Overview on (alpha,n) reaction measurements on light nuclei

---new project awarded from NA-22 via Nuclear Data InterAgency Working Group (NDIAWG) FOA

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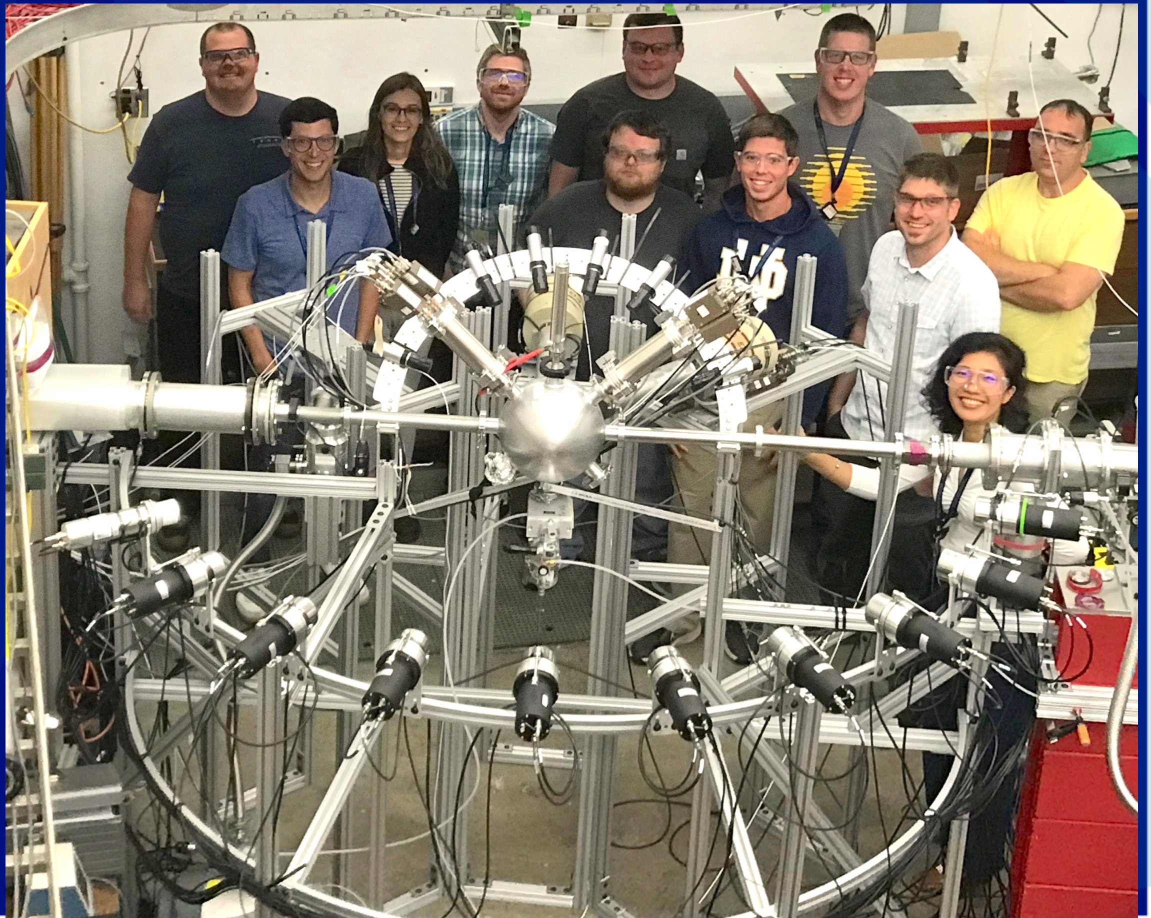


LA-UR-23-32964

Cross Section Evaluation Working Group (CSEWG) meeting
Charged Particle Evaluation Session, Nov. 15-17, 2023

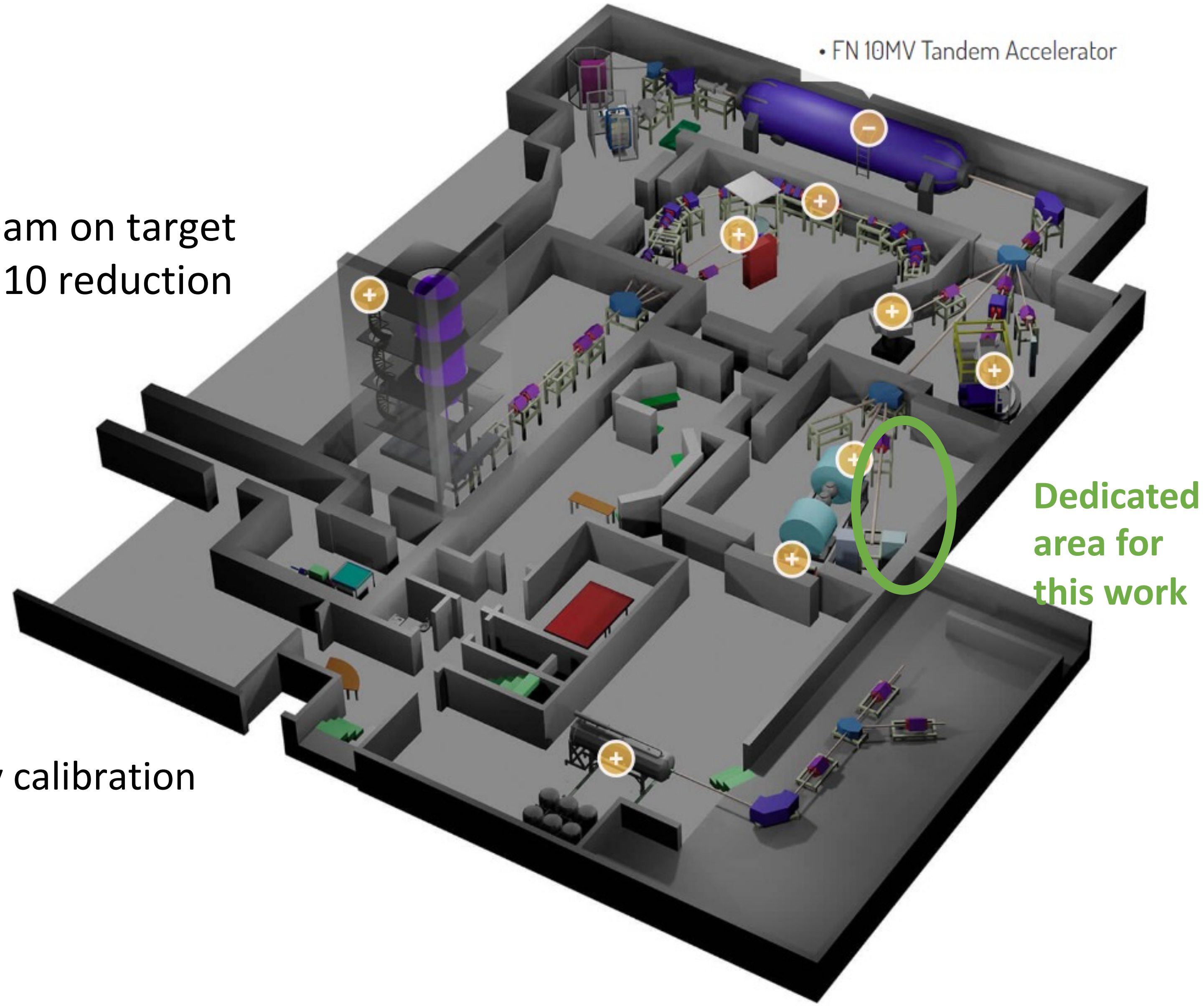
Current status of experimental data on (α,n) reactions

