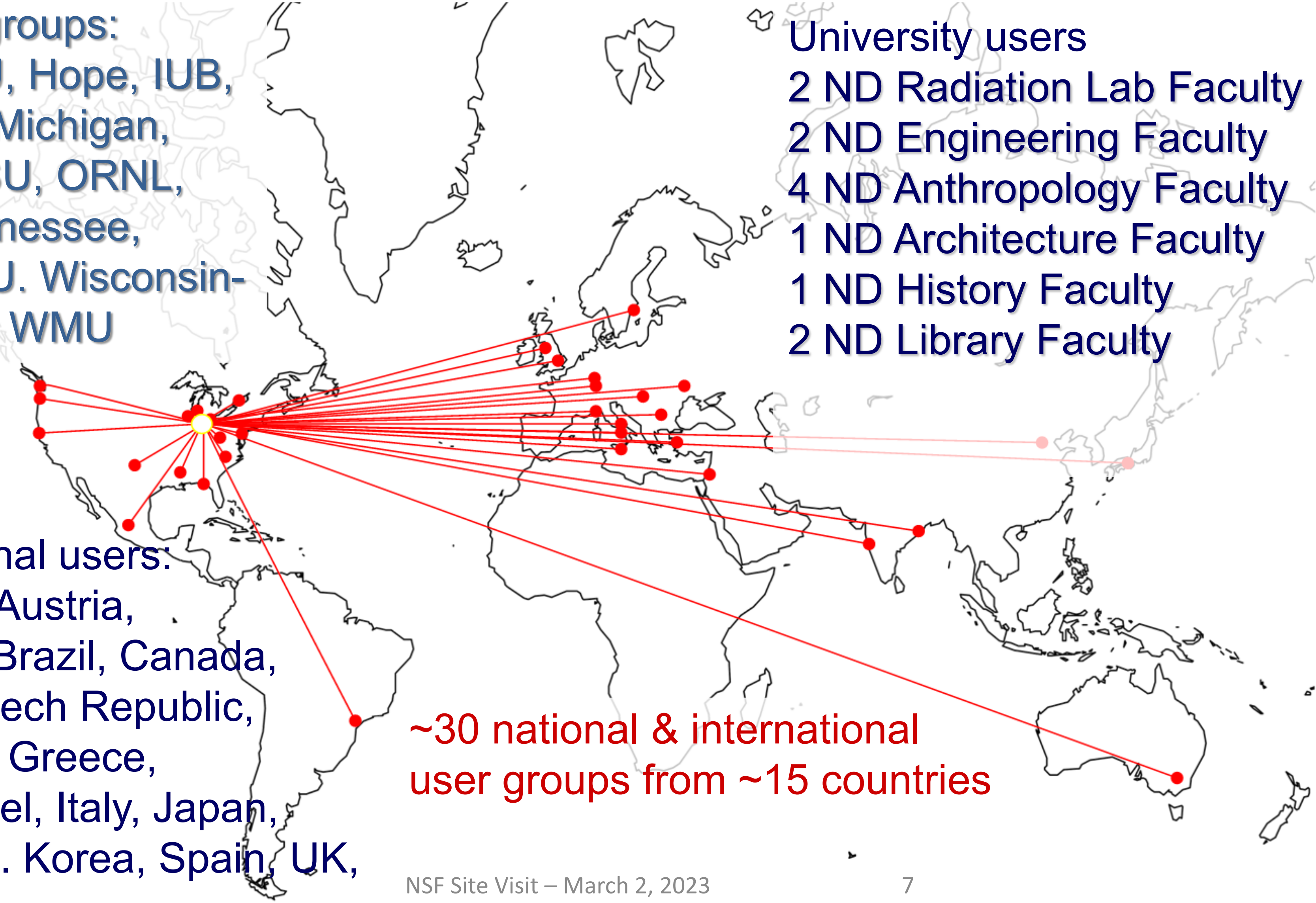
The Notre Dame Nuclear Science Laboratory operates 3 low-energy accelerators



NSL users and collaborators come from locations world-wide

US user groups:
ANL, FSU, Hope, IUB, IUSB, U. Michigan, NSCL/MSU, ORNL, Ohio, Tennessee, Rutgers, U. Wisconsin-Lacrosse, WMU

University users
2 ND Radiation Lab Faculty
2 ND Engineering Faculty
4 ND Anthropology Faculty
1 ND Architecture Faculty
1 ND History Faculty
2 ND Library Faculty

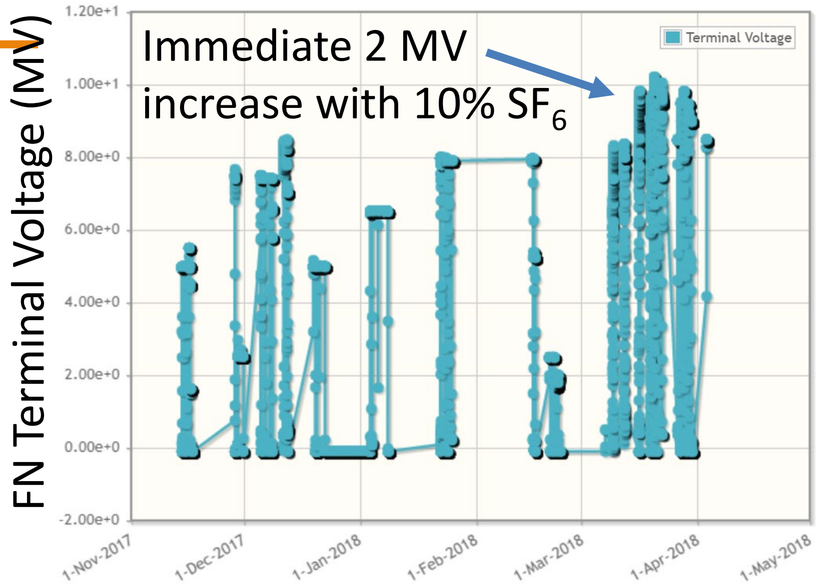


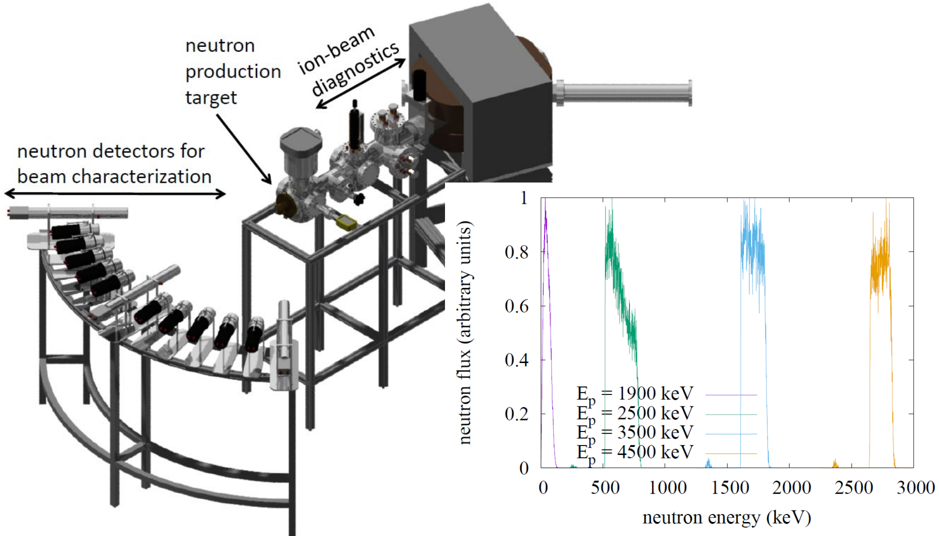
International users:
Armenia, Austria, Belgium, Brazil, Canada, China, Czech Republic, Germany, Greece, India, Israel, Italy, Japan, Mexico, S. Korea, Spain, UK, US

~30 national & international user groups from ~15 countries

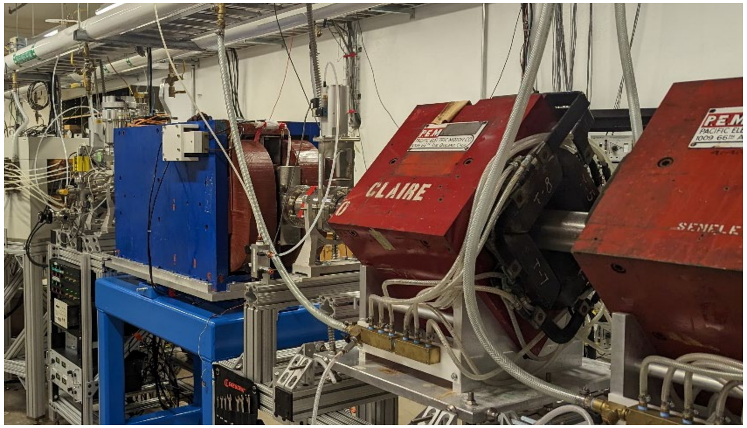
NSL facility upgrades strengthen capabilities

$2.0M investment from University.
Higher voltages critical for higher mass AMS and TwinSol RIB experiments.





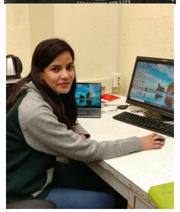
Intense "monoenergetic" neutron source from (p,n) and (α,n) reactions on various targets.

