REACTION CROSS SECTIONS, SECONDARY GAMMA-RAY YIELDS, AND MEASURED NEUTRON SPECTRA FOR ALPHA-INDUCED REACTIONS ON LIGHT NUCLEI

James deBoer

University of Notre Dame

Workshop for Applied Nuclear Data Activities (WANDA)

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This work was funded by Defense Nuclear Nonproliferation Research and Development under ProjectOR24-ML-AlphaInducedRxnsOnLightNuclei-PD3OB.

PROJECT BACKGROUND/ OBJECTIVES

- Prompted by 2020 scoping study
- Light elements like lithium and boron are common impurities in oxides, fluorides and carbide compounds – materials used in the nuclear fuel cycles.
- Intrinsic **alpha decays, with energies up to 8 MeV, from actinides** can interact with these light elements, distorting the neutron spectrum from the fuel.
- Improved (α,n) studies from **2-8 MeV** alpha energies need to be made to holistically account for any significant source of neutrons in interrogation techniques.
- We are measuring $^{7}Li(\alpha,n)^{10}B$, **$^{10}B(\alpha,n)^{13}N$, $^{11}B(\alpha,n)^{14}N$**, $^{13}C(\alpha,n)^{16}O$ and $^{19}F(\alpha,n)^{22}Na$

ORNL/TM-2020/1789

(α,n) Nuclear Data Scoping Study

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David Brown
Stephen Croft
Andrea Favalli
Les Nakae
Marco Pigni
Steve Skutnik
Michael S. Smith
William Wieselquist
Michael Zerkle

PROJECT TEAM

- Seth McConchie (PI)
- Benjamin Thomas

- James deBoer (Co-PI)
- Ed Stech
- Dan Robertson
- Wanpeng Tan
- Khachatur Manukyan
- **Maxwell Sorensen (postdoc)**

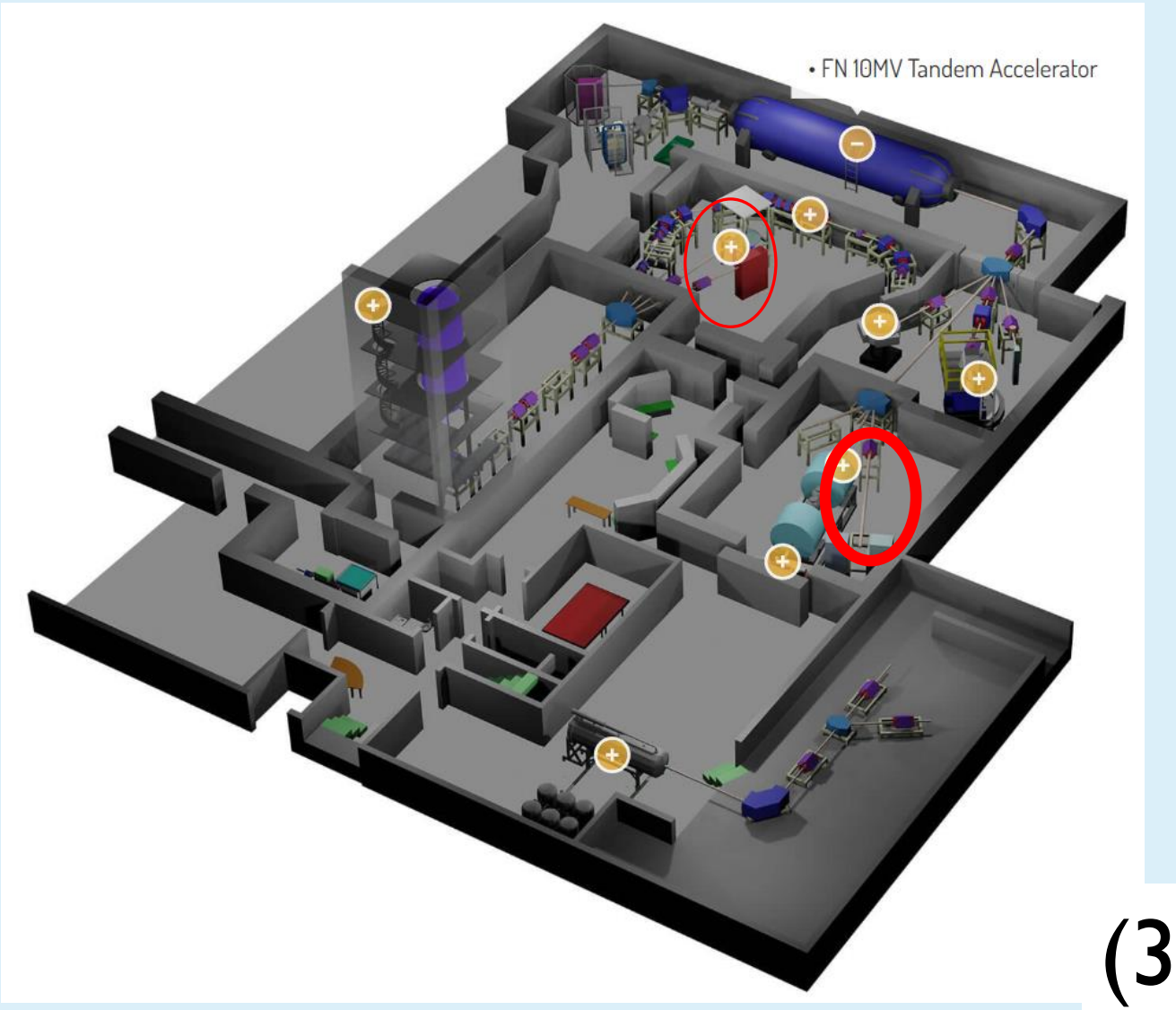
- Hye Young Lee (Co-PI)
- Sean Kuvin
- **Som Paneru**
- Chris Prokop

- Michael Febbraro (Co-PI)
- Juan Manfredi
- Tyler Smith (student)

EXPERIMENTAL MEASUREMENTS AT THE UNIVERSITY OF NOTRE DAME NUCLEAR SCIENCE LABORATORY

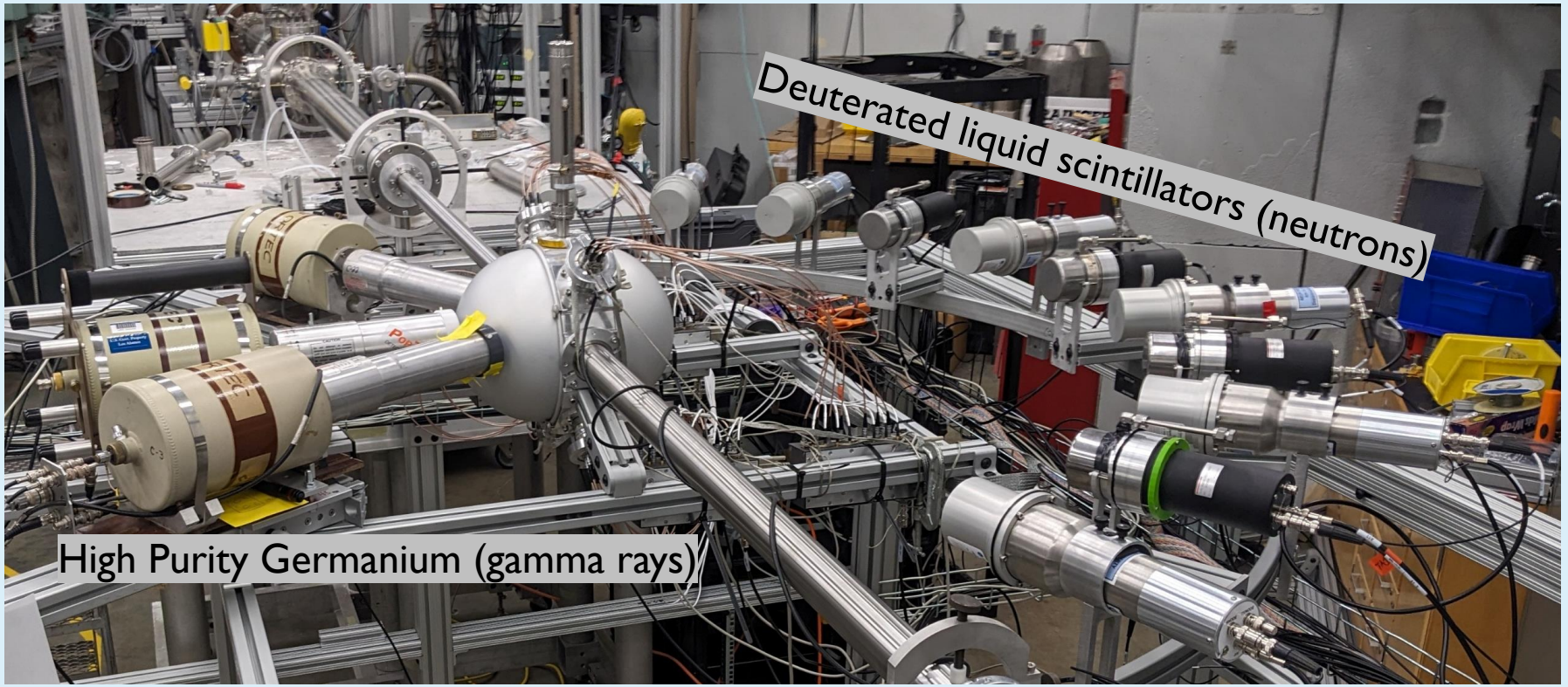
- FN tandem Van de Graaff
  - 1 to 10 MV
  - 200 nA (unbunched), 20 nA bunched
  - Energy resolution 0.05%, calibration 0.1%
- 5U single ended Van de Graaff
  - 0.3 to 4.5 MV
  - 50 uA (no bunching available)
  - Energy resolution 0.05%, calibration 0.1%

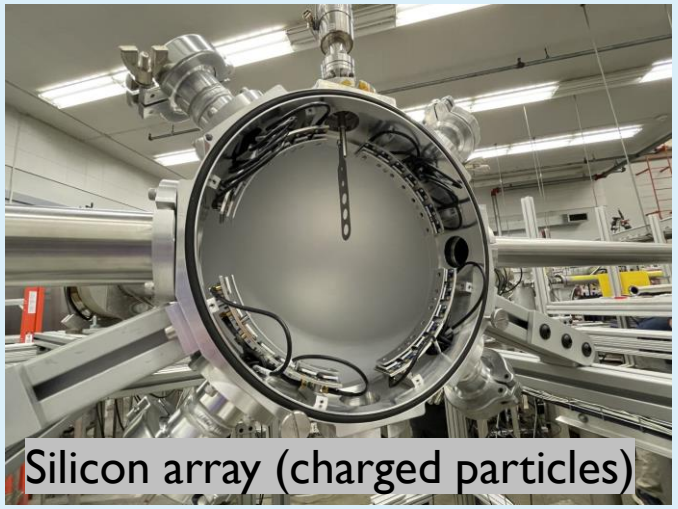
- The FN setup, built for optimal performance of these measurements is preferred, but we have a **backup setup** on the 5U to **mitigate risk**



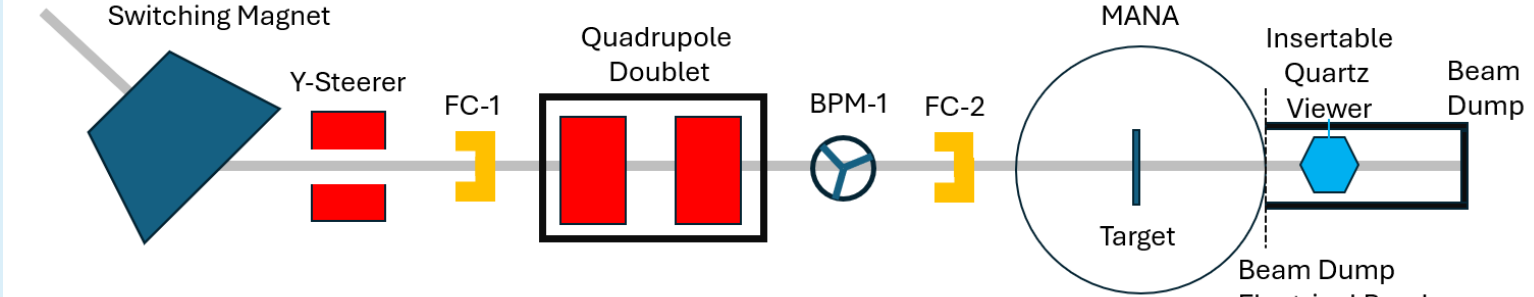
The Multi-channel (α,n) Array MαnA

See Maxwell Sorensen's Poster





Low mass chamber
(reduce neutron scattering)



We want to be able to measure not just (α,n) but as many alpha induced reactions as we can

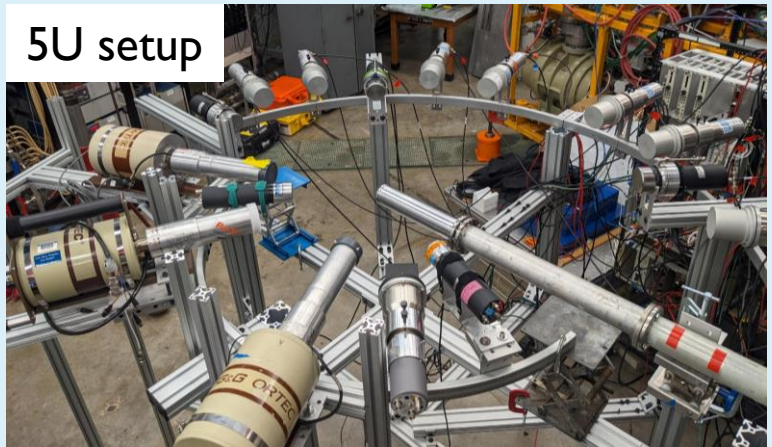
- **Check systematics**
- **Are needed for R-matrix evaluation**
- **Broader scope**

SUMMARY OF MEASUREMENTS IN 2025

- We are starting year three of this project
- Deuterated scintillator response matrix measured at Ohio University in February
- Production runs of $^{10,11}B(\alpha,n)^{13,14}$ reactions (March, June, December)
  - Complication: The aged alpha ion source on the FN provided low beam intensity (≈10 nA instead of 200 nA)
    - We were still able to make many measurements even with this reduced beam current
  - Mitigation: Replaced ion source on the FN with a newly procured alphatross ion source. The low energy portions of the $^{10,11}B(\alpha,n)^{13,14}N$ cross section were also measured using a complementary setup with the 5U machine in.
  - Complication: Right before the December run, the FN accelerator experienced major problem with charging system and the December FN run had to be cancelled
  - Mitigation: Luckily, Notre Dame was able to do to last minute rescheduling of the $^{13}C(\alpha,n)^{16}O$ reaction from the FN to the 5U accelerator which saved the December run.
- General comment: We are seeing similar situations at many US accelerator facilities due to aging US nuclear science infrastructure - as a nuclear data community

