Alpha-Induced Reactions on Light Nuclei – Project Overview

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February 26 – 29, 2024
Crystal City, VA, USA

Project High-Level Summary

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Project objectives

1. Experimentally determine alpha-induced cross sections, secondary gamma-ray yields, and neutron spectra.

   ^{7}Li(a,n), ^{10}B(a,n), ^{11}B(a,n), ^{13}C(a,n), ^{19}F(a,n)

2. Perform an R-matrix assessment and dissemination of results.
3. Perform calculations to evaluate the impact of these new data sets compared using codes such as SOURCES4C, Geant4, and/or MCNP.

A Comprehensive Self-Consistent Campaign to Determine Reaction Cross Sections, Secondary Gamma-Ray Yields, and Measured Neutron Spectra for Alpha-Induced Reactions on Light Nuclei

(OR23-ML-AlphaInducedRxnsOnLightNuclei-PD3Ob)

Timeline - 5-yr (FY24-28)

Sponsor – NNSA DNN NA22
PM – David Matters
TA – Elizabeth Heckmaier

Comprehensive → Measure all outgoing channels (neutrons, gammas, charge particles)
Self Consistent → Same experimental setup for all reactions

Project Team

Dr. Jason Nattress (PI)
Dr. Ben Thomas
(UofM Student)

Dr. James DeBoer (Co-PI)
Dr. Ed Stech
Dr. Dan Robertson
Dr. Wanpeng Tan
Dr. Khachatur Manukyan
Post Doctoral Scholar

Dr. Hye Young Lee (Co-PI)
Dr. Som Paneru
Dr. Sean Kuvin
Dr. Chris Prokop

Dr. Michael Febbraro (Co-PI)
Dr. Juan Manfredi
Mr. Tyler Smith
(TBD Military Student)

AFIT will offer Military and Civilian graduate students opportunities for involvement throughout the 5-yr life cycle of this project.

It is envisioned that, potentially, multiple Masters theses will come from this project

We will actively involve the NNSA consortia to engage with students

Project timeline

FY24 - Experiment setup and commissioning

FY25 - $^{13}C(\alpha,n)$ and $^{10}B(\alpha,n)$

FY26 - $^{11}B(\alpha,n)$ and $^{19}F(\alpha,n)$

FY27 – $^{7}Li(\alpha,n)$

FY28 – Impact calculation

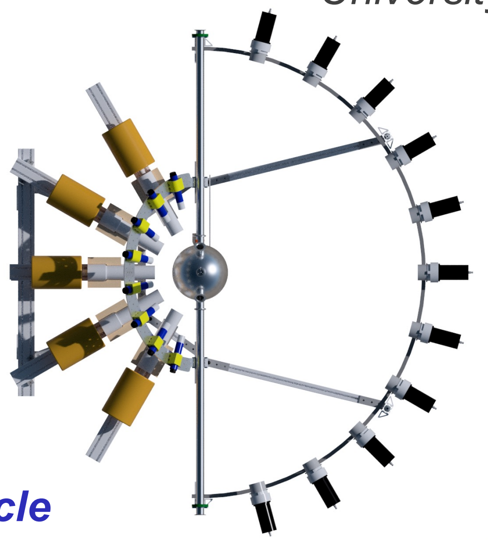
Beamline characterization and target testing beginning next week!

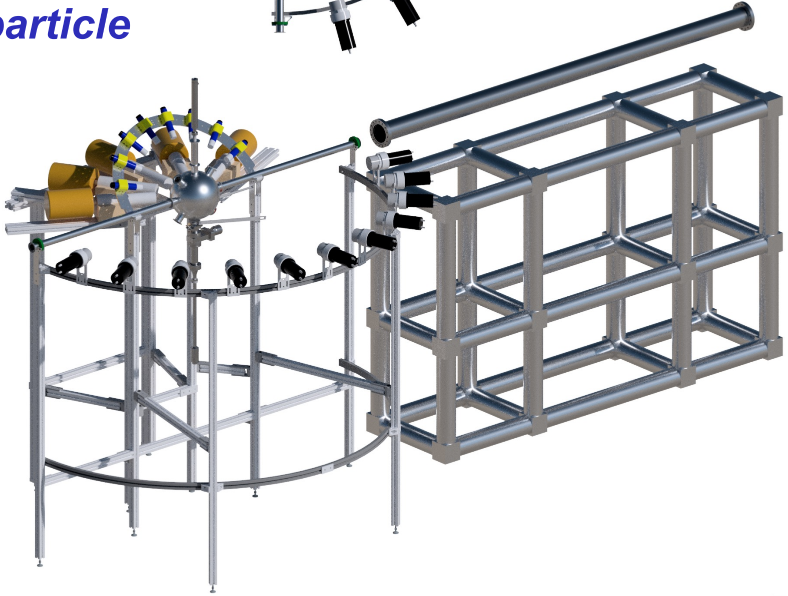
Task	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
2.2.1 Project Baseline Review	■											
2.2.2 Install experimental end station on FN	■	■	■									
2.2.3 Accelerator target preparation and evaluation	■	■	■	■								
2.2.4 Commission (α,n) beamline on the FN				■								
2.2.5 $^{13}C(\alpha,n)$ & $^{10}B(\alpha,n)$ measurements					■	■						
2.2.6 $^{13}C(\alpha,n)$ & $^{10}B(\alpha,n)$ analysis and assessment						■	■	■	■			
2.2.7 $^{11}B(\alpha,n)$ measurement							■	■	■			
2.2.8 Prepare for $^{19}F(\alpha,n)$									■	■		
2.2.9 $^{11}B(\alpha,n)$ analysis and assessment									■	■	■	■
2.2.10 $^{19}F(\alpha,n)$ measurements											■	■
2.2.11 $^{19}F(\alpha,n)$ analysis and assessment												
2.2.12 $^{7}Li(\alpha,n)$ measurements												
2.2.13 $^{7}Li(\alpha,n)$ analysis and assessment												
2.2.14 Impact calculations												