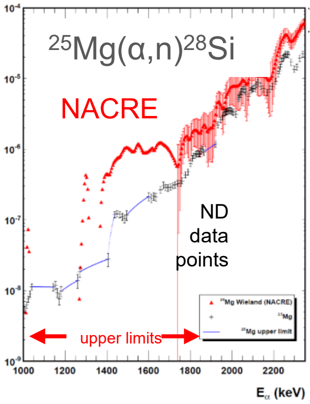


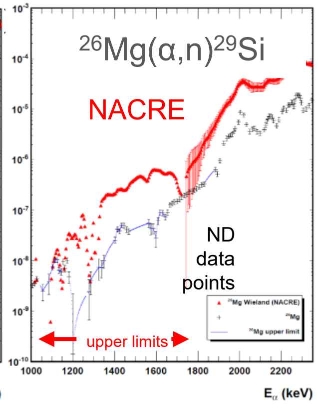
New Wien Filter on 5U beamline.

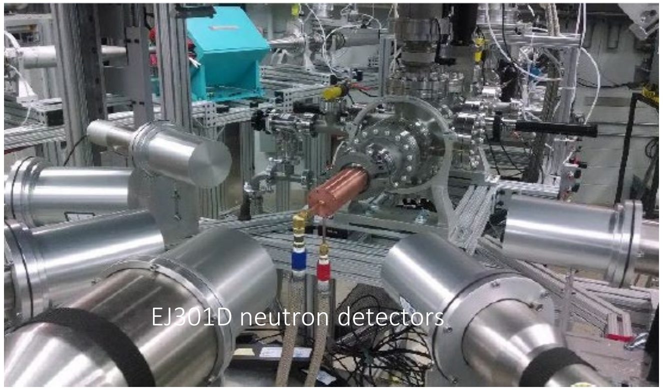
Neutron sources

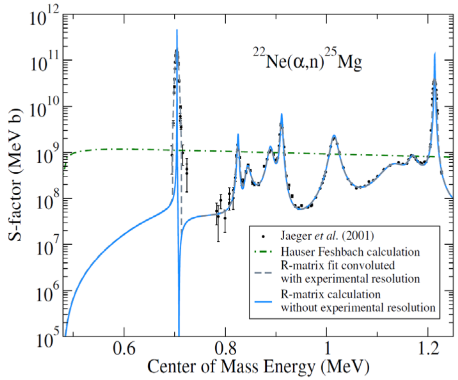
- New deuterated scintillator detector development (ORNL)
- Measurement of ^{22}Ne(α,n), ^{25}Mg(α,n), and ^{26}Mg(α,n) (with ^{3}He counter), will be pursued at ND







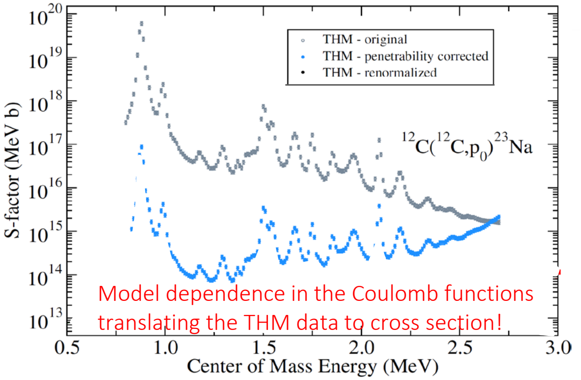


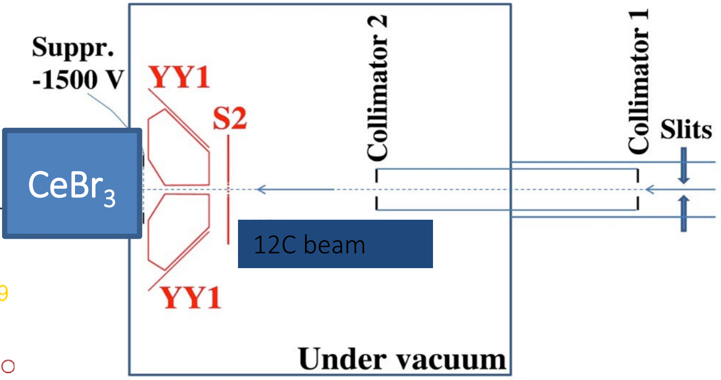


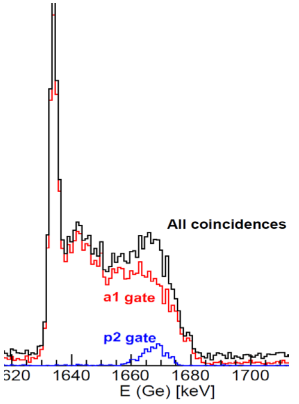
De Boer et al. First near-threshold measurements of the ^{13}C(α ,n$_1$)^{16}O reaction for low-background-environment characterization. Physical Review C 106, 2022, 055808

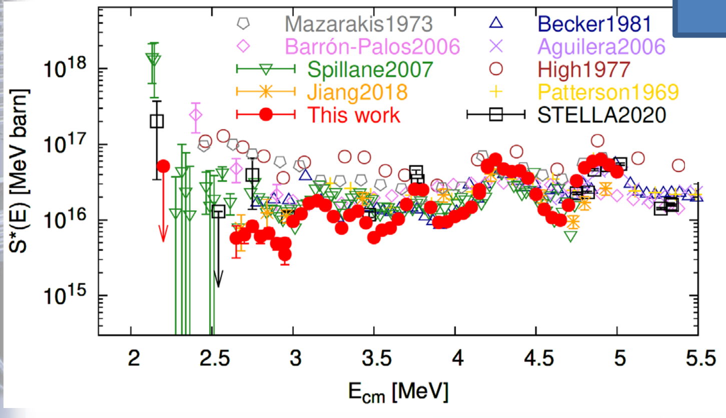
$^{12}C+^{12}C$ fusion studies

- $^{12}C+^{12}C$ measurement towards lower energies with better efficiency using $CeBr_3$ detectors!
- THM measurements at Texas A&M using $^{12}C(^{13}C,^{24}Mg^*)n$!
- Complementary $^{20}Ne(\alpha,p)^{23}Na$ and $^{23}Na(p,\alpha)^{20}Ne$ towards higher energies for R-matrix analysis!



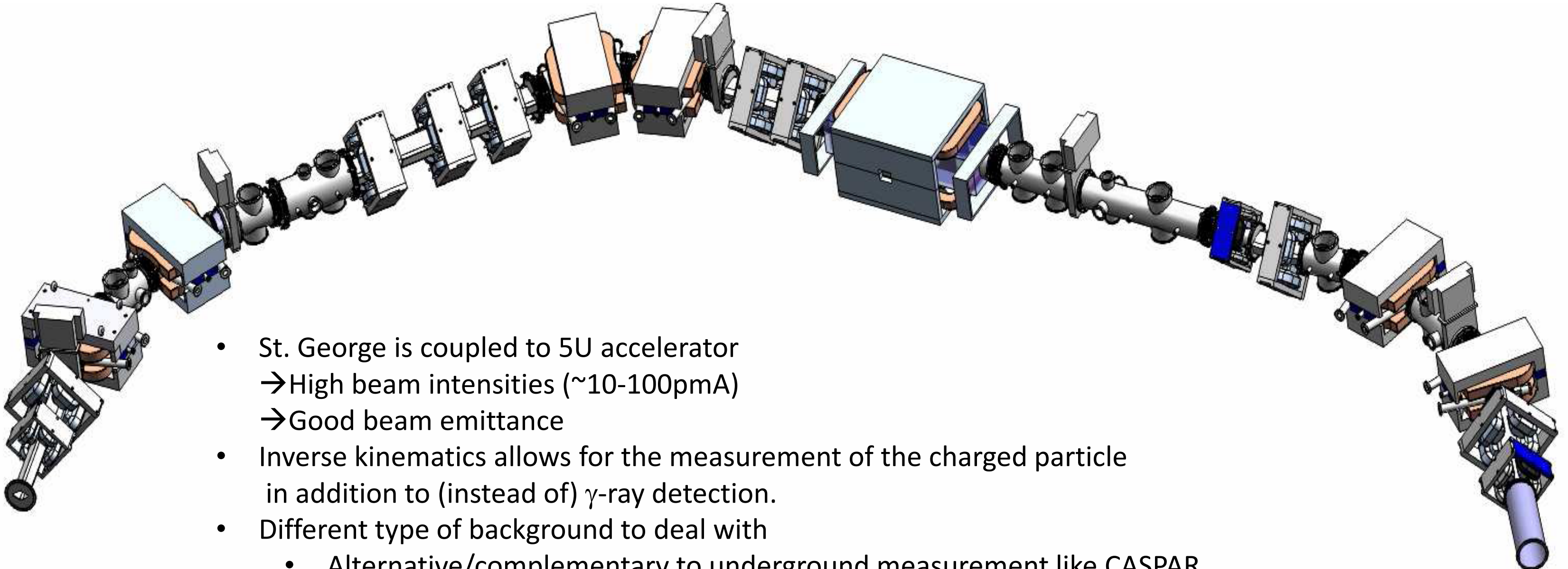






Tan et al. New Measurement of C 12 +C 12 Fusion Reaction at Astrophysical Energies. Physical Review Letters 124, 2020. 192702