1. Long counters were used for measurement, lacking neutron energy details
2. Differential/total cross-section data are limited, with some reactions measured only below 2 MeV and no comprehensive coverage across a broad energy range
3. Limited angular distribution measurements for complete analyses
4. Underestimations in uncertainties, particularly from branching ratio implementations for secondary gamma-ray measurements
5. Energy-dependent neutron efficiency contributes to overall normalizations from populated different final states and angular distributions
6. Some final states are closely spaced, necessitating high-resolution spectroscopy data and improved signal-to-background ratios

Institute for Structure and Nuclear Astrophysics at Notre Dame

FN

-Lower current, tandem type
-1 to 10 MV
-Around 200 nA of proton or alpha particle beam on target
-Bunching available, but comes with factor of 10 reduction in beam intensity
-Similar energy characteristics

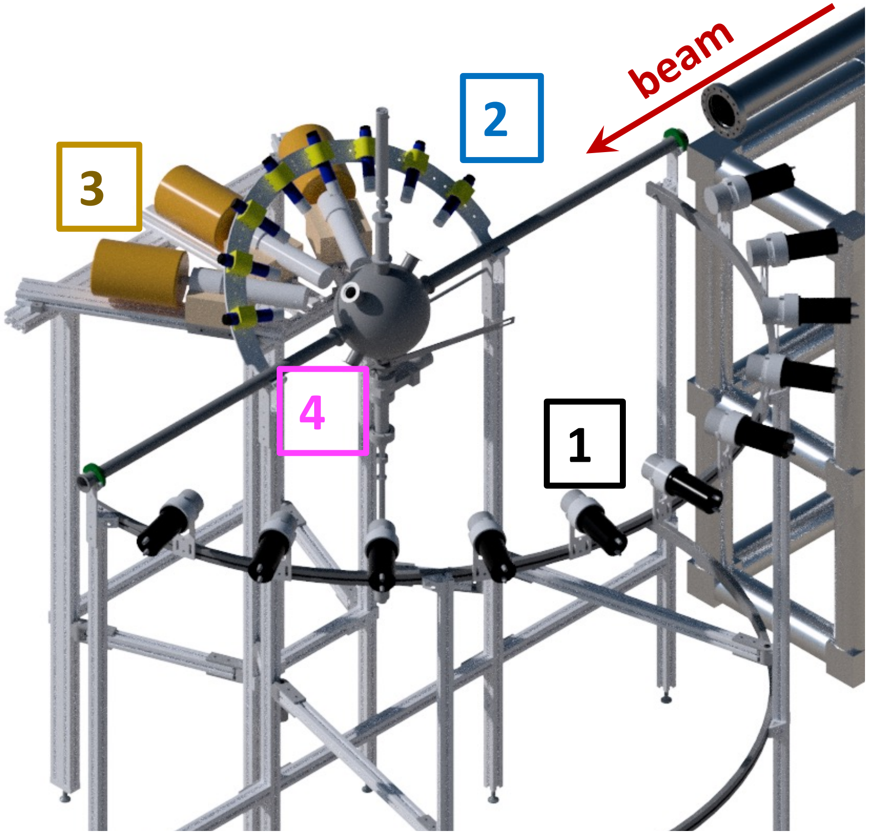


5U

-High current, single ended
-0.3 to 4 MV range
-Around 50 uA of proton or alpha particle beam
-No bunching capability, so no time-of-flight
-0.05% energy resolution and about 0.1% energy calibration

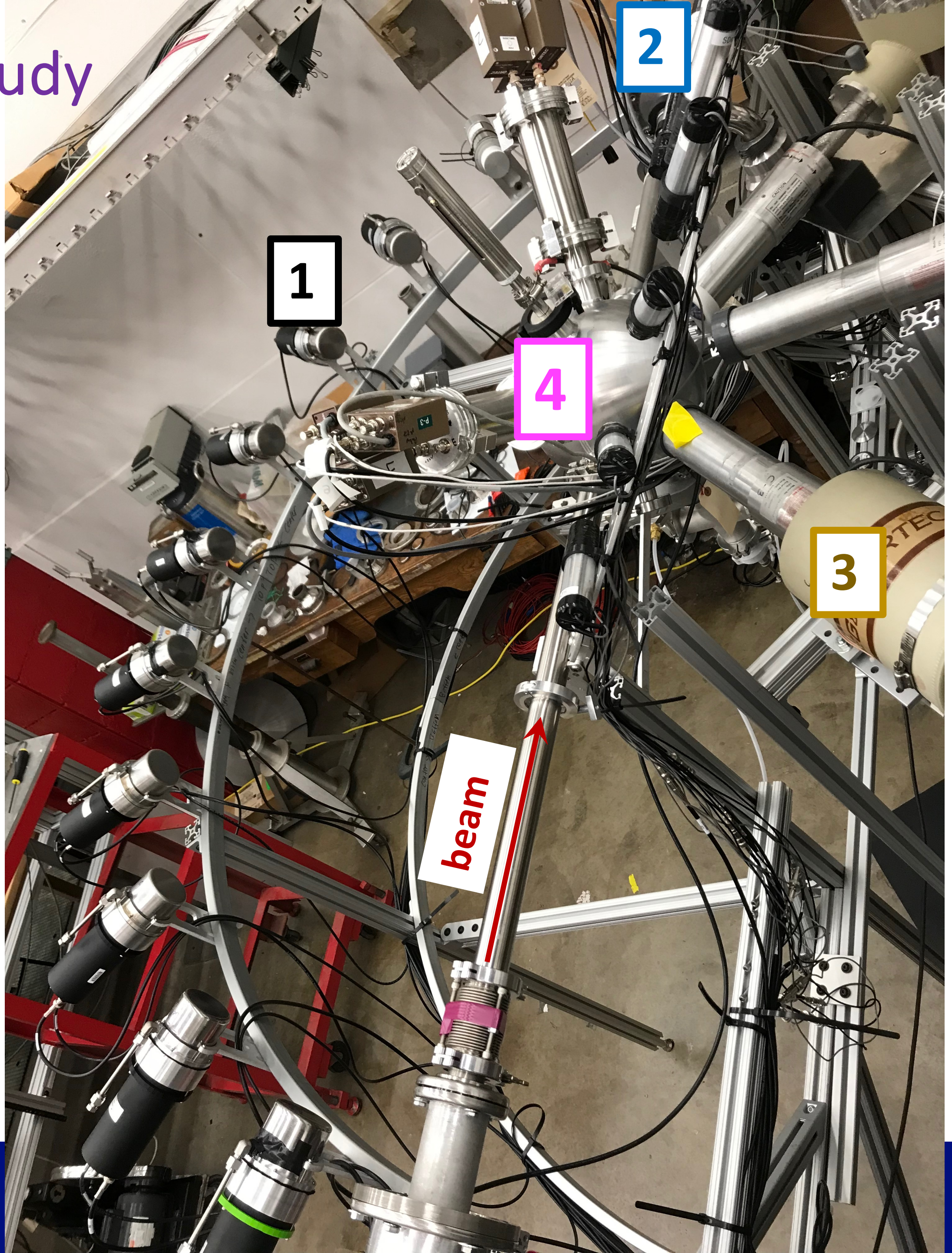
Experimental Setup, demonstrated for (d,n) study