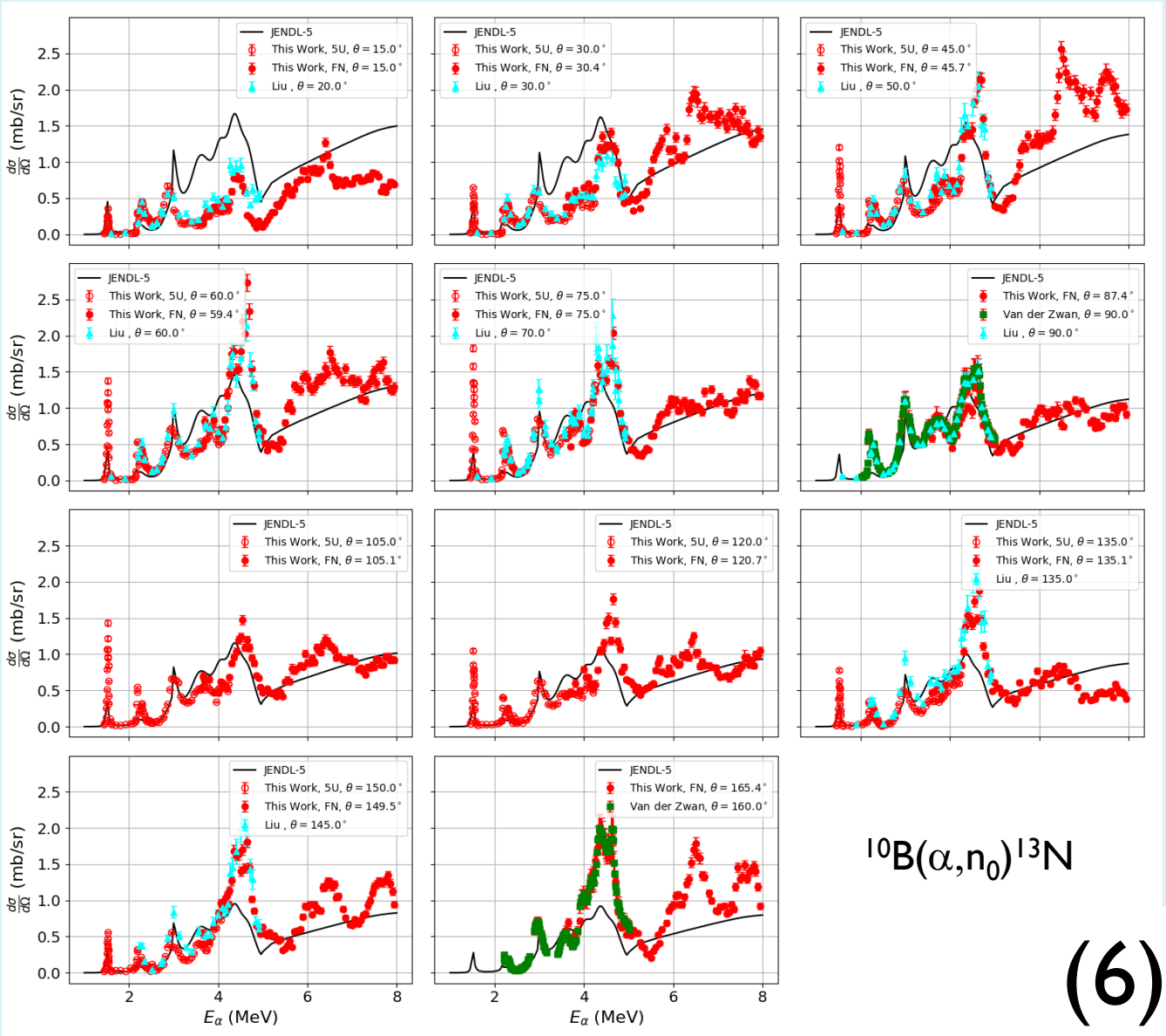
Reaction	Alpha energy range (MeV)	Angular range	Number data points
$^{10}B(\alpha,n_0)^{13}N$	2 - 8	0 - 165°	1721
$^{10}B(\alpha,\alpha)^{10}B$	4 - 8	34-167°	1185
$^{10}B(\alpha,p_0)^{13}C$	4 - 8	34-167°	1440
$^{10}B(\alpha,p_1)^{13}C$	4 - 8	34 - 167°	1707
$^{10}B(\alpha,p_2)^{13}C$	4 - 8	44 - 167°	1232
$^{10}B(\alpha,p_3)^{13}C$	4 - 8	36 - 167°	1343
$^{10}B(\alpha,d)^{12}C$	4 - 8	34-167°	1199
$^{11}B(\alpha,n_0)^{14}N$	2 - 8	0 - 165°	2100
$^{11}B(\alpha,n_1\gamma)^{14}N$	3 - 8	28 - 116°	361
$^{11}B(\alpha,n_2\gamma)^{14}N$	5 - 8	55°, 80°	108
$^{11}B(\alpha,n_4\gamma)^{14}N$	6.8 - 8	55°, 80°	100
$^{11}B(\alpha,\alpha)^{11}B$	4 - 8	125 - 165°	362
$^{11}B(\alpha,p_0)^{14}C$	4 - 8	26 - 167°	1802

5U setup



$^{10}B(\alpha,n_0)^{13}N$ DATA FROM 2025
DIFFERENTIAL CROSS SECTIONS

- **No previous measurements above 5 MeV!**
- **Scoping study recommends measurements above 4.9 MeV to cover alpha decay energies from uranium, thorium and actinium that have decays up to 8 MeV**
- Differential cross sections at 11 angles between 15 and 160 degrees
- JENDL-5 assumes an isotropic angular distribution and doesn't model the resonance structure accurately

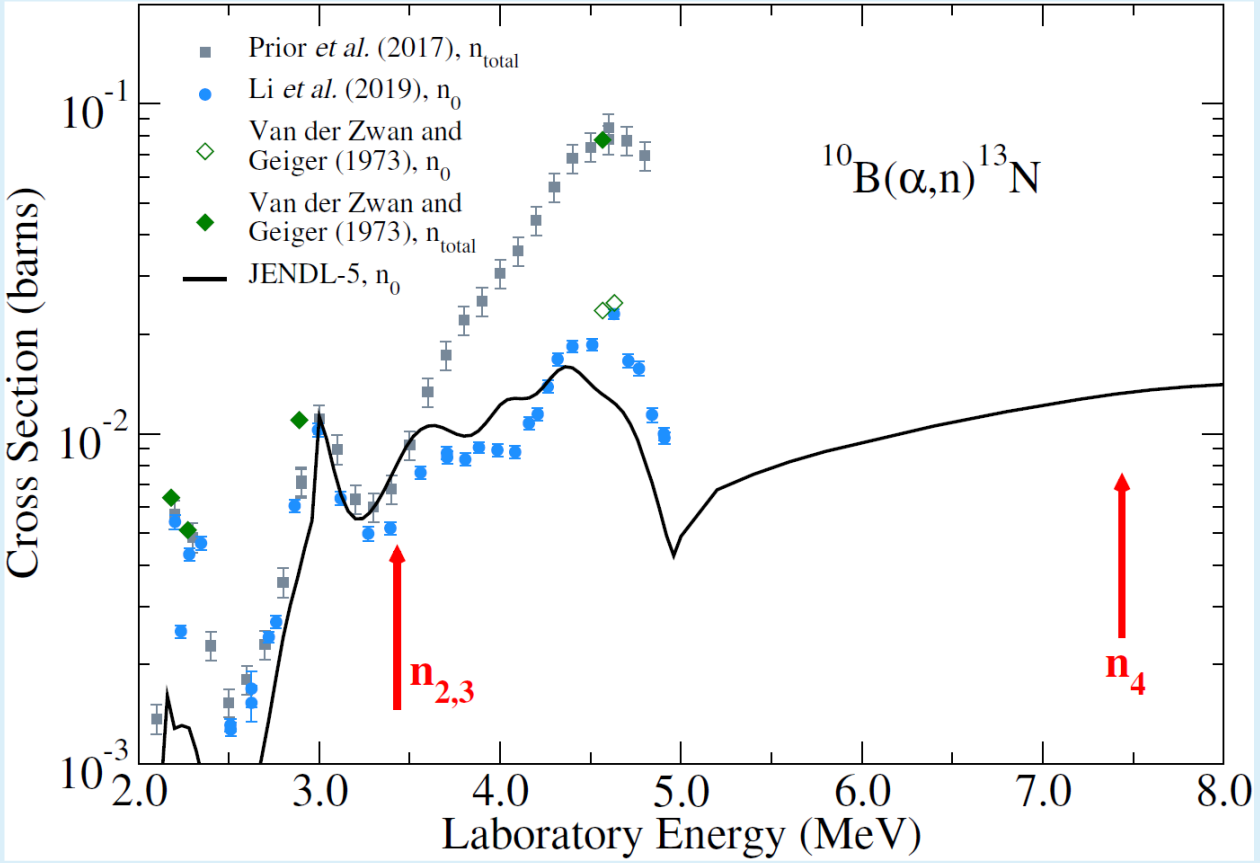


$^{10}B(\alpha,n_0)^{13}N$

$^{10}B(\alpha,n)^{13}N$ MEASUREMENTS: ANGLE INTEGRATED PARTIAL CROSS SECTIONS

$$W(\theta) = \sum_k a_k P_k(\cos(\theta))$$

BEFORE



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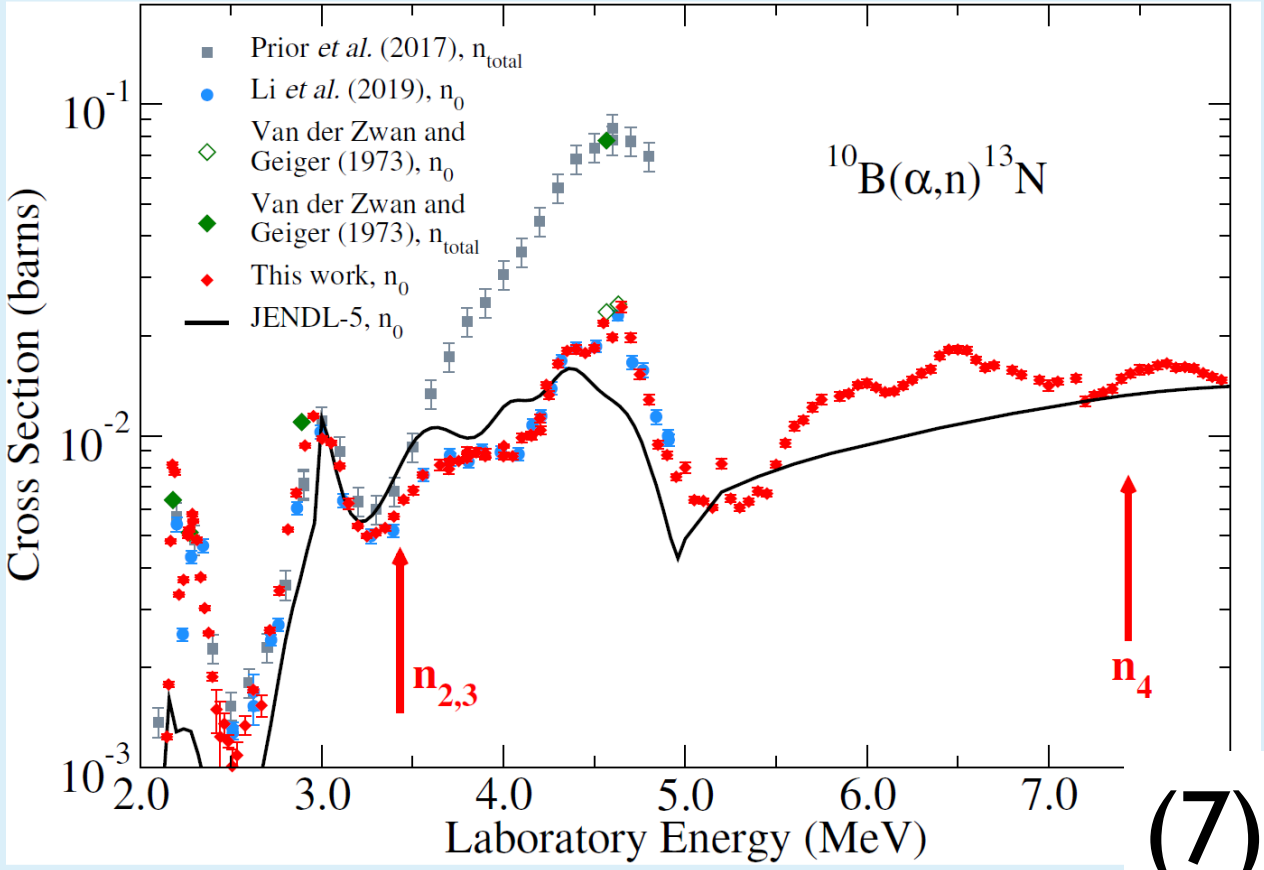
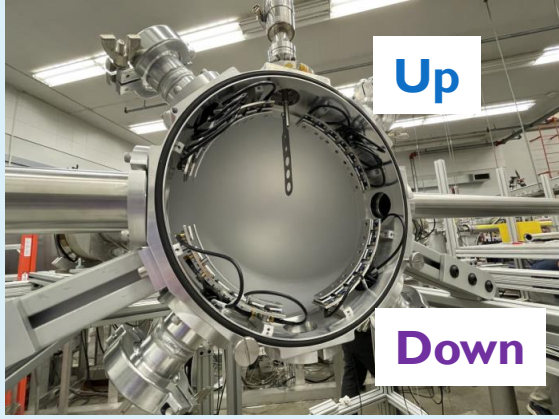


