$^{13}C(\alpha,n)^{16}O$ studies at the University of Notre Dame

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University of Notre Dame and The Joint Institute for Nuclear Astrophysics

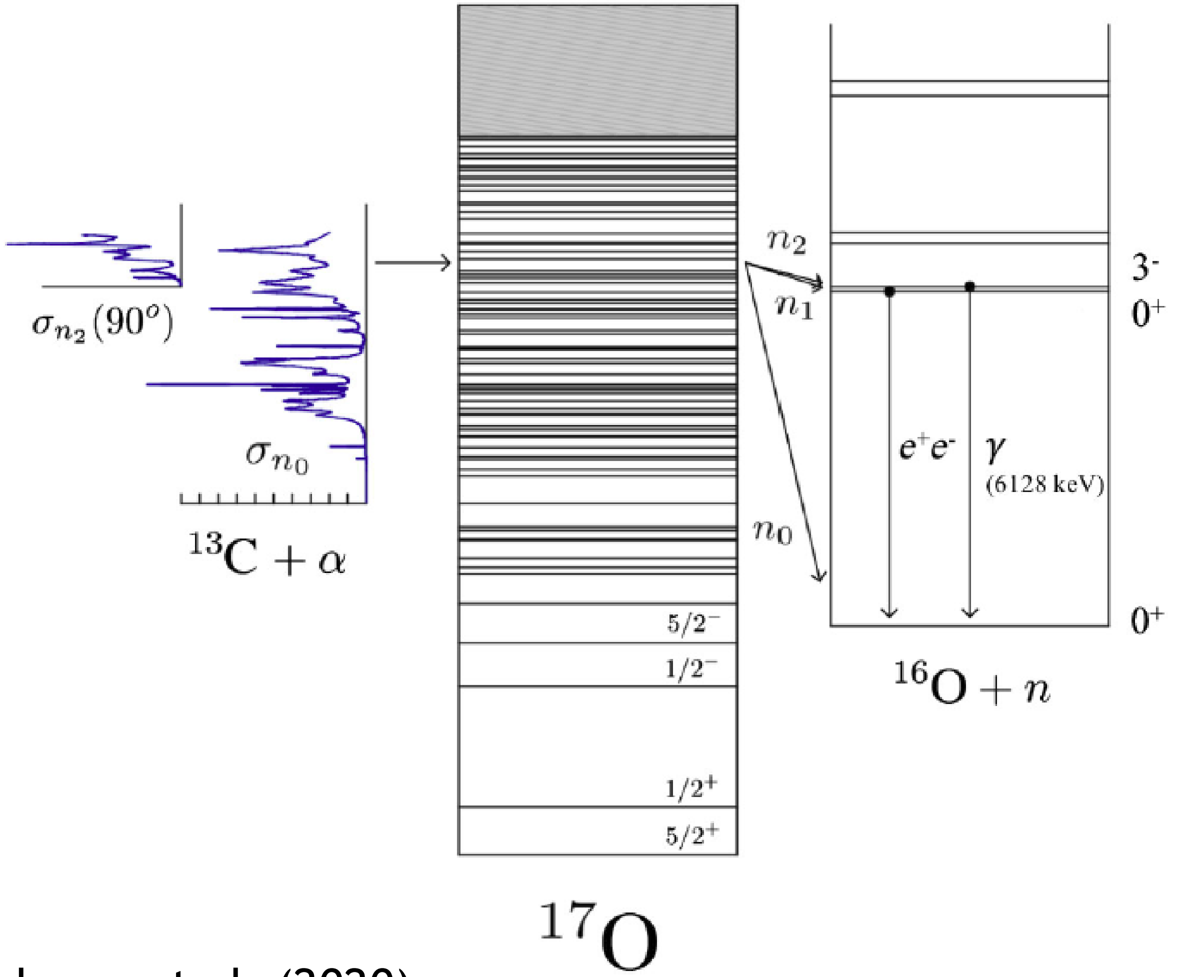
IAEA TM on (α,n) nuclear data evaluation and data needs, 8-12 November 2021

Motivations

- Nuclear Astrophysics
  - s-process neutron sources
- Essentially all α-beam accelerator studies
  - since carbon is everywhere, the reaction is a background for all other X + α accelerator studies, mainly (α,n) and (α,γ)
- Large mass detectors for neutrino and dark matter detection
  - Actinides and carbon are hard to completely remove from setups
  - Actinide decays → up to 9 MeV α-particles → (α,n) on light nuclei in the environment
  - In particular ^{13}C(a,n_1) can mimic inverse beta decay $(p + \bar{\nu}_e \rightarrow n + e^+)$
- Data evaluation of the ^{17}O system

Level diagram of ^{17}O system

- Lots of levels!
- First excited state is 0^+
  - De-excites via pair production
- 2nd, 3rd, and 4th excited states decay through γ-ray emission with nearly 100% probability to the ground state

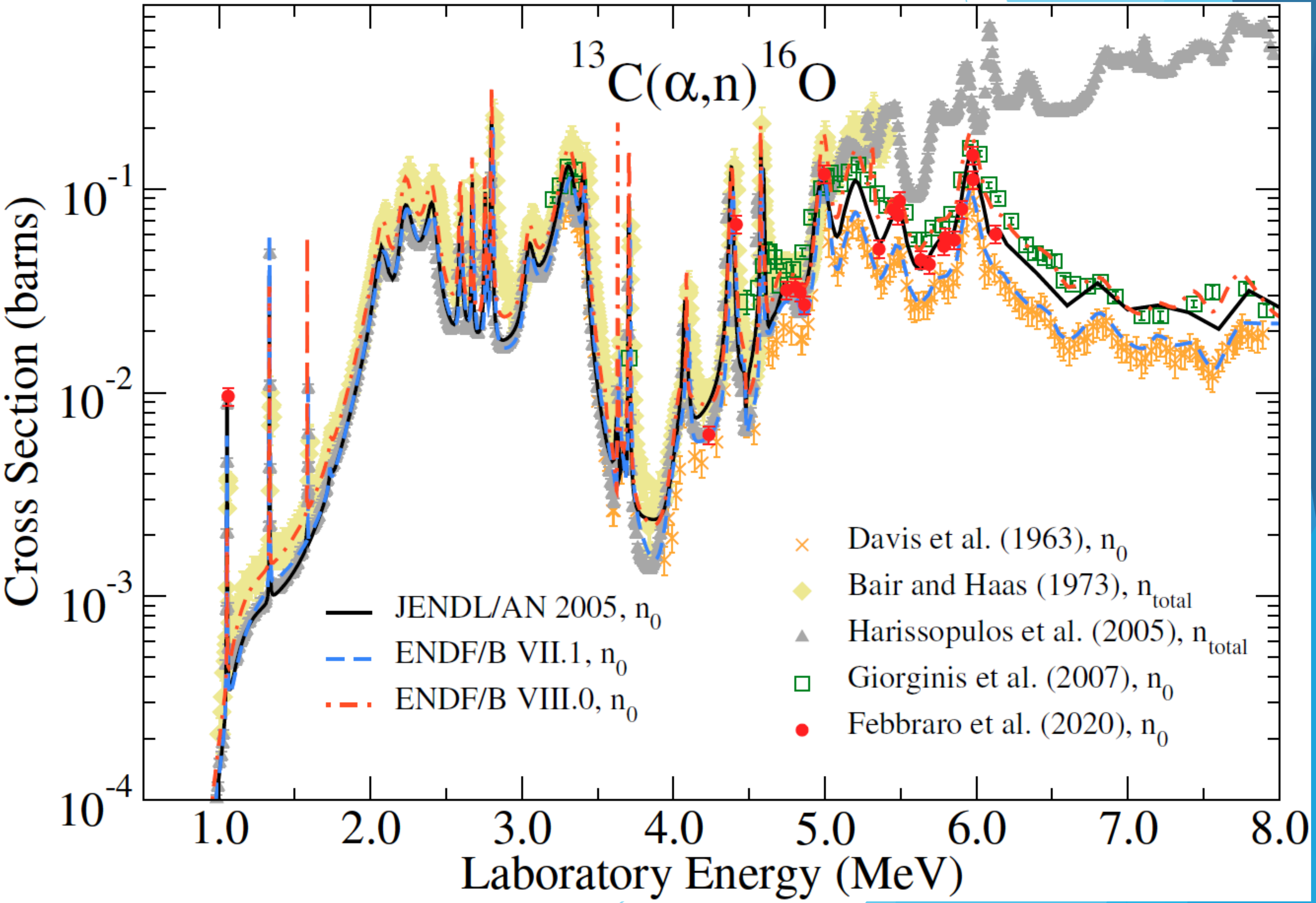


Febbraro et al. (2020)

FIG. 1. Level schematic of ^{17}O depicting the pertinent details of the $^{13}C(\alpha, n)^{16}O$ reaction.

“High Energy” Measurement overview

- Around 30% differences in recent ENDF/B overall normalizations of the cross sections
- Above 5 MeV, de-excitation can occur to excited states in ^{16}O
- Previous counter experiments of the total reaction cross section
- Efficiency changes with energy, don’t know the neutron energy
- Bill Peters (2017) & Peter Mohr (2018)
- Mainly this is an issue with the high energy Harissopulos et al. (2005) data

