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, the "(α,n) project"

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U.S. DEPARTMENT OF ENERGY

Office of Science

NNSA

National Nuclear Security Administration

Calls for measurements

ORNL/TM-2020/1789

(α,n) Nuclear Data Scoping Study

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NUCLEAR DATA INTERAGENCY WORKING GROUP (NDIAWG) RESEARCH PROGRAM

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Table 1. List of priority isotopes for improved (α,n) reaction data.

First Priority		Second Priority	
^{19}F	Additional measurement data and evaluation, including secondary gamma rays and neutron spectrum to reduce uncertainties as low as possible. Energy range 2-8 MeV.	^{10}B	Measurement data and evaluation, including secondary gamma rays and neutron spectrum. Energy range 2- 8 MeV.
^{13}C	New measurement data and evaluation required, including secondary gamma rays and neutron spectrum. Differential partial cross sections from 5 to 9 MeV are of particular interest. Integration with international efforts is encouraged.	^{11}B	Measurement data and evaluation, including secondary gamma rays and neutron spectrum. Energy range 2- 8 MeV.
^{17}O	Integral measurements specific to NDA applications, including coincidence gamma rays.	^{7}Li	Measurement data and evaluation, including secondary gamma rays and neutron spectrum. Energy range 2- 8 MeV.
^{18}O	Integral measurements specific to NDA applications, including coincidence gamma rays.	^{27}Al	Measurement data and evaluation, including secondary gamma rays and neutron spectrum. Energy range 2-8 MeV.

Reference C. Romano et al., *(α,n) Nuclear Data Scoping Study*, ORNL/TM-2020/1789 (https://info.ornl.gov/sites/publications/Files/Pub148054.pdf) for additional information.

Motivation, Example $^{18}O(\alpha,n)^{21}Ne$

Pigni *et al.* (2020)

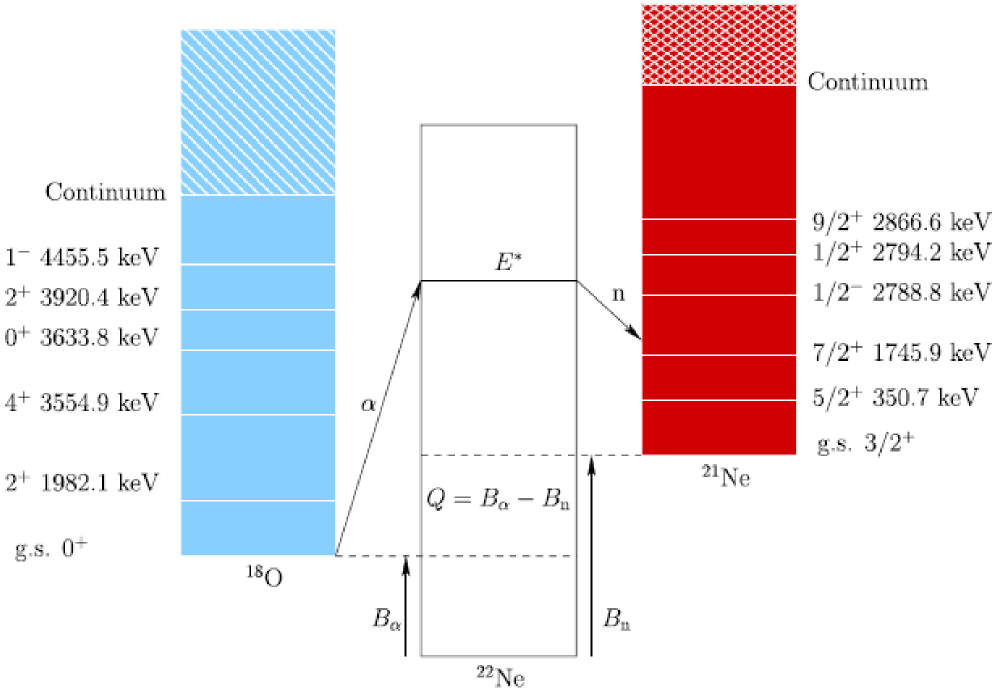

Fig. 5. Reaction scheme for $\alpha + {}^{18}O$ cross sections, including neutron emission. B_α and B_n are the α-particle and neutron binding energies, respectively. These values are based on the AME2016 atomic mass evaluation (Wang et al., 2017).

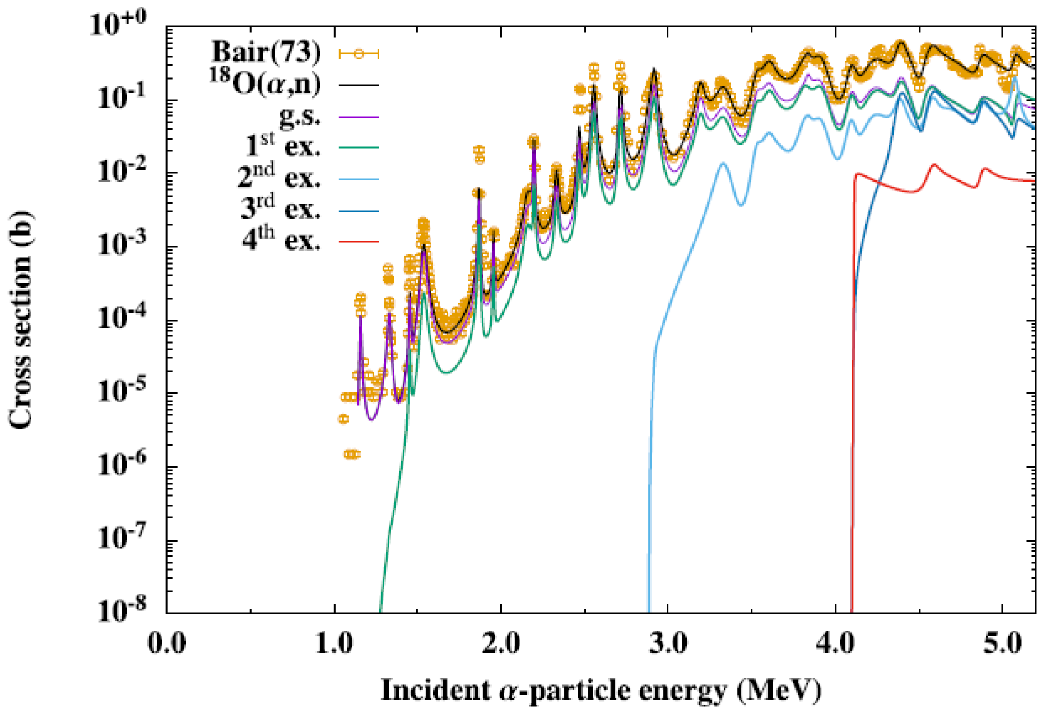

Fig. 3. $^{18}O(\alpha$,n) cross sections reconstructed from the preliminary set of resonance parameters in the energy range of 1–5 MeV compared with Bair's experimental data (Bair and Haas, 1973). Partial cross section components related to the g.s. and five excited states are shown.