1. 10 Deuterated liquid scintillator arrays
   -good n/γ separation,
   -spectrum unfolding provides neutron energy without TOF
2. 10 Stilbene scintillator array – good n/γ separation



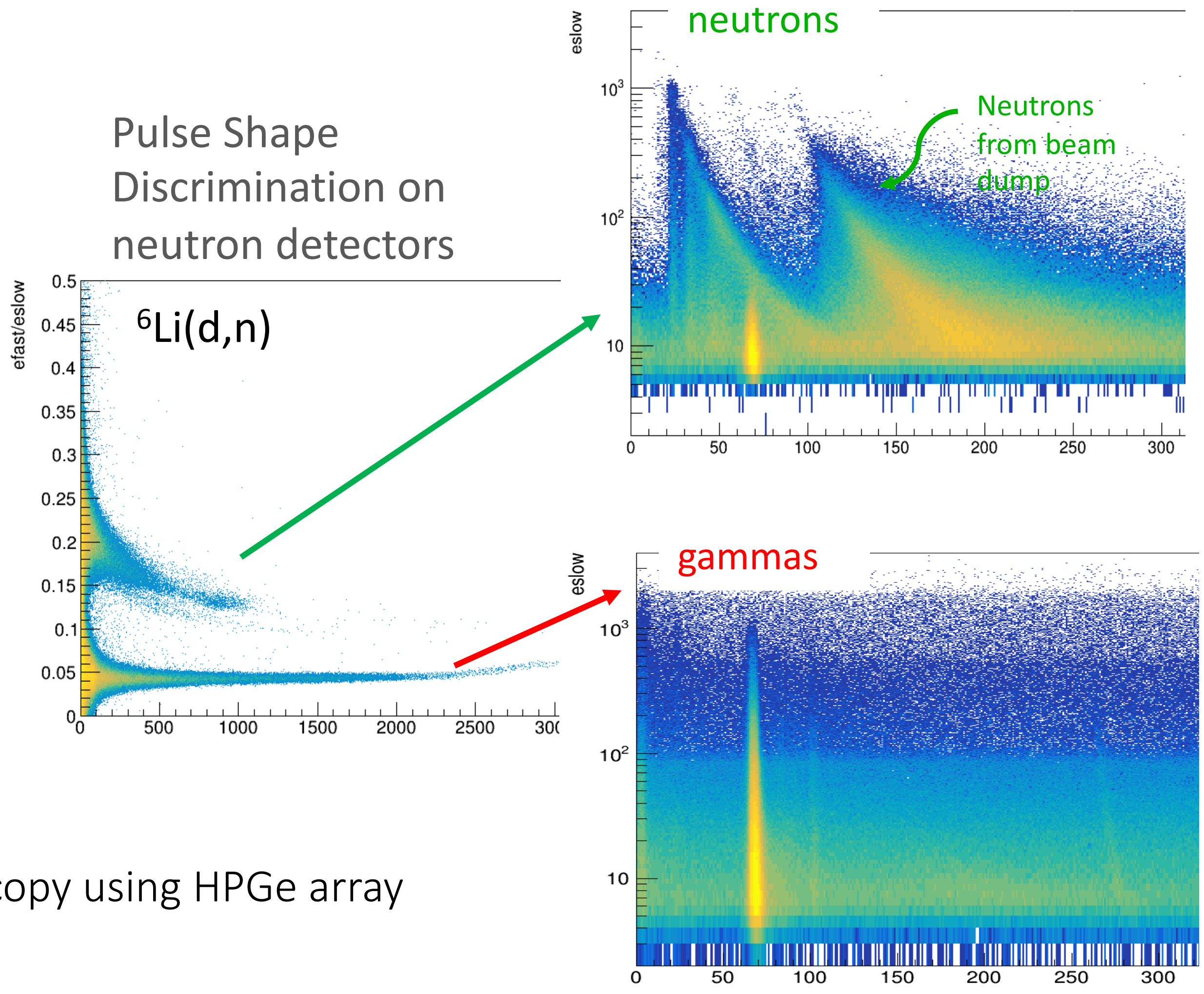
3. 3 GENIE HPGe and plan to purchase up to 3 additional HPGe – γ spectroscopy

4. 2 sets of charge particle detectors (ΔE1 + ΔE2 + ΔE3) – p, d, t, 3He and 4He detection from beam scattering, particle unbound states, and reaction products