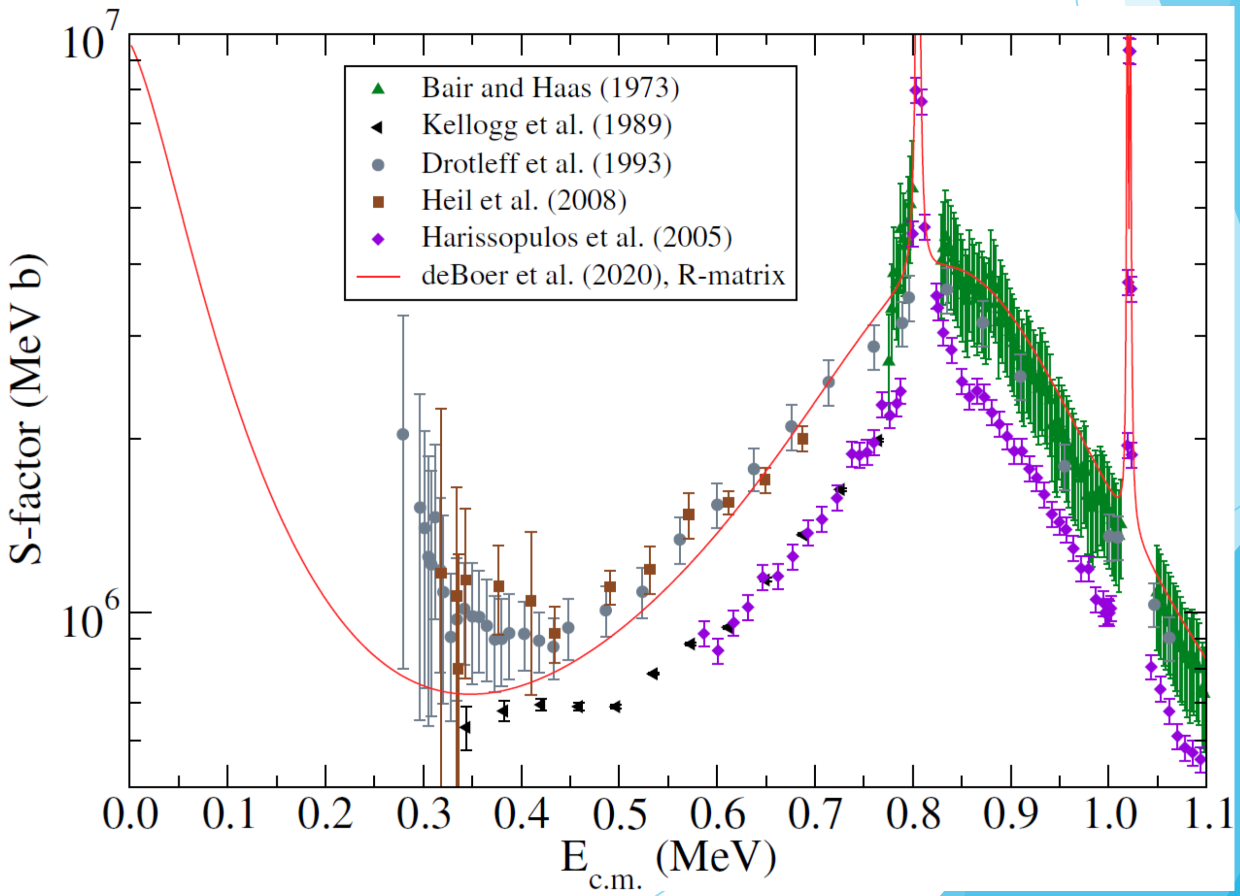


“Low Energy” Measurement Overview

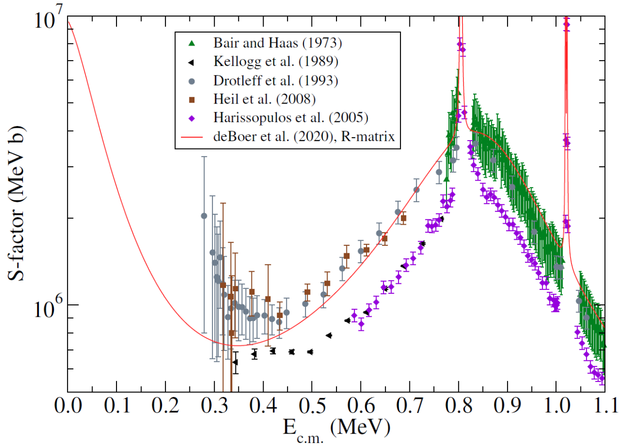
- Low energy cross section is dominated by
  - Broad 3/2+ state and
  - Broad 1/2+ subthreshold state
- Strength of the threshold state is needed
  - α-particle ANC from transfer
  - Direct data provide much constraint
- Background contribution from higher energy states

$$S(E) = \sigma(E) E e^{2\pi\eta}$$

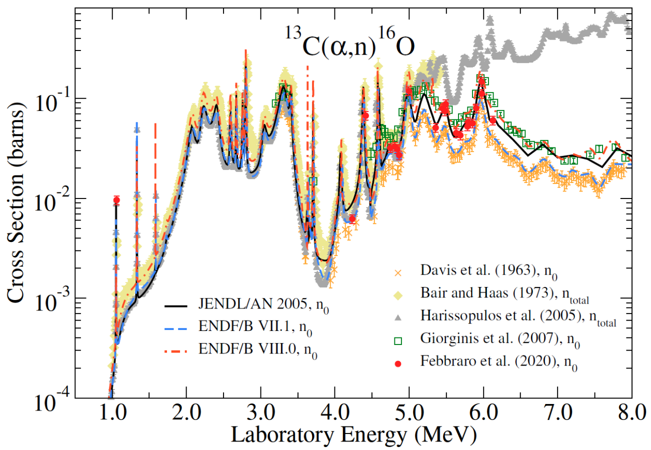
Sommerfeld parameter $\left(\sqrt{\mu/2E} Z_1 Z_2 e^2/\hbar^2\right)$



Utilization of many experimental techniques is critical → **global R-matrix fit (see LANL EDA)**

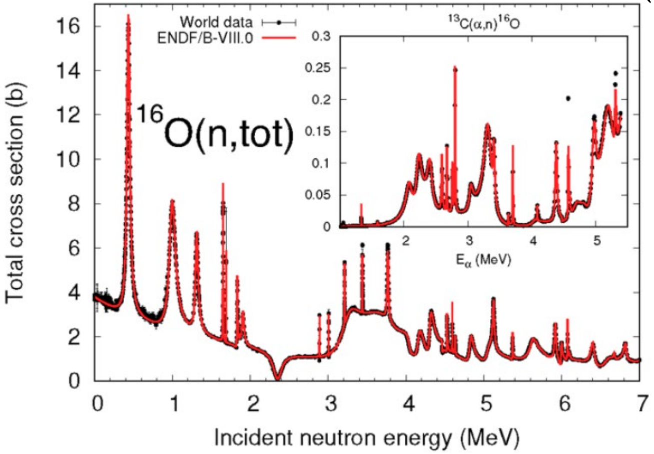


Low energy data



High energy data

Brown et al. (2018)



Neutron induced data

Avila et al. (2015)

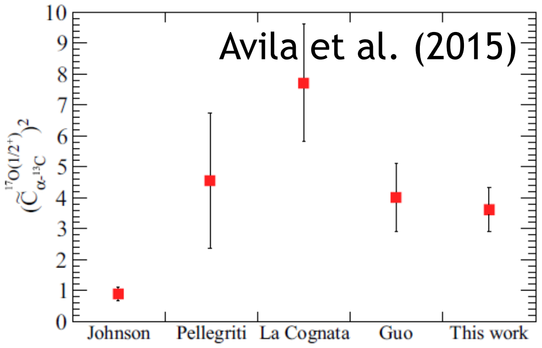
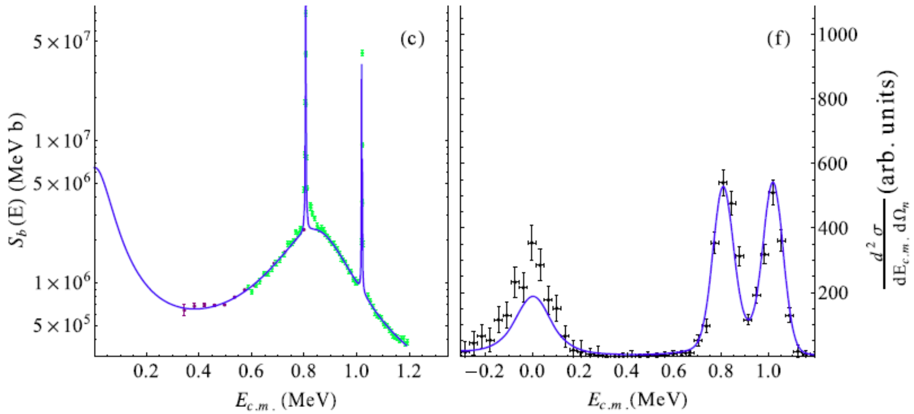


FIG. 4. (Color online) Squared Coulomb-modified ANC value obtained in this work, for the $1/2^+$ at excitation energy of 6.356 MeV in ^{17}O, compared with previous results from Johnson *et al.* [5], Pellegriti *et al.* [6], Cognata *et al.* [9], and Guo *et al.* [8].

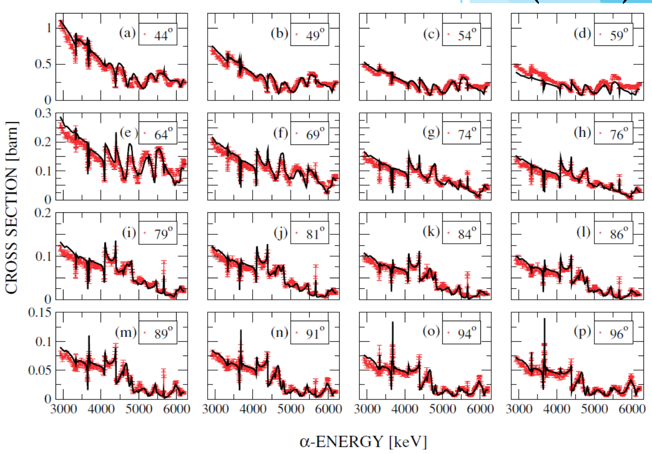
ANCs from transfer data

Trippella and La Cognata (2017)



Trojan Horse data

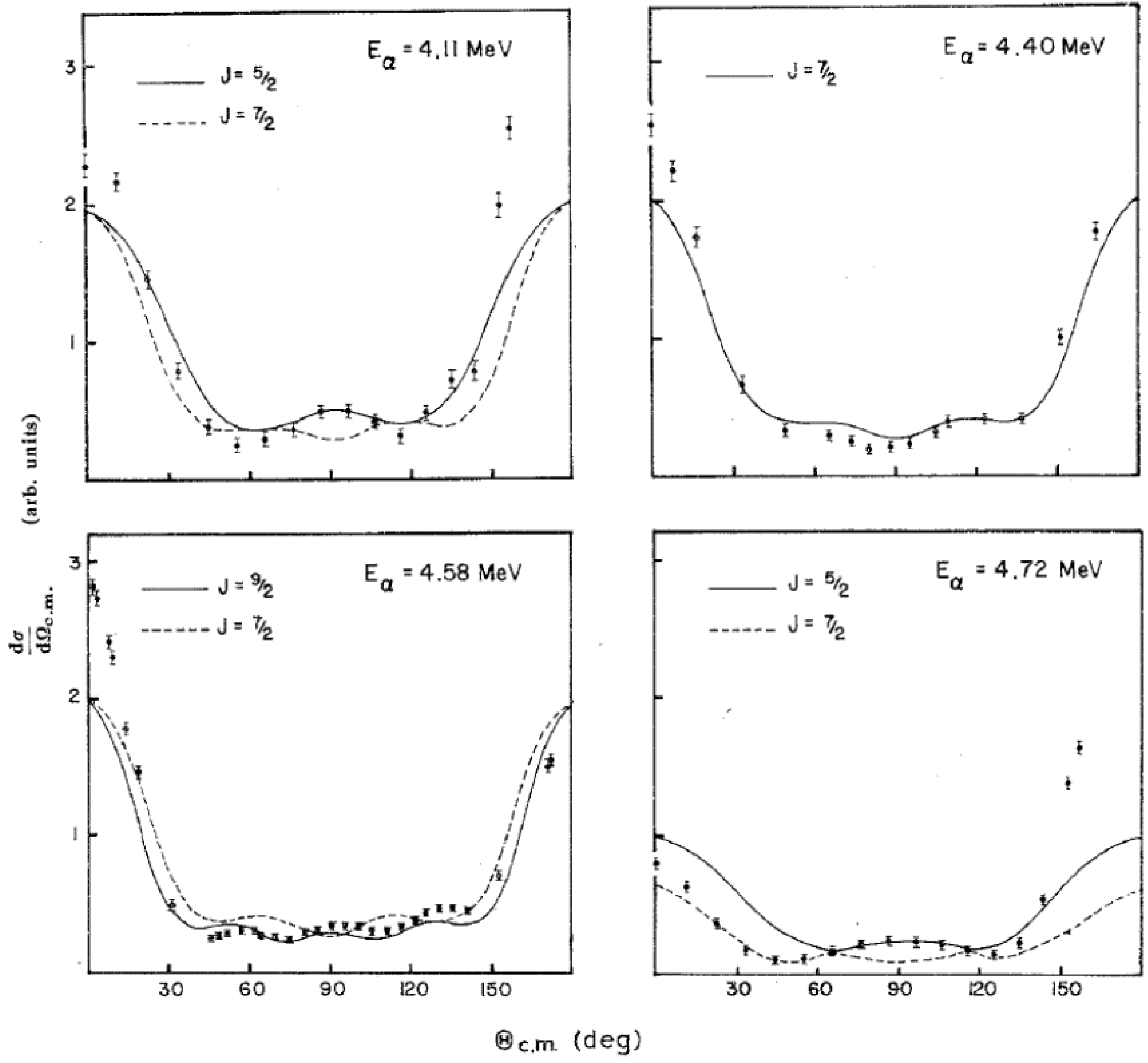
Heil et al. (2008)