Motivation

- We only have measurements that tell us the total number of neutrons produced for a given incoming alpha particle energy
- We don't know which final state is being populated
- We then can't predict the energy that the neutrons from the reaction will have

Neutron energy spectrum from a plutonium oxide matrix

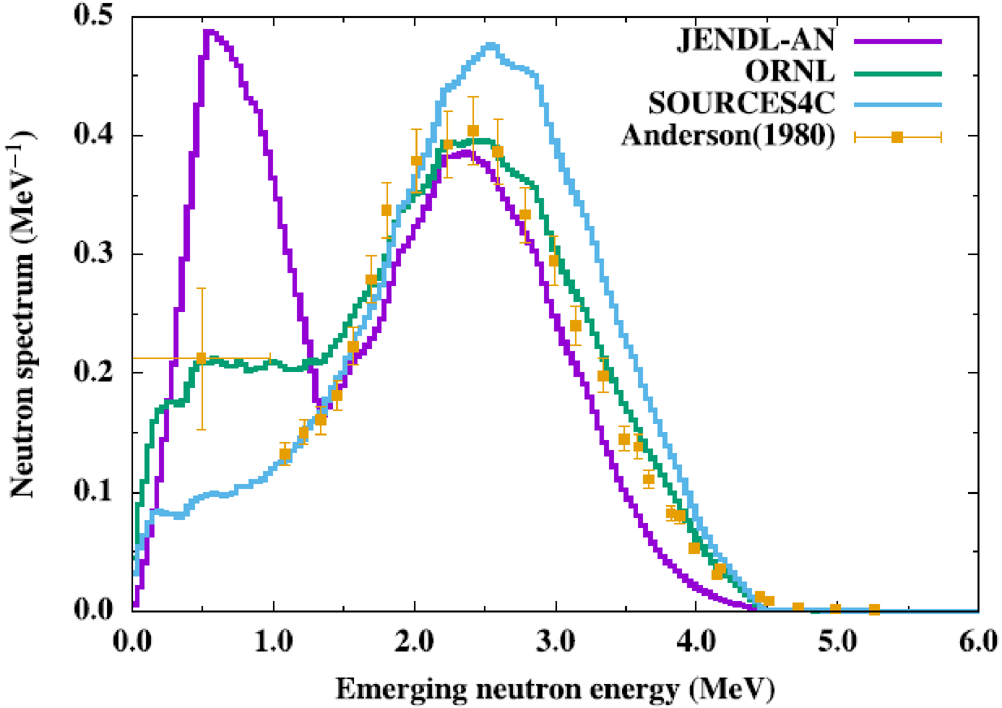

Fig. 7. Total neutron energy distribution calculated by using different nuclear data for the $^{17,18}O(\alpha,n)$ cross sections and related partial cross section components. The calculated spectra are also shown together with Anderson's measured data (Anderson, 1980).

Pigni *et al.* (2020)