St. George Enables Studies of Weak (α,γ) Reactions

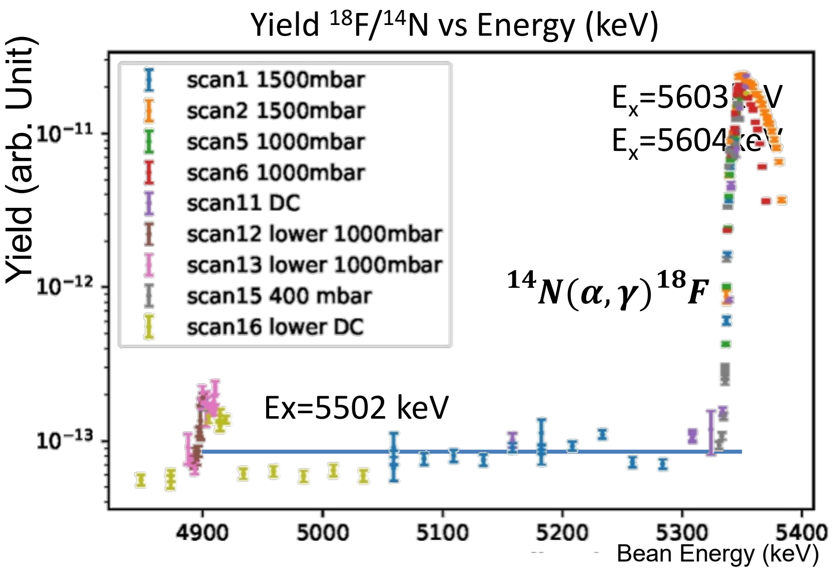


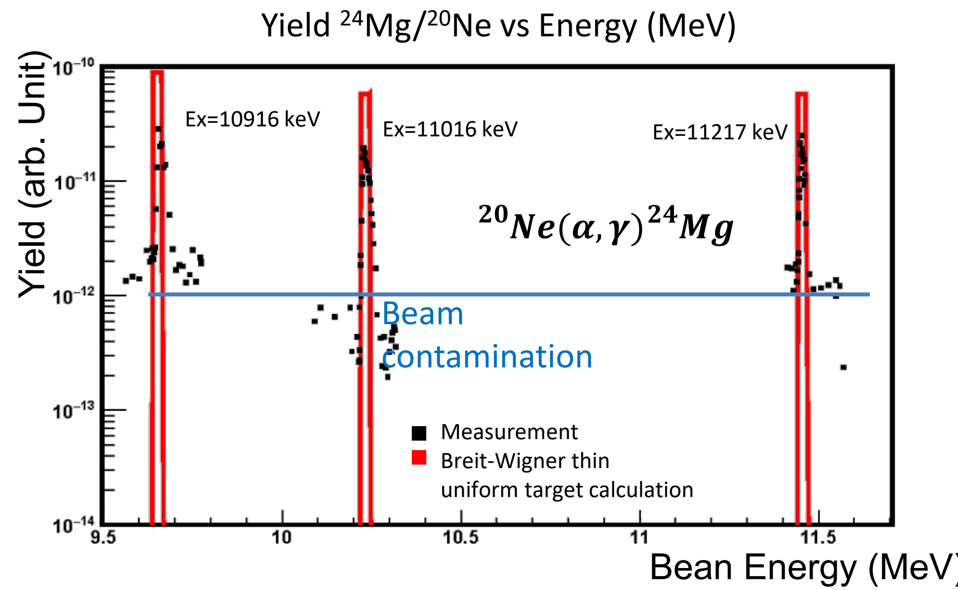
- St. George is coupled to 5U accelerator
  →High beam intensities (~10-100pmA)
  →Good beam emittance
- Inverse kinematics allows for the measurement of the charged particle in addition to (instead of) γ-ray detection.
- Different type of background to deal with
  - Alternative/complementary to underground measurement like CASPAR
- Designed for large angular/energy acceptance
  - +/-40mrad and +/-7.5% in energy

Design of SECAR@FRIB is based on St. George

Well Known-Resonance Measured with St. George

- Reproducing existing/published data
- Demonstrate acceptable beam rejection for ~$1 p\mu A$ incoming beam intensity with clear path for improvements
- Establishing presence of beam contamination





- Origin of the neutrons required for the s-process
  - $^{14}N(\alpha,\gamma)^{18}F(\beta)^{18}O(a,g)^{22}Ne(\alpha,n)^{25}Mg$
    - and competing $^{22}Ne(\alpha,\gamma)^{26}Mg$
- Origin of ^{19}F in AGB star
  - $^{15}N(\alpha,\gamma)\ ^{19}F$
- Nucleosynthesis of ^{24}Mg in neon burning
  - $^{20}Ne(\alpha,\gamma)^{24}Mg$
  - low energy resonances, evaluation of direct capture contribution

From the Big Bang to the First Stars

Three particle fusion reactions:

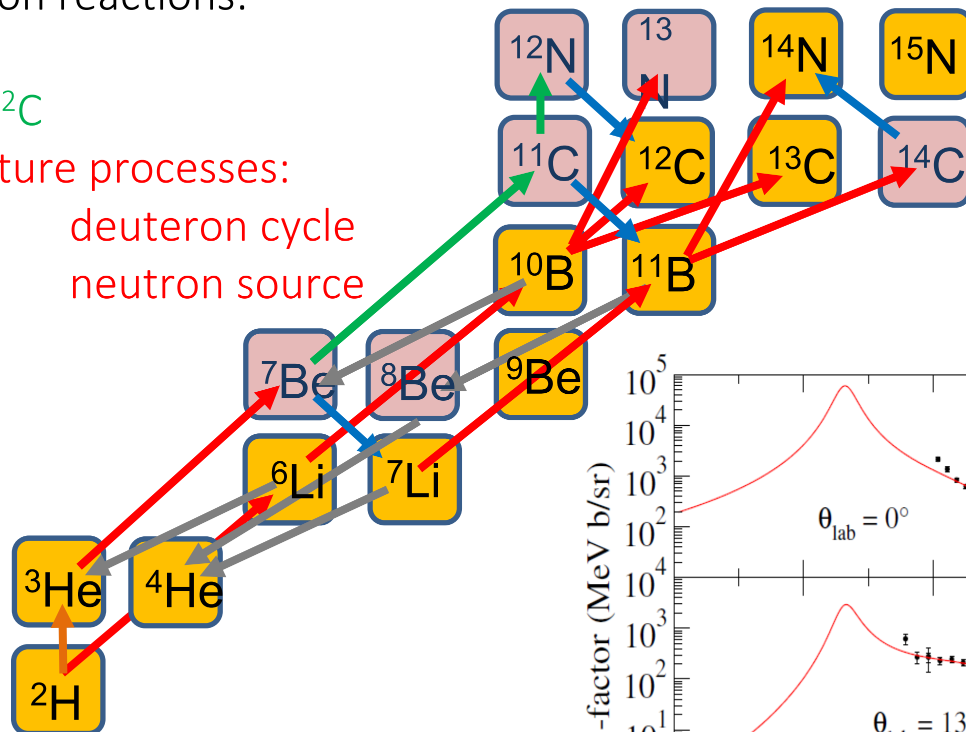
$^{4}He(\alpha\alpha,\gamma)^{12}C$

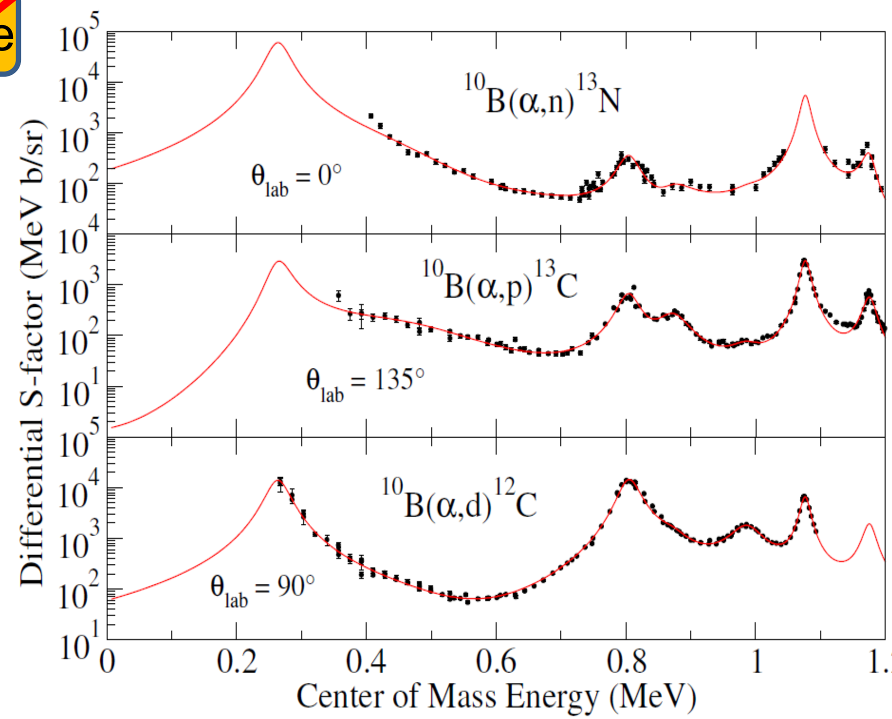
$^{4}He(\alpha n,\gamma)^{9}Be(\alpha,n)^{12}C$

and Li induced capture processes:

$^{6}Li(\alpha,\gamma)^{10}B(\alpha,d)^{12}C$ deuteron cycle

$^{7}Li(\alpha,\gamma)^{11}B(\alpha,n)^{14}N$ neutron source

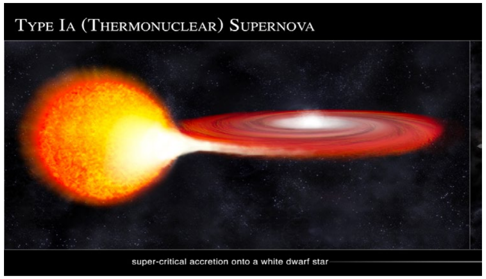




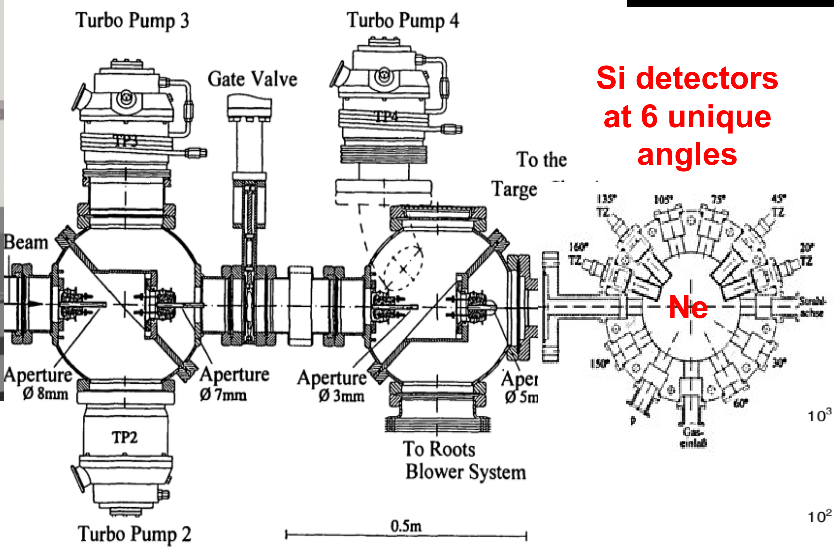
Converting He and Li through α cluster states to C and O

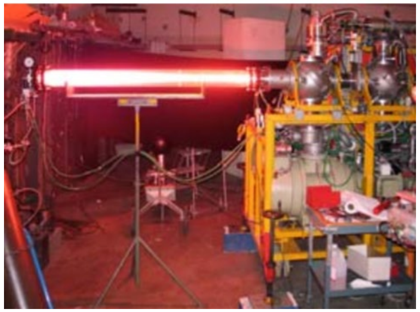
^{20}Ne(α,p)^{23}Na studied with Rhino

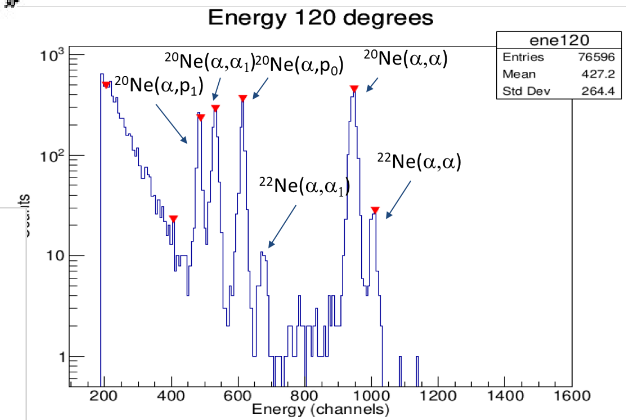
Parikh (2013) found ^{20}Ne(α,p)^{23}Na was 1 of 5 most important reactions in SNIa.

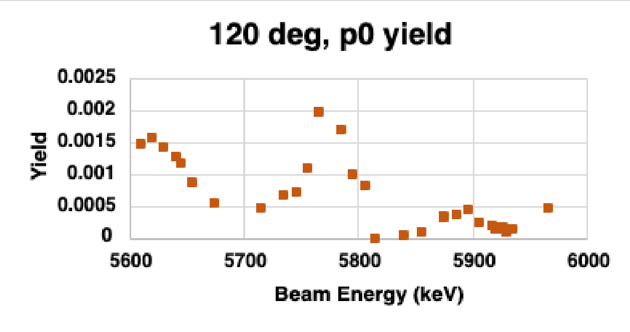


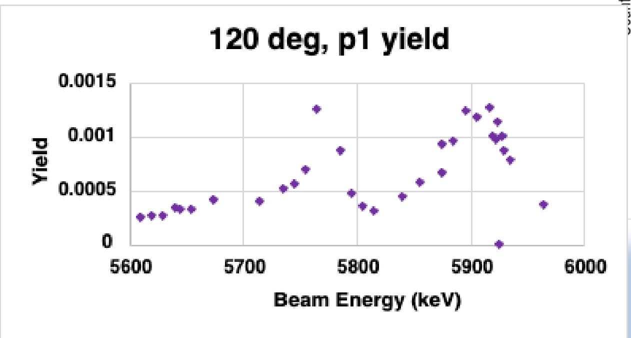
Rhinoceros* Gas Target











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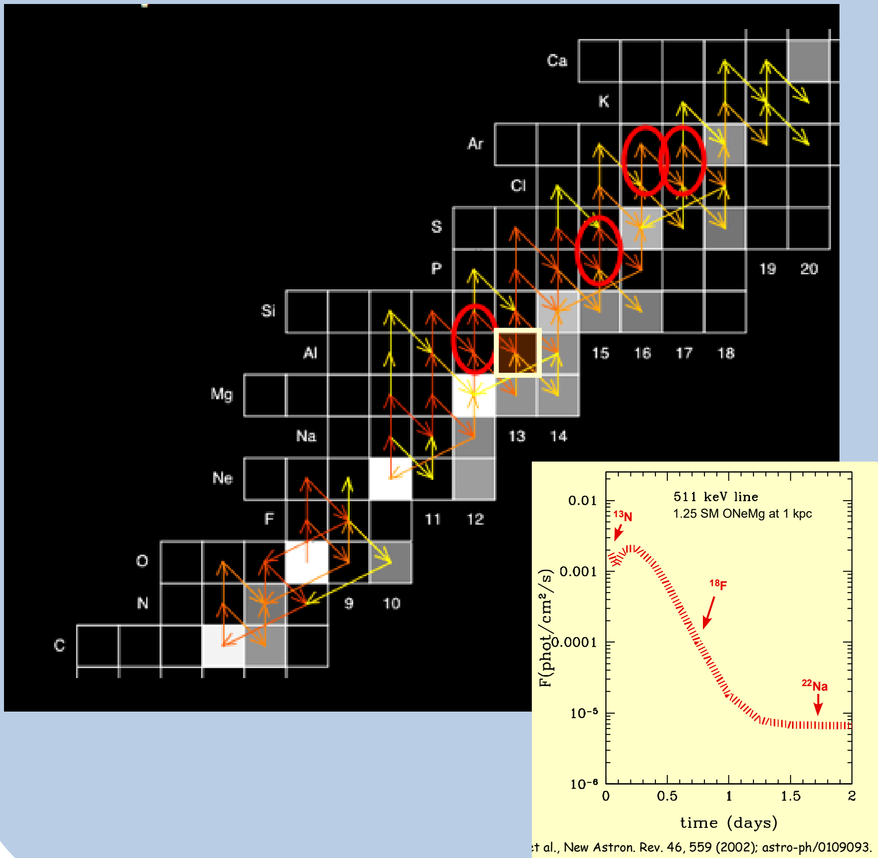
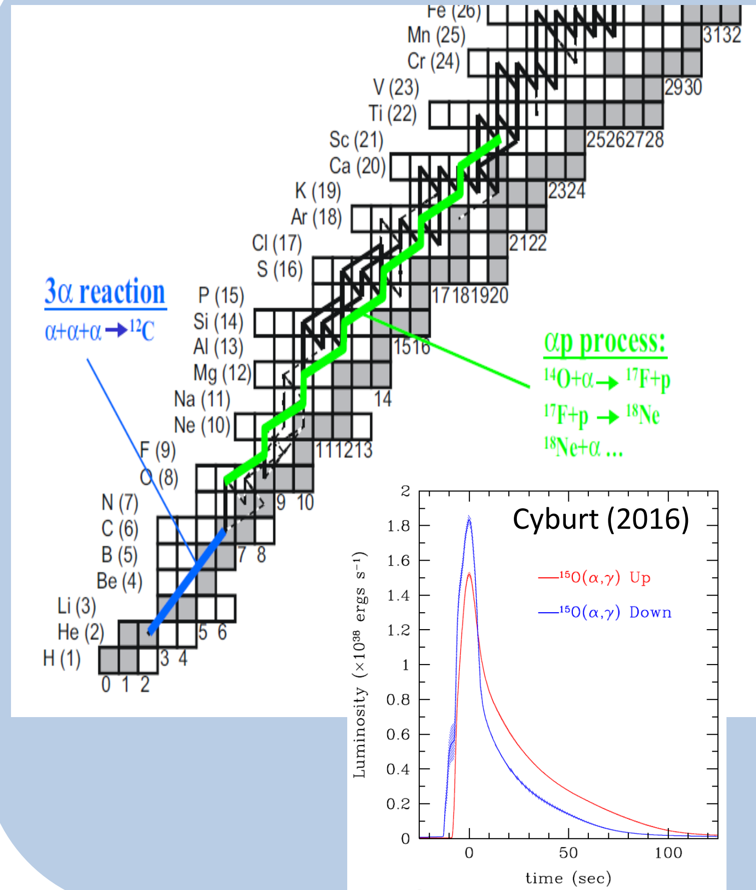
Explosive Nucleosynthesis