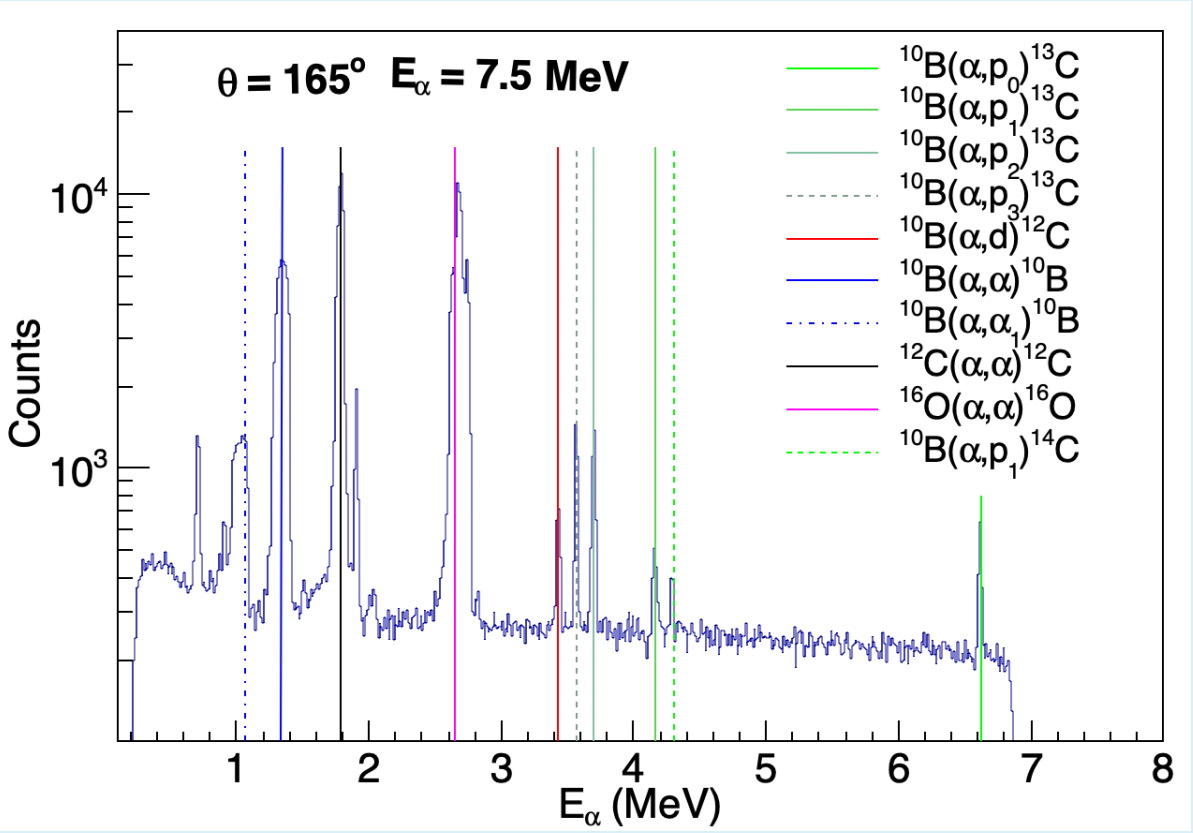
$^{10}B+\alpha$: CHARGED PARTICLE CHANNELS

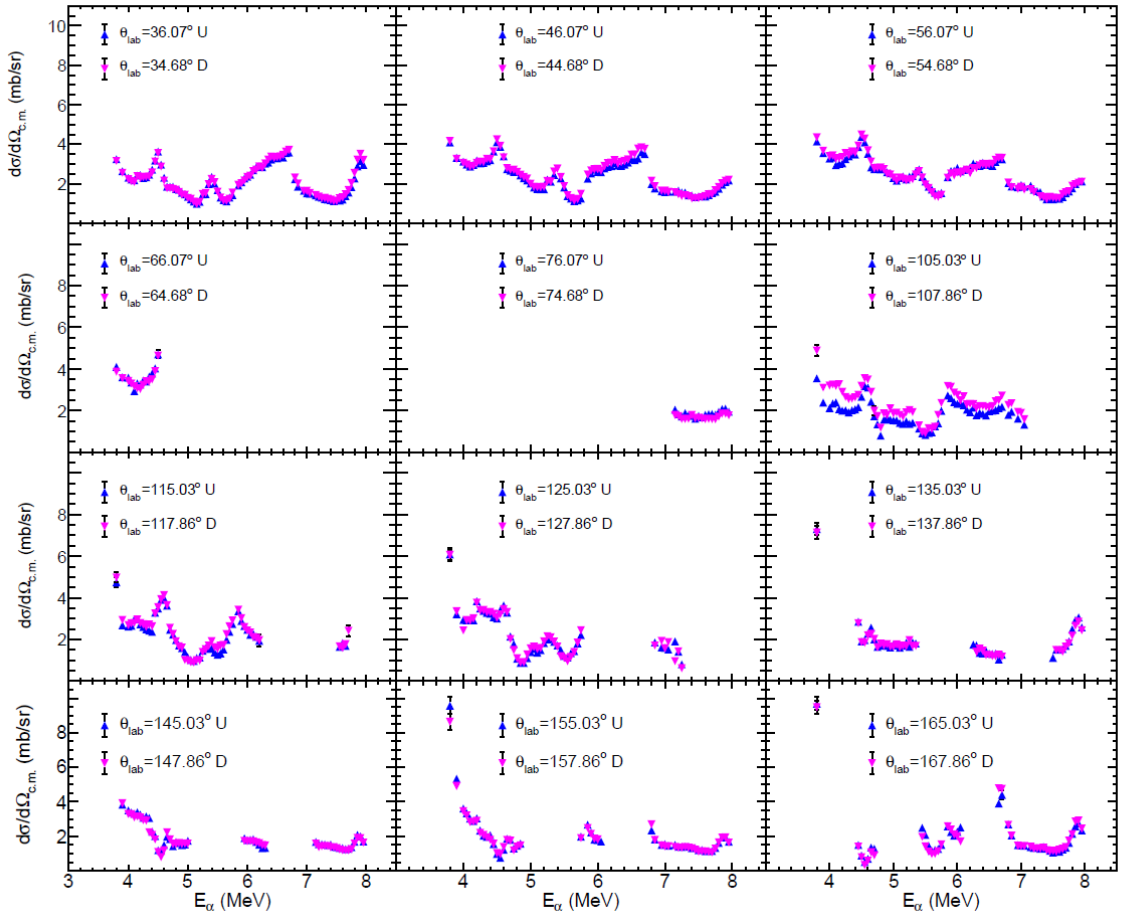


Our Data (D = down position)
Our Data (U = upper position)

$^{10}B(\alpha,d_0)^{12}C$

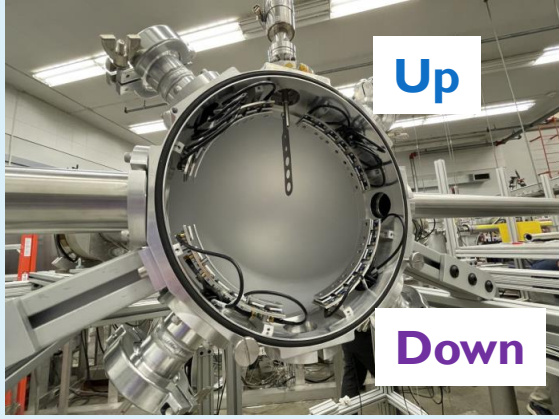
Example charge particle spectrum





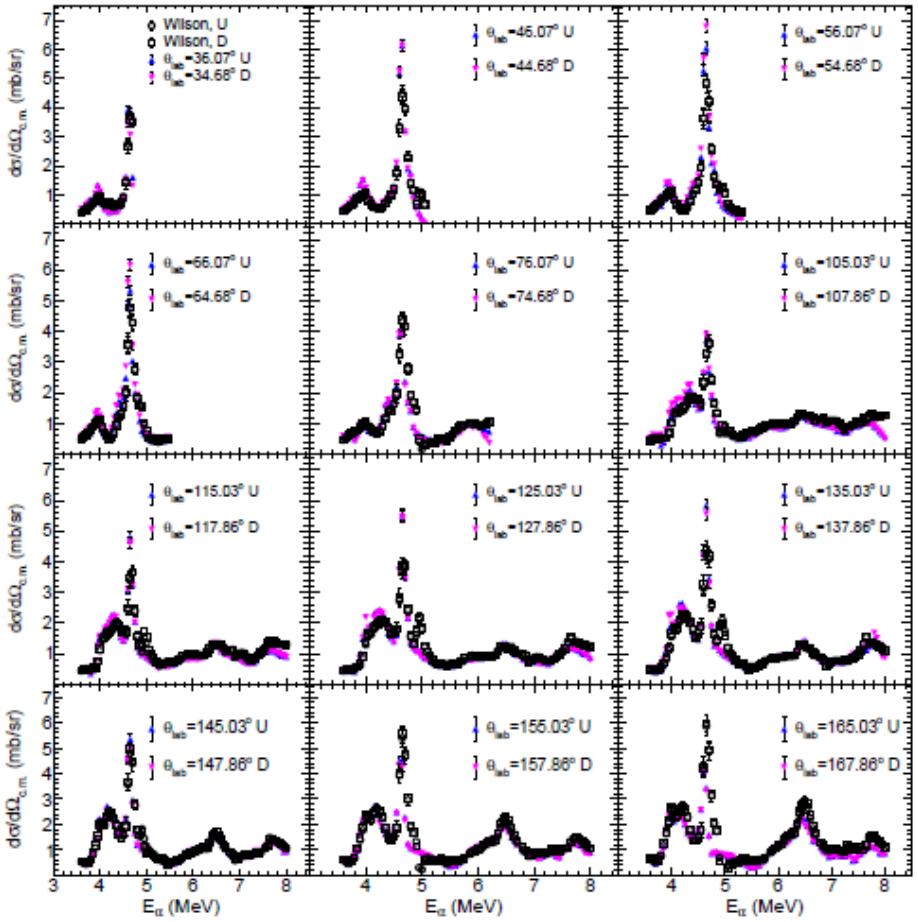
- Compared to data of Wilson (1975)

$^{10}B+\alpha$: CHARGED PARTICLE CHANNELS

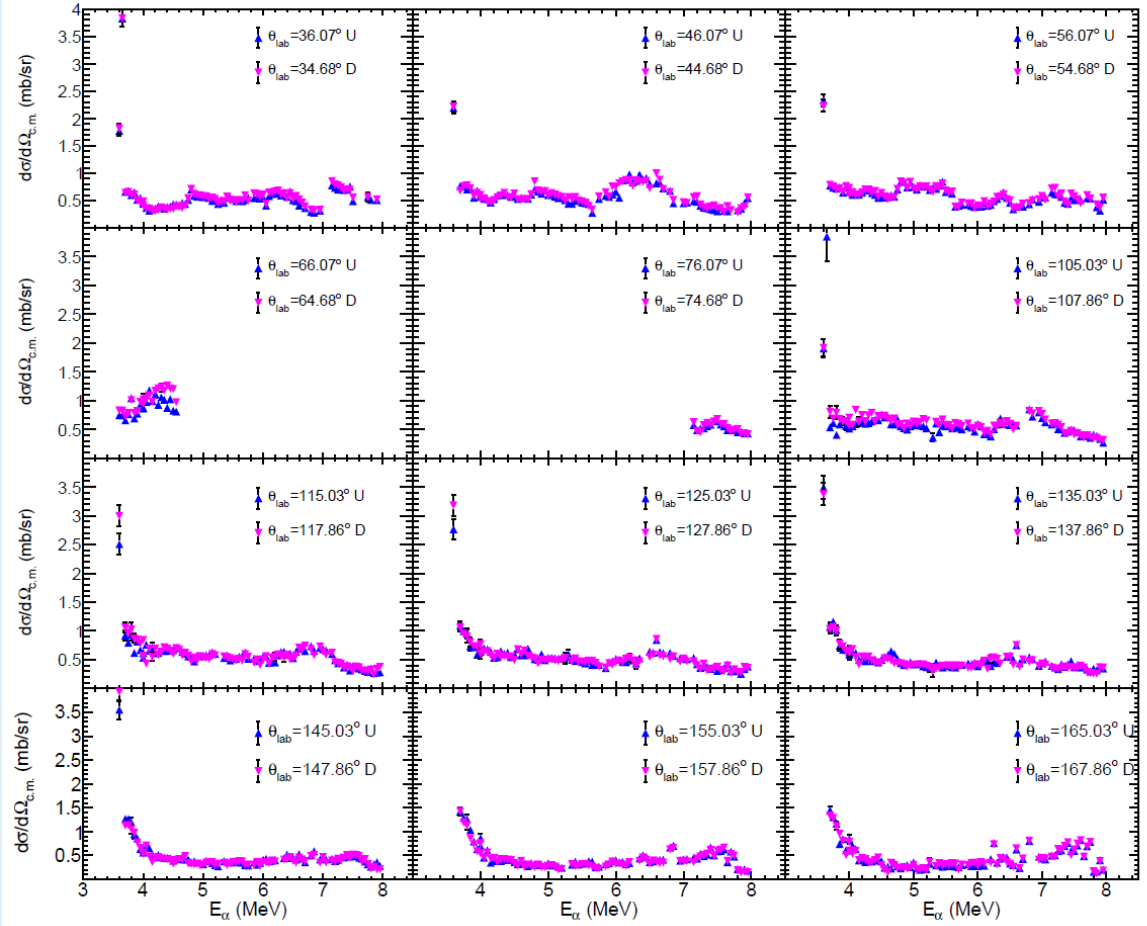


Our Data (D = down position)
Our Data (U = upper position)
Wilson *et al.* (1975)