The team

PI: Hye Young Lee

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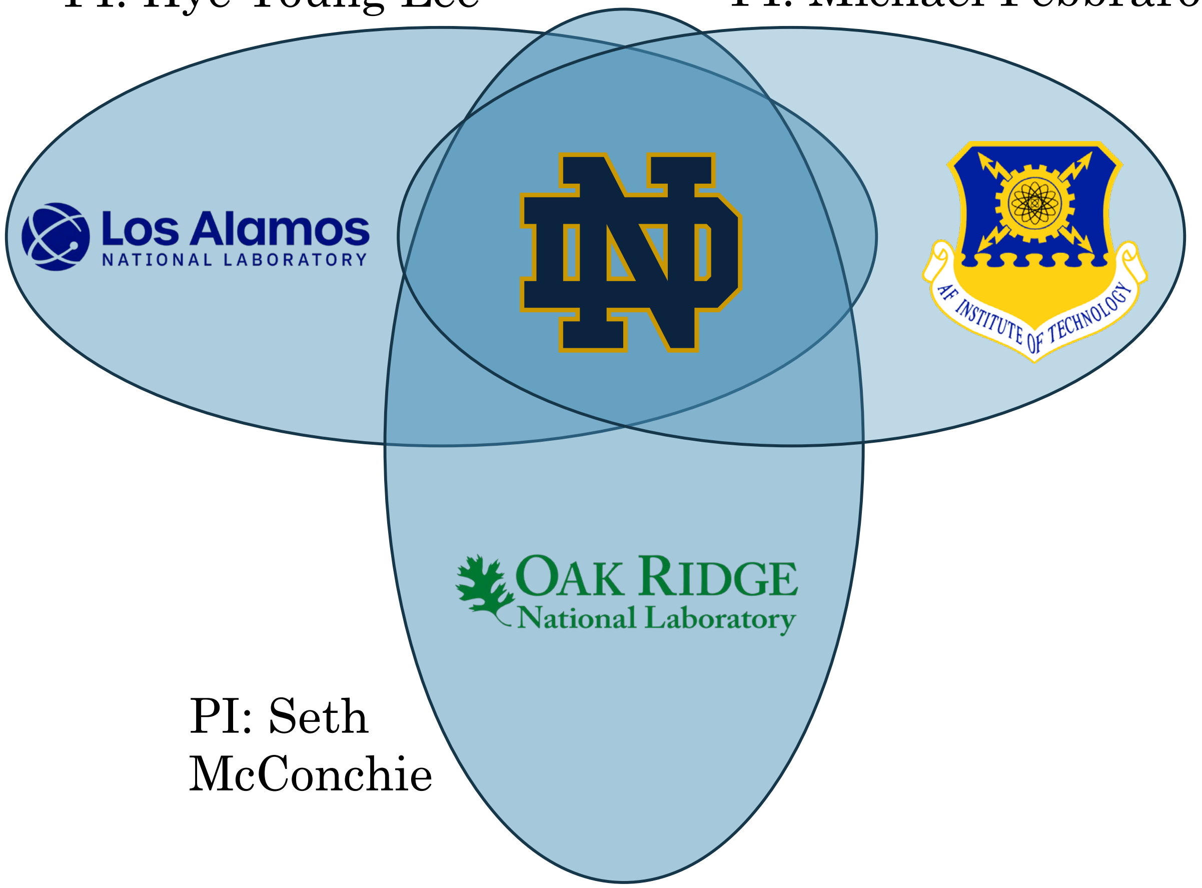
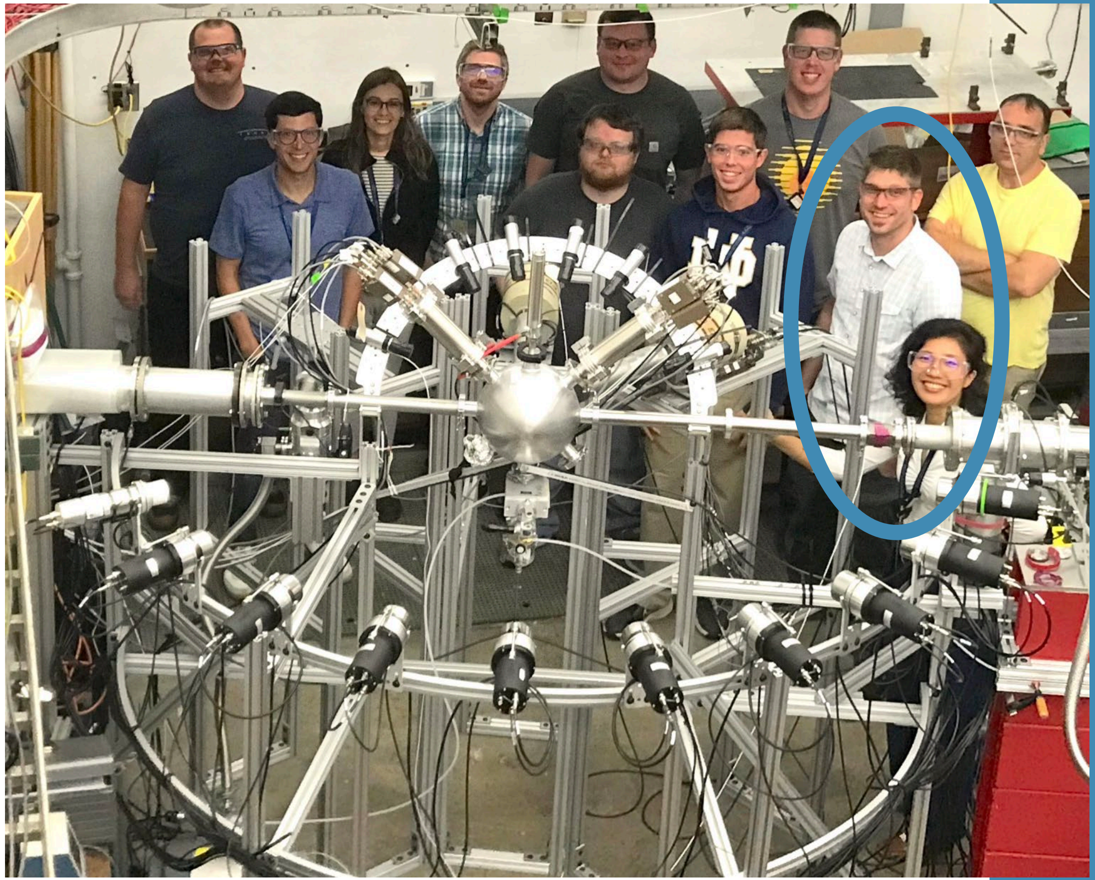


PI: Seth McConchie



What we're going to tackle

First Priority		Second Priority	
^{19}F	Additional measurement data and evaluation, including secondary gamma rays and neutron spectrum to reduce uncertainties as low as possible. Energy range 2-8 MeV.	^{10}B	Measurement data and evaluation, including secondary gamma rays and neutron spectrum. Energy range 2- 8 MeV.
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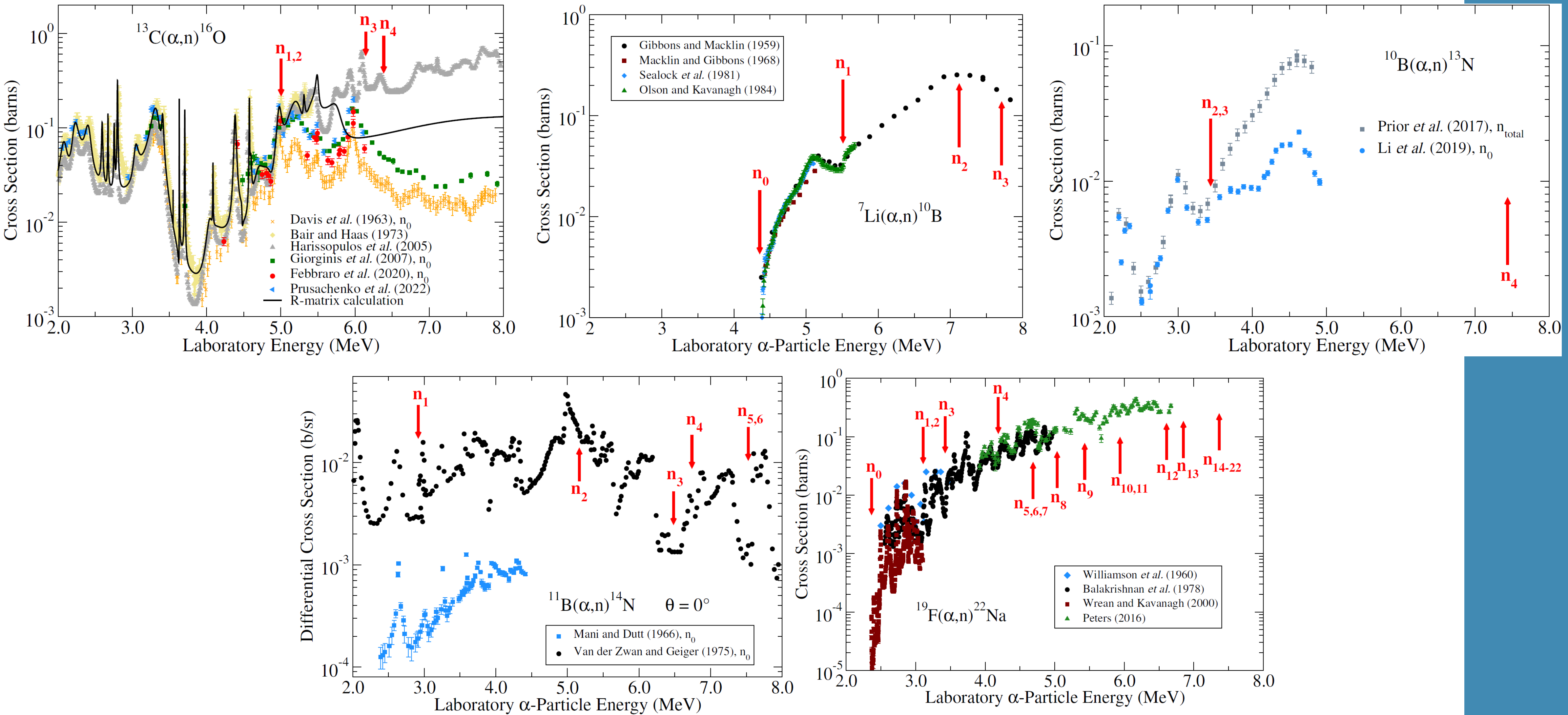
		^{7}Li	Measurement data and evaluation, including secondary gamma rays and neutron spectrum. Energy range 2- 8 MeV.