Novae

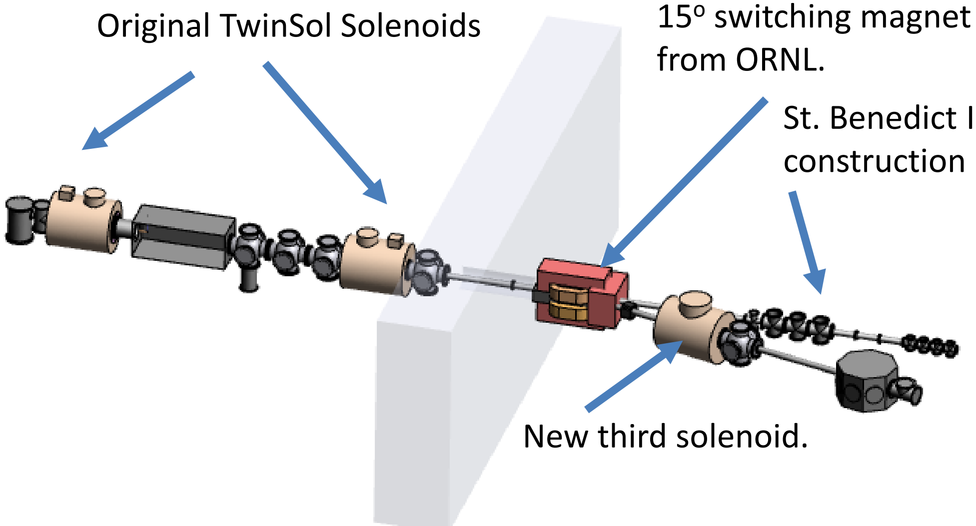


X-ray bursts

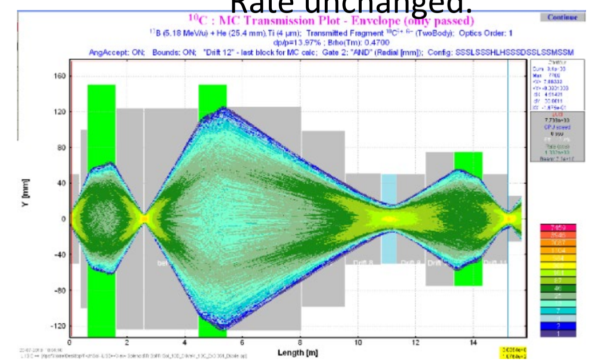


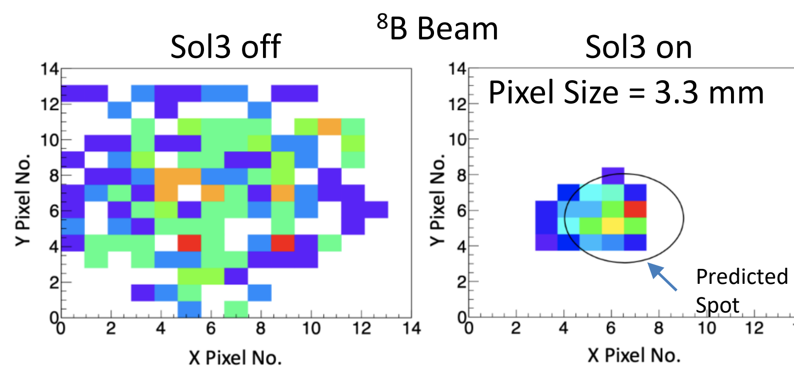
1. Direct: Using RIBs to measure reactions for astrophysics.
2. Indirect: Using stable beams/target to extract structure of proton-rich nuclei

TwinSol becomes TriSol



Beam Spot decreased to 8 mm (from 25 mm). Rate unchanged.





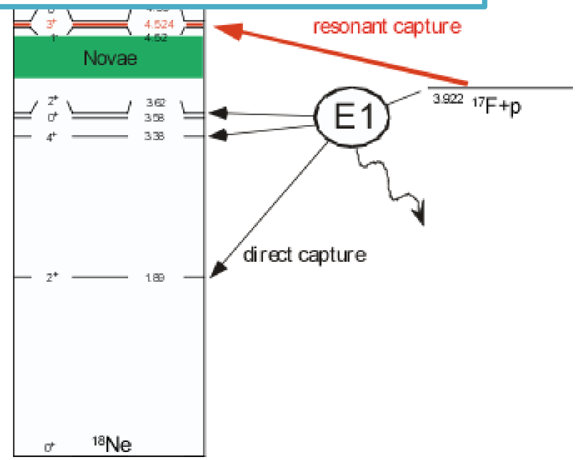
Beams of ^{7}Be, ^{8}B, ^{11}C, ^{14}O, ^{17}F demonstrated summer 2022.

$^{17}F(p,\gamma)^{18}Ne$ constrained through $^{17}F(d,n)$

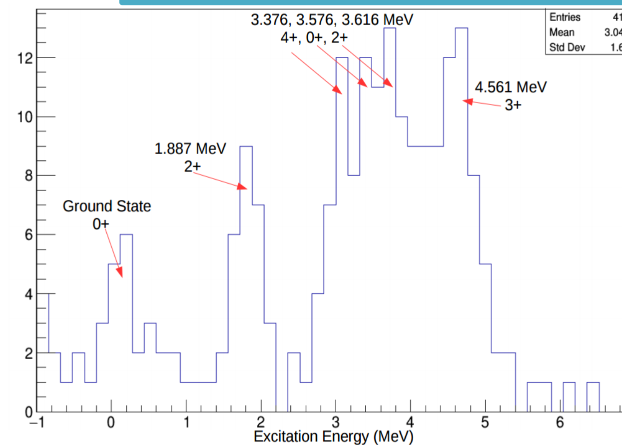
P. O'Malley

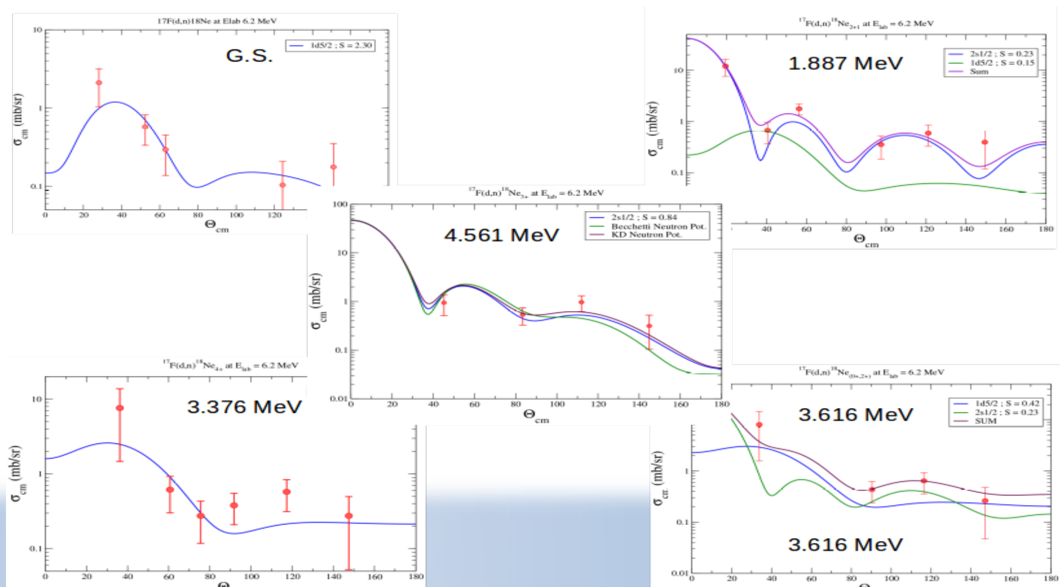
Neutrons detected in array of VANDLE plastic scintillators and U. Michigan deuterated Benzene detectors.

$^{17}F(p,\gamma)^{18}Ne$ populates bound states in direct capture.

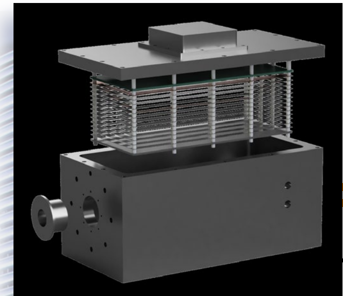


Excitation energies determined via n TOF.



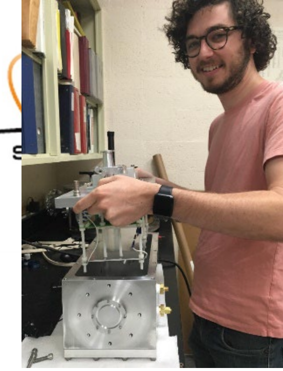


O'Malley et al., PRL (submitted).