Task	Year 4				Year 5			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
2.2.11 $^{19}F(\alpha,n)$ analysis and assessment	■	■	■	■				
2.2.12 $^{7}Li(\alpha,n)$ measurements		■	■					
2.2.13 $^{7}Li(\alpha,n)$ analysis and assessment			■	■	■	■		
2.2.14 Impact calculations					■	■	■	■

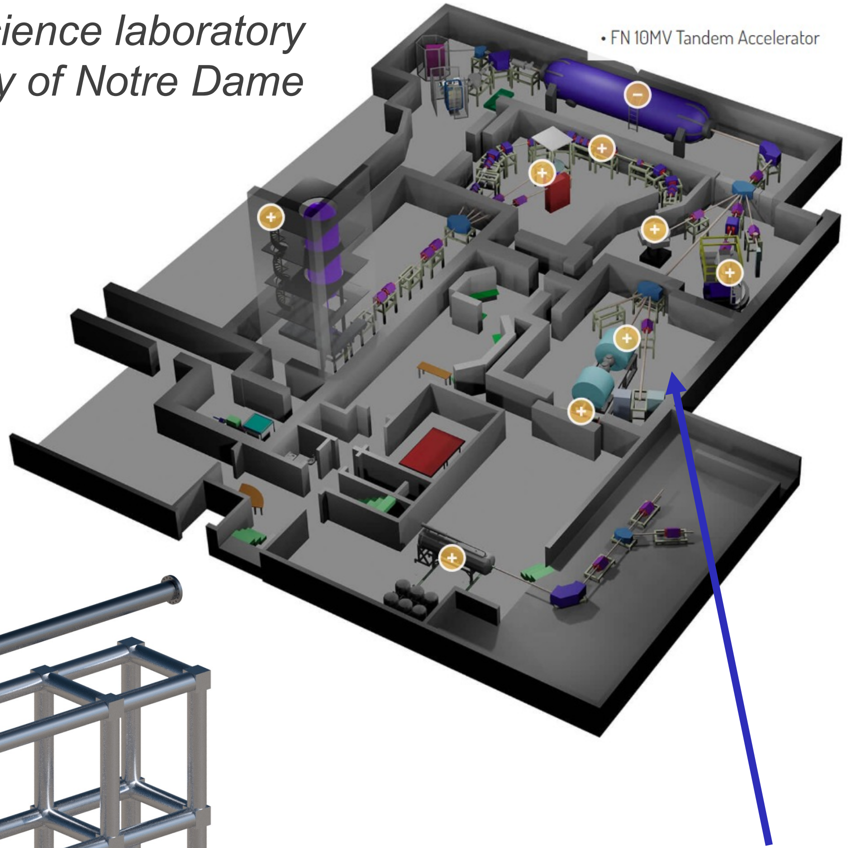
Experimental setup

- Dedicated beamline at the University of Notre Dame Nuclear Science Laboratory for the life of the project!
  - FN beamline
- Full suite of detectors
  - Deuterated scintillator arrays → ***Neutron***
  - GENIE n-type HPGe → ***Gamma***
  - Silicon detectors → ***Charge particle***
- Dedicated target fabrication and characterization
  - Apparatus for enriched ^{12}C foil production
  - Air-free metallic lithium handling
  - Isotopically enriched ^{13}C, ^{10}B, ^{11}B, ^{7}Li