Alpha scattering

Some needed data

- **Angular distribution** data
  - Not much out there
  - Bonner et al. (1956), Walton et al. (1957), Kerr et al. (1968), and Robb et al. (1970)
- At higher energy, very little **partial differential cross section** information
  - That is, we want $^{13}C(\alpha,n_0)$, $^{13}C(\alpha,n_1)$, $^{13}C(\alpha,n_2)$, $^{13}C(\alpha,n_3)$, $^{13}C(\alpha,n_4)$
  - Spear et al. (1963), secondary γ-ray study → $^{13}C(\alpha,n_2)$, $^{13}C(\alpha,n_3)$, $^{13}C(\alpha,n_4)$
  - $^{16}O(n,\alpha_0)^{13}C$ measurements give ground state cross section through detailed balance → $^{13}C(\alpha,n_0)$

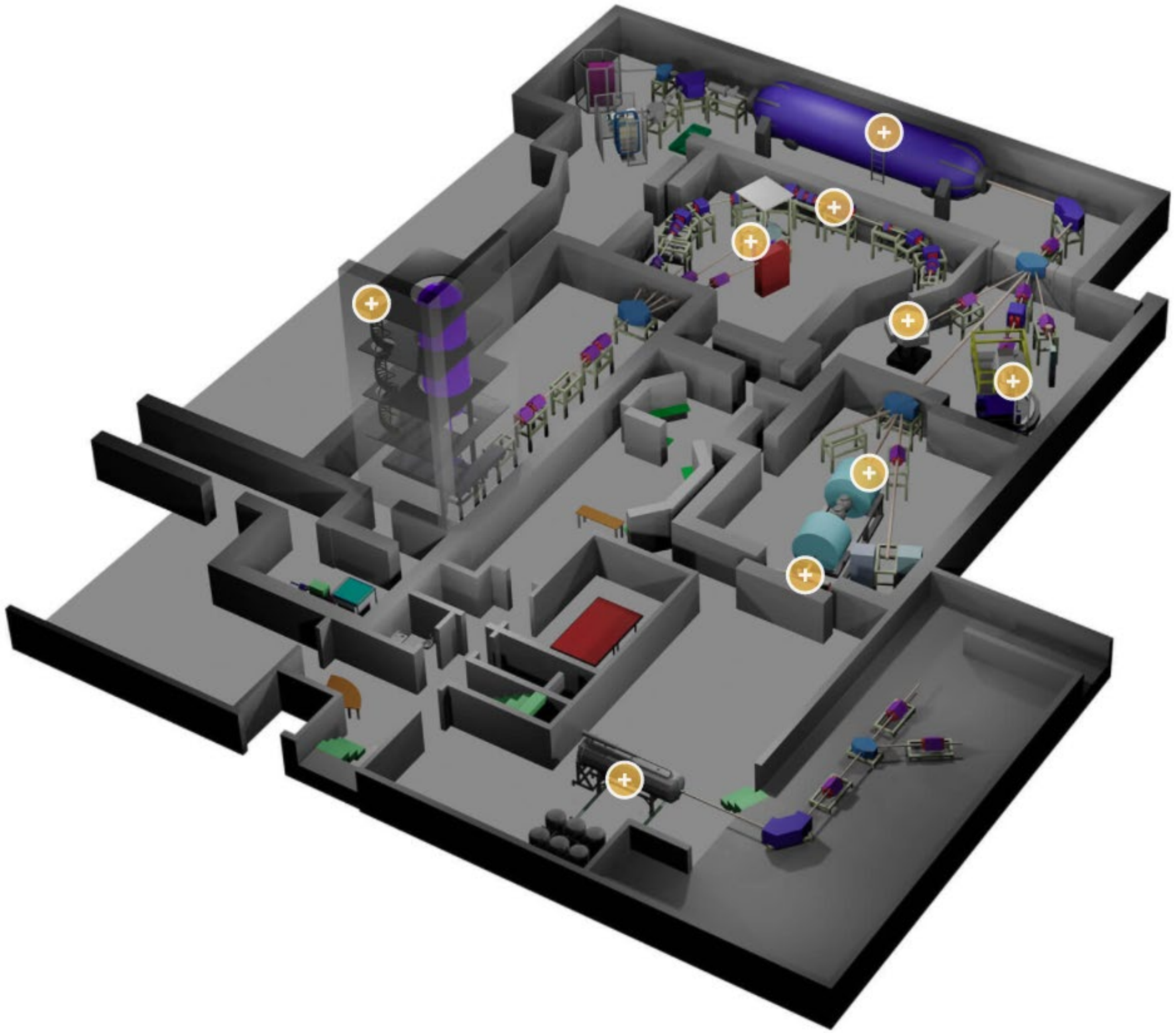


Nuclear Science Laboratory (NSL) at the University of Notre Dame

- isnap.nd.edu

- 5 MV single ended accelerator
  - dc alpha beam from 300 keV up to 9 MeV
  - up to 100 uA of beam on target
  - Usually using 10 uA for these studies

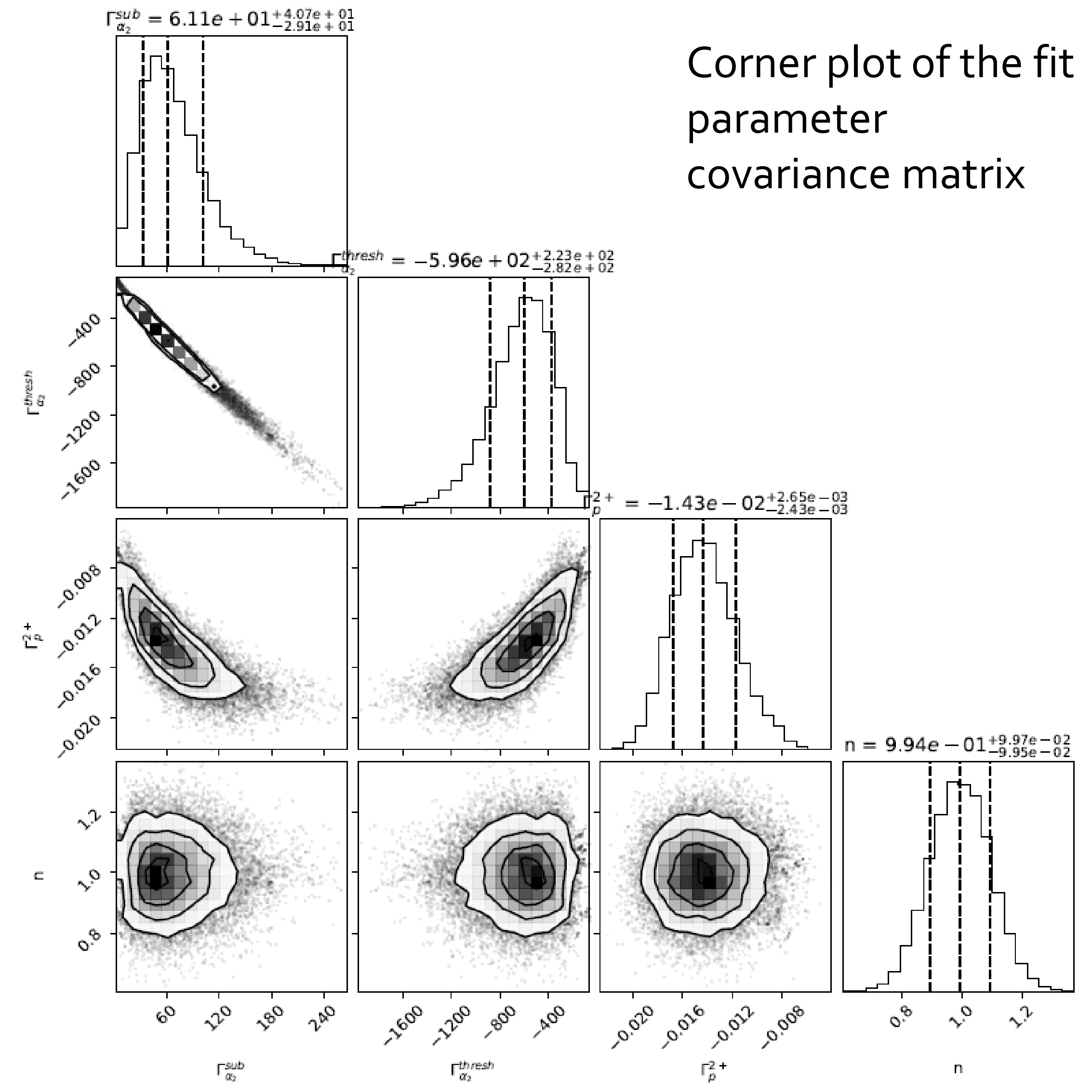
- 10 MV FN tandem
  - bunched alpha beam from 4 to 30 MeV
  - bunched beam intensity of a few 10's of nA (unbunched, up to 200 nA)