Footnote: Rebecca Toomey *et al.* at LLNL will measure the Oxygen isotopes and $^{27}Al(\alpha,n)$

How are we going to do it?

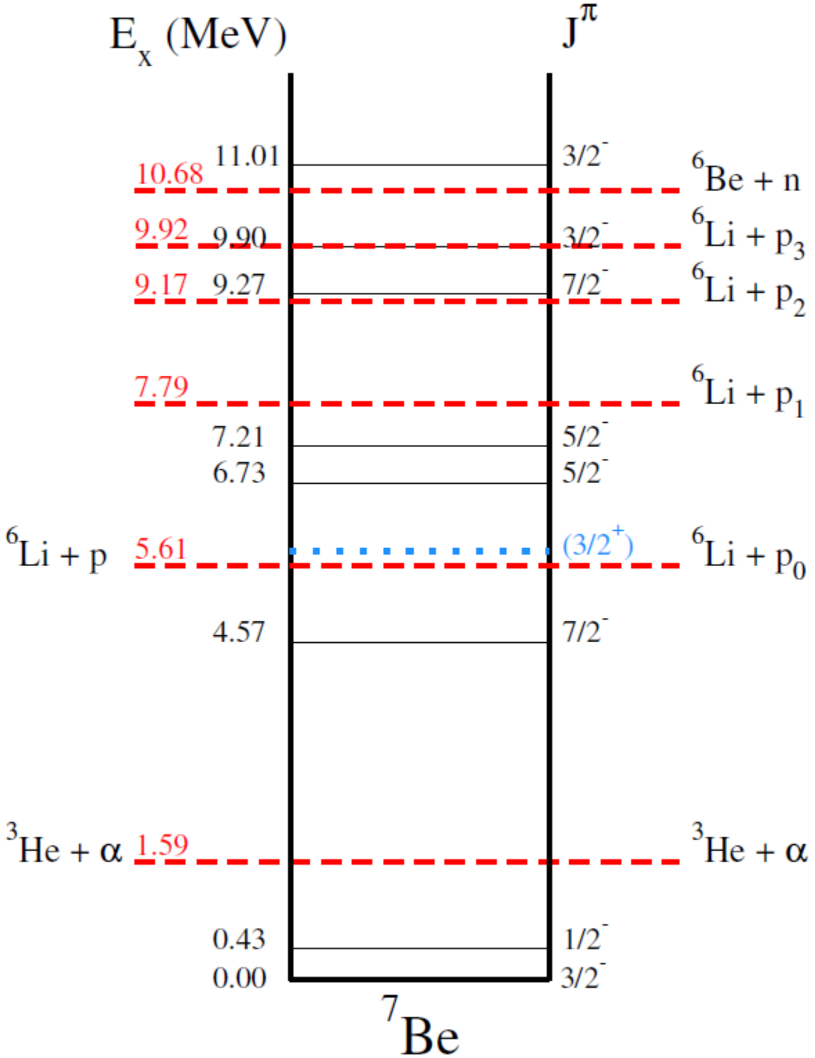
- We need to measure, potentially hundreds, of angular distributions at many energies depending on the reaction
  - Some reactions are much easier than others
    - ^{7}Li(α,n) has only broad resonance structures and only a few final states, maybe only 30 energies are needed
    - ^{19}F(α,n) has many narrow resonances with many possible final states
- The Nuclear Science Laboratory at **Notre Dame** is in a somewhat unique situation, we have two **low energy Van de Graff accelerators**
  - Good energy resolution (0.025% energy uncertainty for our FN accelerator, with significantly better energy resolution)
  - Typical DC beam intensities of a few hundred nanoamps on target, about 1/10 of this for bunched beams (200ns bunches with 2ns resolution)
- **Deuterated liquid scintillators** from **ORNL / ND / AFIT**
  - Neutron spectroscopy without time of flight
  - High intrinsic efficiency (30% for 2 MeV neutrons, somewhat threshold dependent)
- **Digital electronics and data processing** for all detectors (scintillators, HPGes, silicon) from **LANL**