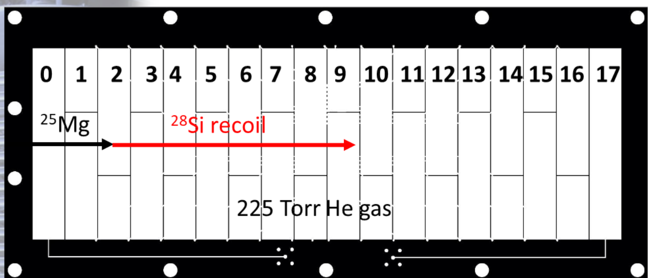


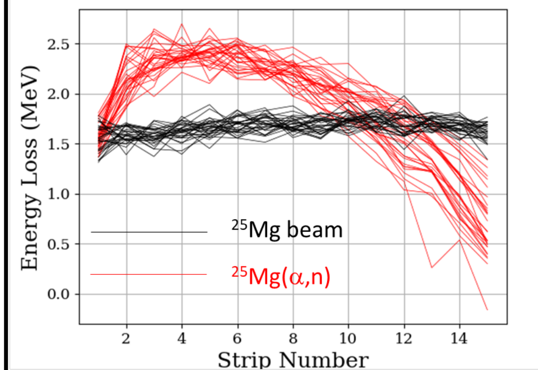
ATHENA built for RIB experiments

(Active Target High Efficiency detector for Nuclear Astrophysics)

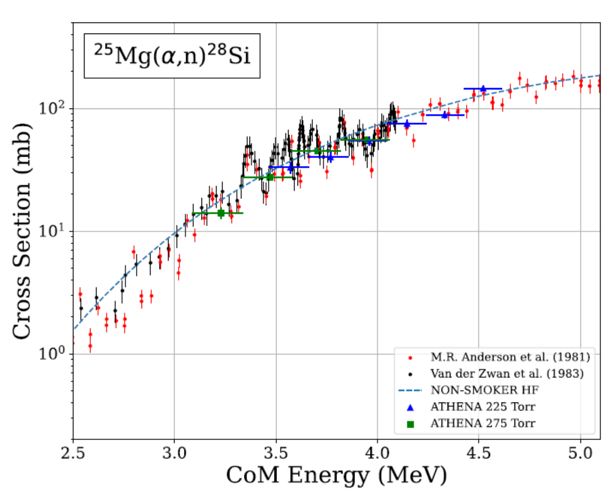


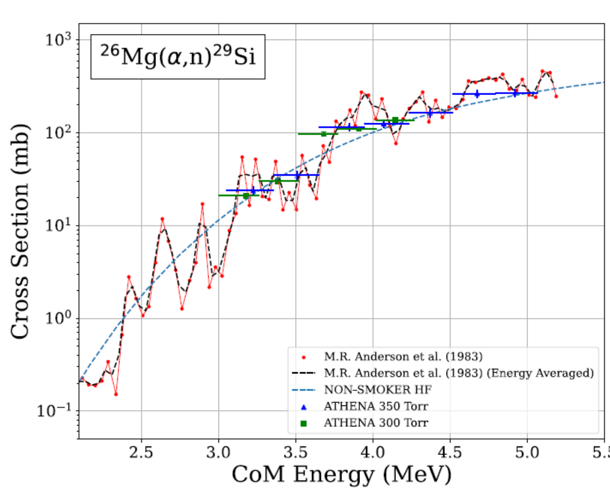
Drew Blankstein





- **Self Normalizing** - Beam and reaction products are measured simultaneously in one detector without any extra beam monitors.
- **Total Cross Section** - Many experimental setups consist of measurement of angular distributions from which the total cross section is extrapolated.
- Measurement over excitation energy range with **single beam energy**. This is especially important with radioactive beams, as beam tune is very sensitive to incident energy.
- Ability to utilize **different targets** depending on the reaction. This allows for a wide range of reactions to be measured with one detector.
- **Identify beam ion** on event by event basis. Important for cocktail beams.
- Can just as easily study reactions with **neutron ejectiles**.





Blankstein et al., NIMA (2023); Ph. D. thesis (2023)

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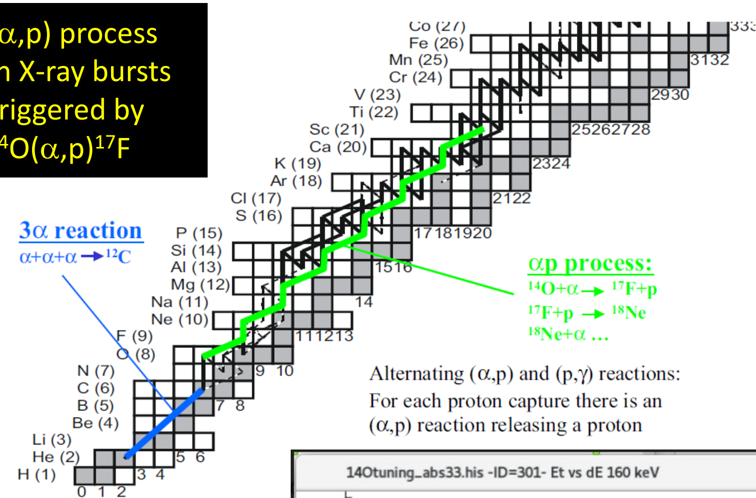
(α,p) to be measured with ATHENA

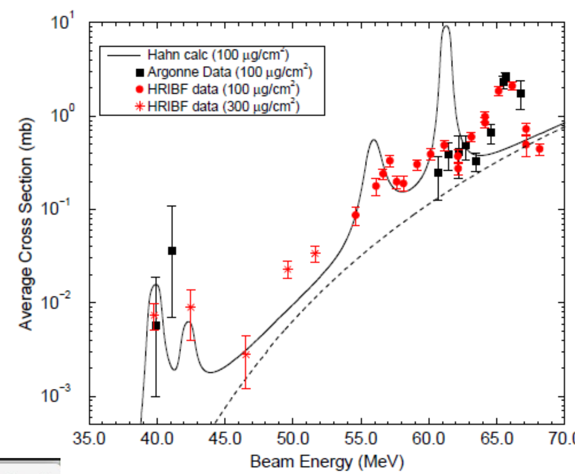
In detail: αp process

(α,p) process in X-ray bursts triggered by $^{14}O(\alpha,p)^{17}F$



Alternating (α,p) and (p,γ) reactions:
For each proton capture there is an (α,p) reaction releasing a proton

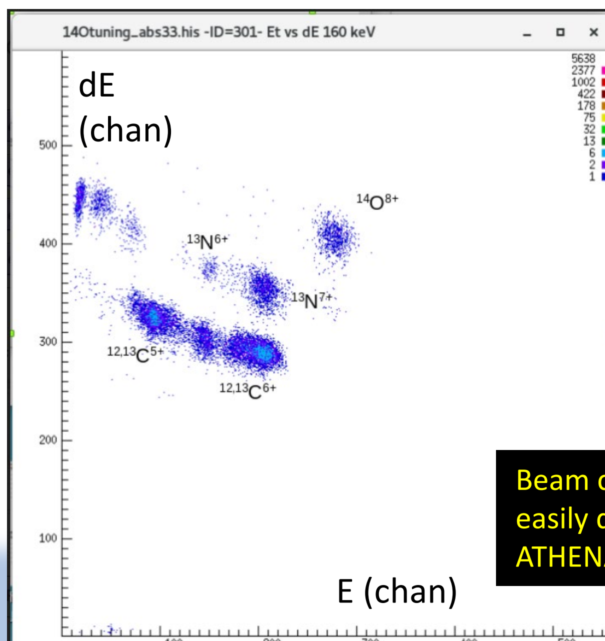
$^{17}F(p,\alpha)^{14}O$ Total Cross Section



Will von Seeger

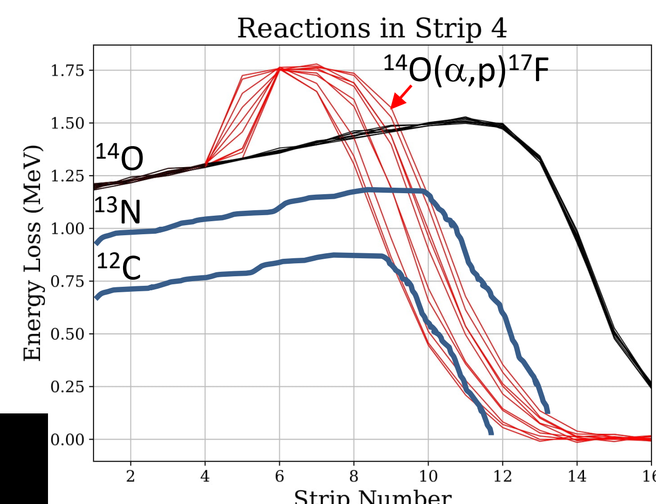
Best estimates are from inverse reaction which ignores contributions to excited ^{17}F levels

^{14}O beam developed at TriSol: $^{3}He(^{12}C,^{14}O)$ production reaction. ~5 kHz ^{14}O, 20% purity. ^{12}C and ^{13}N were main contaminants.



Beam contaminants easily distinguished in ATHENA

Reactions in Strip 4



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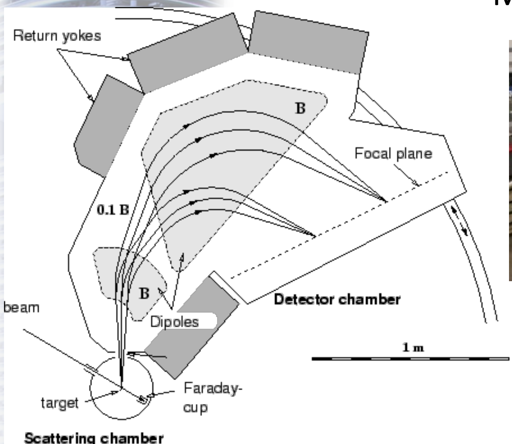
ND Enge Spectrometer In Progress

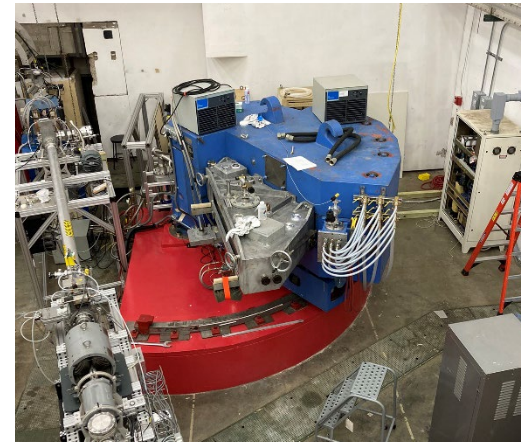
Measuring nuclear structure (for nuclear astrophysics) via transfer reactions.