Improvement in uncertainty analysis

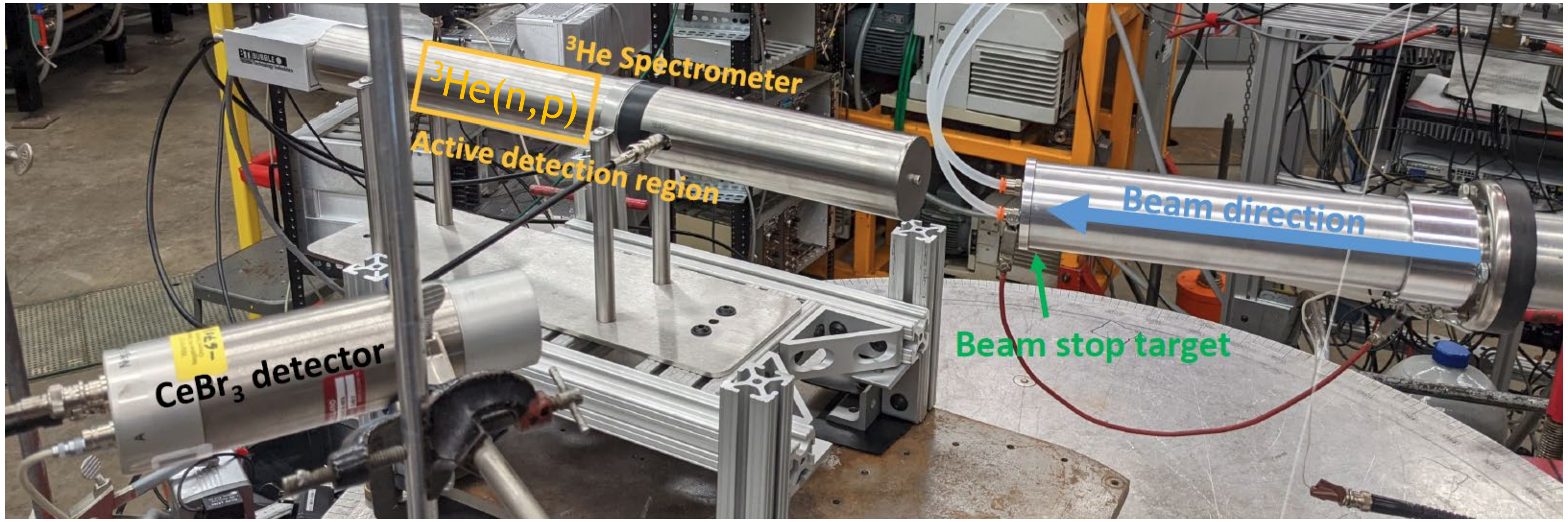
- Development of a Bayesian uncertainty analysis routine for the AZURE2 R-matrix code has been ongoing
- **Daniel Odell**, a postdoc at OU, is the main developer
- This work is possible thanks to **Daniel Phillips and Carl Brune** and a grant from

NNSA
National Nuclear Security Administration

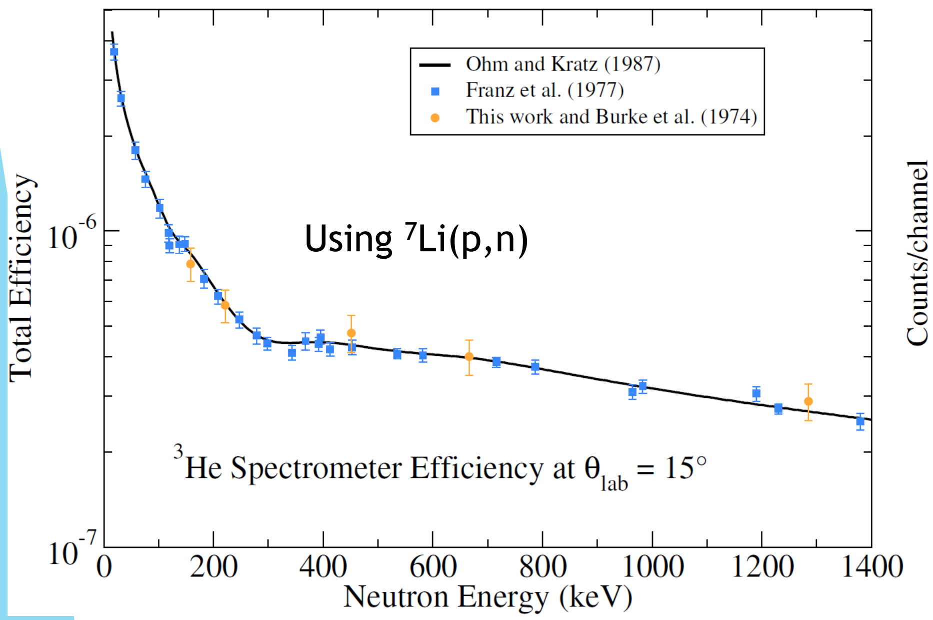


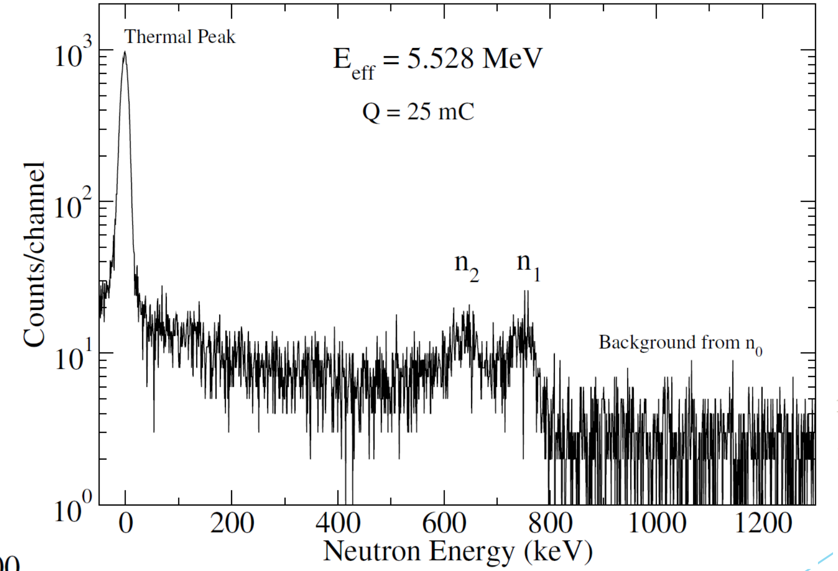
Corner plot of the fit parameter covariance matrix

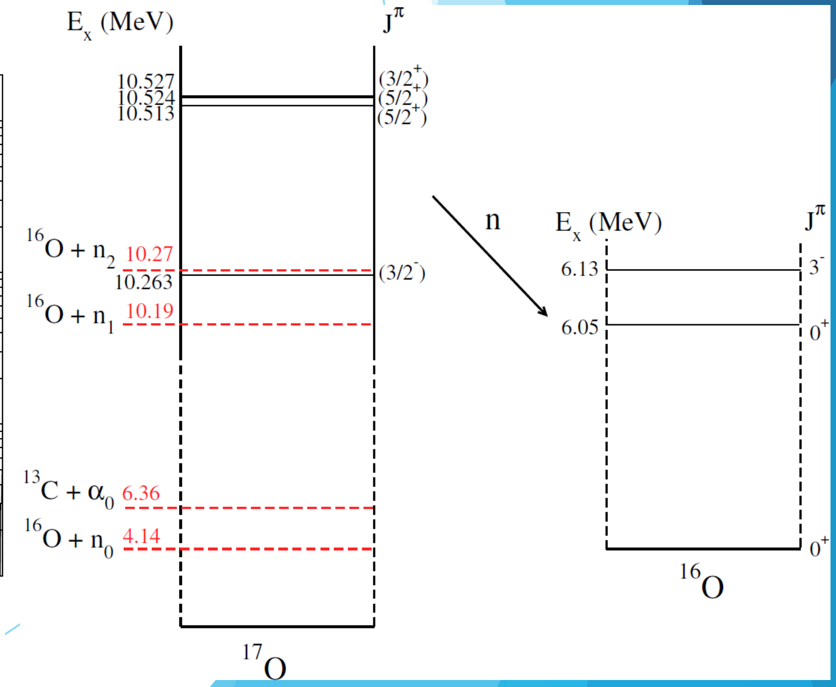
$^{13}C(\alpha,n_1)$ measurements



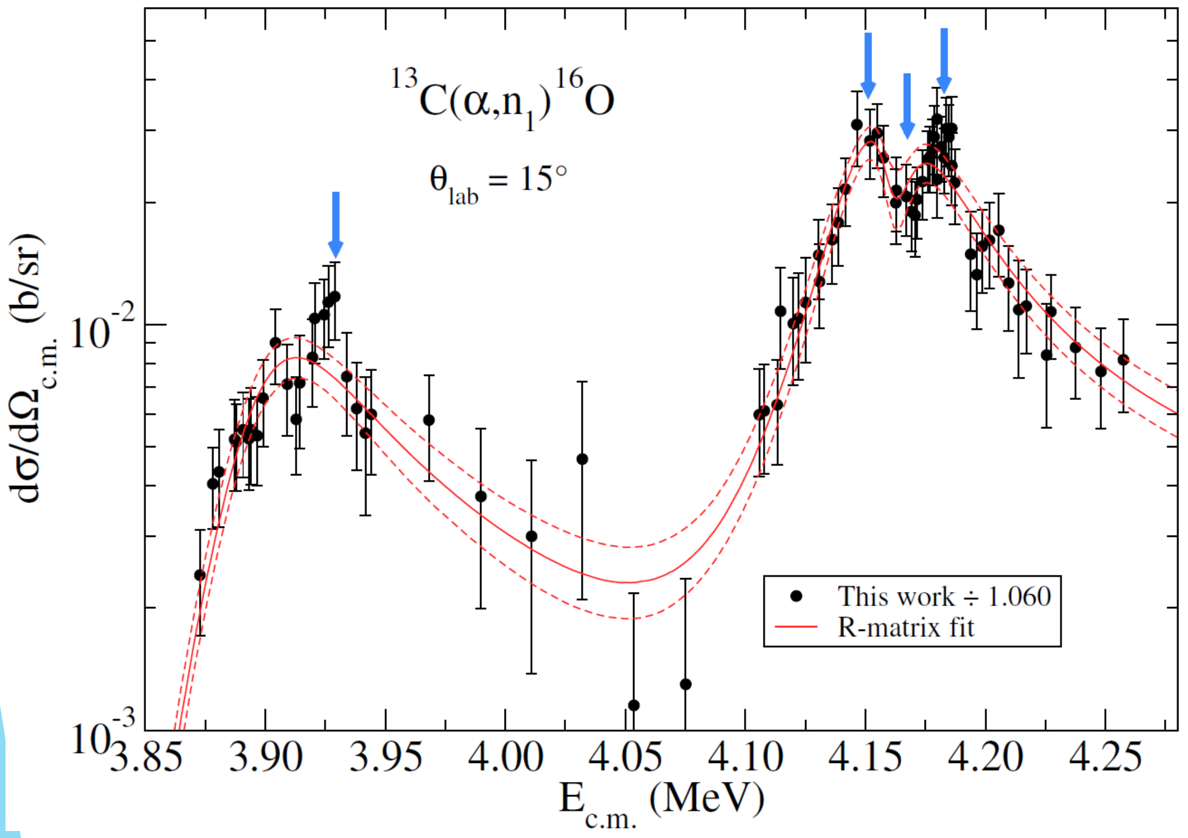
- Michael Wiescher
- ND 5U accelerator
- DC alpha beam
- 10 ug/cm^2 ^{13}C target (György Gyürky)
- 30 uA on target
- 30 minute runs
- Typically a few hundred counts