Some idea of what needs to be done



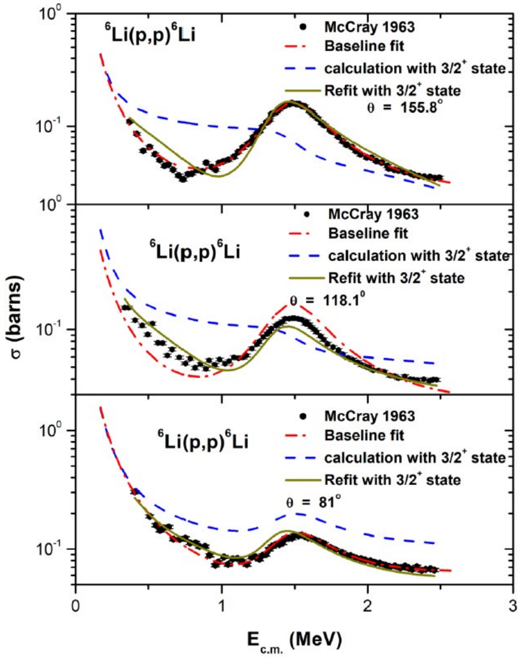
Evaluation updates

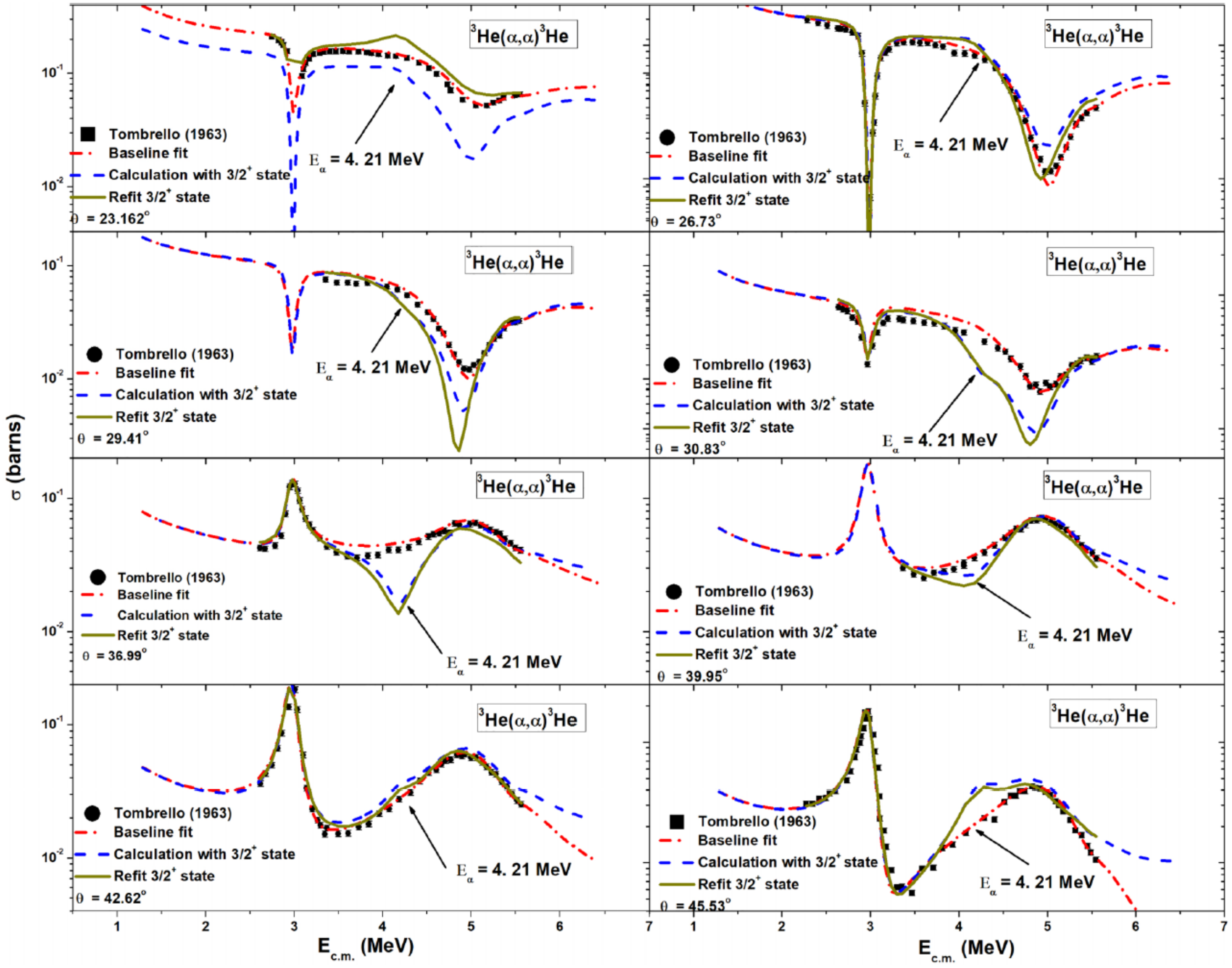
- ^{7}Be system
  - I've got what I think is a pretty good fit for both the ^{4}He+^{3}He (about E_x = 9 MeV) and ^{6}Li+p (as high as E_x = 11.6 MeV)
  - Ground state transitions look good
  - I've never been able to get especially good fits for the inelastic proton channels however
  - Pretty good fits for radiative capture data for both ^{3}He(α,γ)^{7}Be and ^{6}Li(p,γ)^{7}Be but these data are all near threshold
  - Also, I'm "stuck" in the ^{4}He+^{3}He kinematics, as I've found it is extremely time consuming, for me anyway, to try to convert to ^{3}He+^{4}He.