$^{10}B(\alpha,p_0)^{13}C$

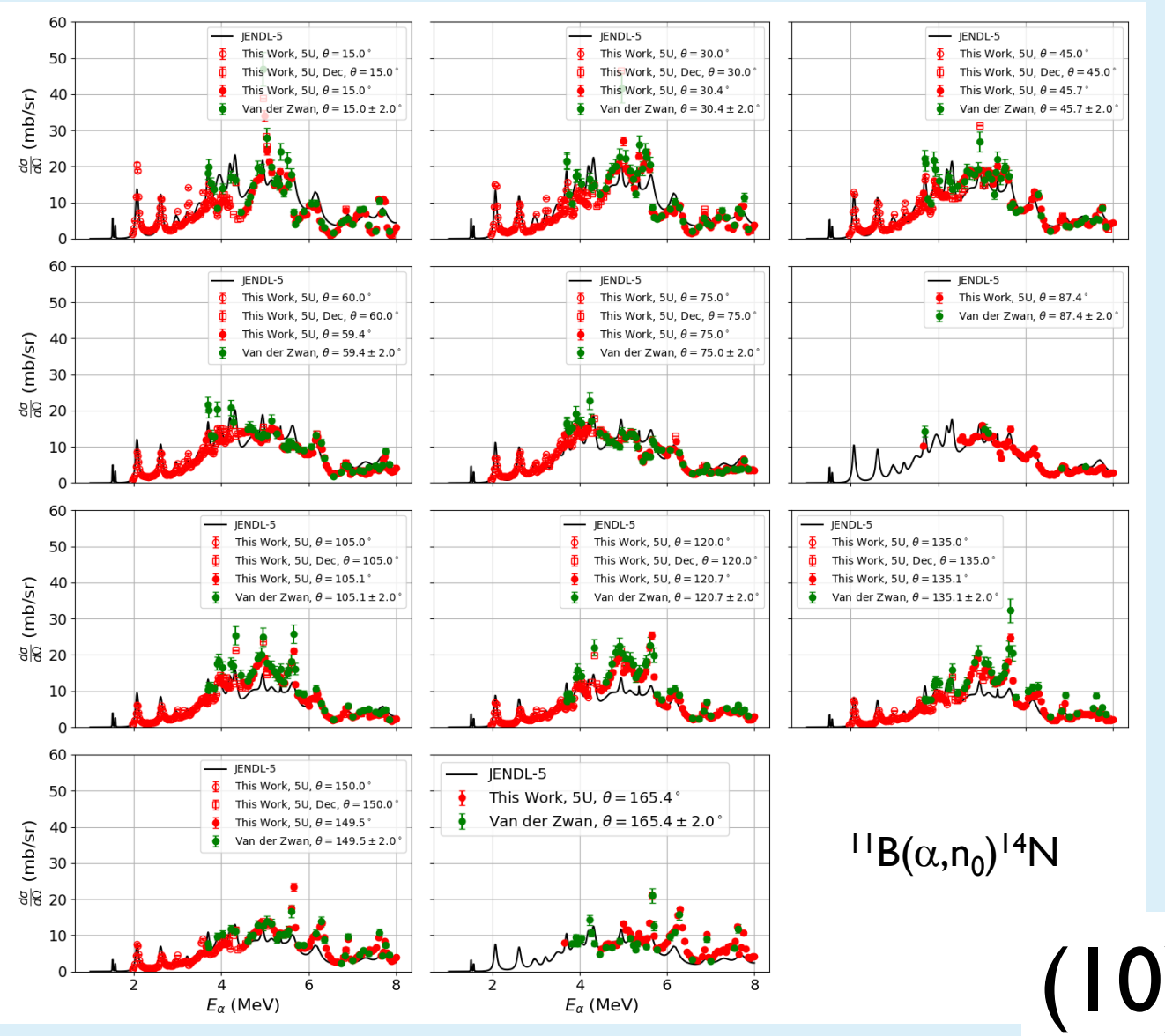


$^{10}B(\alpha,p_1)^{13}C$



$^{11}B(\alpha,n)^{14}N$ DATA FROM 2025: PARTIAL DIFFERENTIAL CROSS SECTIONS

- Ground state differential cross section determined from prompt neutron detection

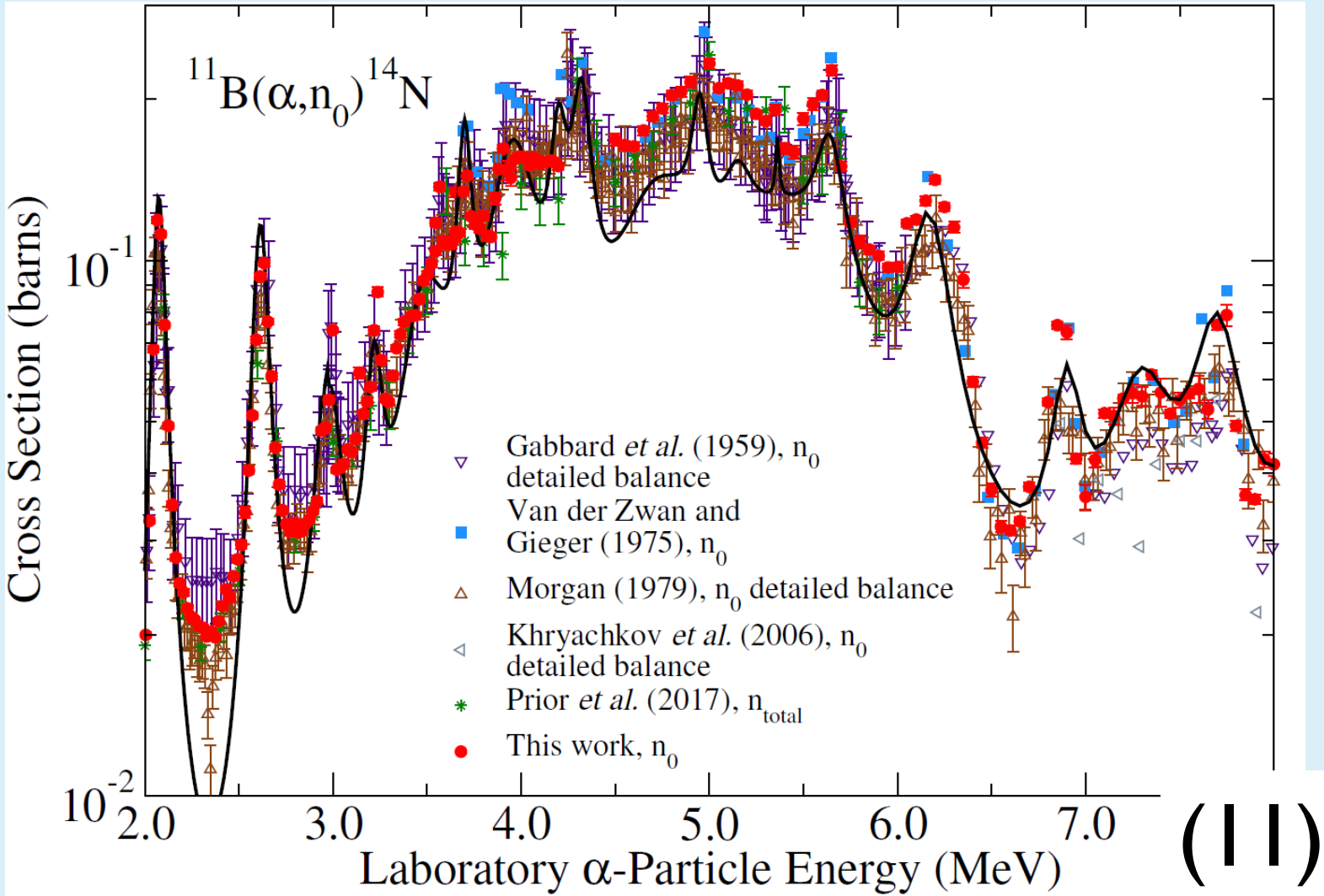


$^{11}B(\alpha,n_0)^{14}N$

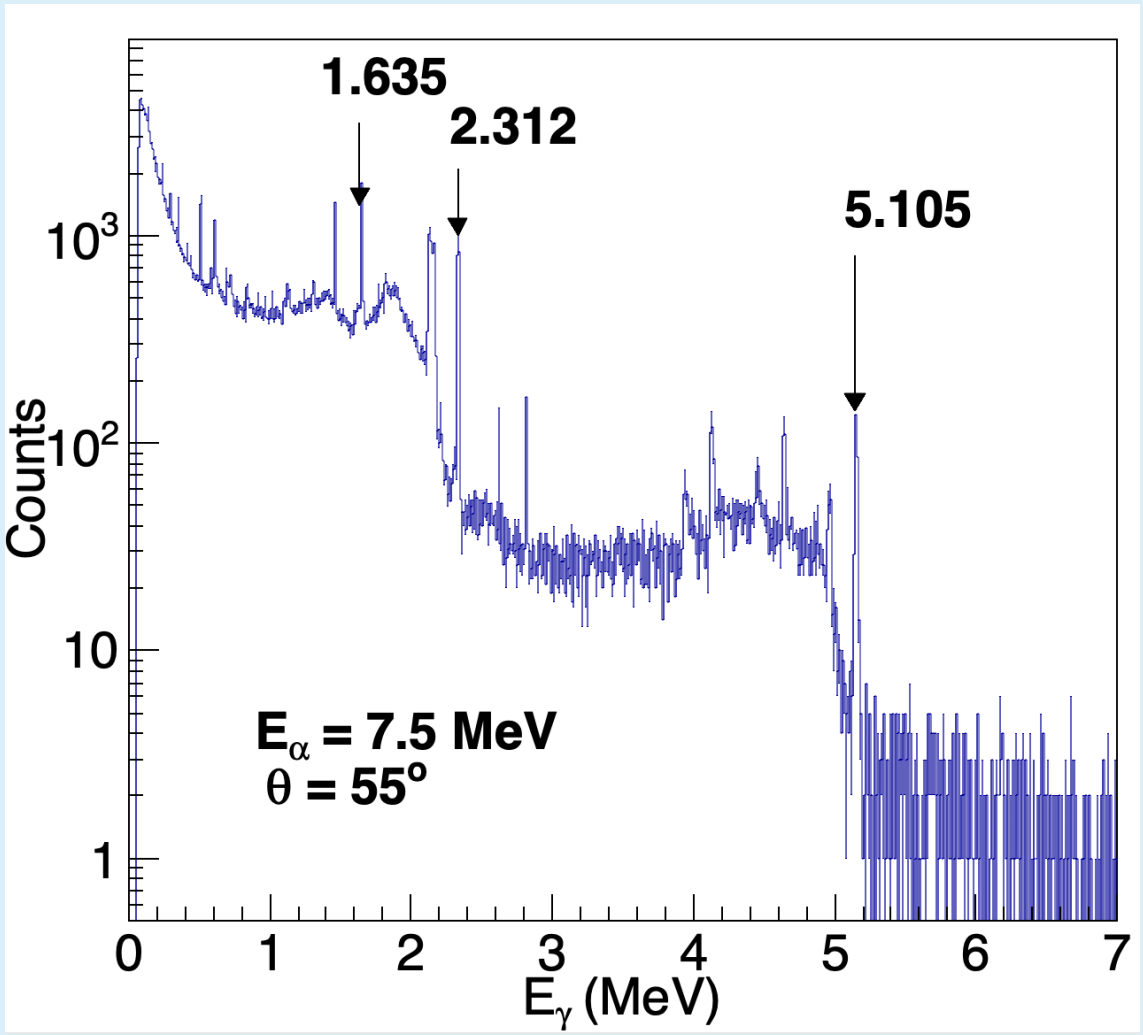
$^{11}B(\alpha,n)^{14}N$ MEASUREMENTS: ALSO INCLUDING INVERSE $^{14}N(n,\alpha)^{11}B$ DATA

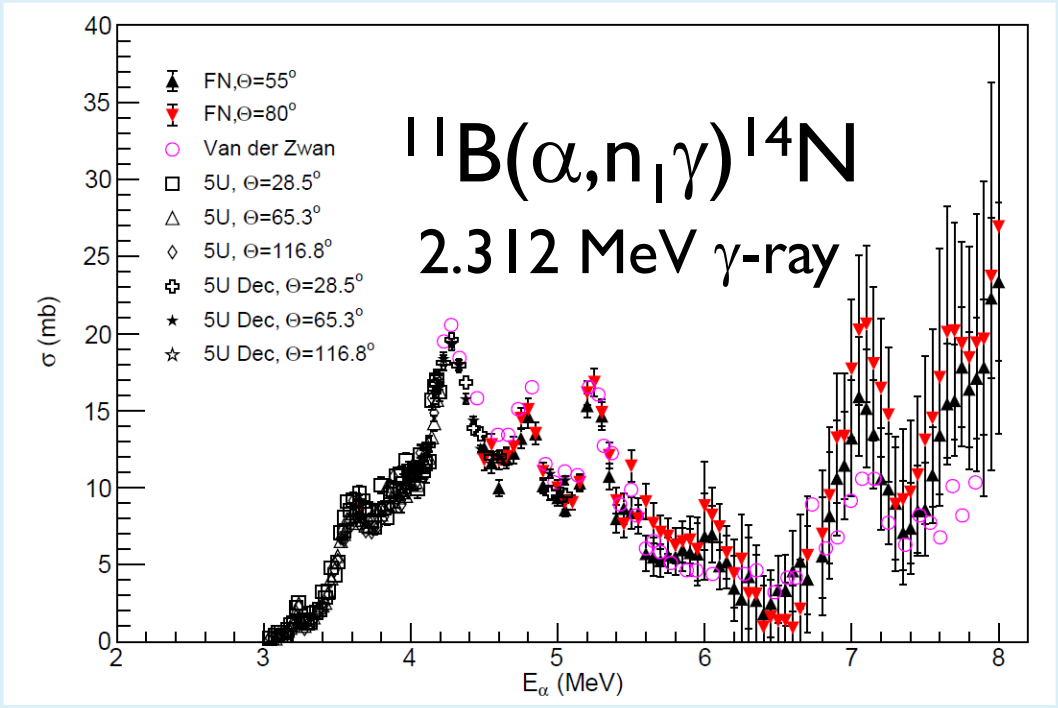
- Additional $^{14}N(n,\alpha_0)^{11}B$ data makes $^{11}B(\alpha,n_0)^{14}N$ a good benchmark reaction
- **$^{11}B(\alpha,n_0)^{14}N$ uncertainties are significantly smaller than those of $^{14}N(n,\alpha_0)^{11}B$**
  - **High stats**
  - **Low background**
  - **Shared systematic uncertainty better constrains the covariance matrix over the full energy range**

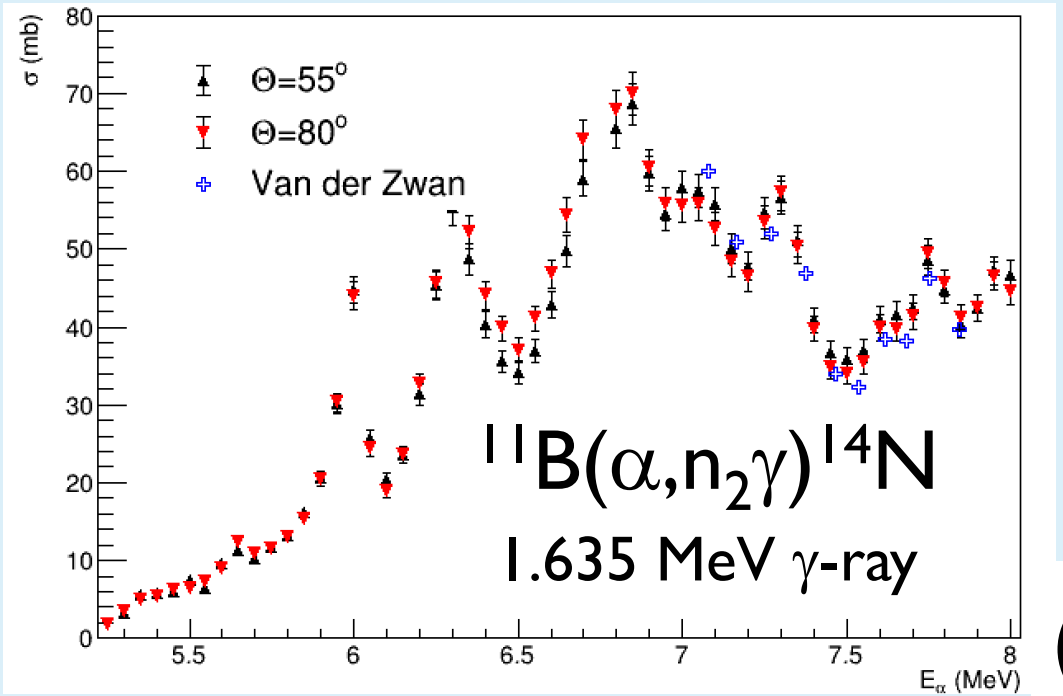
$^{11}B(\alpha,n_0)^{14}N$ and $^{14}N(n,\alpha_0)^{11}B$