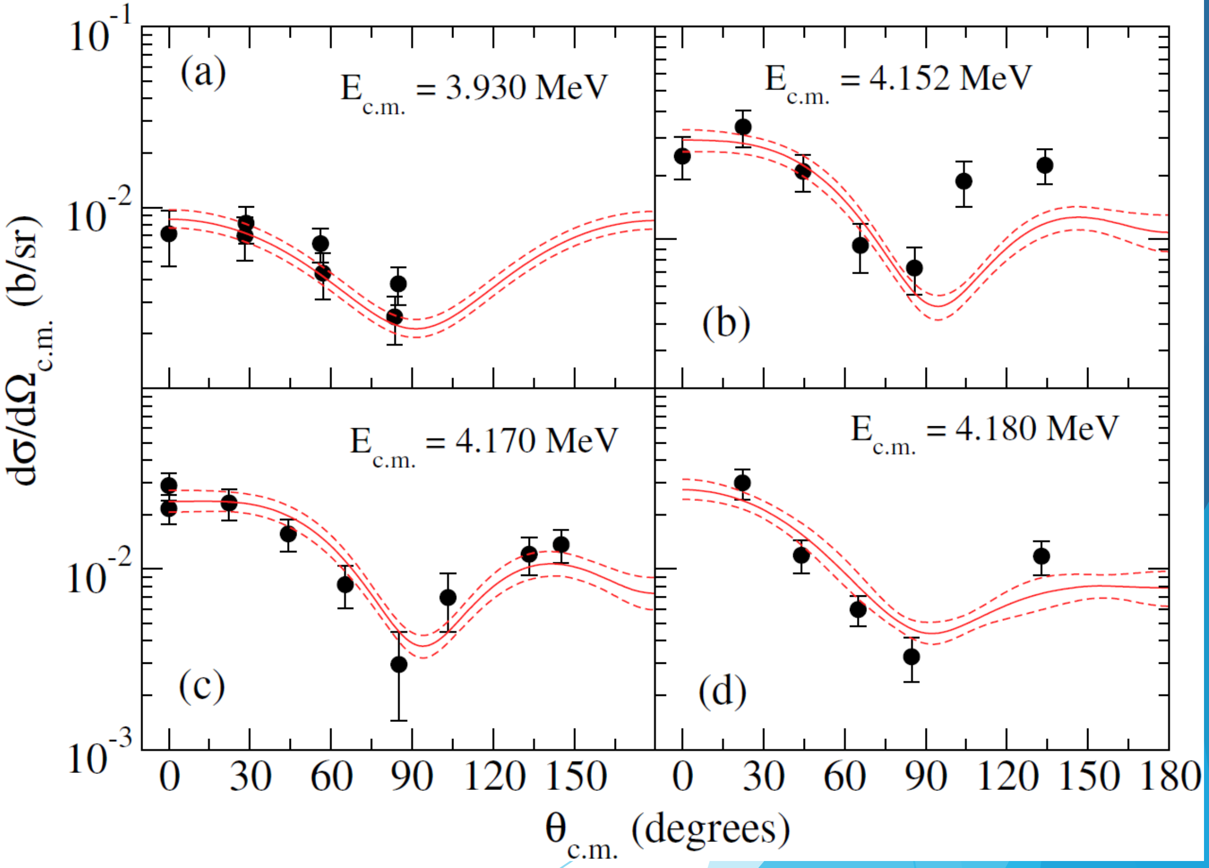




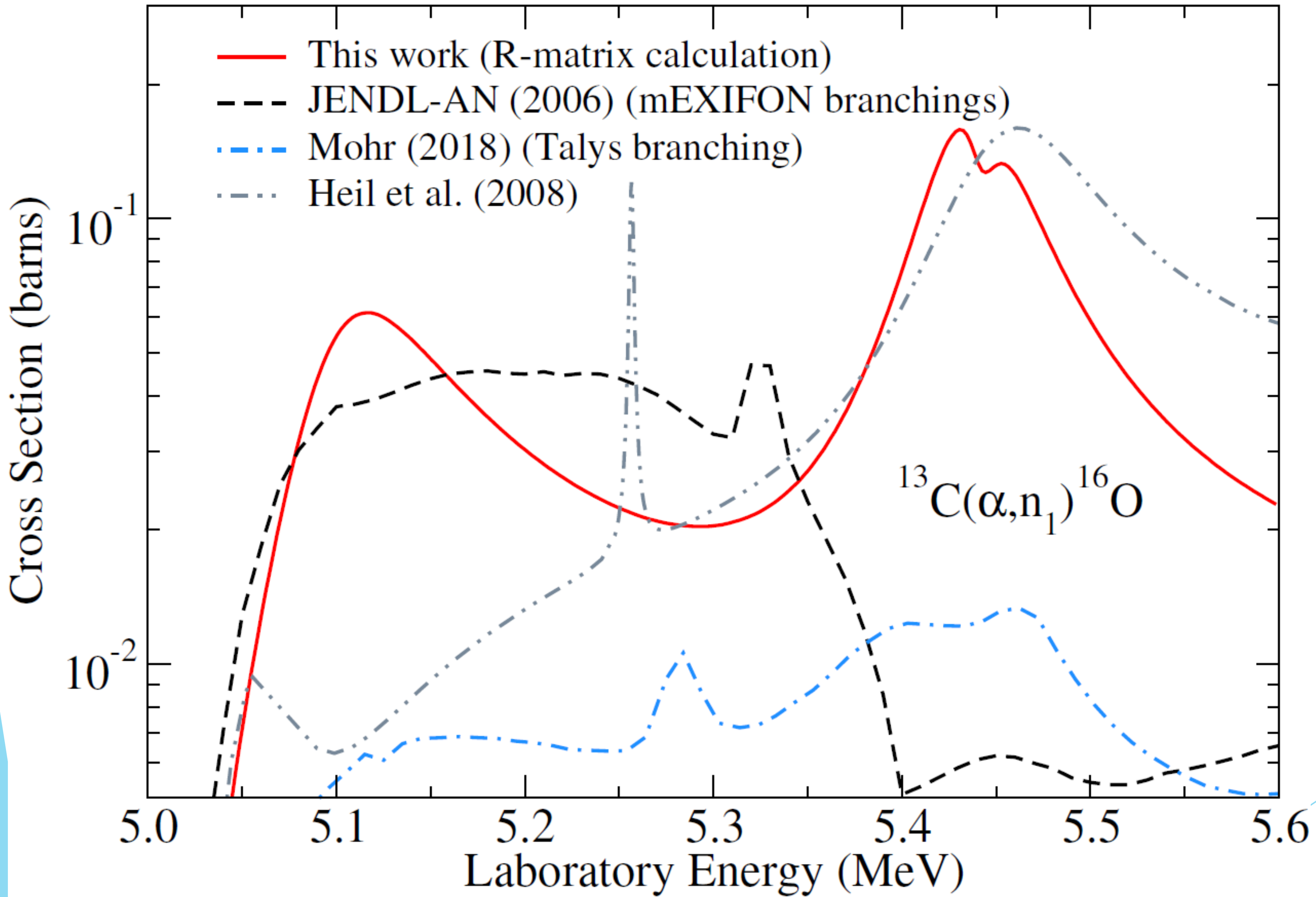


First measurement of $^{13}C(\alpha,n_1)$ cross section (plus MCMC analysis)