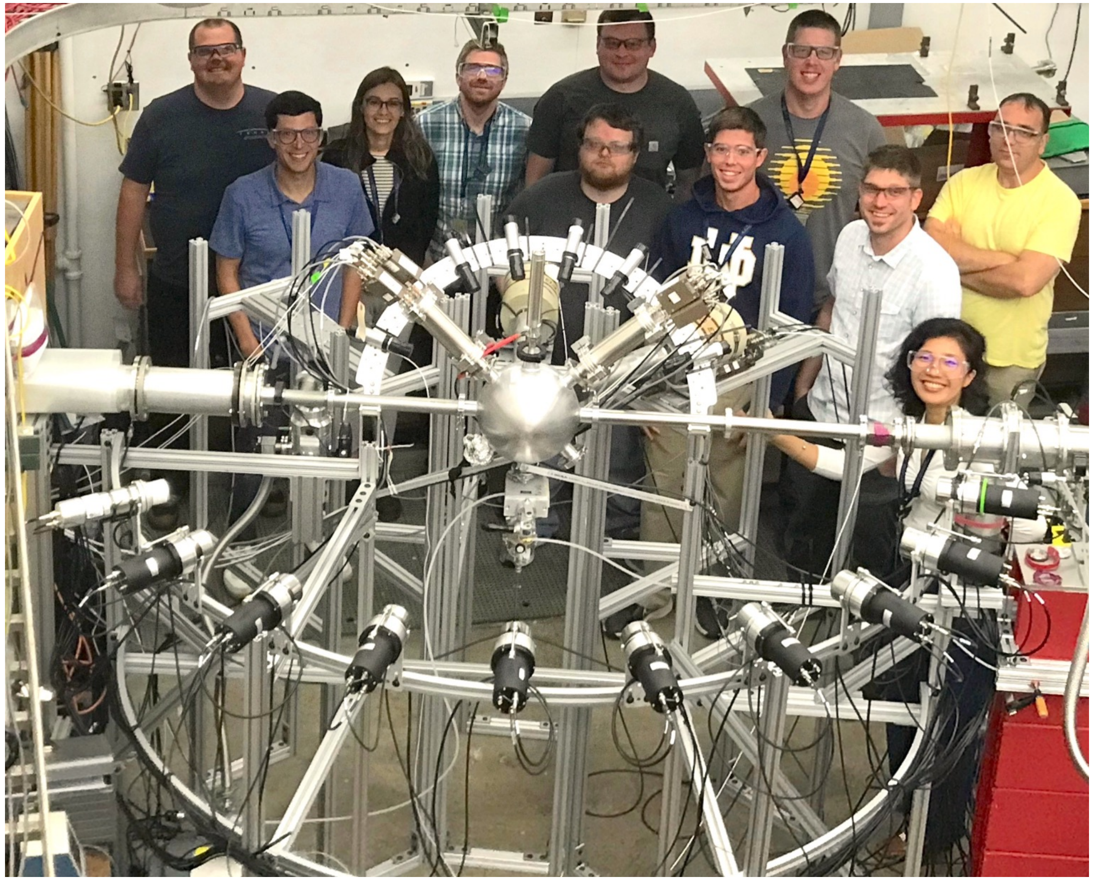
Nuclear science laboratory
University of Notre Dame



Dedicated area for this work

Conclusion

- 5-yr project to measure (a,n) cross section on light nuclei underway!
- Campaign will provide neutron, gamma-ray, and charge particle data up to 8 MeV
- R-Matrix assessment and impact calculations will be performed to assess the reach of this new nuclear data



BACKUP SLIDES

Selected Prior Work

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PHYSICAL REVIEW C **106**, 055808 (2022)

First near-threshold measurements of the $^{13}C(\alpha, n_1)^{16}O$ reaction for low-background-environment characterization

R. J. deBoer,[1,*] A. Gula,[1] M. Febbraro,[2] K. Brandenburg,[3] C. R. Brune,[3] J. Görres,[1] Gy. Gyürky,[4] R. Kelmar,[1] K. Manukyan,[1] Z. Meisel,[3] D. Odell,[3] M. T. Pigni,[2] Shahina,[1] E. Stech,[1] W. Tan,[1] and M. Wiescher[1]
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(Received 3 September 2022; accepted 7 November 2022; published 21 November 2022)

PHYSICAL REVIEW C **101**, 025808 (2020)

Low-energy cross-section measurement of the $^{10}B(\alpha, n)^{13}N$ reaction and its impact on neutron production in first-generation stars

Q. Liu,[1] M. Febbraro,[2] R. J. deBoer,[1] S. Aguilar,[1] A. Boeltzig,[1,*] Y. Chen,[1] M. Couder,[1] J. Görres,[1] E. Lamere,[1,†] S. Lyons,[1,‡] K. T. Macon,[1,3] K. Manukyan,[1] L. Morales,[1] S. Pain,[2] W. A. Peters,[2] C. Seymour,[1] G. Seymour,[1,§] R. Toomey,[4] B. Vande Kolk,[1] J. Weaver,[5] and M. Wiescher[1]
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PHYSICAL REVIEW C **105**, 044608 (2022)

Direct measurement of $^{59}Ni(n, p)^{59}Co$ and $^{59}Ni(n, \alpha)^{56}Fe$ at fast-neutron energies from 500 keV to 10 MeV

S. A. Kuvin,* H. Y. Lee, B. DiGiovine, C. Eiroa-Lledo, A. Georgiadou, M. Herman, T. Kawano, V. Mocko, S. Mosby, C. Vermeulen, D. Votaw, M. White, and L. Zavorka†
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

G. Perdikakis and P. Tsintari
Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA

H. I. Kim
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(Received 10 February 2022; accepted 11 March 2022; published 11 April 2022)

PHYSICAL REVIEW LETTERS **125,** 062501 (2020)

New $^{13}C(\alpha,n)^{16}O$ Cross Section with Implications for Neutrino Mixing and Geoneutrino Measurements