$^{11}B(\alpha,n)^{14}N$ DATA FROM 2025:
PARTIAL CROSS SECTIONS VIA SECONDARY γ-RAY TRANSITIONS



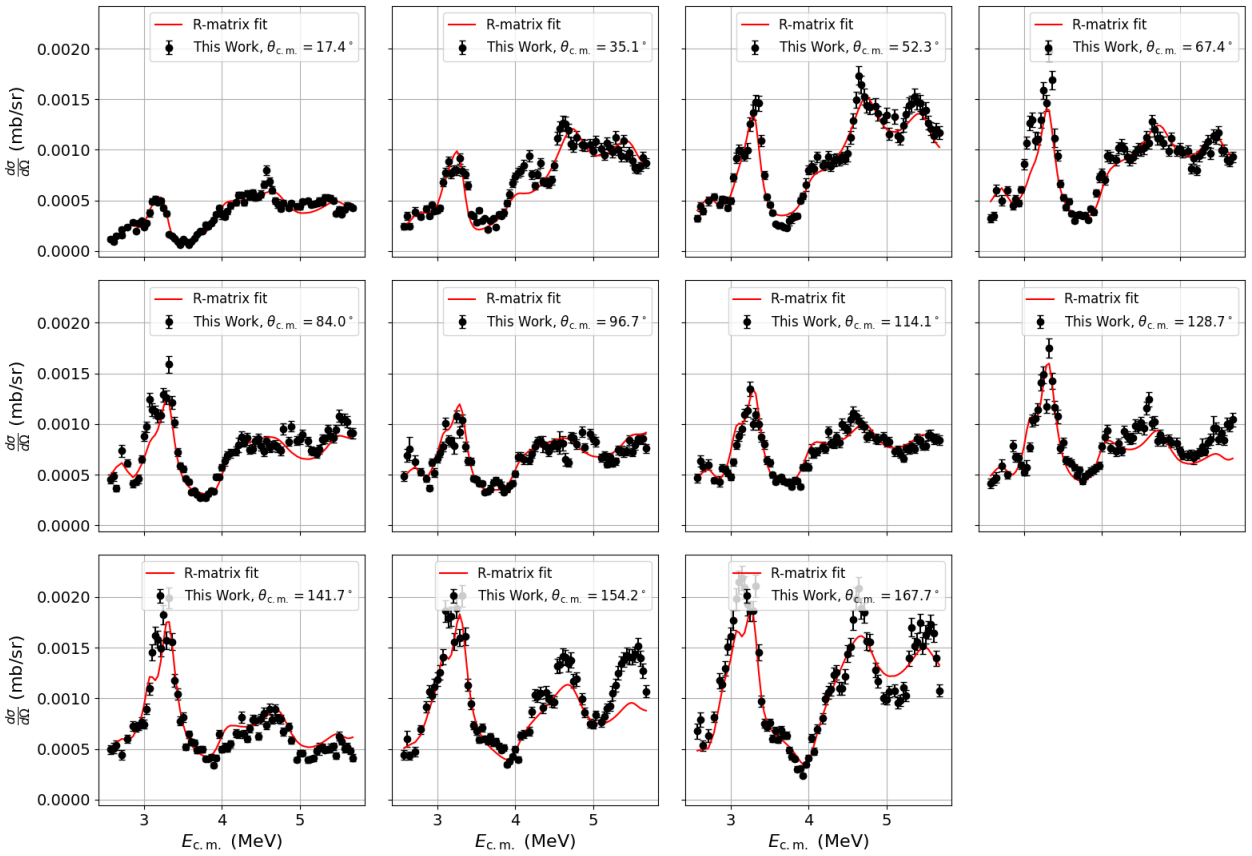




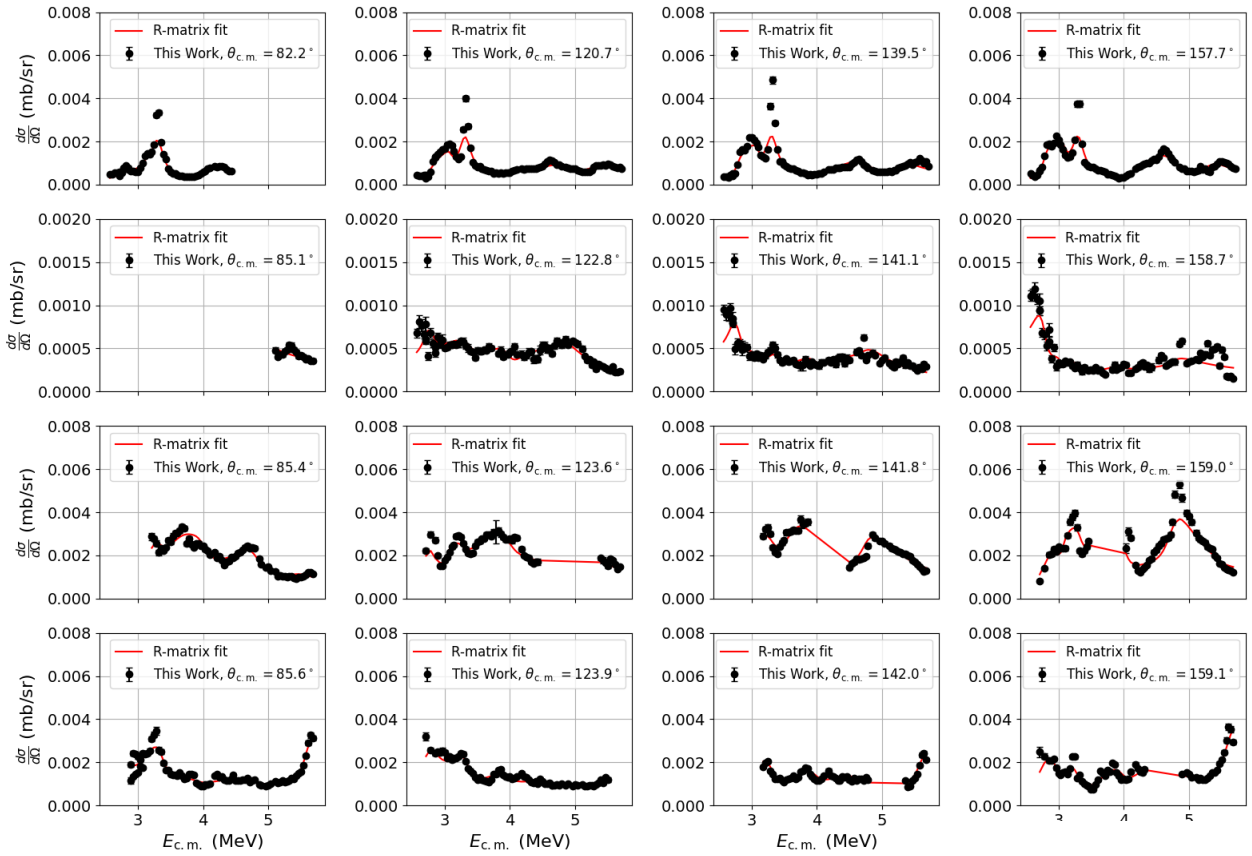
PRELIMINARY R-MATRIX ASSESSMENT: $^{10}B(\alpha,n)^{13}N$ WITH $^{10}B(\alpha,p)^{13}C$

- Our data — R-matrix assessment

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

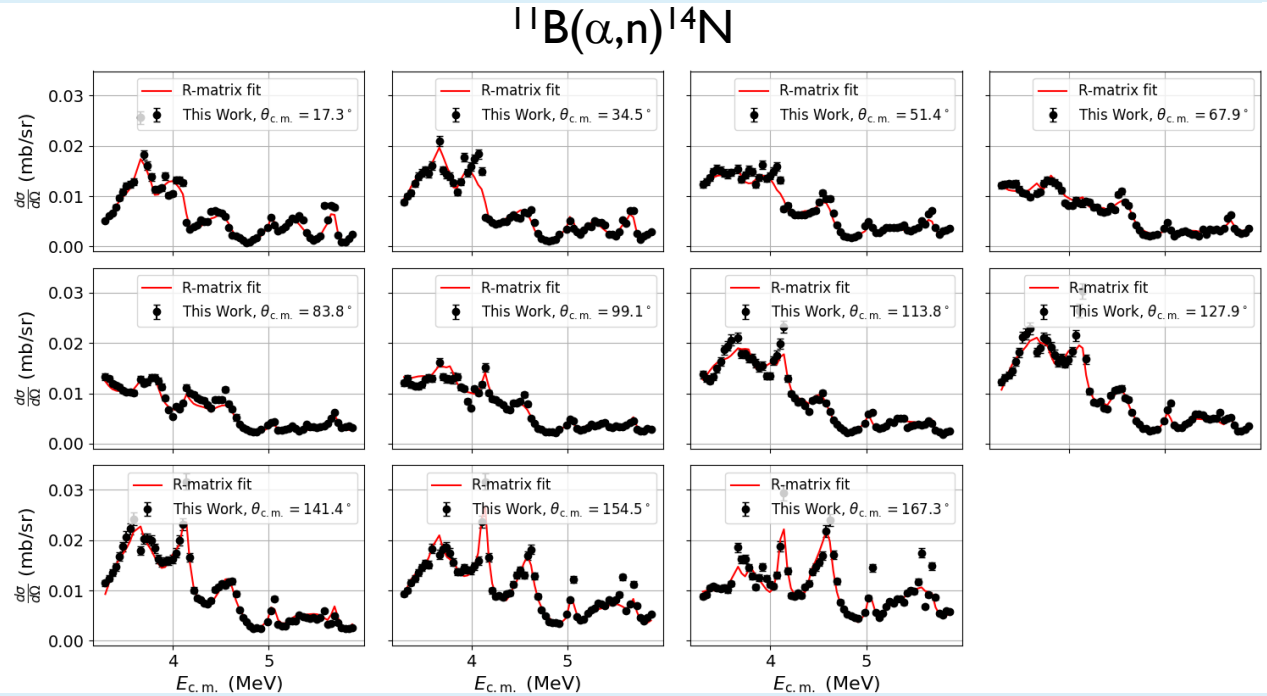


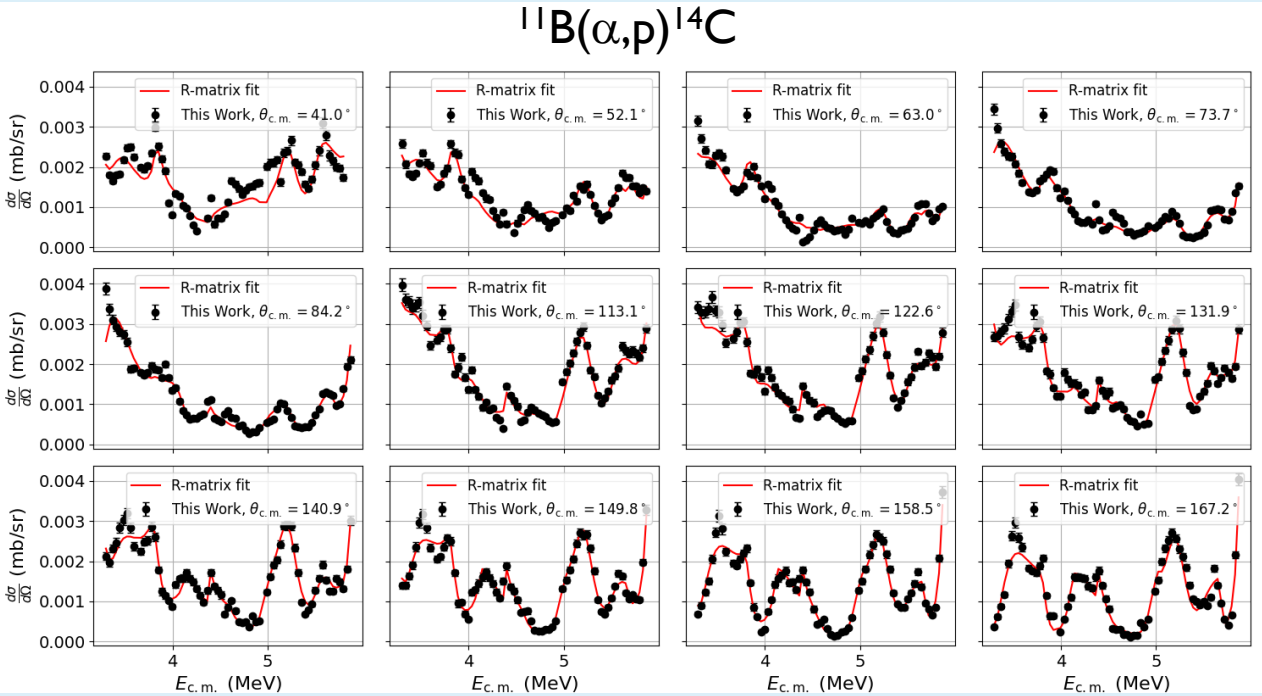
$^{10}B(\alpha,p)^{13}C$



PRELIMINARY R-MATRIX ASSESSMENT: $^{11}B(\alpha,n)^{14}N$ WITH $^{11}B(\alpha,p)^{14}C$