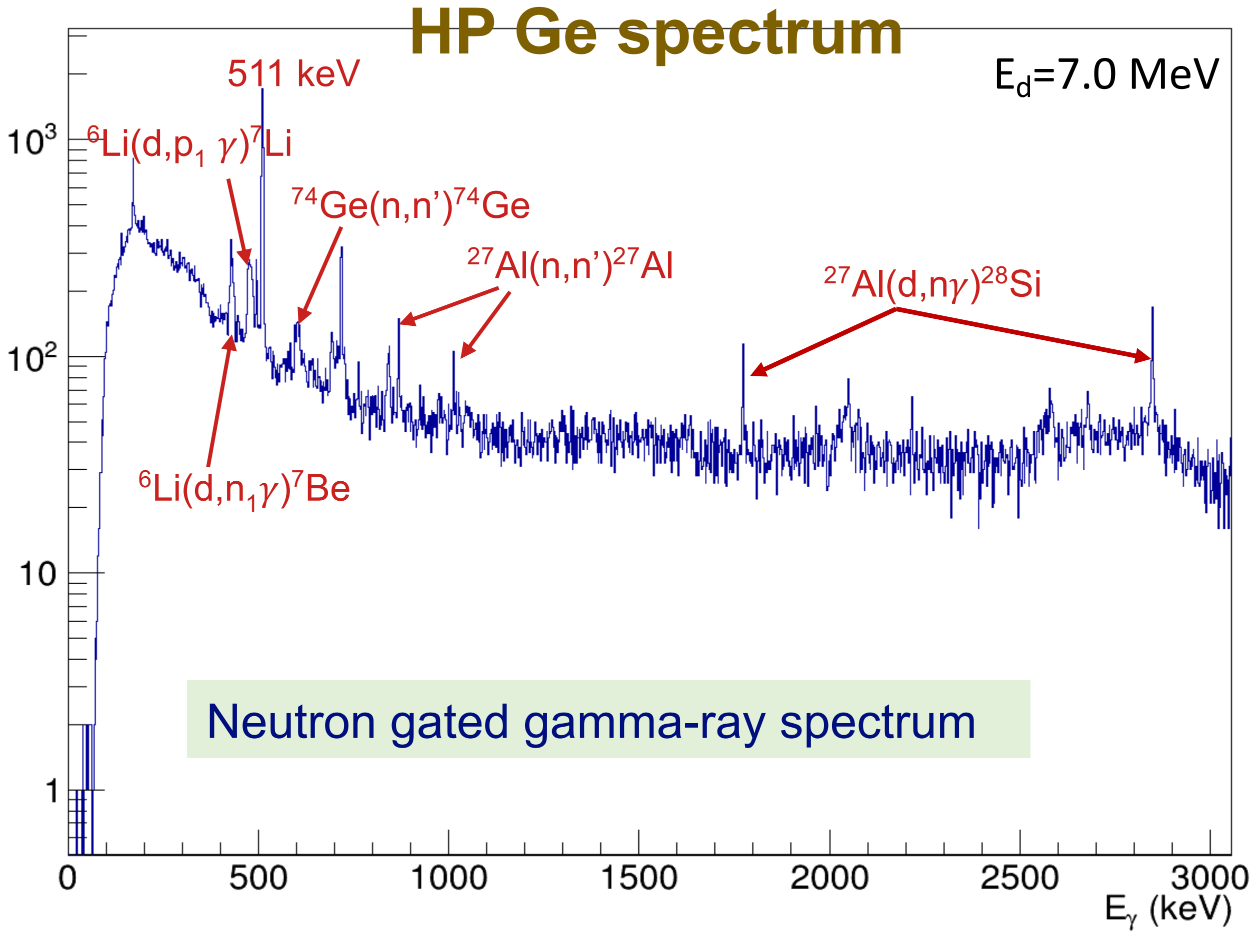


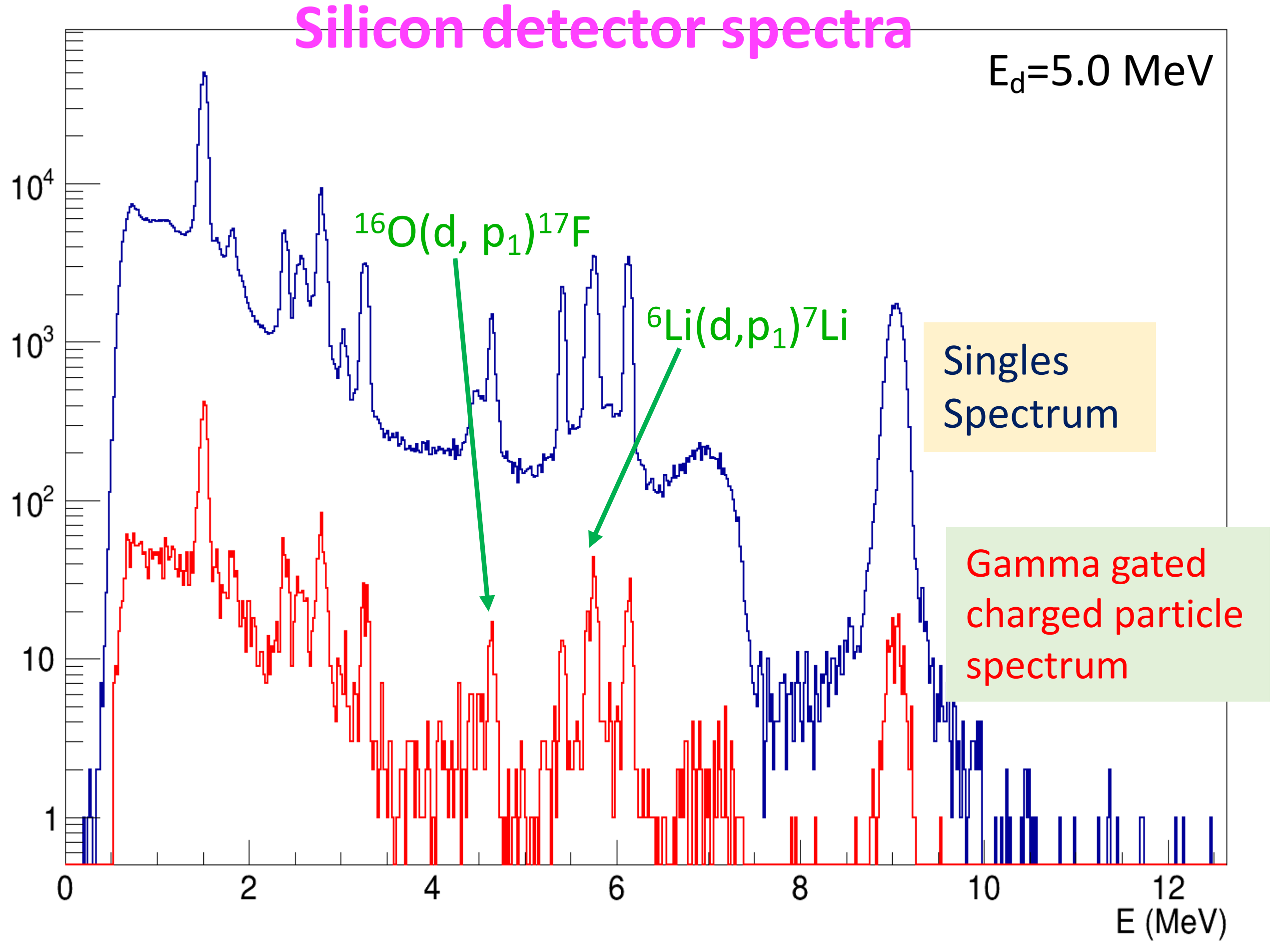
Improved experimental setup in the current project