M. Febbraro,[1] R. J. deBoer,[2] S. D. Pain,[1] R. Toomey,[3,4] F. D. Becchetti,[5] A. Boeltzig,[2,*] Y. Chen,[2] K. A. Chipps,[1] M. Couder,[2] K. L. Jones,[6] E. Lamere,[2,†] Q. Liu,[2] S. Lyons,[2,‡] K. T. Macon,[2] L. Morales,[2] W. A. Peters,[1,6] D. Robertson,[2] B. C. Rasco,[6,1] K. Smith,[6,‖] C. Seymour,[2] G. Seymour,[2,§] M. S. Smith,[1] E. Stech,[2] B. Vande Kolk,[2] and M. Wiescher[2]
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PHYSICAL REVIEW C **100**, 034601 (2019)

Measurement of the $^{10}B(\alpha, n_0)^{13}N$ cross section for $2.2 < E_\alpha < 4.9$ MeV and its application as a diagnostic at the National Ignition Facility

Q. Liu,[1] M. Febbraro,[2] R. J. deBoer,[1] A. Boeltzig,[1,*] Y. Chen,[1] C. Cerjan,[3] M. Couder,[1] B. Frentz,[1] J. Görres,[1] E. A. Henry,[3] E. Lamere,[1,†] K. T. Macon,[1,4] K. V. Manukyan,[1] L. Morales,[1] P. D. O'Malley,[1] S. D. Pain,[2] W. A. Peters,[2] D. Schneider,[3] C. Seymour,[1] G. Seymour,[1,‡] E. Temanson,[2] R. Toomey,[5] B. Vande Kolk,[1] J. Weaver,[6] and M. Wiescher[1]
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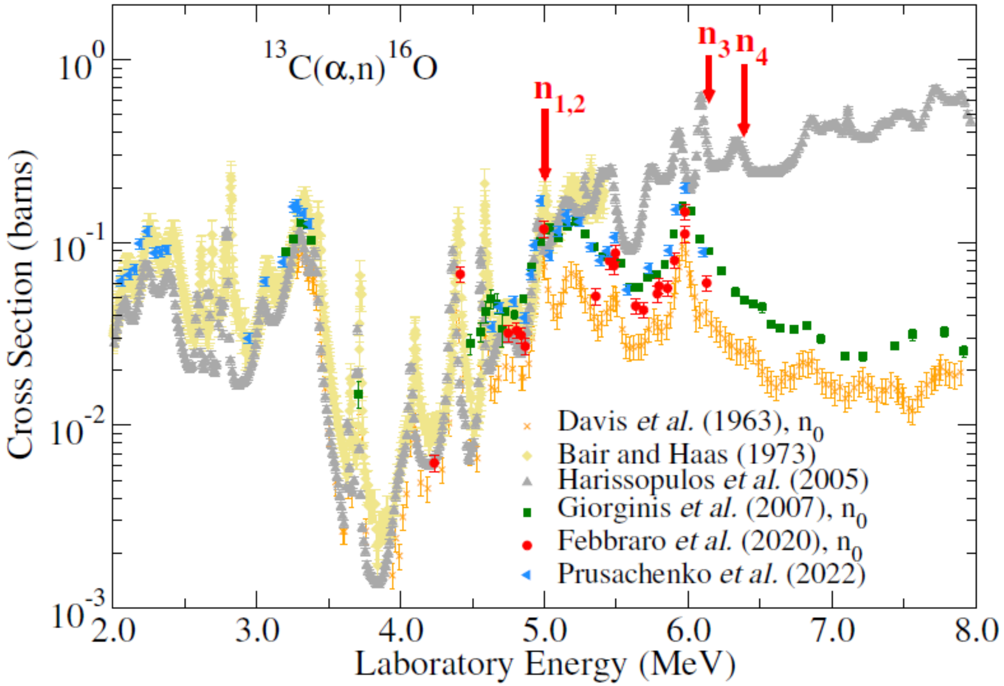
Previous experience with (a,n) cross section measurements!
2+ articles under review, more to come!

$^{13}C(\alpha,n)^{16}O$

	Q-value (MeV)	Threshold (MeV)	Proposed energy range to measure
$^{13}C(\alpha,n)^{16}O$	2.216	0	7 – 9 MeV*

Target – Isotopically enriched ^{13}C foil

We will use the HPGe array to obtain the cross sections for the $n_{2,3,4}$, and can then obtain n_1 by taking the (n_1+n_2) neutron yields and subtracting the n_2 obtained from the γ-rays (at least for the angle integrated cross section)