- Our data — R-matrix assessment

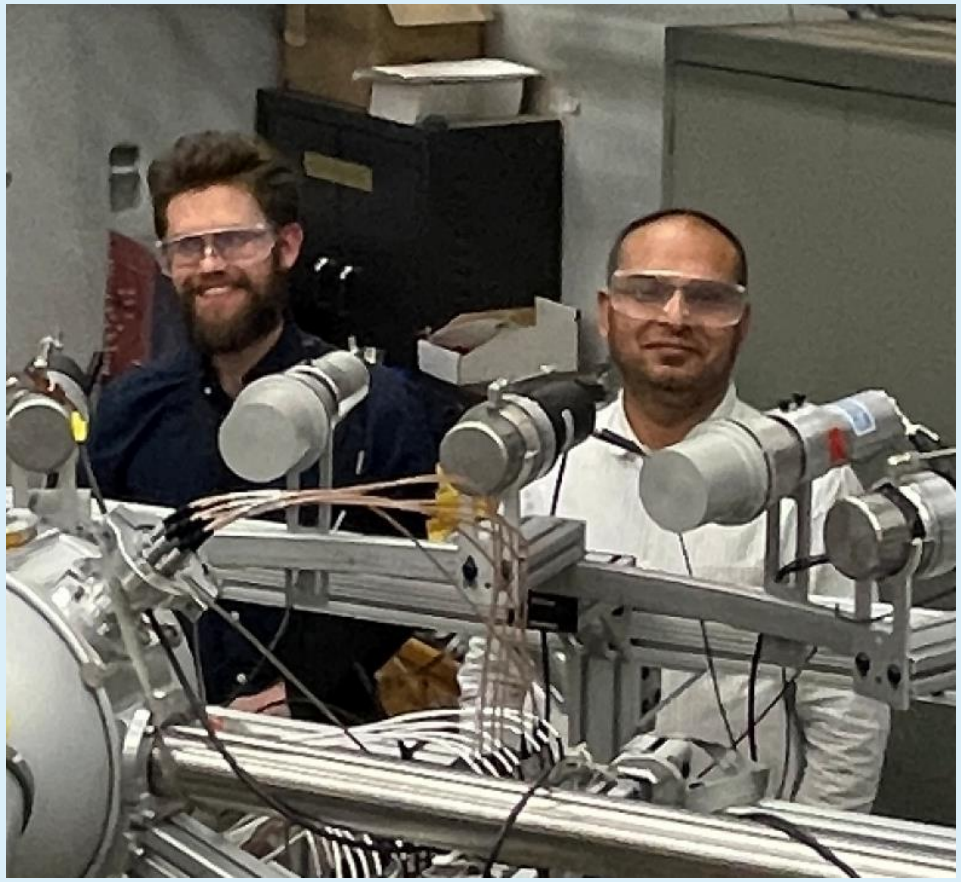




See Som Paneru's poster for more details

MVP'S: EARLY CAREER RESEARCHERS

- **Som Paneru**
  - Started as a postdoc and has become a staff scientist at LANL during this project
- **Maxwell Sorensen**
  - Postdoc working full time on this project at the University of Notre Dame



- Analyzed 3687 unfolded neutron spectra, 1059 γ-ray spectra and 4396 charged particle spectra… and counting

WORKFORCE DEVELOPMENT: UNDERGRADUATE RESEARCH

- Ben Thomas at ORNL
- Beginning engagement in 2025
- Expose undergraduate students to as much research experience as possible
  - Join bi-weekly collaboration meeting
  - An independent bi-weekly data analysis meeting
    - Amy Roberts
  - **Summer research experience at UND**
    - 3 weeks in July in 2025
    - Could really engage students in hands-on work in-person
    - Planned for 6 weeks in 2026
- Very positive feedback from students for 2025 program
- Try to ramp up engagement further in 2026

- Stephanie Bold (left)
- Kaliya Jenkins (right)

LOOKING AHEAD

Year 1 (FY24): Campaign Readiness measurements ✓

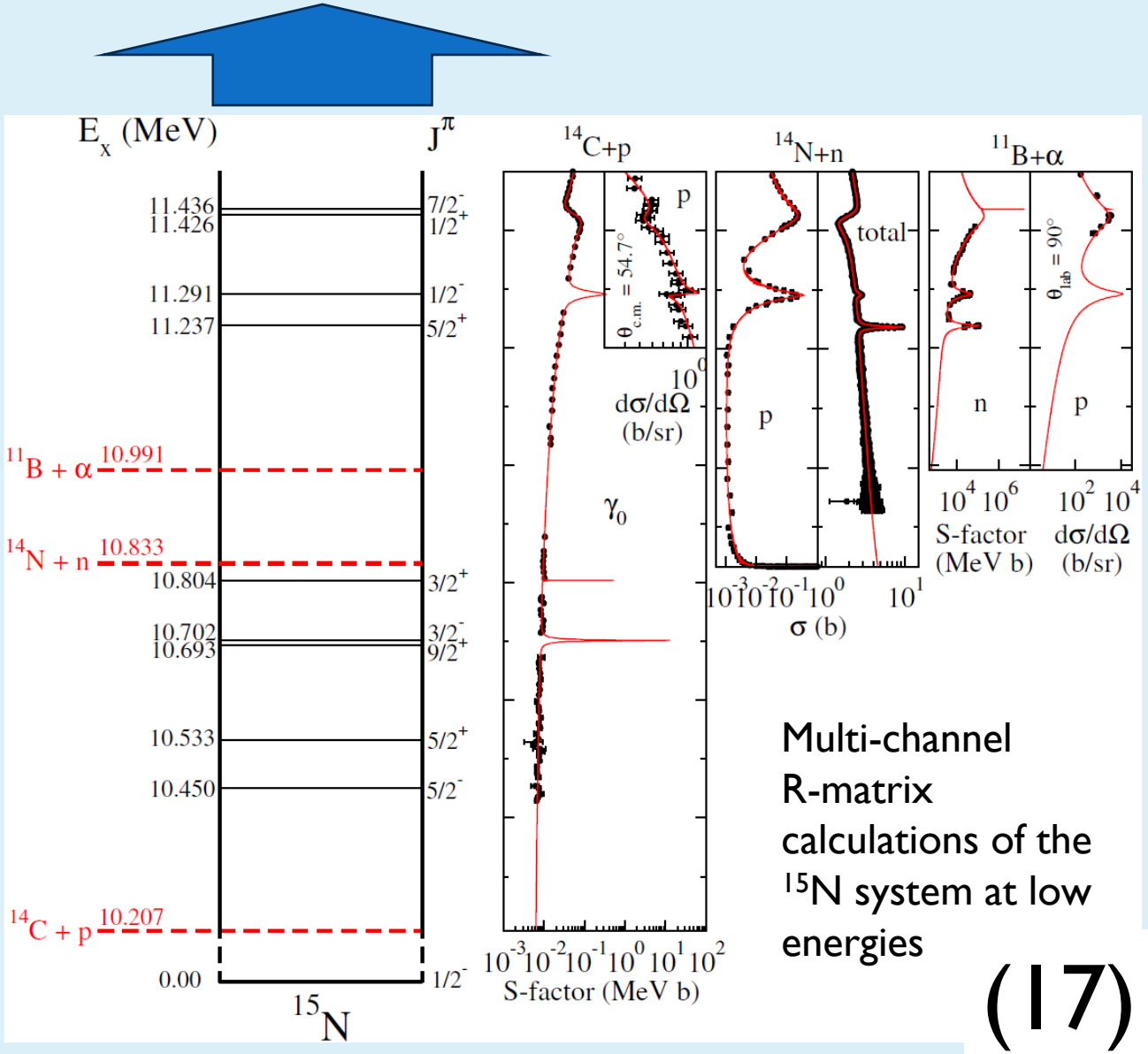
Year 2 (FY25): $^{10}B(\alpha,n)^{13}N$ and $^{11}B(\alpha,n)^{14}N$ ✓

Year 3 (FY26): $^{13}C(\alpha,n)^{16}O$ (measurements completed)

Year 4 (FY27): $^{19}F(\alpha,n)^{22}Na$ (initial test measurements made from 7 to 8.5 MeV)

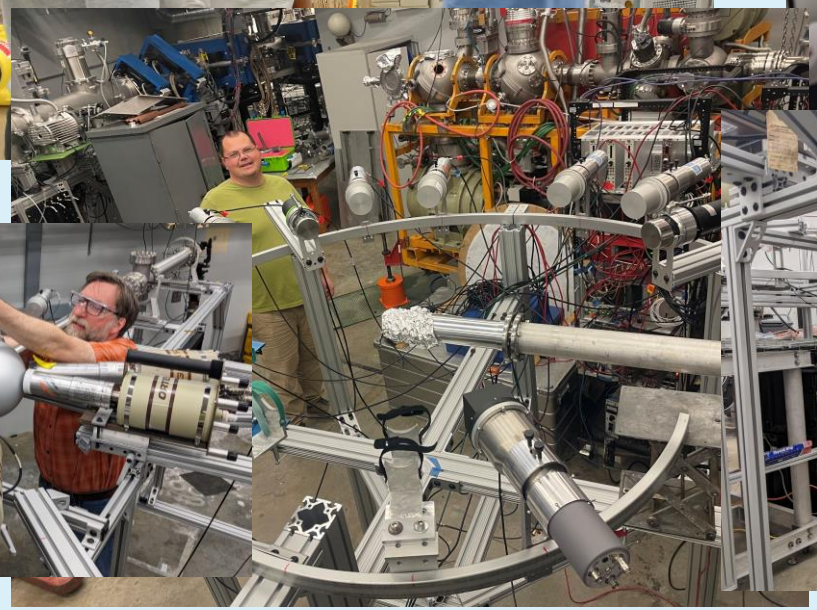
Year 5 (FY28): $^{7}Li(\alpha,n)^{10}B$

- Keeping the evaluation in mind
  - Partial differential cross section measurements of (α,n) reactions from 2 to 8 MeV
  - Charged particle and secondary γ-ray cross sections for other reactions (MαnA)
- Sources4C calculations

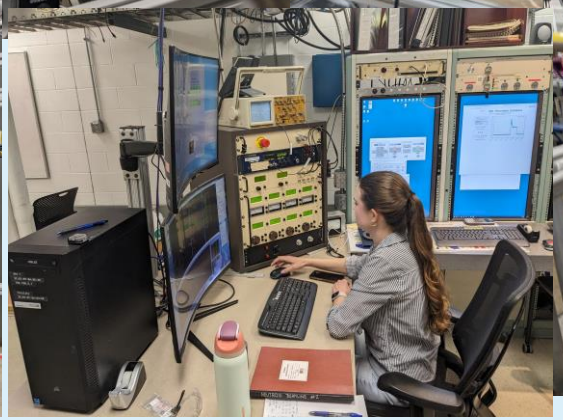
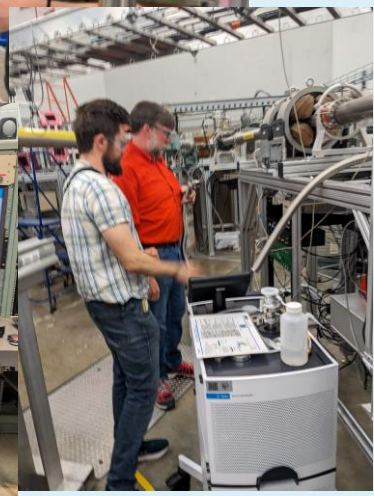


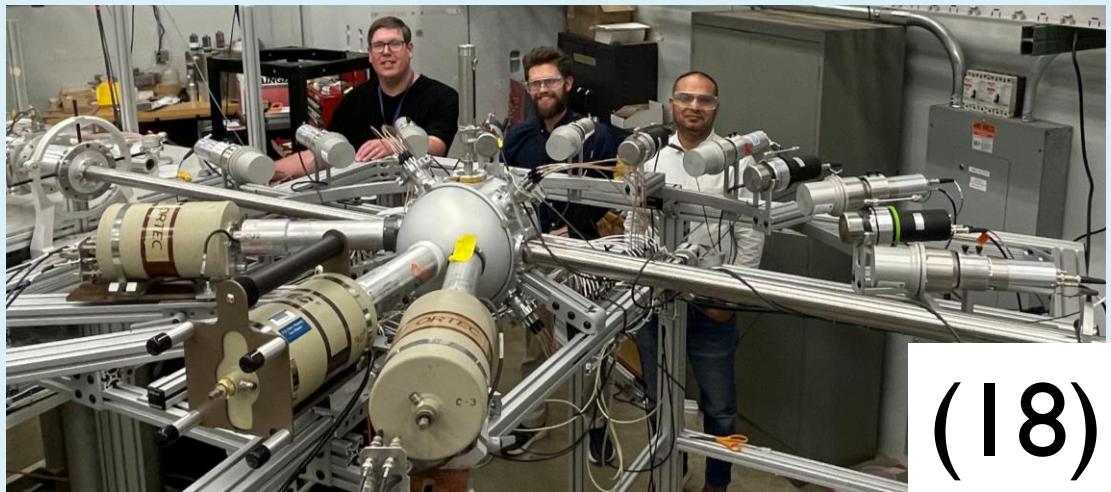
Multi-channel R-matrix calculations of the ^{15}N system at low energies