1. **Transmission targets and shielded beam stop will greatly reduce background** -- enriched ^{13}C thin foils, $^{10,11}B$ and ^{7}Li, CaF_2 evaporated onto ^{12}C enriched thin foils. Evaporation of material onto thick Ta backings
2. **Much less massive target holder and uniform chamber reduces and simplifies the conversion of the experimental yields to cross sections**
   --Activation techniques will be employed to obtain high precision efficiency: $^{7}Li(p,n)^{7}Be$, $^{51}V(p,n)^{51}Cr$, $^{10}B(\alpha,n)^{13}N$, $^{19}F(\alpha,n)^{22}Na$
3. **Expanded detector array and detector types will allow for simultaneous measurement of neutrons, γ-rays, and charged particles**
   --Measurements close to thresholds (low energy neutrons)
4. **Array of HPGe at different angles are needed to extract angle integrated cross sections**
   --Spectrum unfolding of neutron detector data. γ-ray spectroscopy using HPGe array

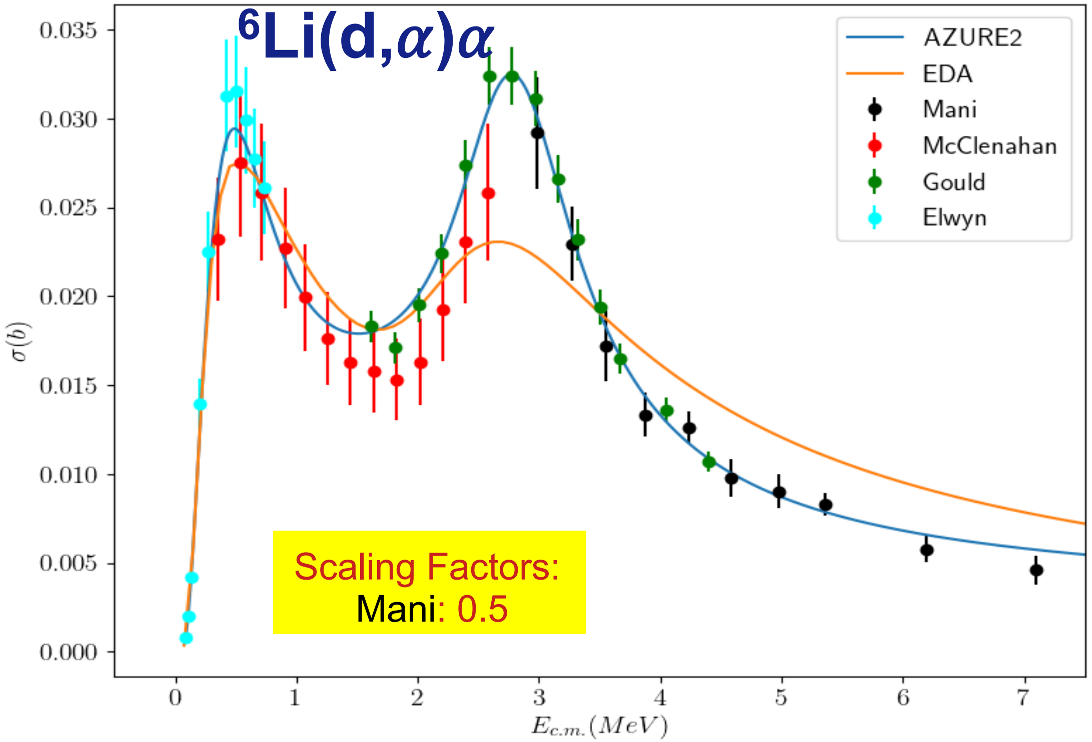


Correlated data among neutron, gamma and charged particles from $^6Li(d,n)$ reaction help self-consistent analyses and enhance signal-to-background ratios

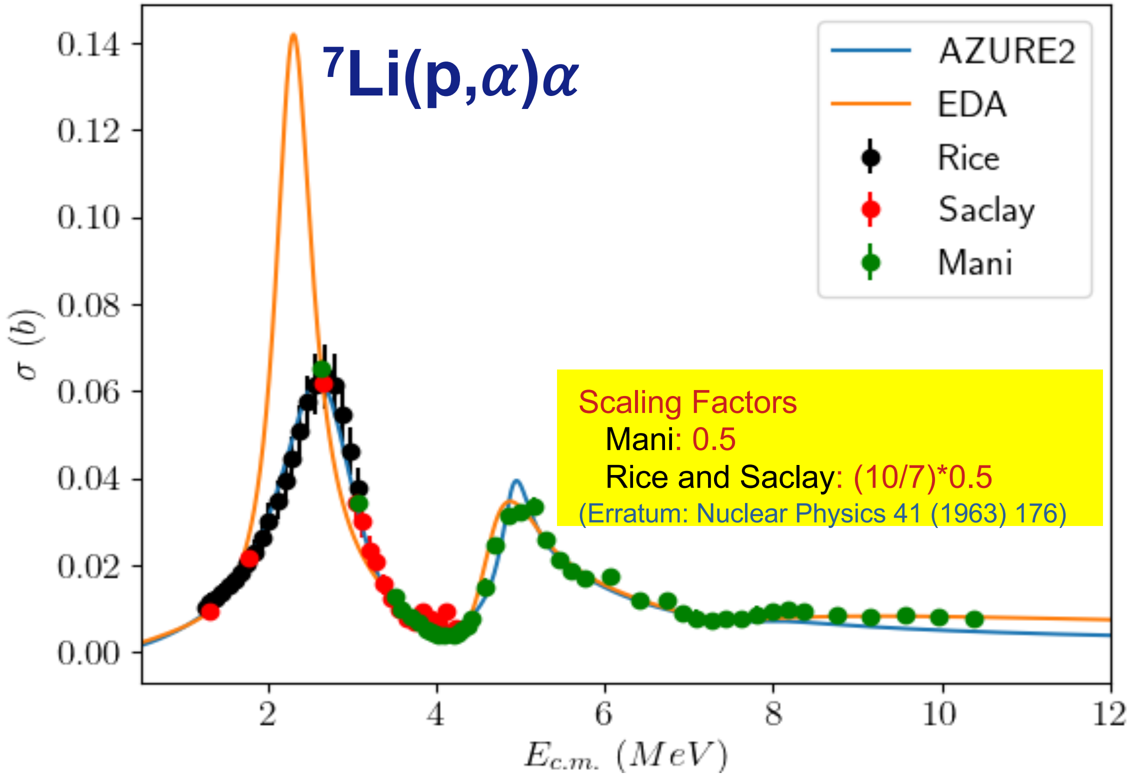




Multi-channel R-matrix analysis on the ^8Be system constrained the discrepant normalization (due to identical particles) among data sets and different calculations, based on the simultaneous fitting of other reaction channels