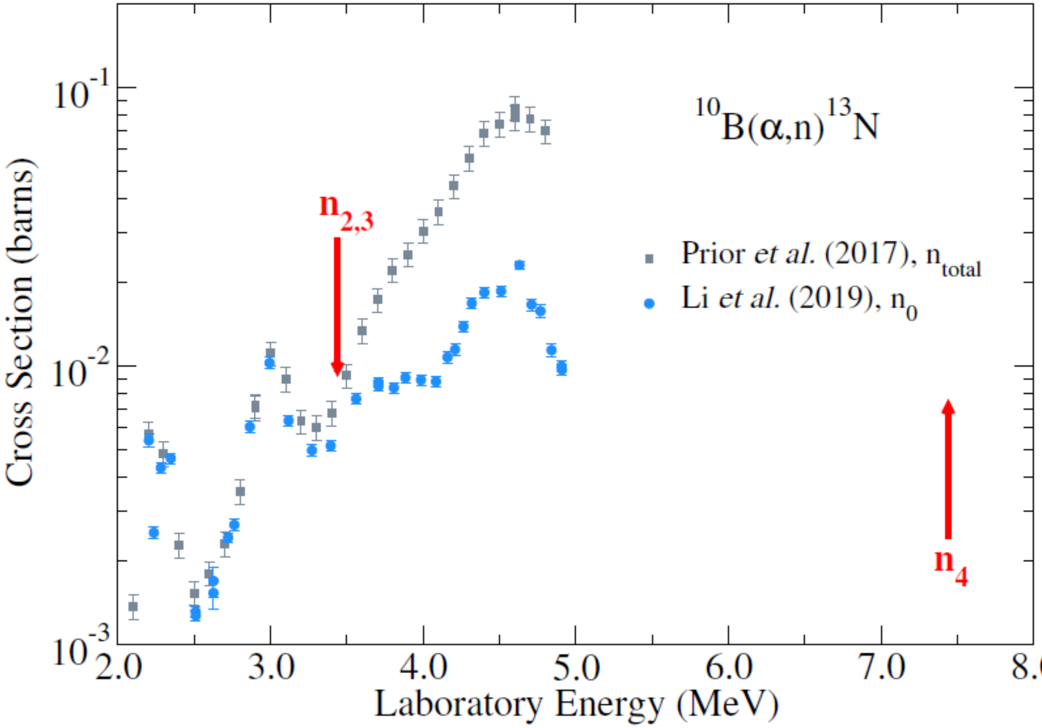
$^{10}B(\alpha,n)^{13}N$

	Q-value (MeV)	Threshold (MeV)	Proposed energy range to measure
$^{10}B(\alpha,n)^{13}N$	1.059	0	2 – 8 MeV**

Target – Isotopically enriched ^{10}B on ^{12}C foil to reduce $^{13}C(\alpha,n)$ background

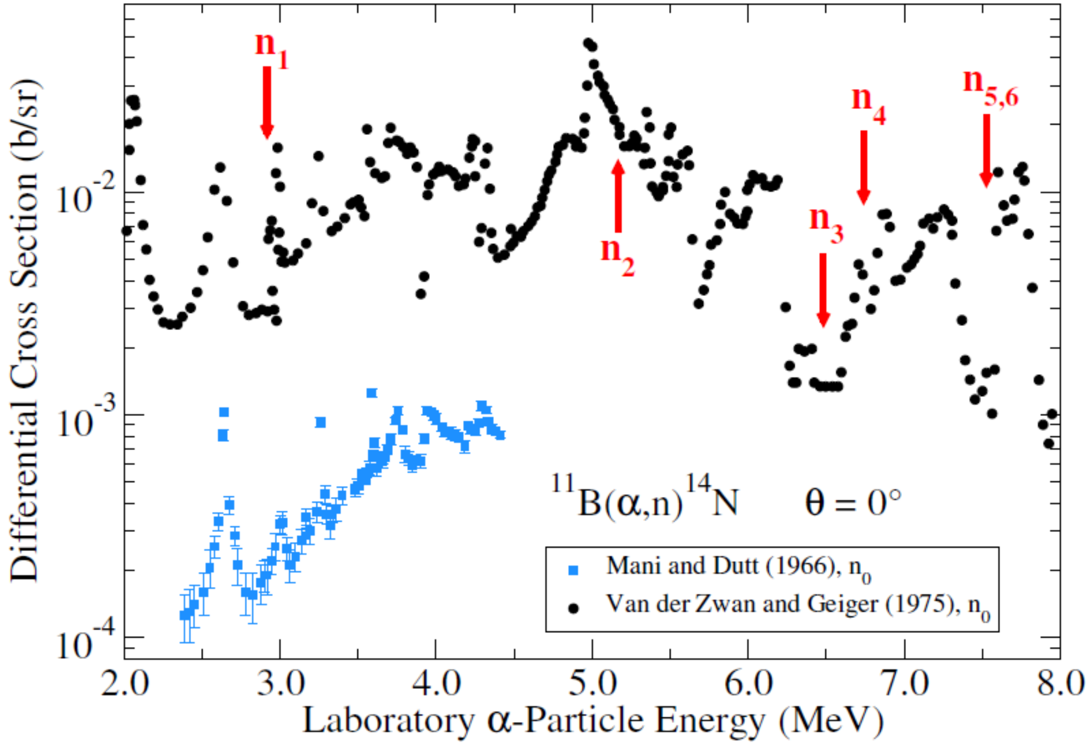
Boron oxidizes so there will be backgrounds from $^{17,18}O(\alpha,n)$, should be able to reduce by purposely oxidizing with enriched ^{16}O gas

Measurements should be relatively straight forward
n_2 and n_3 will not be separable
Unfortunately, they decay through proton emission



$^{11}B(\alpha,n)^{14}N$

	Q-value (MeV)	Threshold (MeV)	Proposed energy range to measure
$^{11}B(\alpha,n)^{14}N$	0.158	0	2 – 8 MeV