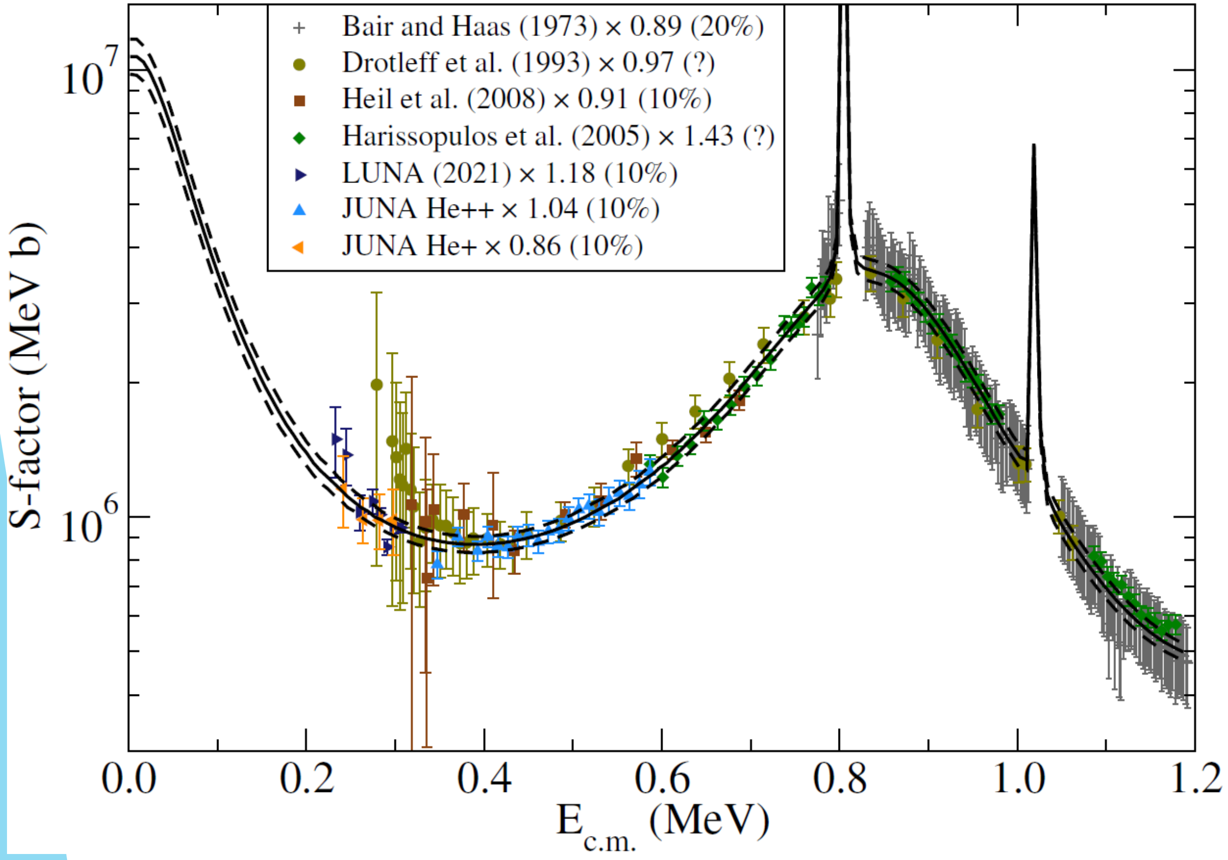


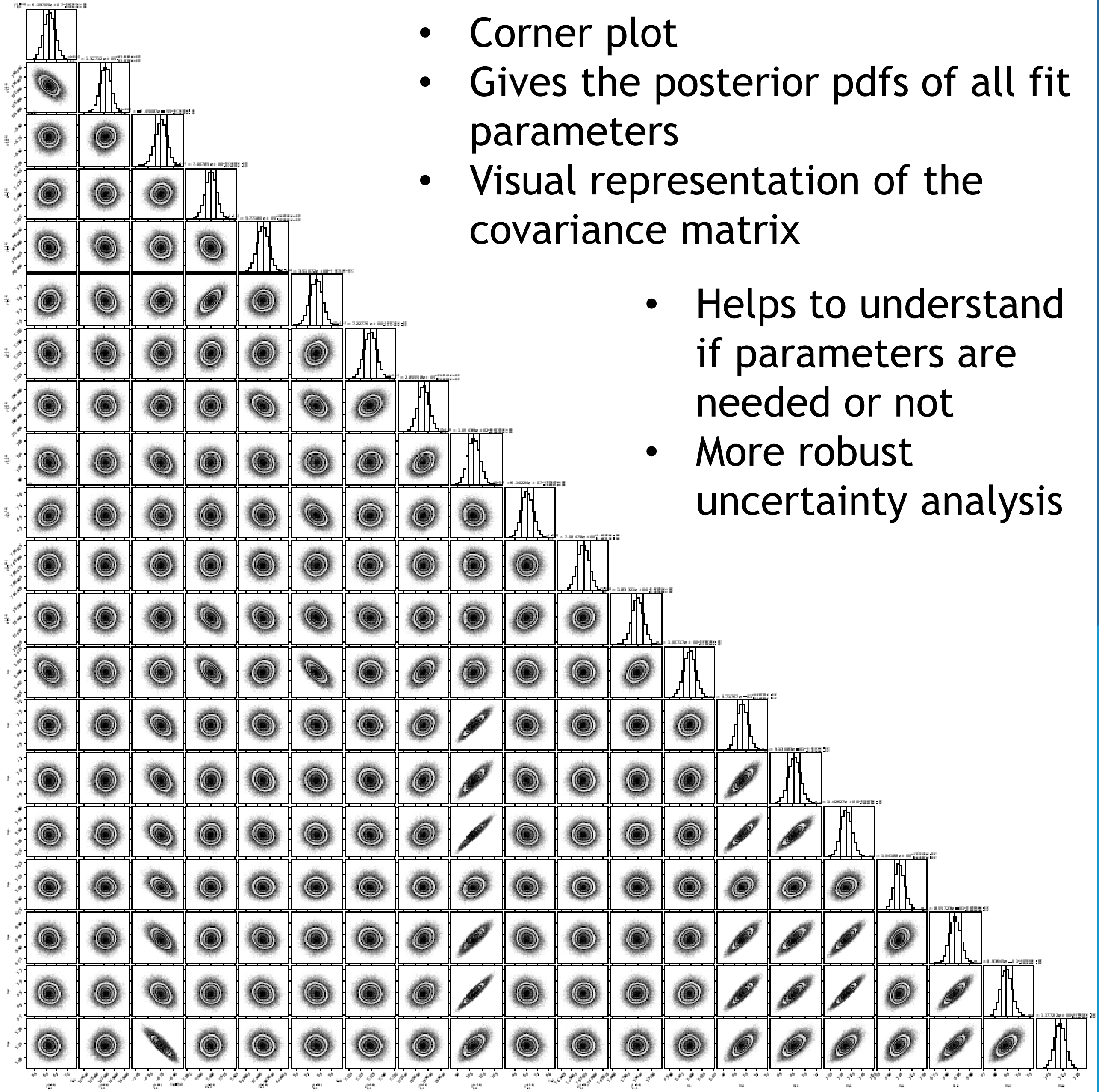
Comparison with evaluations and other data



Thanks to Marco Pigni for SAMMY calculations of Heil's fit!

BRICK MCMC applied to $^{13}C(\alpha,n)$ low energy

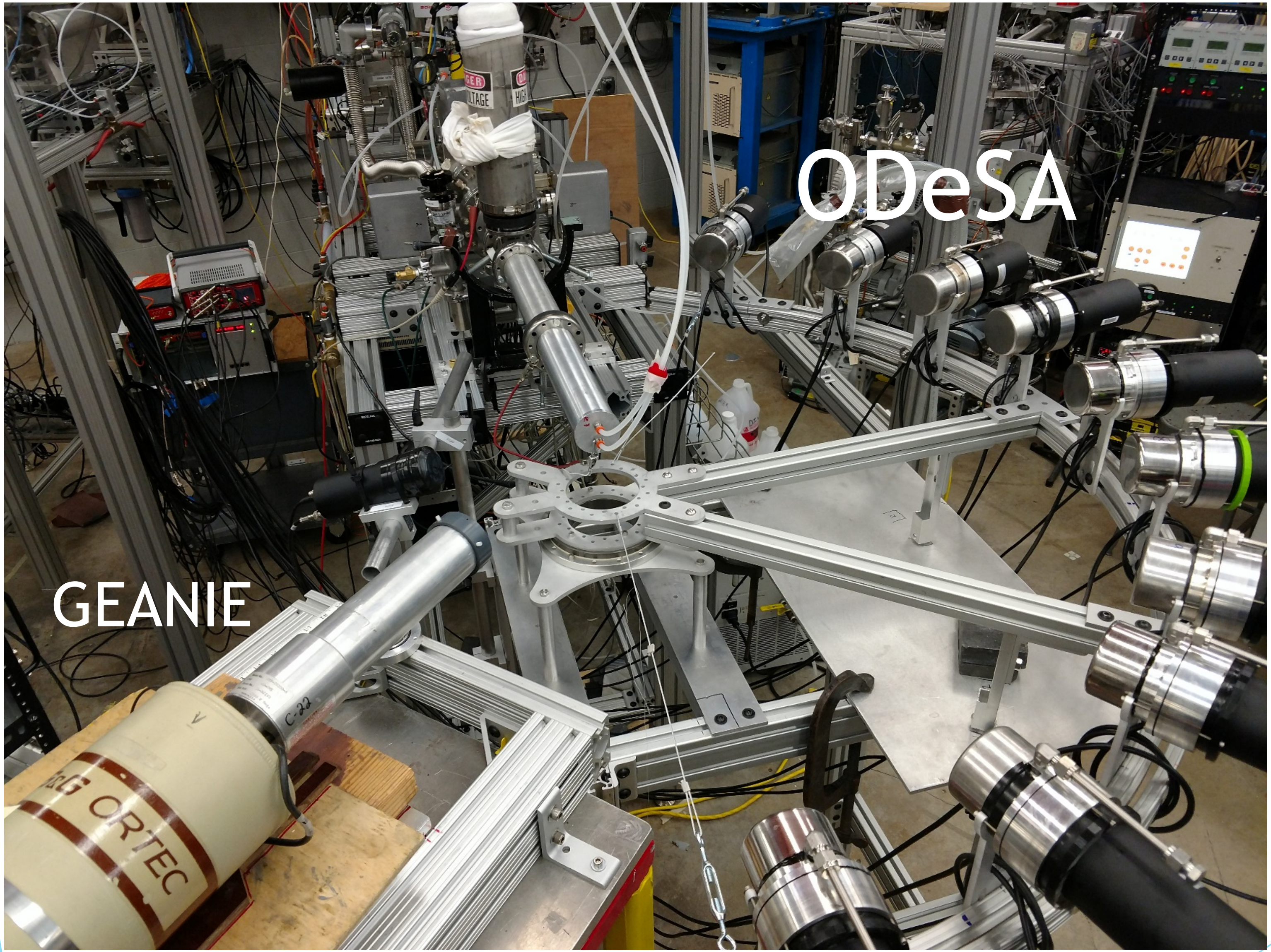


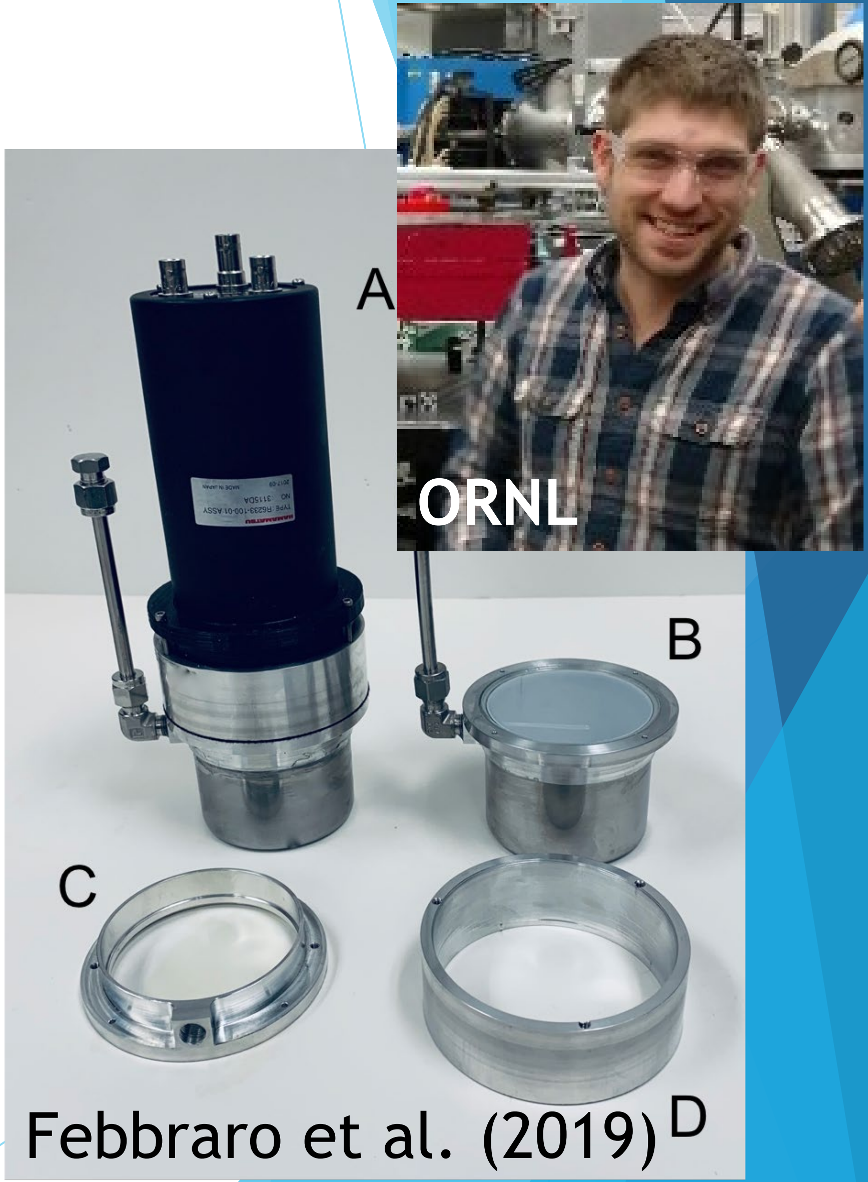


- Corner plot
- Gives the posterior pdfs of all fit parameters
- Visual representation of the covariance matrix