Data Used: Integrated Cross Section:
-Mani *et al.* (Proceedings of the Physical Society , Vol.85, 1965)
-McClenahan *et. al.* (Physical Review, Part C, Nuclear Physics, Vol.11, 1975)
-Gould *et. al.* (Nuclear Science and Engineering, Vol.55, 1974)
-Elwyn *et. al.* (Physical Review, Part C, Nuclear Physics, Vol.16, 1977)
Angular distribution data:
-Foteinou *et. al.* (Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.269, 2011)



Data Used: $^7Li(p,\alpha)\alpha$:Integrated cross section:
-Rice: Cassagnou *et. al.* (Nuclear Physics, Vol.33, Issue.3, p.449 (1962))
Mani *et . al.* (Nuclear Physics, Vol.60, Issue.4, p.588 (1964))
Saclay:Cassagnou *et. al.* (Nuclear Physics, Vol.33, Issue.3, p.449 (1962))

Previous (a,n) and (n,a) publications

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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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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In press in Phys. Rev. C (2023)

Differential cross sections of the $^{16}O(n,\alpha)$ reaction at neutron energies from 3.8 MeV to 15 MeV

H.Y. Lee,[†] S. A. Kuvin, L. Zavorka,[†] S. Mosby, B. DiGiovine, G. Hale, M. Paris, D. Votaw,[‡] and M. White
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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[†]
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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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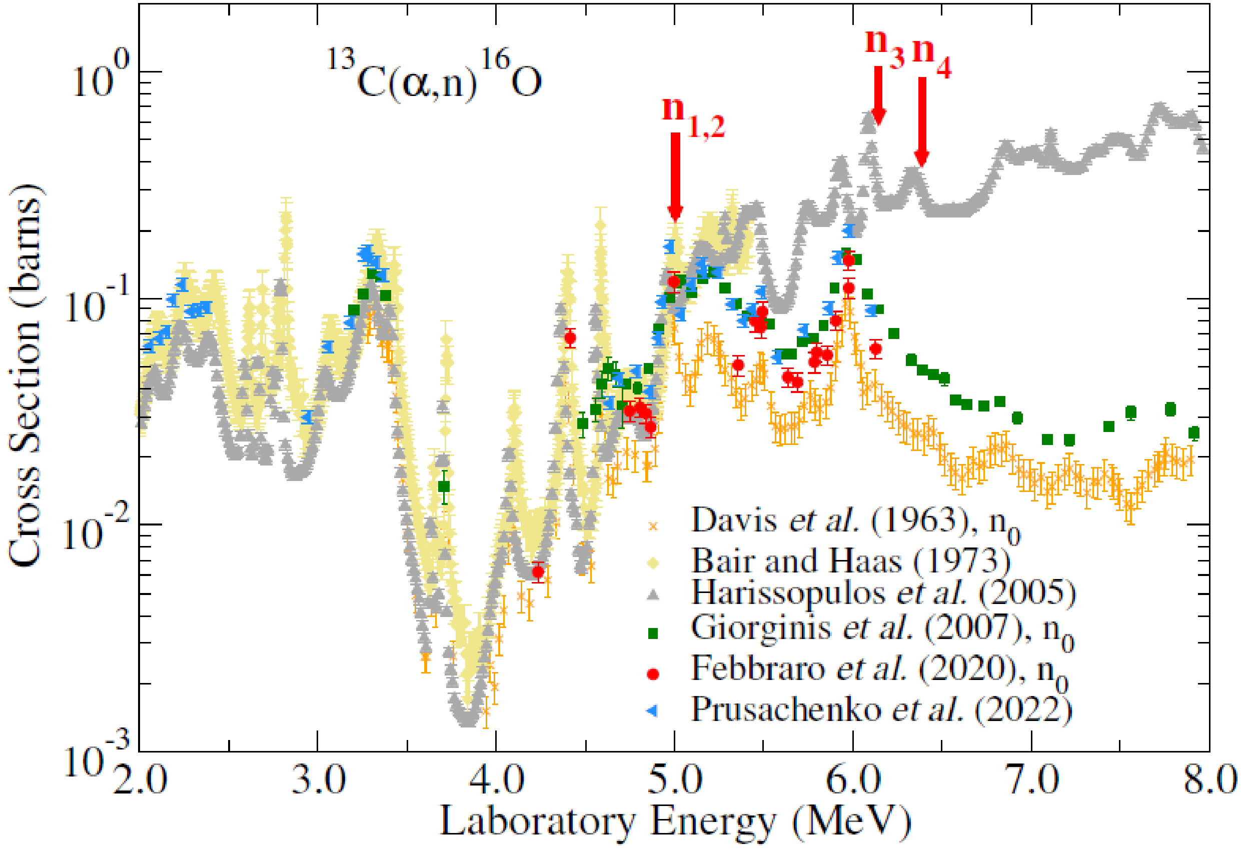
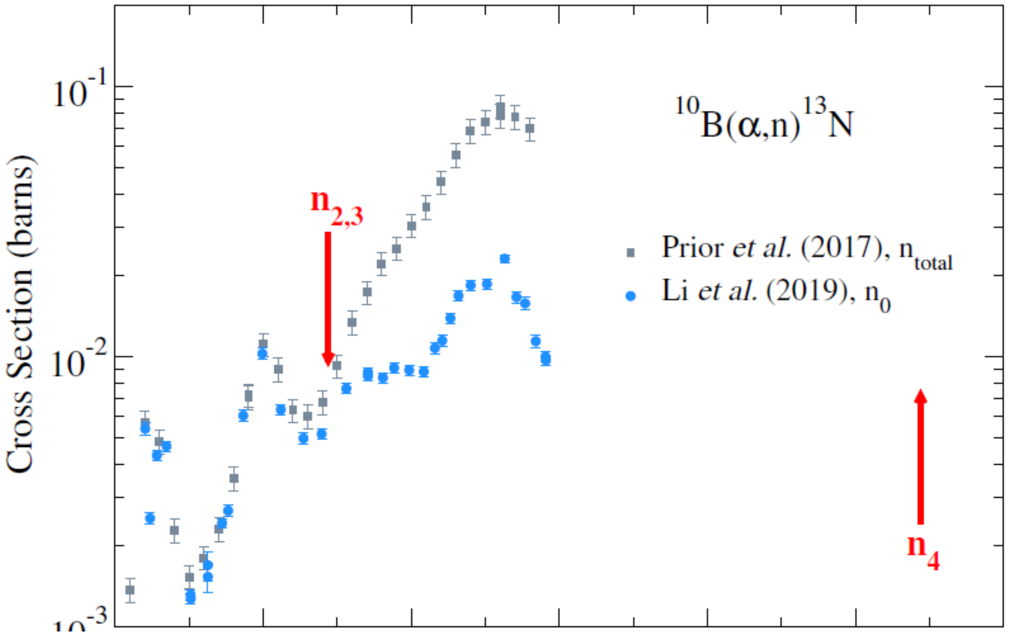
$^{13}C(\alpha,n)^{16}O$