Target – Isotopically enriched ^{11}B on ^{12}C foil to reduce $^{13}C(\alpha,n)$ background

Boron oxidizes so there will be backgrounds from $^{17,18}O(\alpha,n)$, should be able to reduce by purposely oxidizing with enriched ^{16}O gas

Lots of resonance structure, so thin targets and small energy steps will be required

Several excited states, but most are energetically separable until $n_{5,6}$

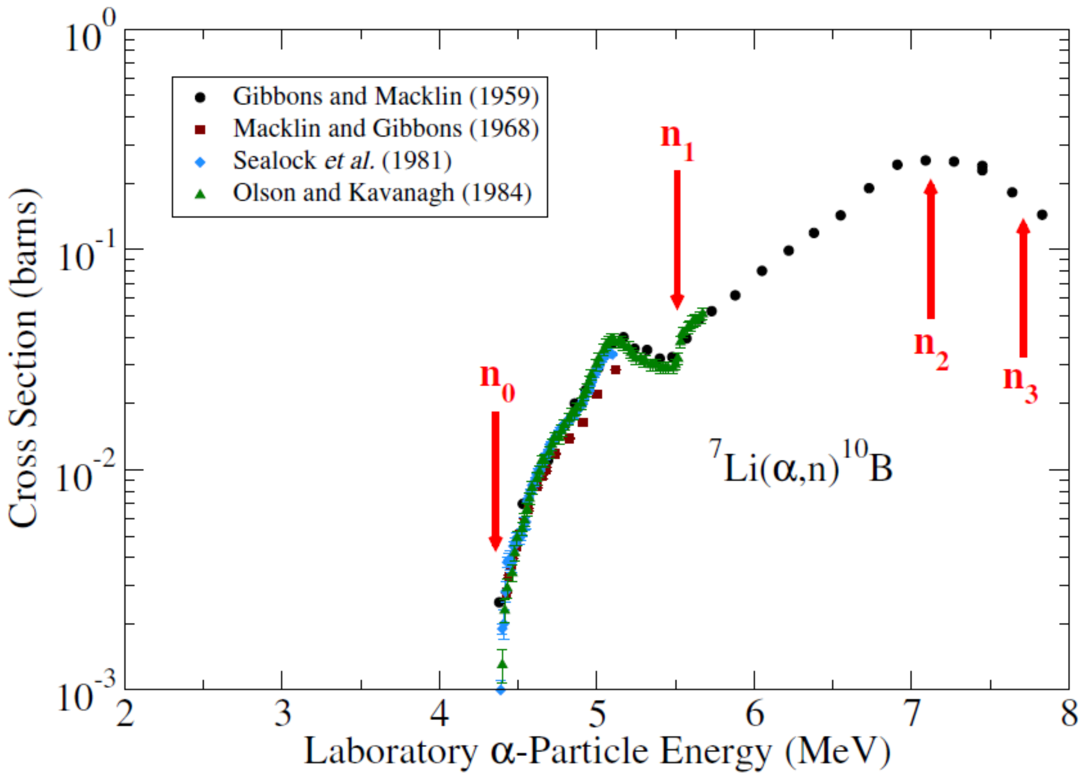
$^{7}Li(\alpha,n)^{10}B$

	Q-value (MeV)	Threshold (MeV)	Proposed energy range to measure
$^{7}Li(\alpha,n)^{10}B$	-2.790	4.366	threshold – 8 MeV

Target – Isotopically enriched metallic ^{7}Li on ^{12}C foil to reduce $^{13}C(\alpha,n)$ background