- Helps to understand if parameters are needed or not
- More robust uncertainty analysis

Dec 2020 setup, ND 5U “solid target” line





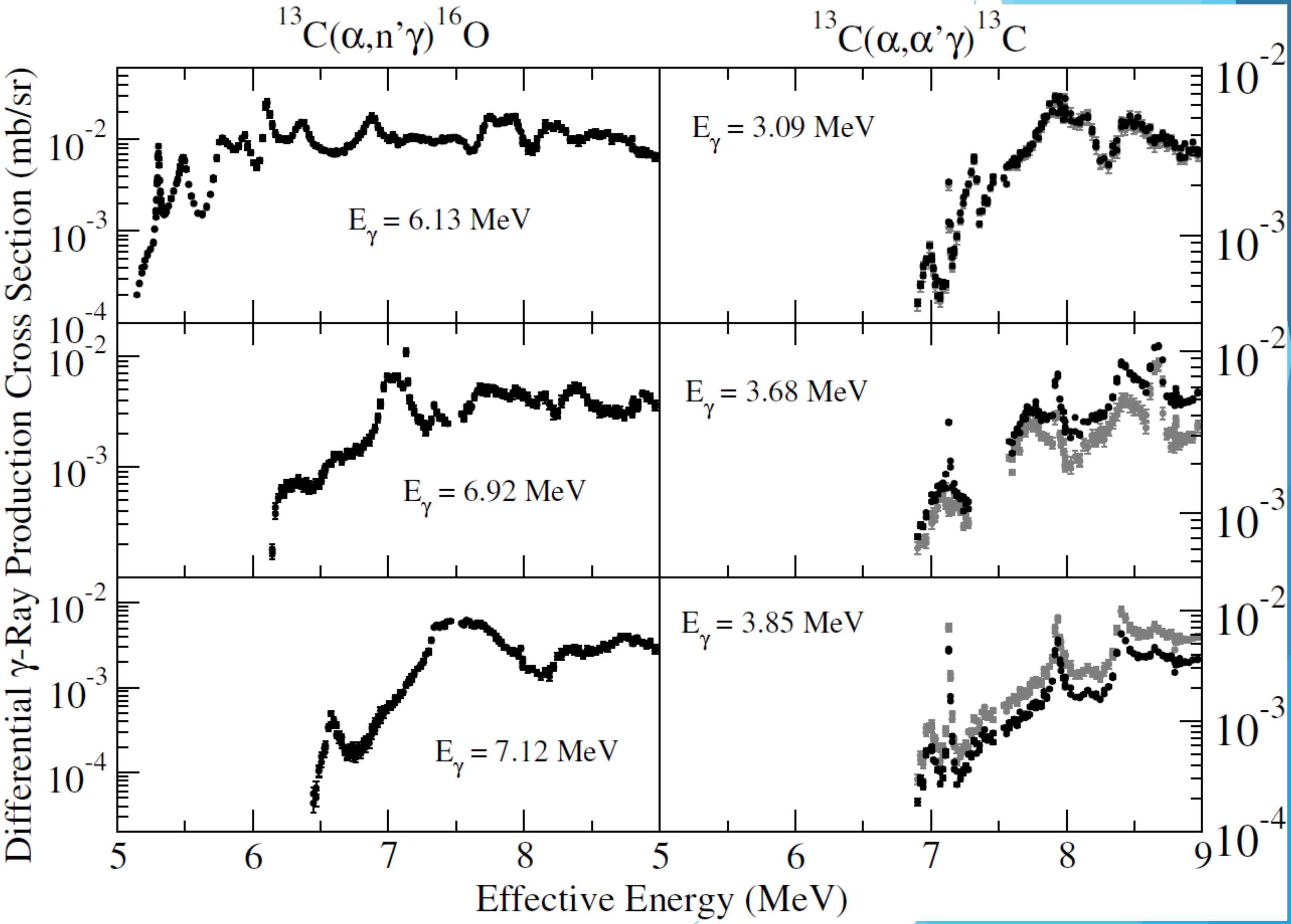
Febbraro et al. (2019)

Michael Febbraro

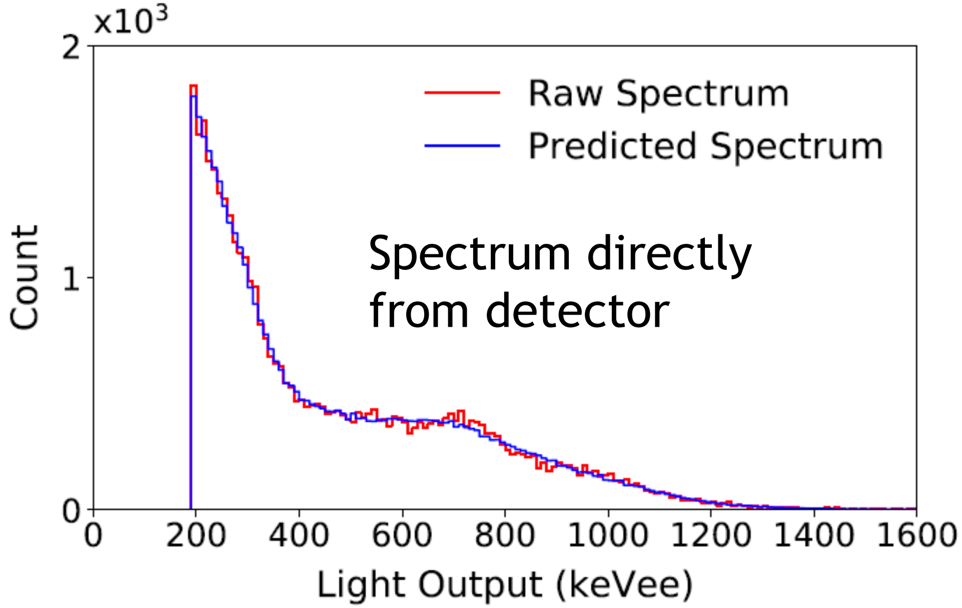
ORNL

New measurements (Dec 2020)

- $^{13}C(\alpha,n\gamma)$ using GEANIE HPGe @ 45 degrees
- First measurements of $^{13}C(\alpha,\alpha\gamma)^{13}C$
- Could separate 6.92 and 7.12 MeV transitions with HPGe