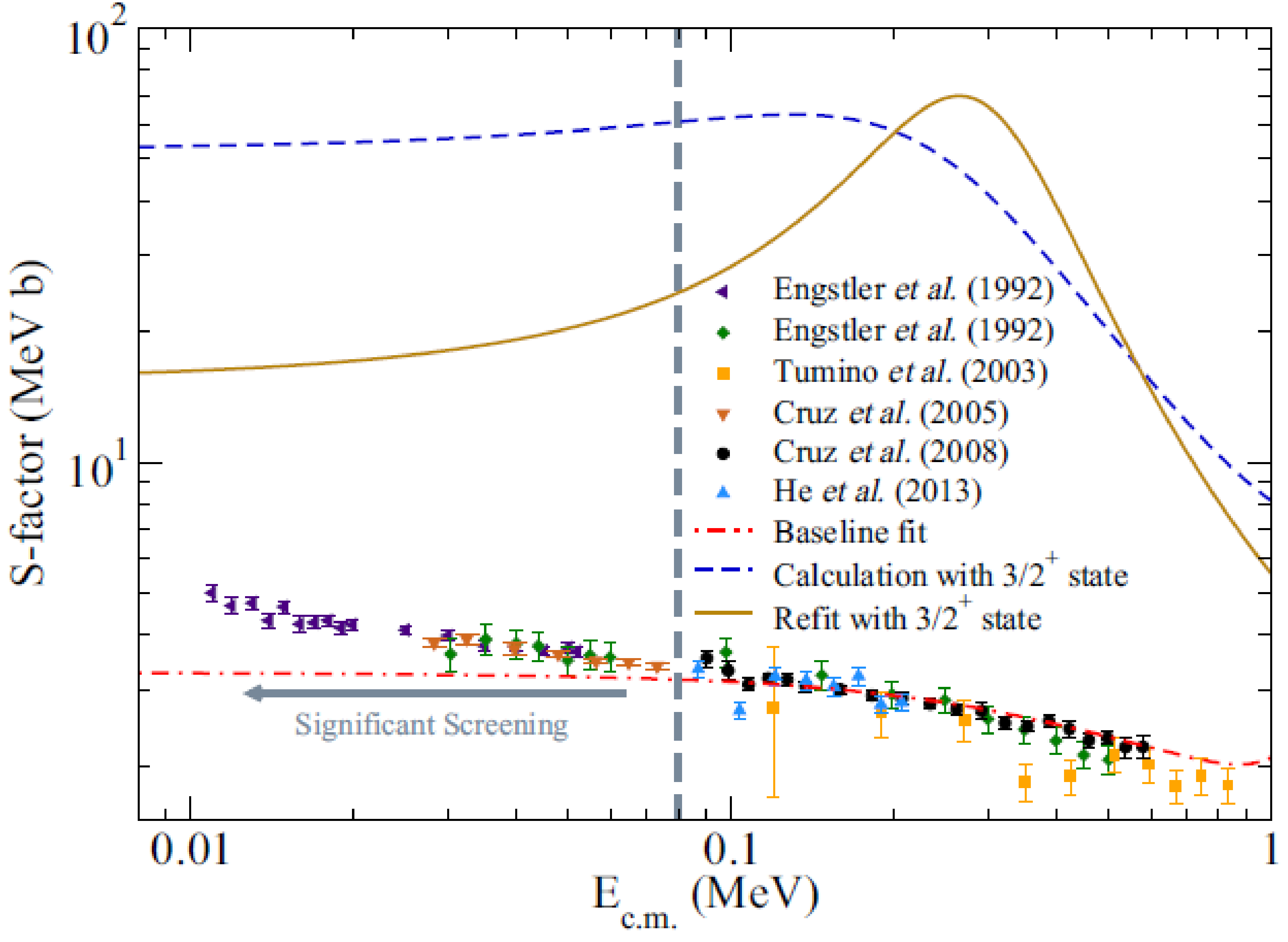


Related project

- Prajapati and deBoer (2024)
- Investigating the existence of a 1/2+ or 3/2+ state very close to the proton separation energy



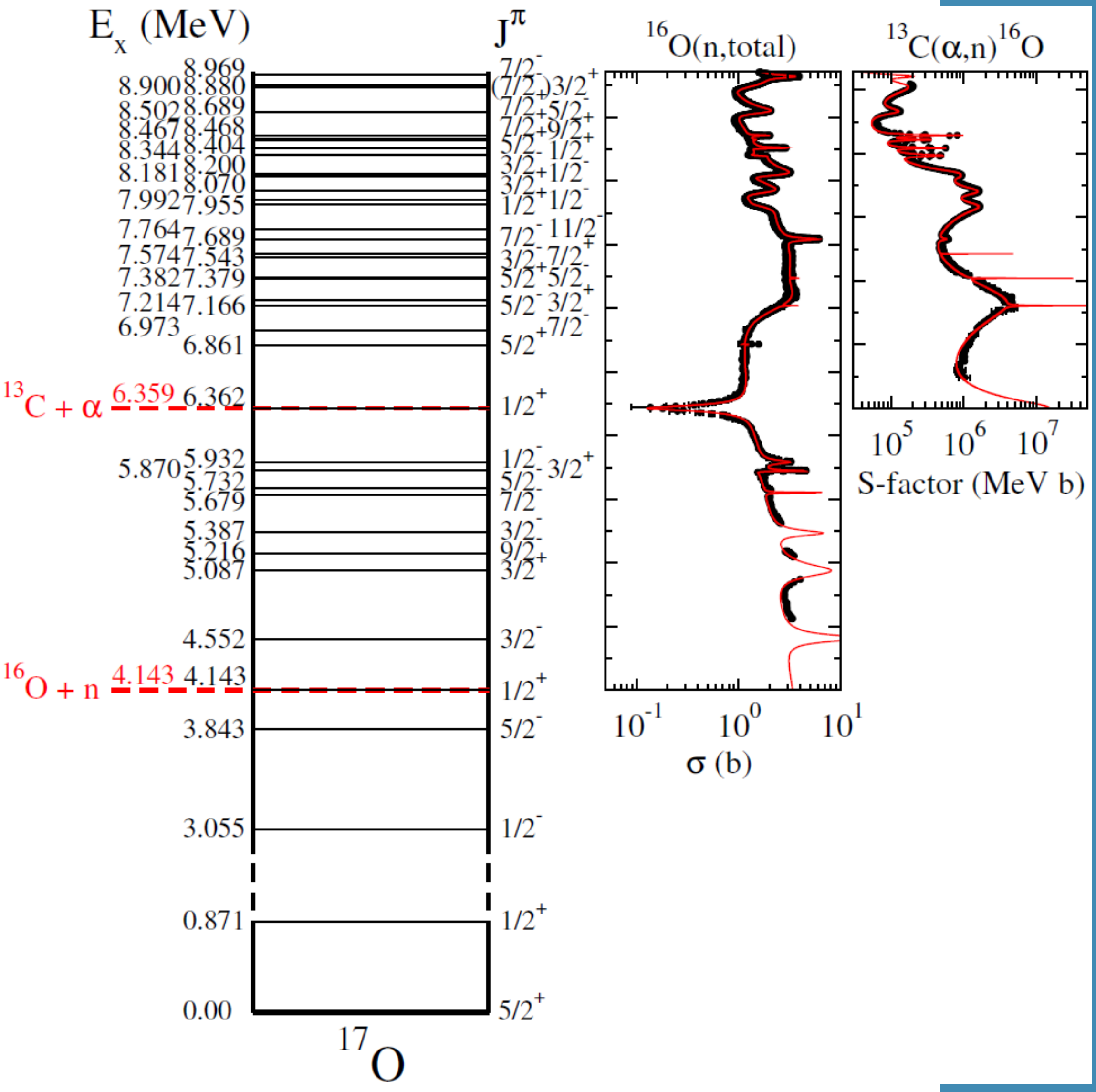




10^2
10^1
S-factor (MeV b)
0.01
0.1
1
$E_{c.m.}$ (MeV)
Engstler *et al.* (1992)
Engstler *et al.* (1992)
Tumino *et al.* (2003)
Cruz *et al.* (2005)
Cruz *et al.* (2008)
He *et al.* (2013)
Baseline fit
Calculation with $3/2^+$ state
Refit with $3/2^+$ state
Significant Screening