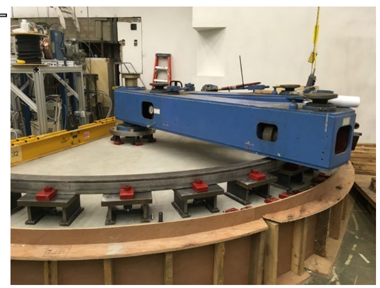
(d,p), (^{3}He,d), (^{3}He,t), (^{3}He,α), (^{6}Li,d), (^{7}Li,t), etc…

January 2018

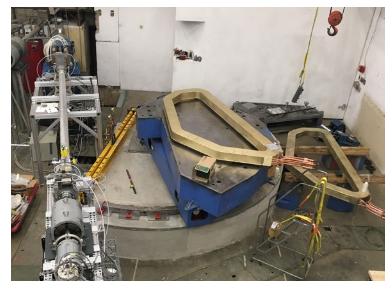
March 2019



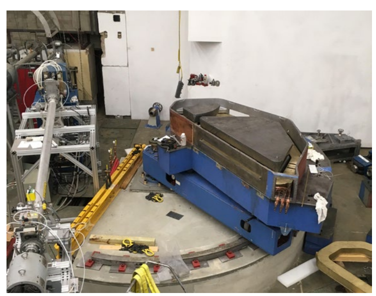
October 2022



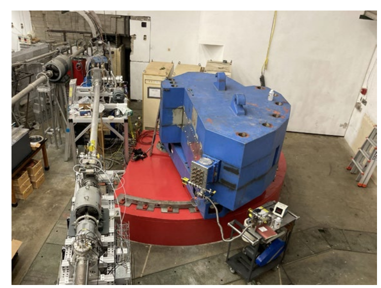
September 2019



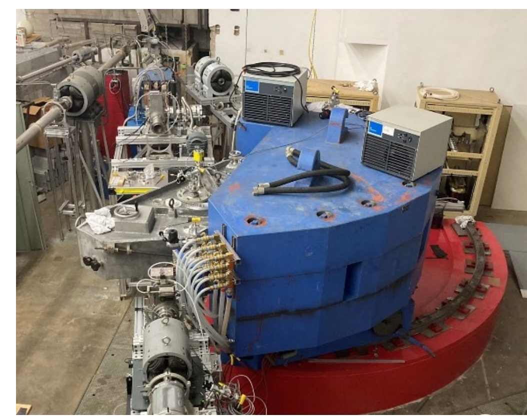
January 2020



March 2020



July 2021



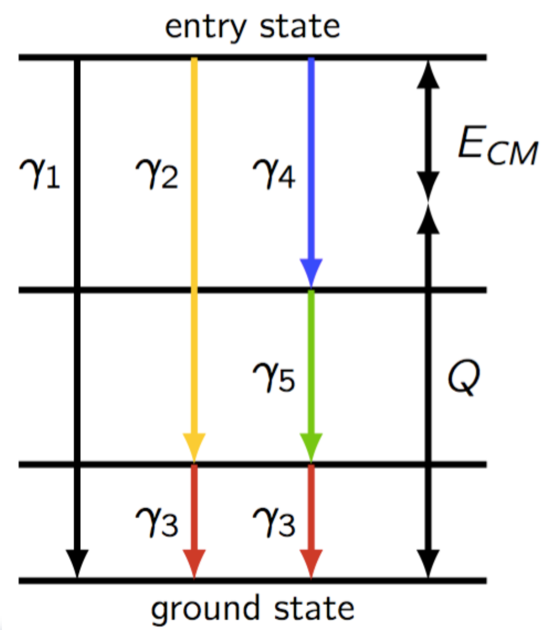
January 2023

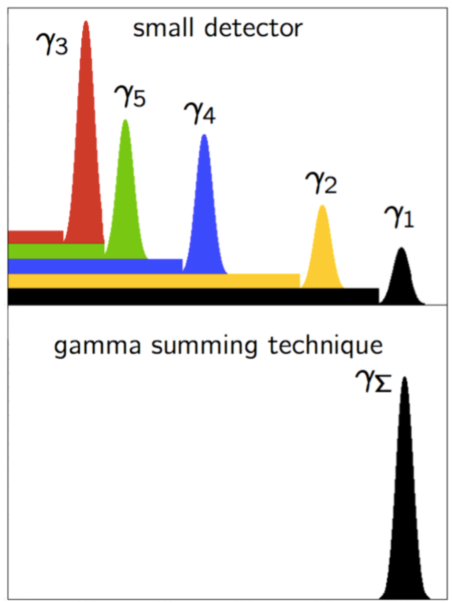
Scott Carmichael

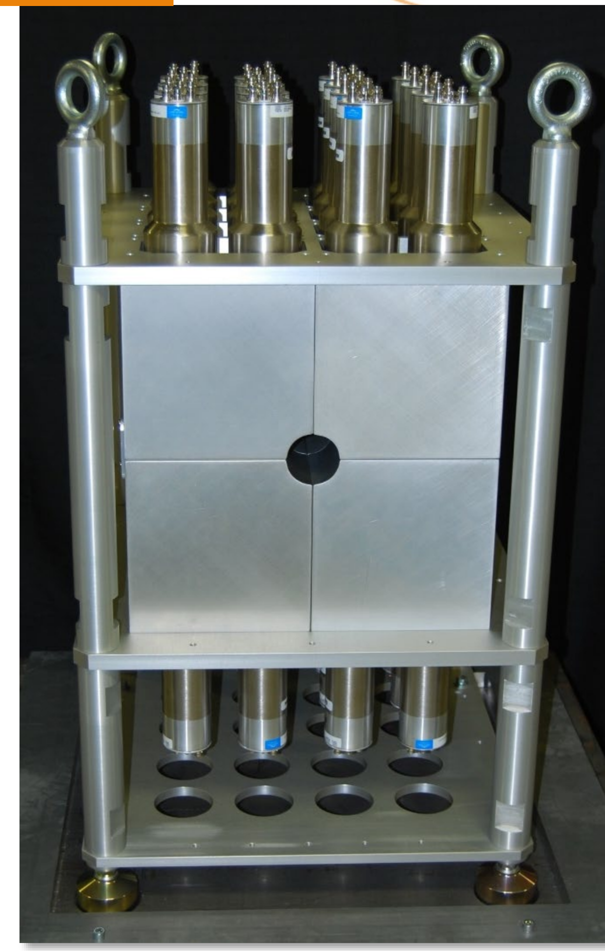
Study ^{58}Ni(^{3}He,t)^{58}Cu to constrain ^{57}Ni(p,γ)^{58}Cu for ^{44}Ti production in core-collapse supernovae.

Cross section measurements: summing technique

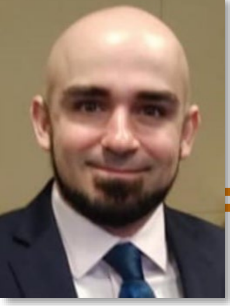
- High Efficiency TOtal absorption spectrometeR
- 16 separate segments, each read by two PMTs
- crystal size: 4x8x8 inch,
- 1 mm Al casing surrounding each crystal
- 12 mm Al on the outer walls of the array
- 60 mm borehole





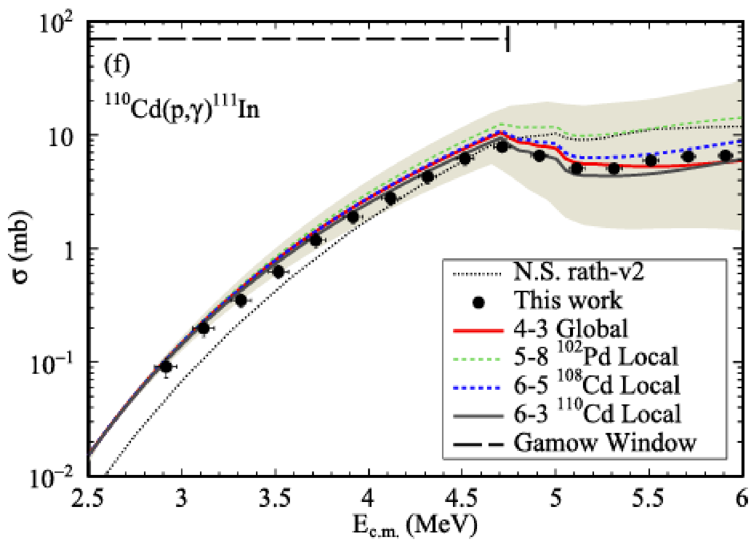


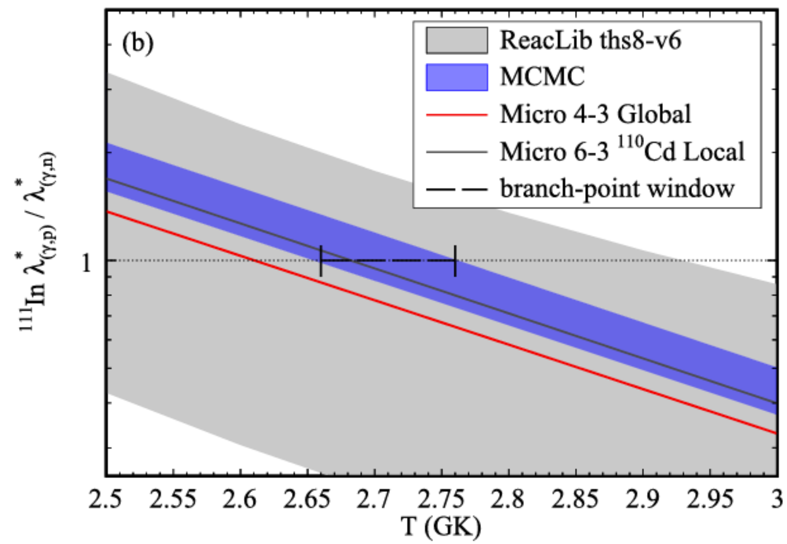
Reingold et al., European Physical Journal A 55 (2019) 77