Well separated excited states

Reduced energy range because of large negative Q-value



$^{19}F(\alpha,n)^{22}Na$

$^{19}F(\alpha,n)^{22}Na$	-1.952	2.350	threshold – 8 MeV

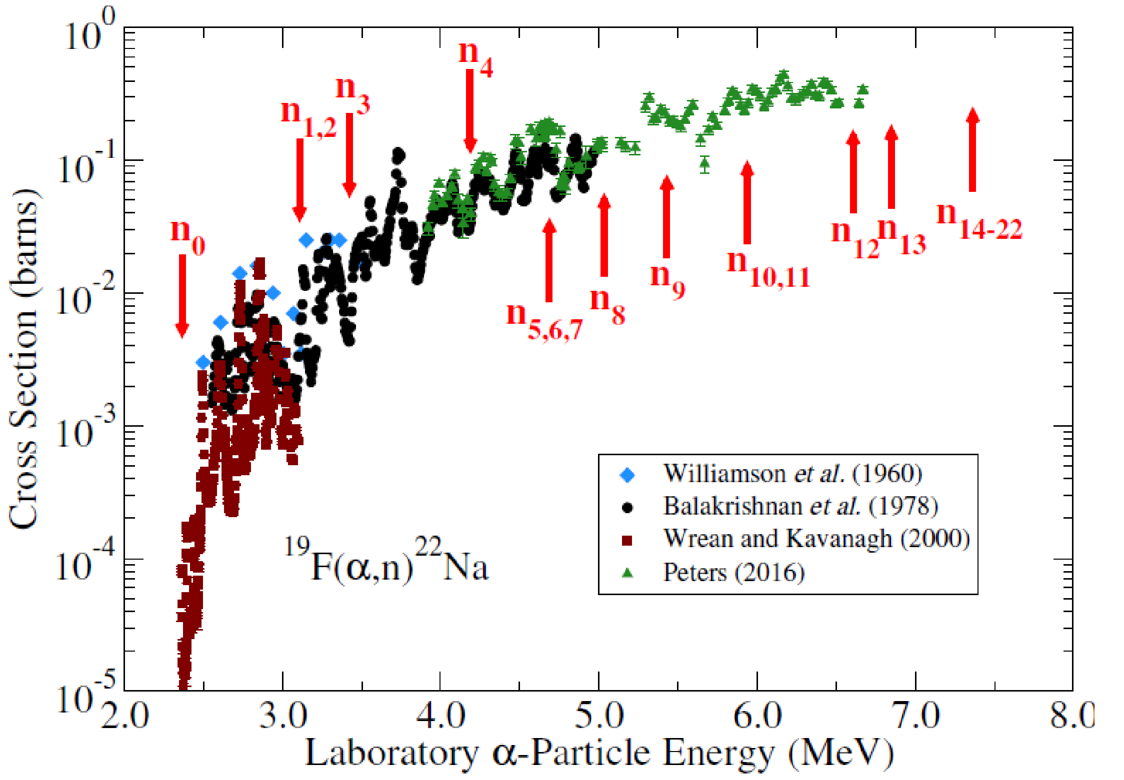
Target – Isotopically enriched $^{40}CaF_2$ on ^{12}C foil to reduce $^{13}C(\alpha,n)$ background

Definitely the most challenging reaction

Many narrow resonances necessitate thin targets

Many excited states will require a lot of time to analyze the data

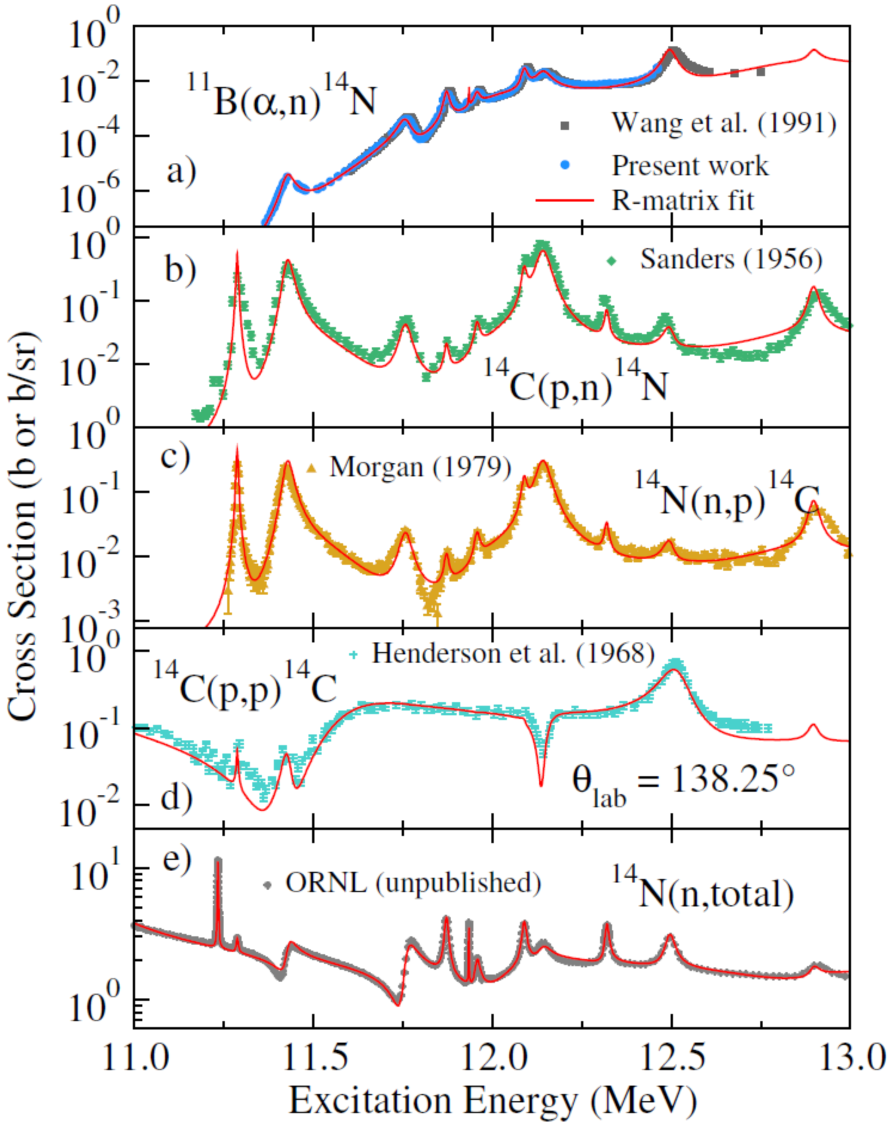
Activation can be used to constrain total cross section