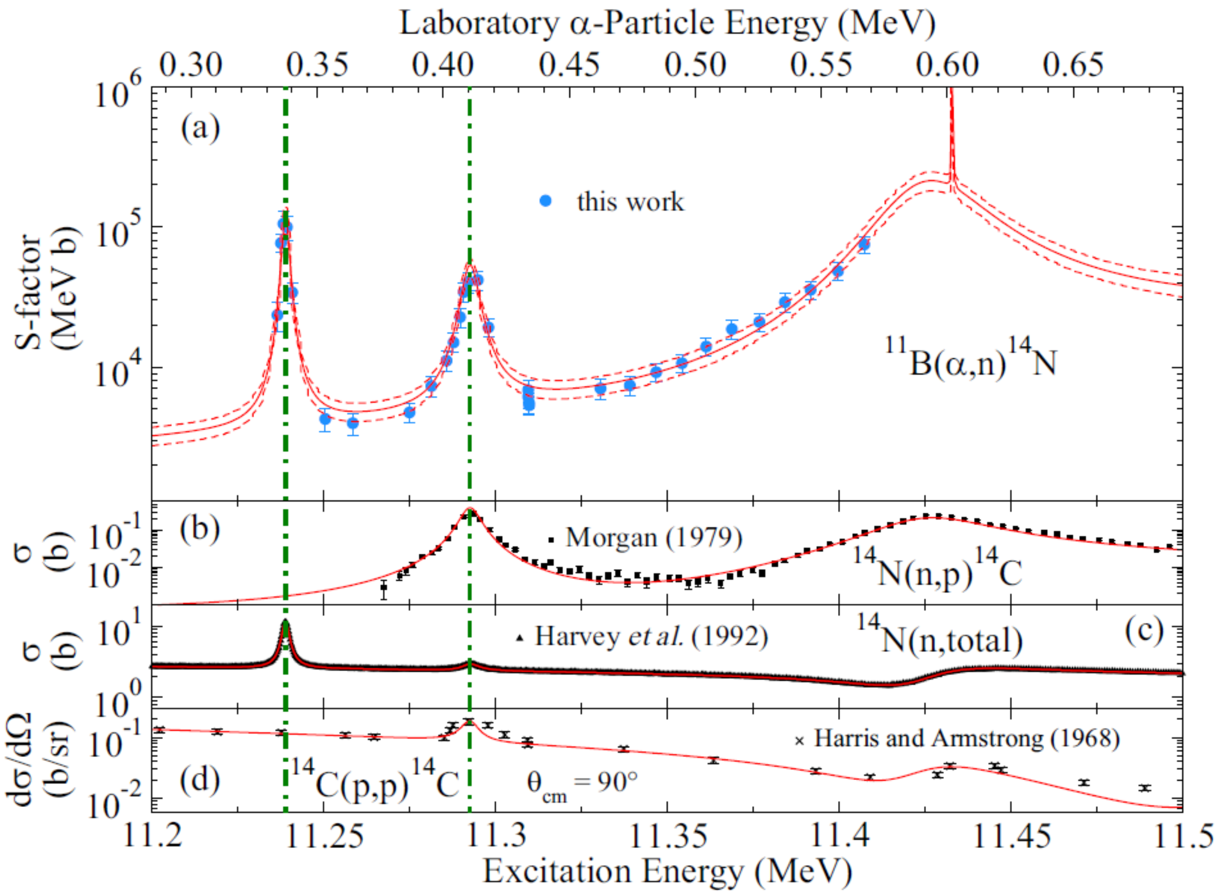
Evaluation updates

- ^{17}O system
  - Started from Gerry's LANL fit, which was already very advanced
  - Mostly just fit $^{16}O(n,total)$ and $^{13}C(\alpha,n)^{16}O$ data up to about E_x = 9 MeV, which was essentially where the EDA fit was already very well established
  - More focused on measurements
    - $^{13}C(\alpha,n_1)^{16}O$ near the threshold
    - $^{13}C(\alpha,n_0)^{16}O$ over a wide energy range, up to about E_x = 13 MeV
    - These are continuing



Evaluation updates

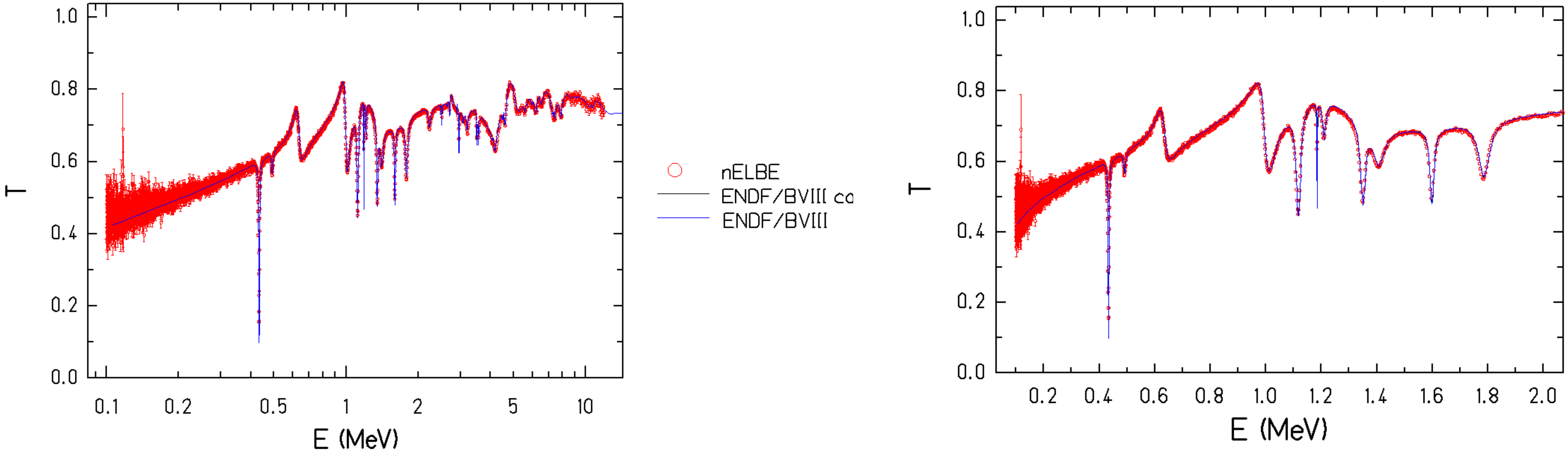
- ^{15}N system
  - Fitting lots of data, most look pretty good except for ^{11}B(α,n)^{14}N
  - I've been stuck there for several years
  - Gerry has shown a much-improved fit for ^{11}B(α,n)^{14}N that I would like to get my hands on
  - Several data sets still need to be published
    - ^{11}B(α,n), ^{11}B(α,p) and ^{14}N(n,total)
  - Maybe some new measurements possible
    - Still trying to figure out how to measure ^{14}N(n,n), maybe at Ohio University