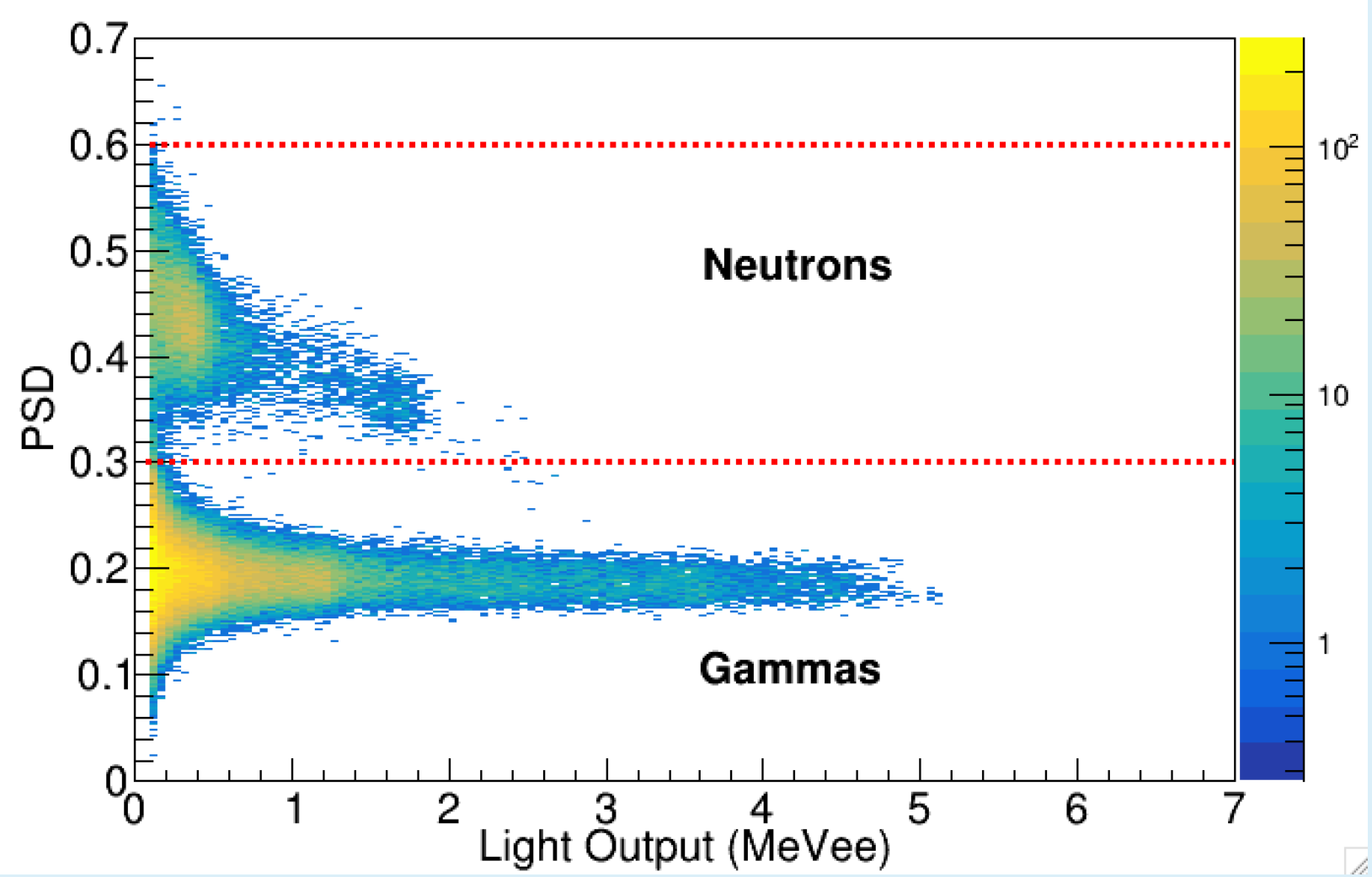


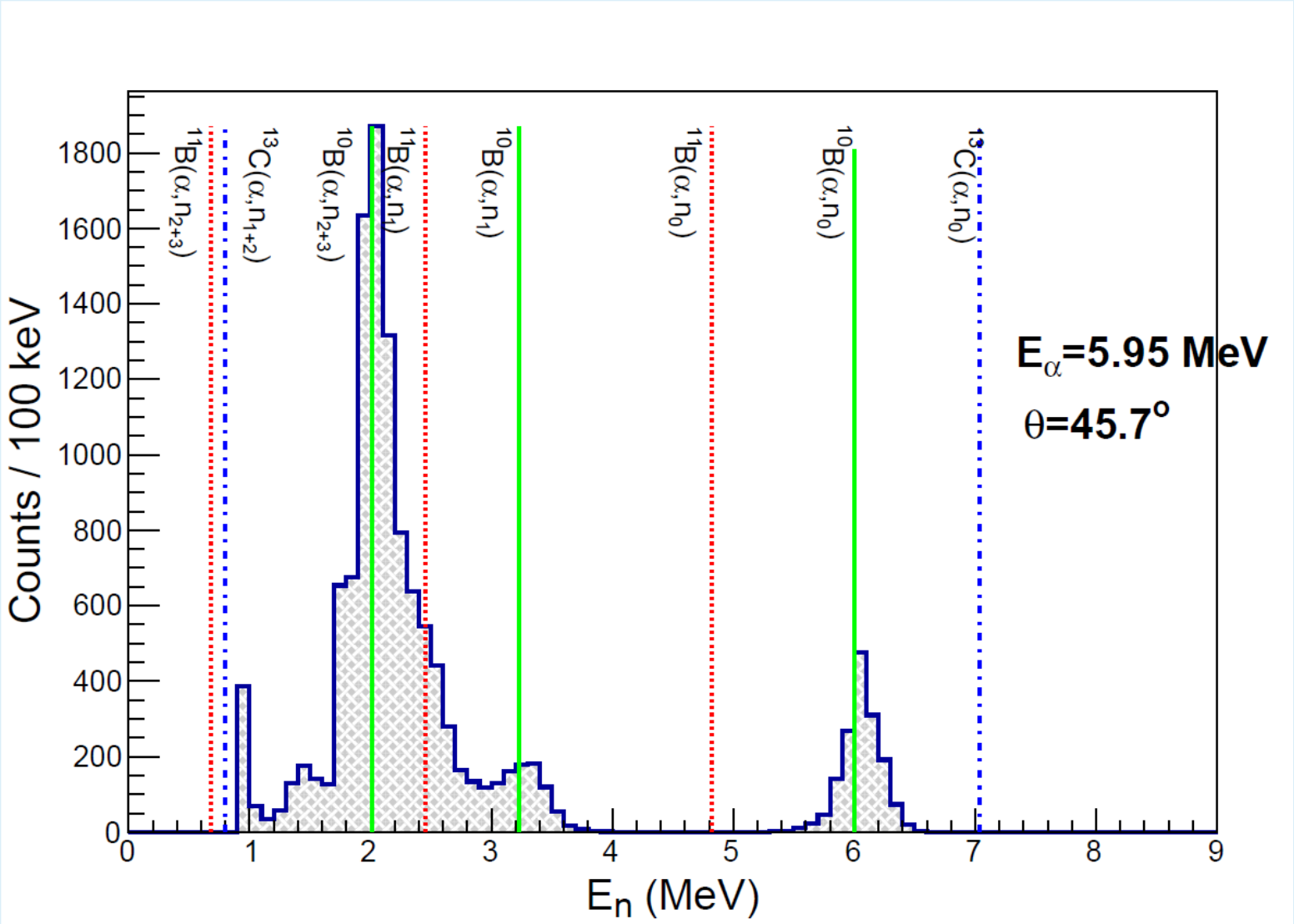
Before and After

(18)

BACKUP SLIDES

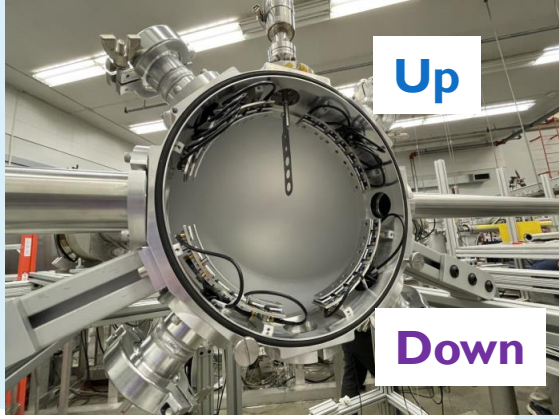
DEUTERATED SCINTILLATOR PSD



^{10}B TARGET
EXAMPLE UNFOLDED NEUTRON SPECTRUM



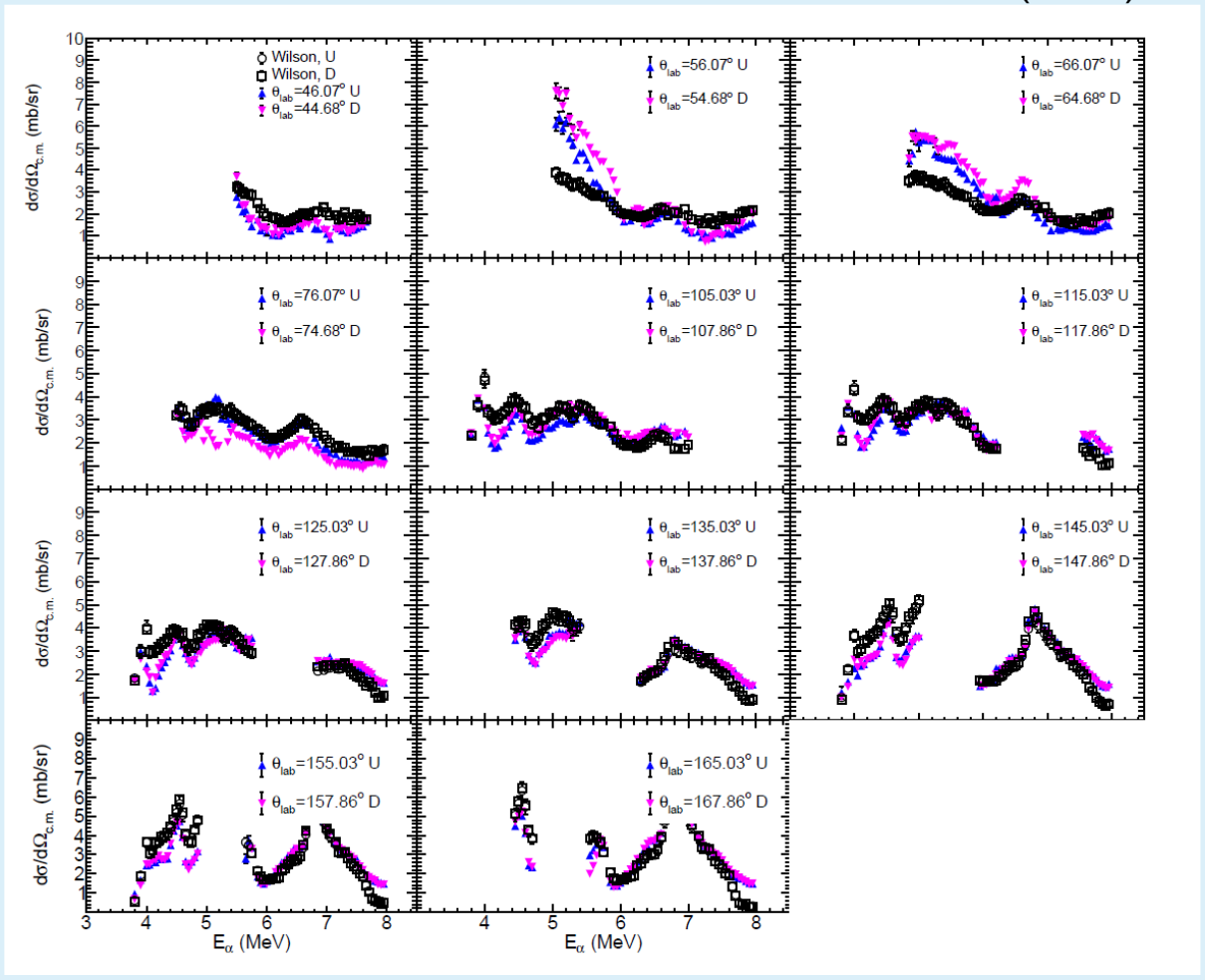
$^{10}B+\alpha$: CHARGED PARTICLE CHANNELS

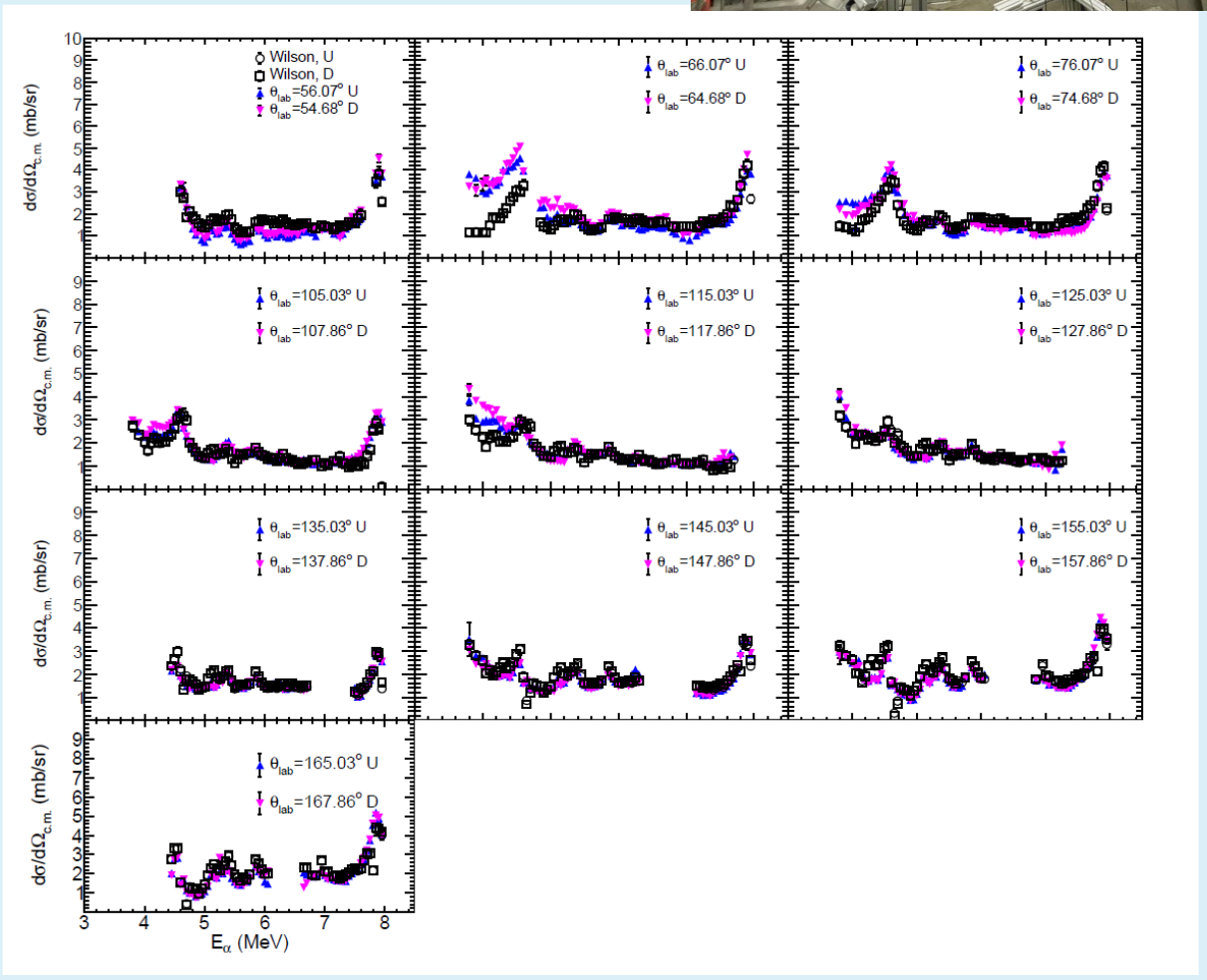


$^{10}B(\alpha,p_2)^{13}C$

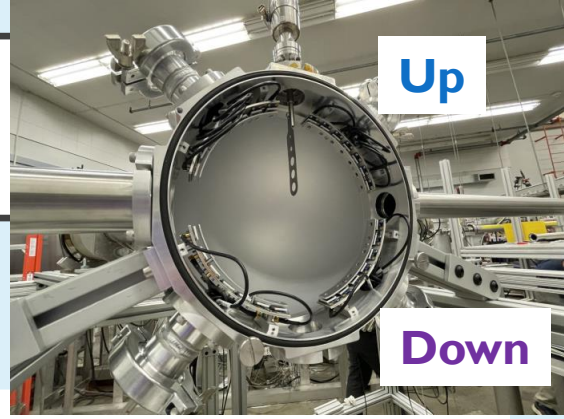
Our Data (D = down position)
Our Data (U = upper position)
Wilson *et al.* (1975)