Completed measurements: Constraining the ^{111}In branching point

- Understand the p-process reaction flow around mass A=100 by constraining the branching temperature between (γ,p)/(γ,n) reactions on ^{111}In
  - measure the proton capture on ^{110}Cd and ^{108}Cd and ^{102}Pd to better constrain the HF model
  - Use HF models to calculate the (γ,p) and (γ,n) rates
  - Identify the branching temperature and its uncertainty



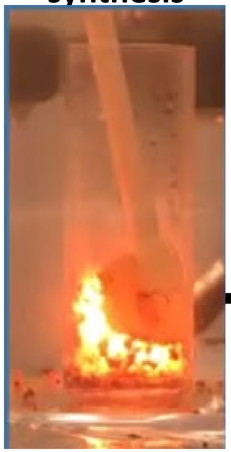


Olivas-Gomez et al., PRC 102 (2020) 055806
Ph.D. thesis February 2022

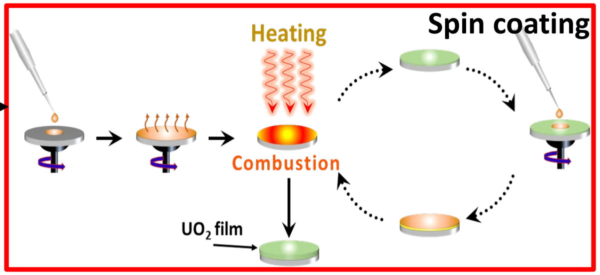
New Emphasis on Target Making at NSL

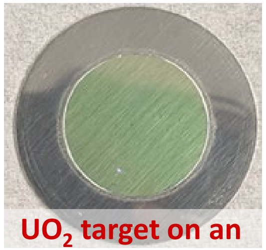
Conventional methods

Solution combustion synthesis

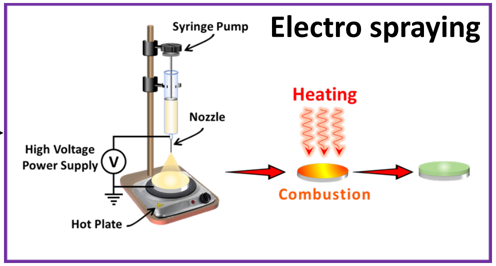


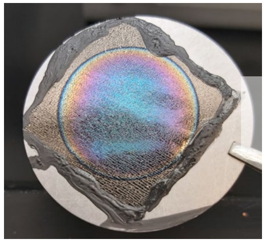
Khachatur Manukyan (NSL)



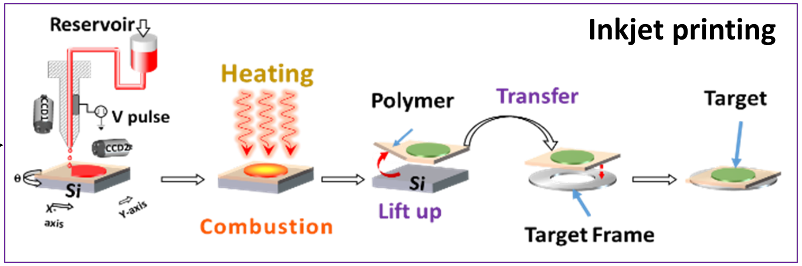


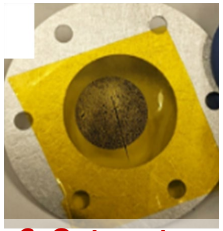
UO_2 target on an aluminum backing





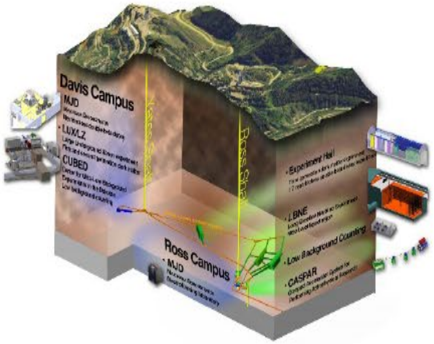
UO_2 target on a carbon backing

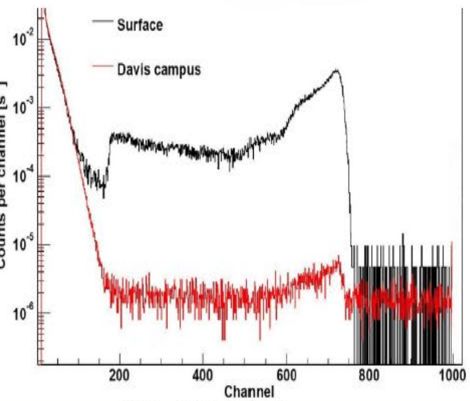




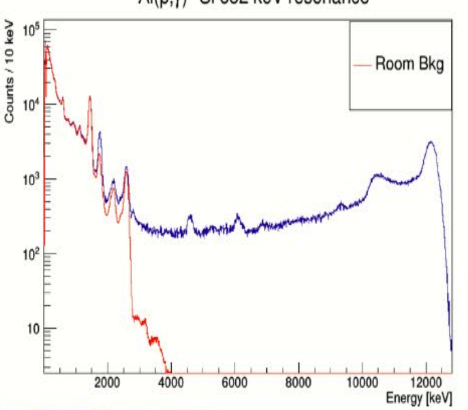
CeO_2 target on Kapton backing

CASPAR





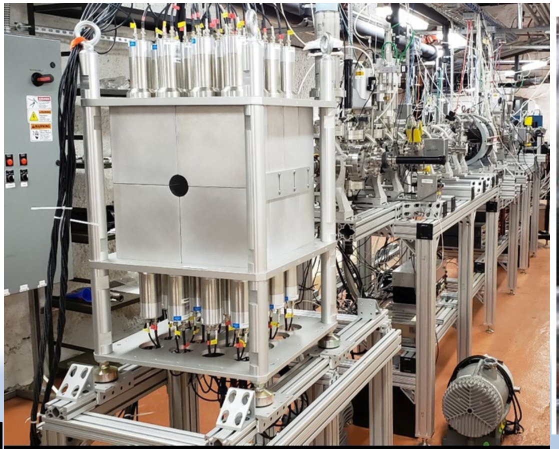
$^{27}Al(p,\gamma)^{28}Si$ 632 keV resonance

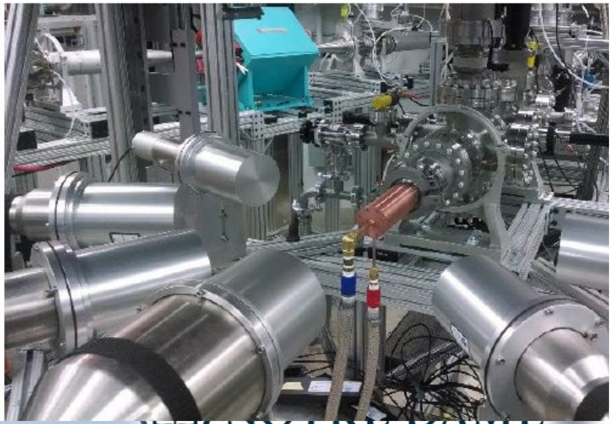


Operational since 2018

- ^{14}N(p,γ) – B. Frentz(PhD)
  - Experiment complete. Analysis in progress.
- ^{11}B(α,n) – T. Borgwardt*)(PhD) & A. Gula
  - Experiment complete. Borgwardt thesis complete and defended. Publication in process
- ^{7}Li(a,γ) – M. Hanhardt*(PhD)
  - Experiment complete. Analysis in process
- ^{27}Al(p,γ) – O. Gomez (PhD)
  - Experiment complete. Publication submitted. Thesis in process.
- ^{22}Ne(a,γ) – Shahina (PhD)
  - Experiment complete. Analysis in process.
- ^{22}Ne(a,n) – T. Kadlecek* (PhD)
  - Experiment complete. Analysis in process.
- ^{18}O(a,γ) – A. Dombos
  - Experiment complete. Publication with co-authors.

Restart 2023/2024





Conclusions

- Variety of tools and techniques are being used to constrain nucleosynthesis in multiple astrophysical sites.

- Strong emphasis on neutron sources, first generation of stars, exotic nuclei affecting observables in astrophysical explosions.

- Didn't have enough time to talk about a number of topics such as
  - Studies of fission
  - r-process sensitivities
  - AMS measurements of cosmic ray chronometers
  - pynonuclear reaction studies with active target detector
  - mass measurements, etc..

  - SSNAPD spectrometer to measure particle branching ratios ~10^{-5}
  - plunger device to measure nuclear lifetimes
  - new stilbene detectors for (α,n)
  - 3-D printing of targets
  - etc…

Thank you
ISNAP
NOTRE DAME
HOLLISTER