Borgwardt *et al.* (2023)

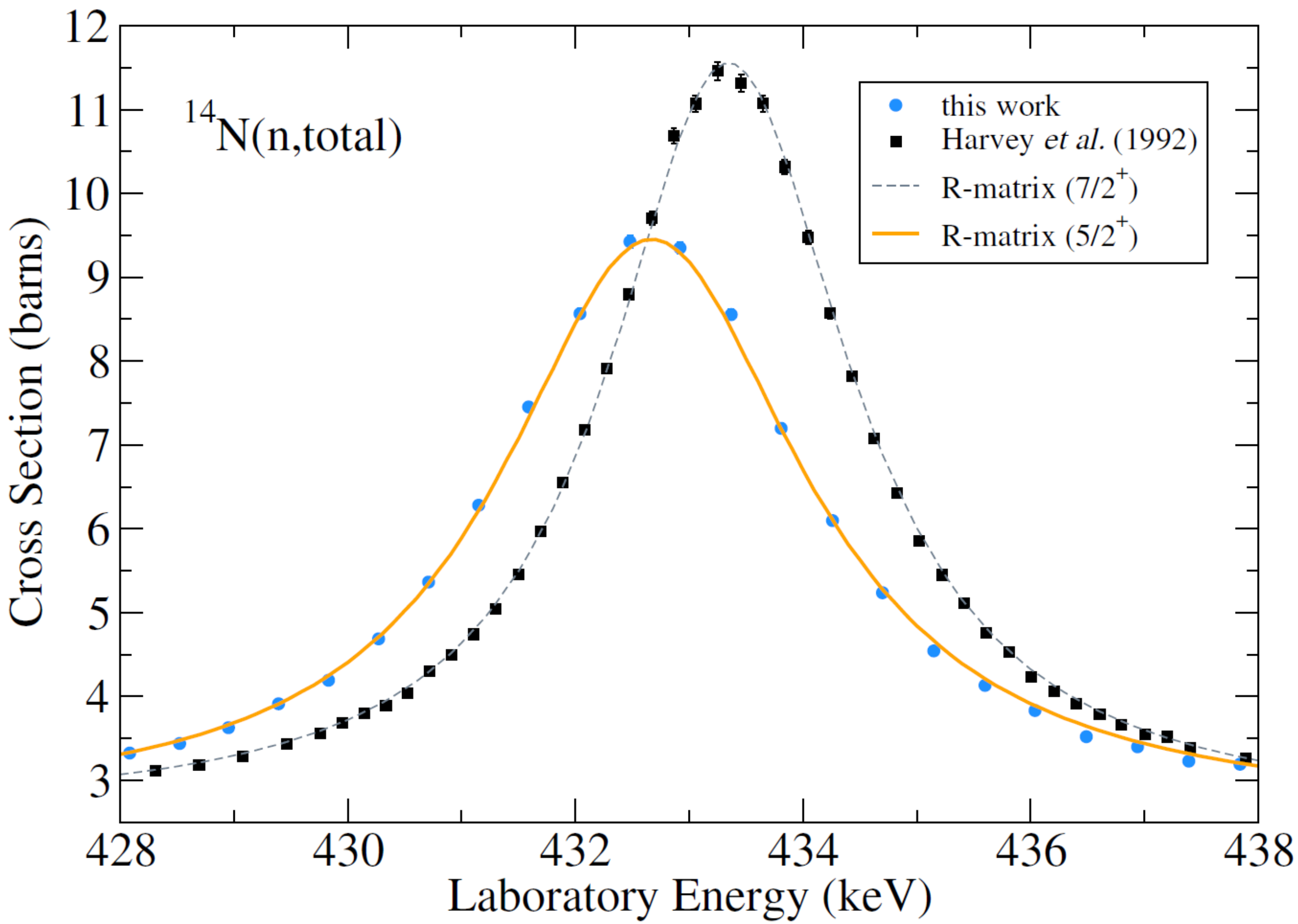
Update on ^{14}N(n,total) analysis

- We haven't found any issues yet
- Arnd has compared out data with the ENDF/B VIII evaluation, convoluted with our resolution function, to our experimental data



Lowest energy resonance

- Still see this difference in height for the 433 keV resonance
- Working with Amy Roberts and her undergrads at UC Denver to implement energy dependent convolution in AZURE2



Future work

- NNSA (α,n) funding will let me get back to work on the ^{17}O and ^{15}N systems over the next four years
  - These $^{13}C(\alpha,n)^{16}O$ and $^{11}B(\alpha,n)^{14}N$ measurement are focused on higher energies, 2 to 8 MeV, so I'll need to work on expanding into those energy ranges
  - Also accompanied by lots of other secondary gamma-ray and charged particle exit channel reaction data
- (α,n) project also means I'll start looking more into $^{10}B(\alpha,n)^{13}N$, $^{7}Li(\alpha,n)^{10}B$ and $^{19}F(\alpha,n)^{22}Na$
- Unfortunately, the ^{7}Be system has been tough to work on because our group's focus has moved away from it
- Still, actual evaluations are beyond the scope of this work