$^{10}B(\alpha,p_3)^{13}C$





$^{11}B+\alpha$: CHARGED PARTICLE CHANNELS

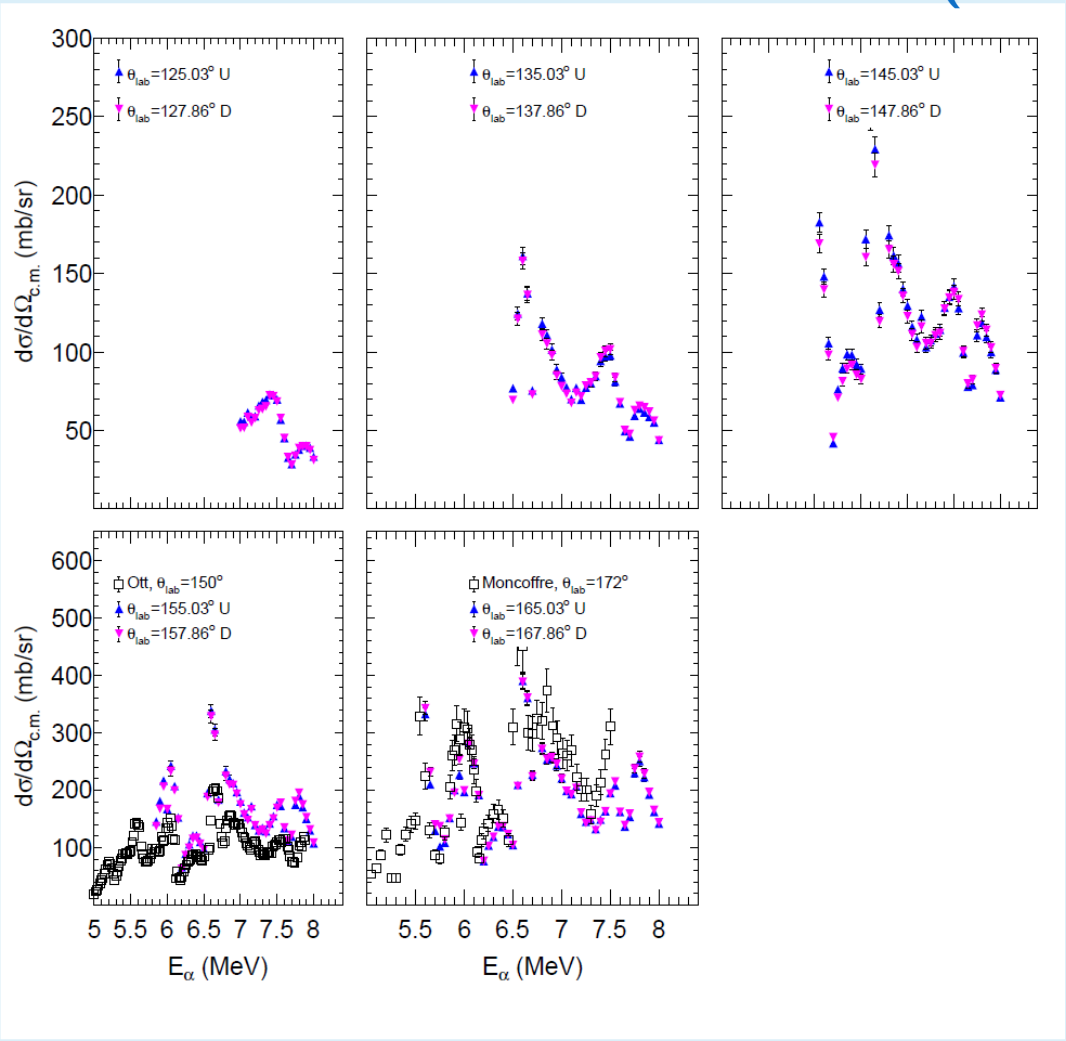


Our new data

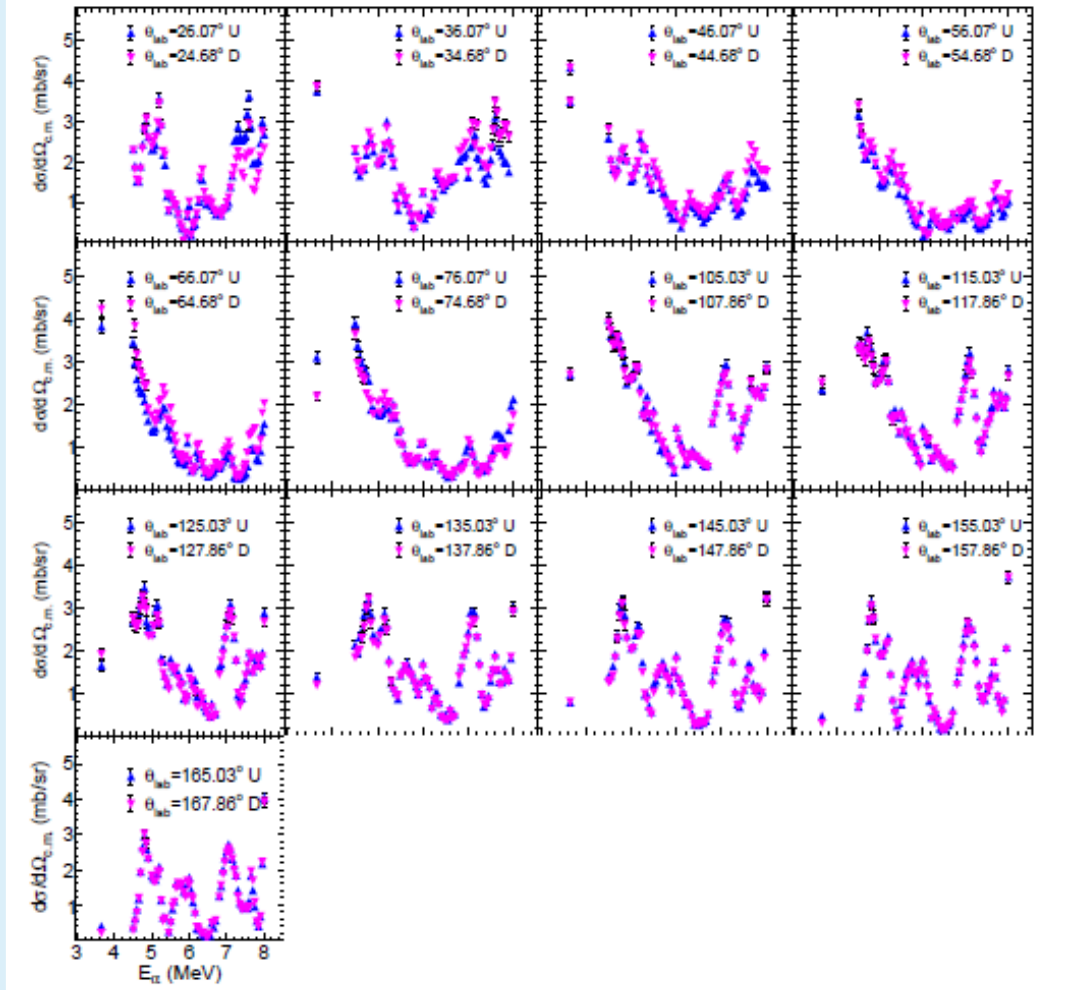
Purple (D = down position)

Blue (U = upper position)

$^{11}B(\alpha,\alpha)^{11}B$



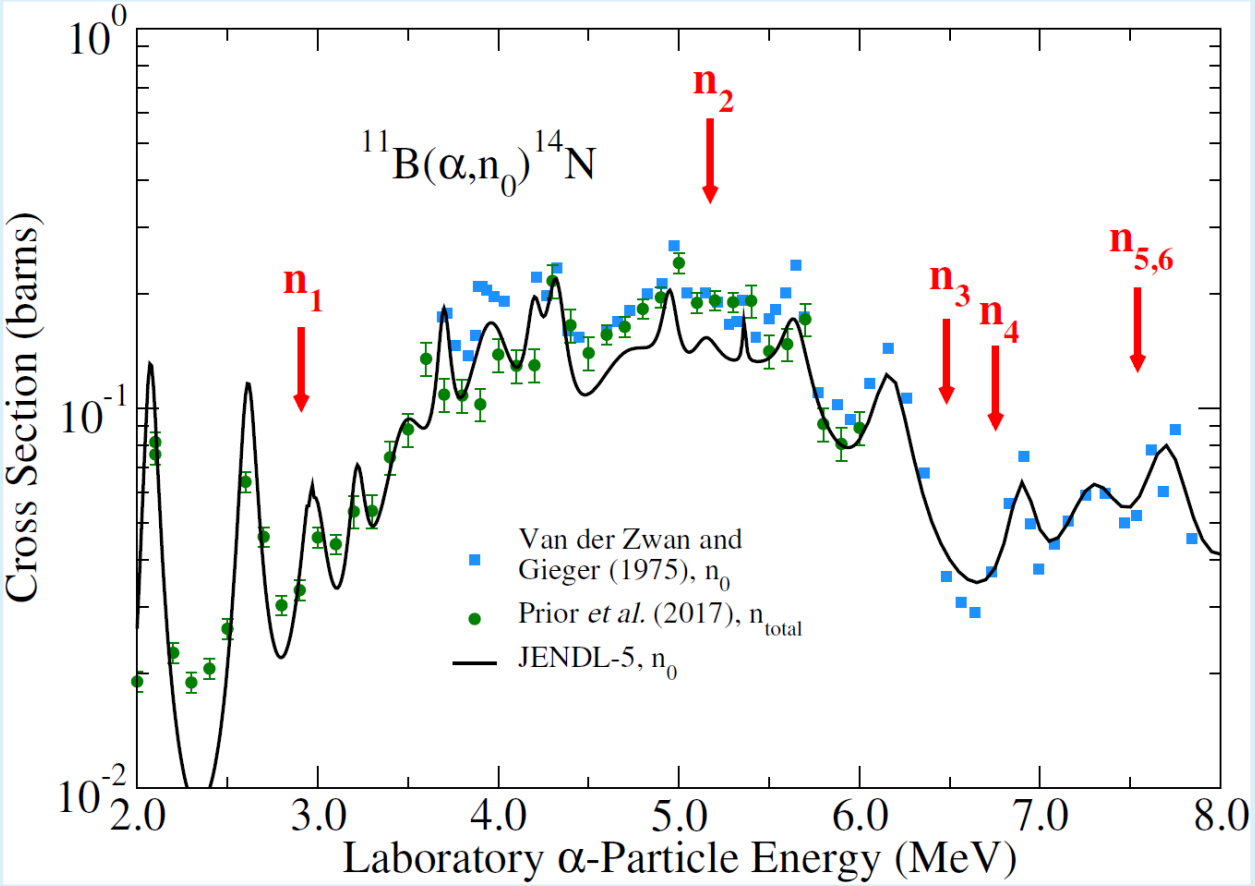
$^{11}B(\alpha,p_0)^{14}C$



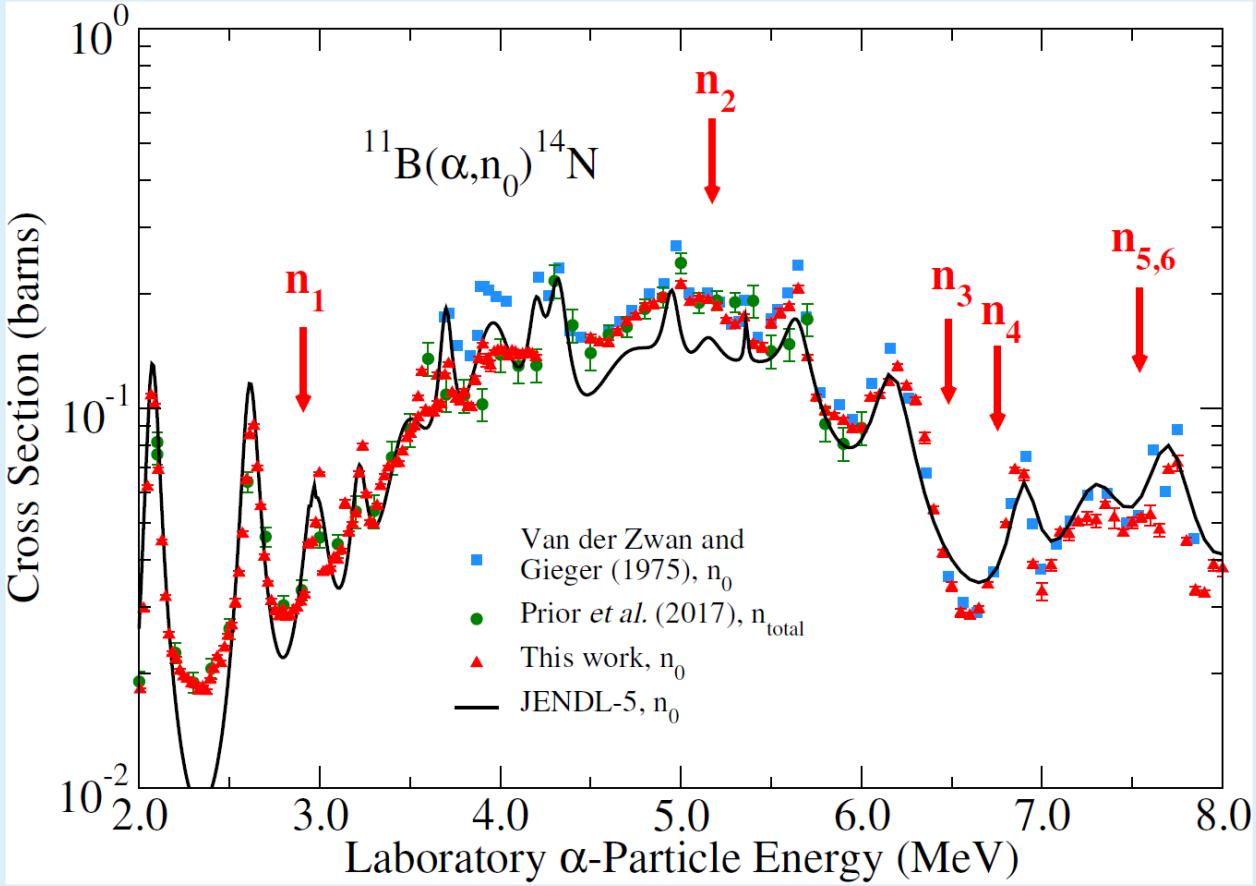
$^{11}B(\alpha,n)^{14}N$ MEASUREMENTS: ANGLE INTEGRATED PARTIAL CROSS SECTIONS

$$W(\theta) = \sum_k a_k P_k(\cos(\theta))$$

BEFORE



AFTER



WORKFORCE DEVELOPMENT: UNDERGRADUATE RESEARCH

- Benjamin Thomas

- James deBoer (Co-PI)

- Felicite Noubissi
- Stephanie Bold (student)
- Kaliya Jenkins (student)

- Amy Roberts
- Anthony Villano
- Joseph Qualantone (student)