- Measurements of the ground state are straightforward with little background contributions
- Measurements of excited state channels (which produce lower energy neutrons) contain background contributions from $^{19}F(\alpha,n)^{22}Na$, if a T backing is used
- Plans to use the HPGe array along with neutron arrays to obtain;
  - cross sections for the $n_{2,3,4}$
  - yield of n_1 by taking the (n_1+n_2) neutron yields and subtracting the n_2 obtained from the γ-rays



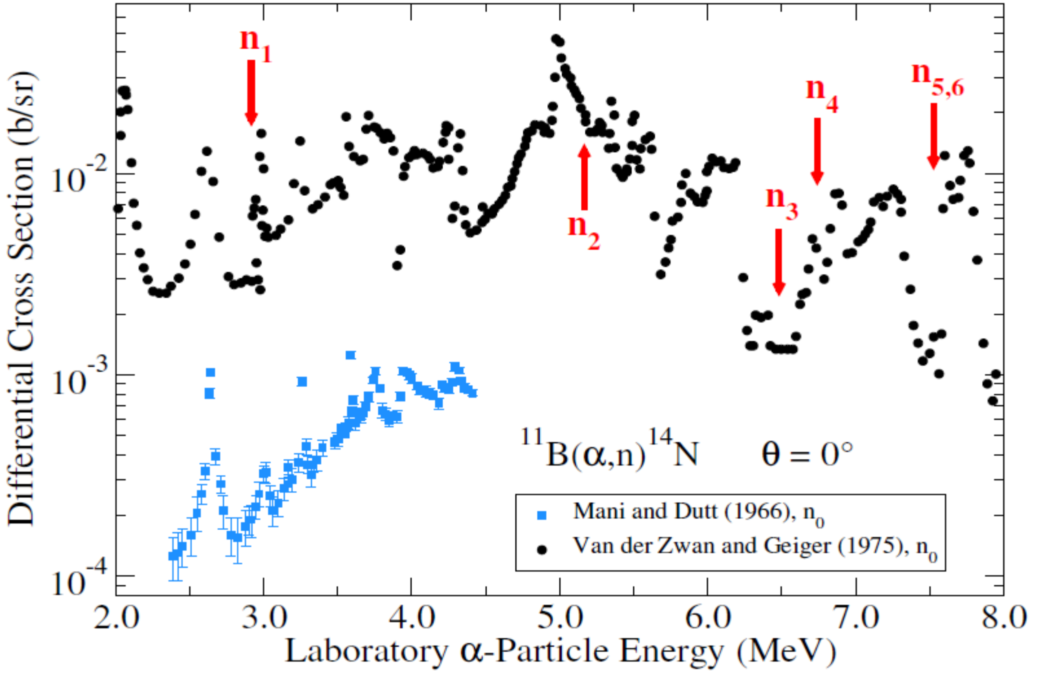
$^{10}B(\alpha,n)^{13}N$

- Measurements should be relatively straight forward
- n_2 and n_3 will not be separable, which Unfortunately decay through proton emission
- 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
- Carbon backings are needed for transmission target, ^{12}C enriched foils will greatly reduce $^{13}C(\alpha,n)$ background
- The ground state part of the cross section can also be measured using the activation method, providing a high precision method of efficiency determination



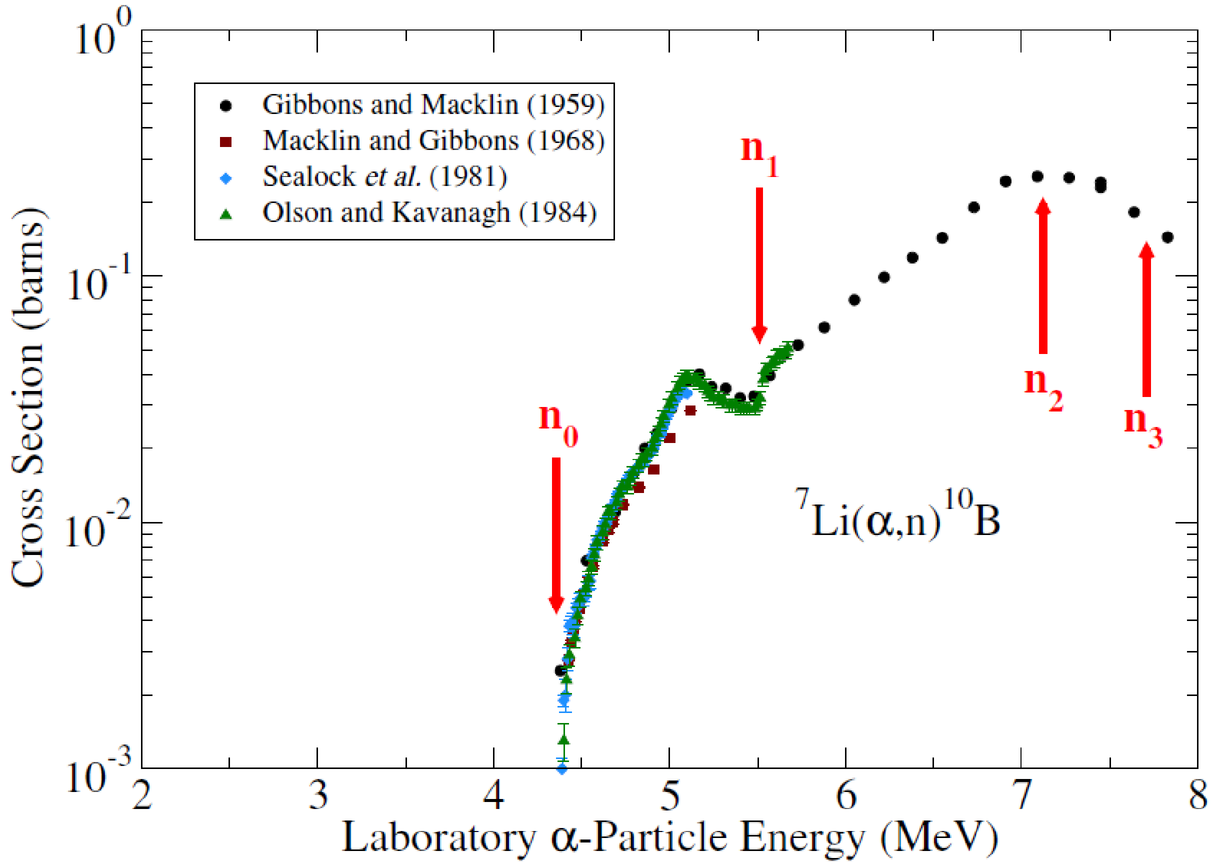
$^{11}B(\alpha,n)^{14}N$

- Lots of resonance structure, so thin targets and small energy steps will be required (similar to $^{13}C(\alpha,n)^{16}O$ in that respect)
- Several excited states, but most are energetically separable until $n_{5,6}$