R-matrix fits using AZURE2

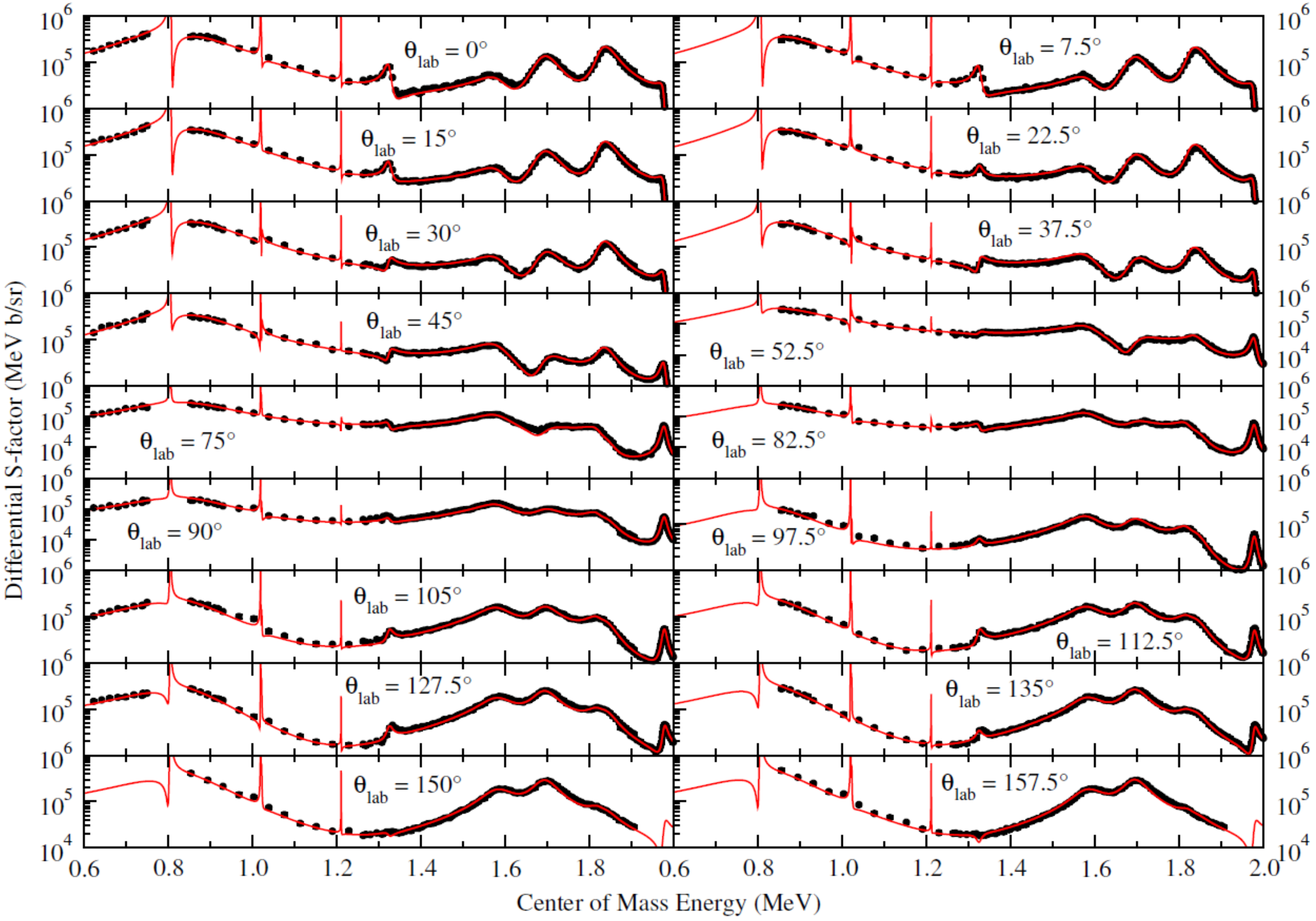
AZURE2 R-matrix code developed at UND

- Specialized for charged particle-induced reactions
- It can also be used for neutron-induced reactions
- We try to take a holistic view of R-matrix data analysis
- We consider not just our reaction data but all reactions that populate the same nucleus through compound nucleus-type reactions
- This provides a framework to compare systematic uncertainties between data sets, both in energy calibration and cross section dependence.



We've started working on $^{13}C(\alpha,n)^{16}O$

- This has been done in collaboration with Gerry Hale and Mark Paris at LANL, the ENDF/B evaluators for this system
- We've taken the EDA R-matrix fit and slightly modified it to fit our new data, just looked at the low energy range from 0.8 to 3.3 MeV so far
- Simultaneous fit to data at all angles
- This is the kind of (α,n) data we expect from the proposed measurements



Impact Calculations

- We will evaluate potential new data sets in the Defense Nuclear Nonproliferation mission space
- Based on feedback from the Cross Section Evaluation Working Group (CSEWG) meeting in Nov. 2023, the Validation Committee chair recommended sealed source (PuF_6 or UF_6) measurements (i.e. n-γ coincidence yields) using the current setup
- Gamma-ray anisotropy data will be tested to improve the current evaluation
- Our first test files based on proposed measurements (neutron yields or γ yields) will be used for immediate testing of any available benchmarks

SOURCES-4C

GEANT4
A SIMULATION TOOLKIT

MCNP