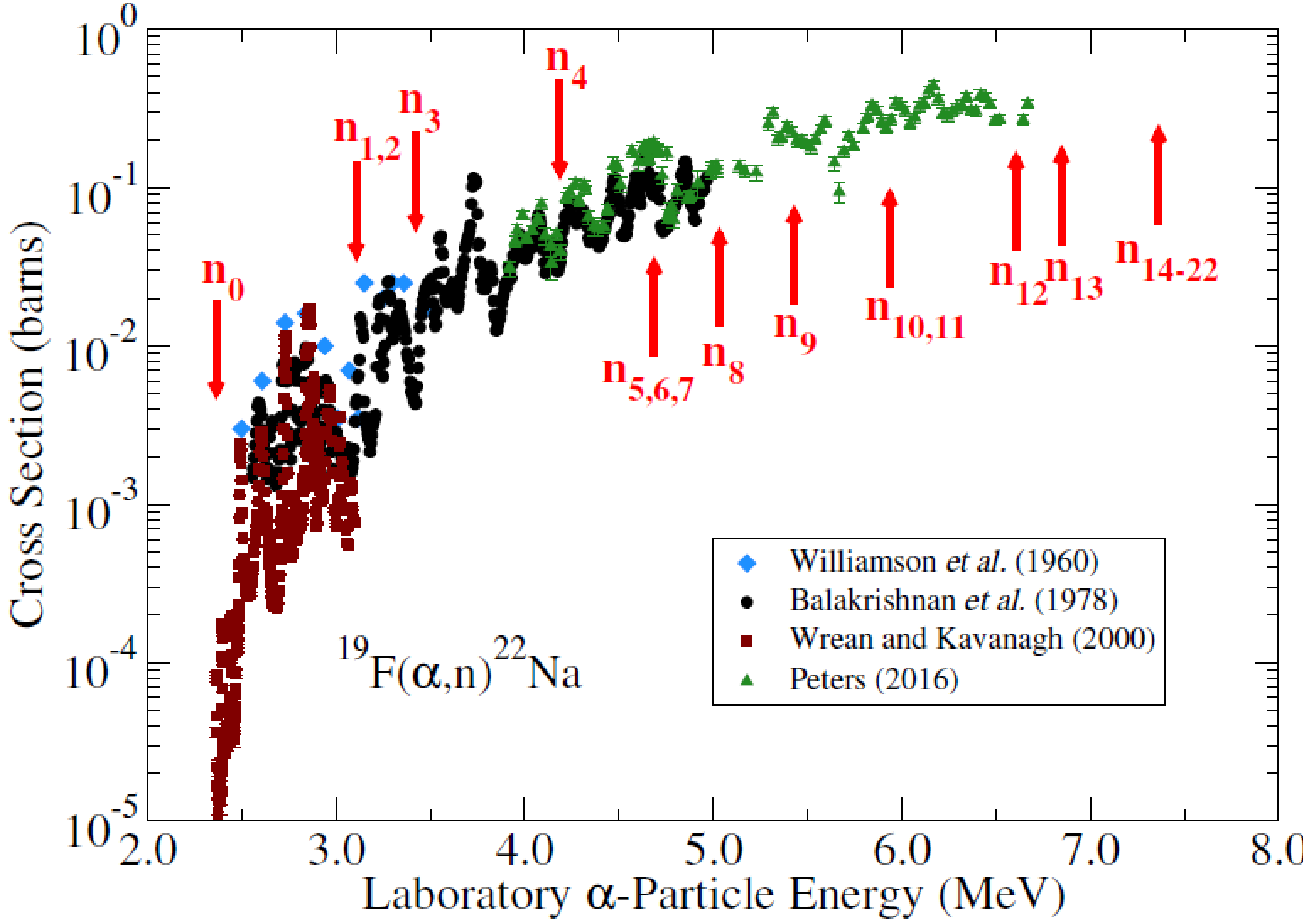
$^{7}Li(\alpha,n)^{10}B$

- Well separated excited states
- Reduced energy range because of large negative Q-value
- Same oxygen and carbon background issue as the boron case, so same solution



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

- The most challenging
- Many narrow resonances necessitate thin targets
- Many excited states will require a lot of time to analyze the data
- Activation can be used for efficiency/normalization checks
- CaF_2 target should be relatively free of background
- Same carbon background issue as the boron case, so same solution
- Expect multiple measurements for high precision



Planned experiments on (α,n) reactions at E_α = 2 – 9 MeV using FN and 5U accelerators at U. of Notre Dame

1. Year 1 (FY24): $^{13}C(\alpha,n)^{16}O$ measurement
2. Year 2 (FY25): $^{10}B(\alpha,n)^{13}N$ measurement
3. Year 3 (FY26): $^{11}B(\alpha,n)^{14}N$ measurement
4. Year 4 (FY27): $^{19}F(\alpha,n)^{22}Na$ measurement
5. Year 5 (FY28): $^{7}LI(\alpha,n)^{10}B$ measurement

Expected comprehensive self-consistent data to share with community

1. Cross sections of total, partial channels
2. Angular distributions on neutrons, gammas, and charged particles
3. Secondary gamma-ray yields, neutron spectra
4. Multi-channel R-matrix analyses with all measured channels for ENDF evaluators
5. Impact assessment using Source4C, MCNP, and Geant4

Additional features during this project

1. In-house target fabrication capability at the Institute for Structure and Nuclear Astrophysics in U. of Notre Dame; providing oxygen free in-situ metal targets; methods with evaporation, electrospray, etc.
2. The experimental end station will be permanent at the dedicated beamline for 5 years during this campaign to preserve systematic uncertainties and self-consistencies between all reactions measured
3. Calibrated activation measurement capability at U. of Notre Dame
4. Fully characterized detector response functions on ODeSA and Stilbene arrays
5. Full list mode data acquisition system using waveform digitizers for time-correlated events from all detector types (neutrons, gammas, and charged particles)
6. R-matrix analysis will be performed using AZURE2 and EDA
7. Great pipeline among LANL, ORNL, AFIT and U. of Notre Dame