Spectrum Unfolding



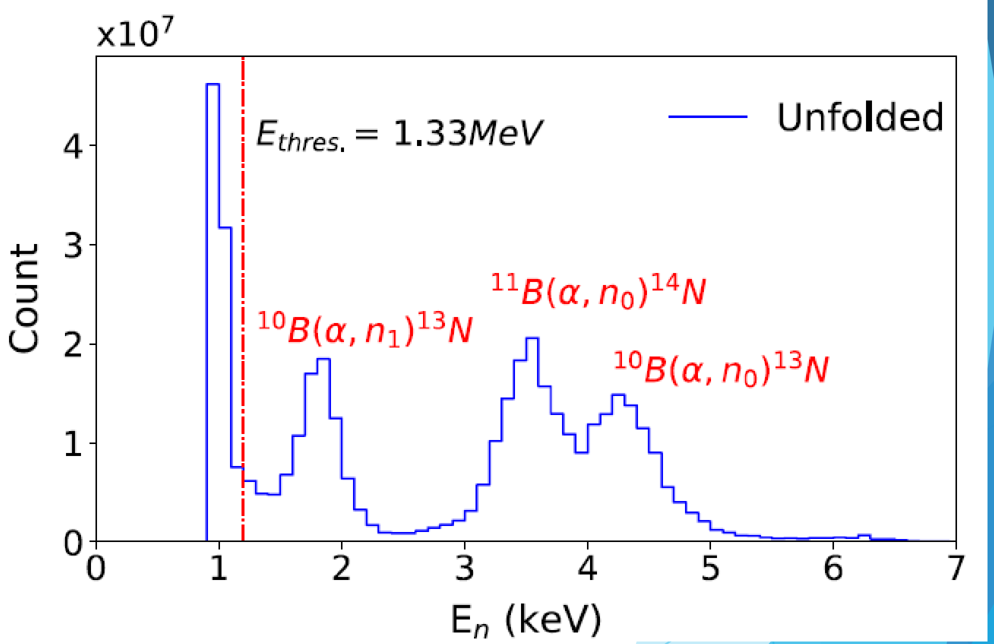
Light output spectrum

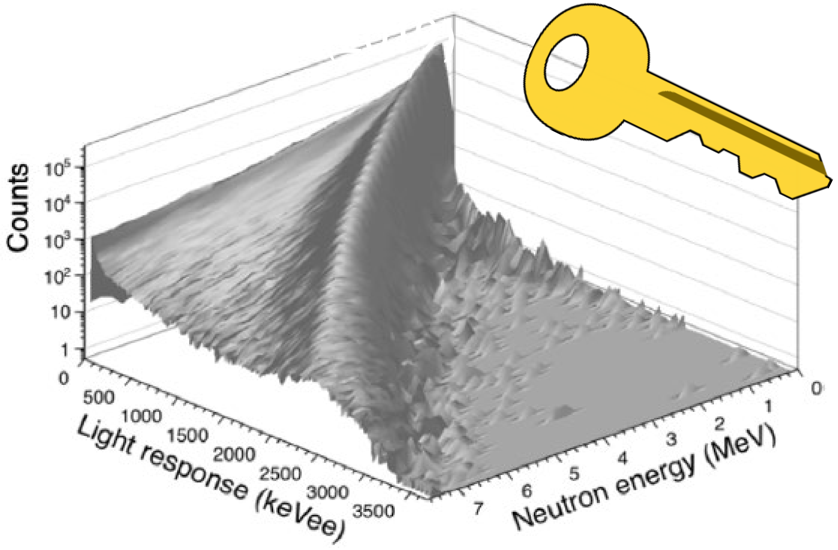
+

Maximum Likelihood

=

Neutron Energy Spectrum





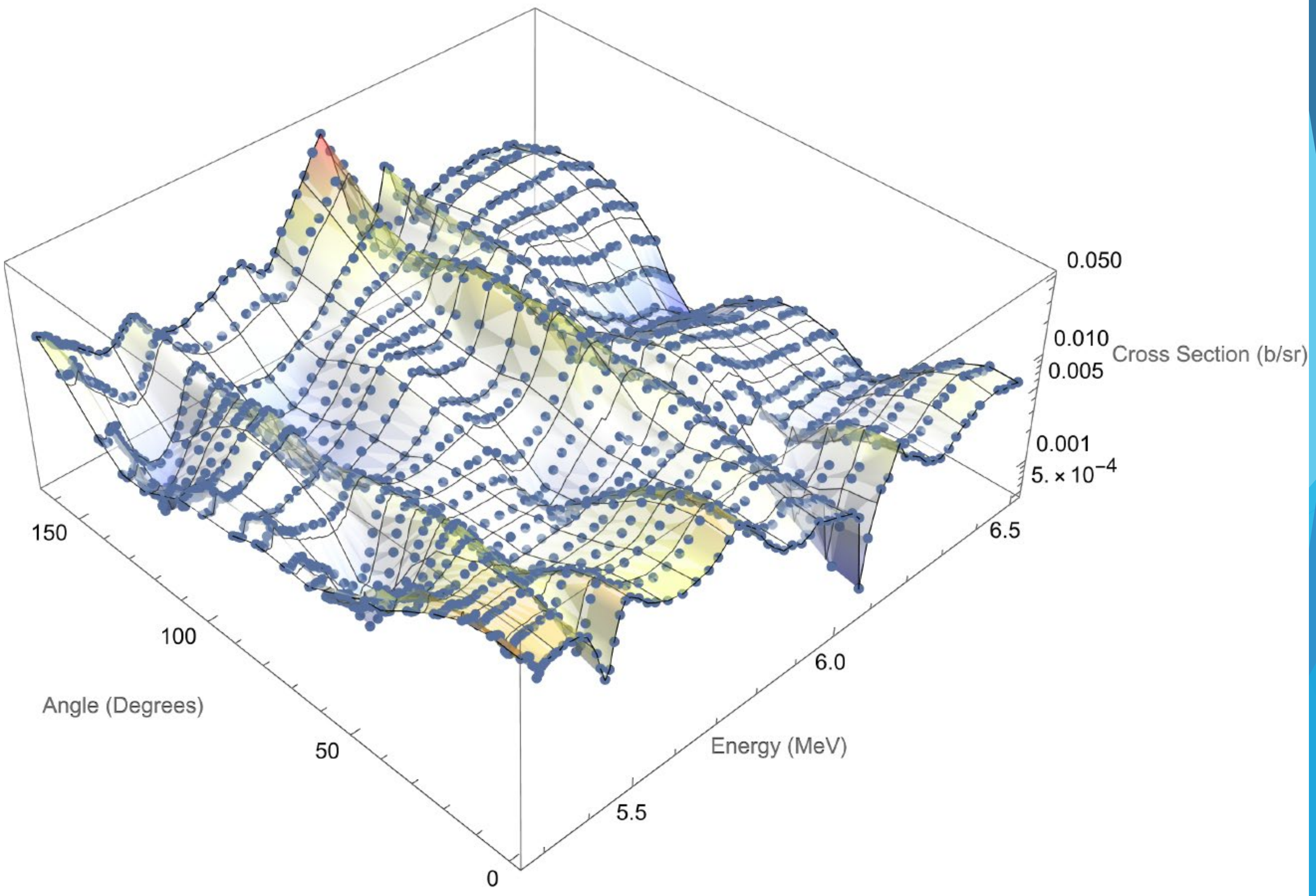
Response matrix (experimentally measured)

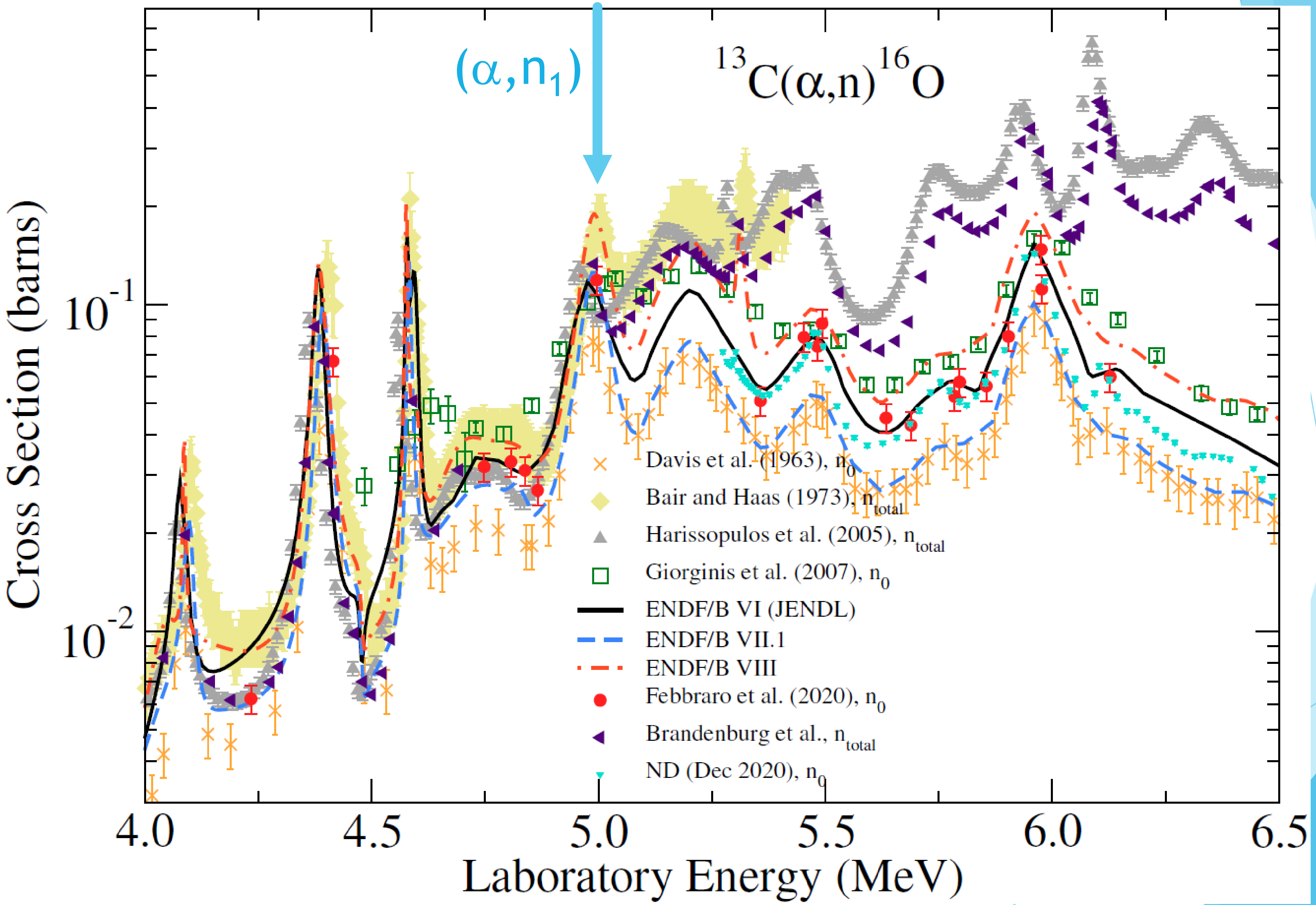
Fig. 9. Response matrix generated using a broad energy neutron source from a thick target ^{27}Al(d, n) reaction at E_d = 7.44 MeV [12].

Calibrations preformed at the Edwards Accelerator Laboratory at OU and now also LANSCE at LANL

$^{13}C(\alpha,n_0)$ angular distributions from ODeSA measurements

- About 20 keV energy steps
- 20 point angular distributions
- Uncertainties are usually about 5% (unfolding dominated)
- Measurements actually go up to 9 MeV, but our current measured detector response only allows us to go up to 6.5 MeV

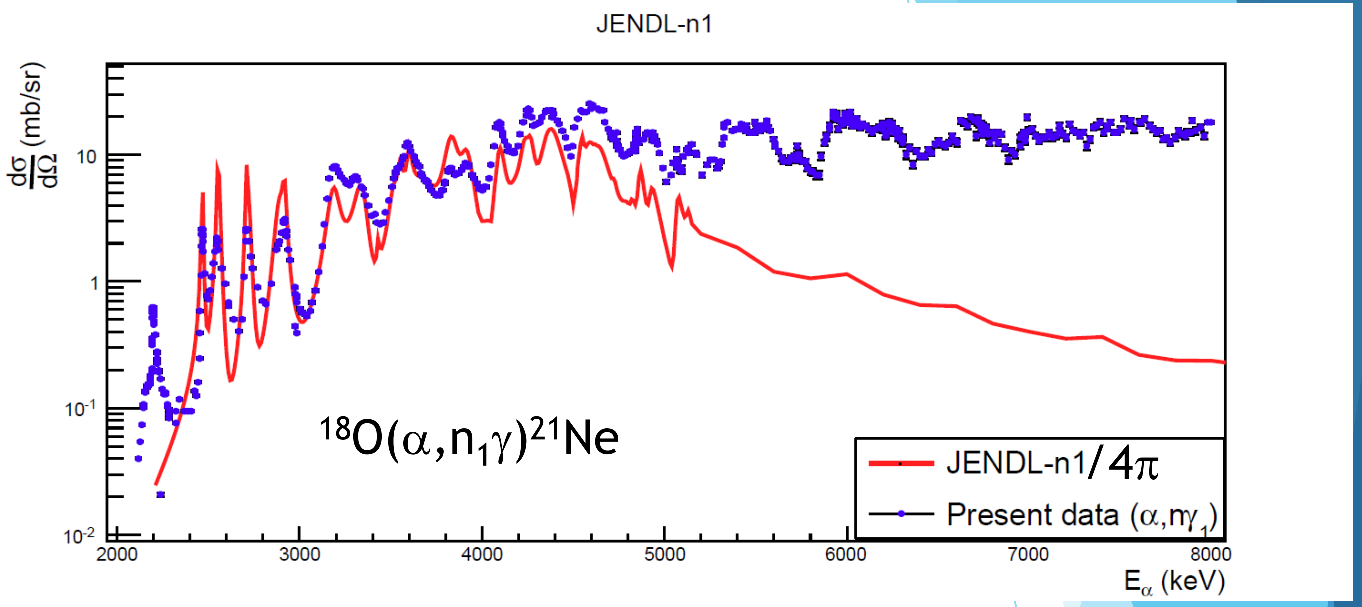


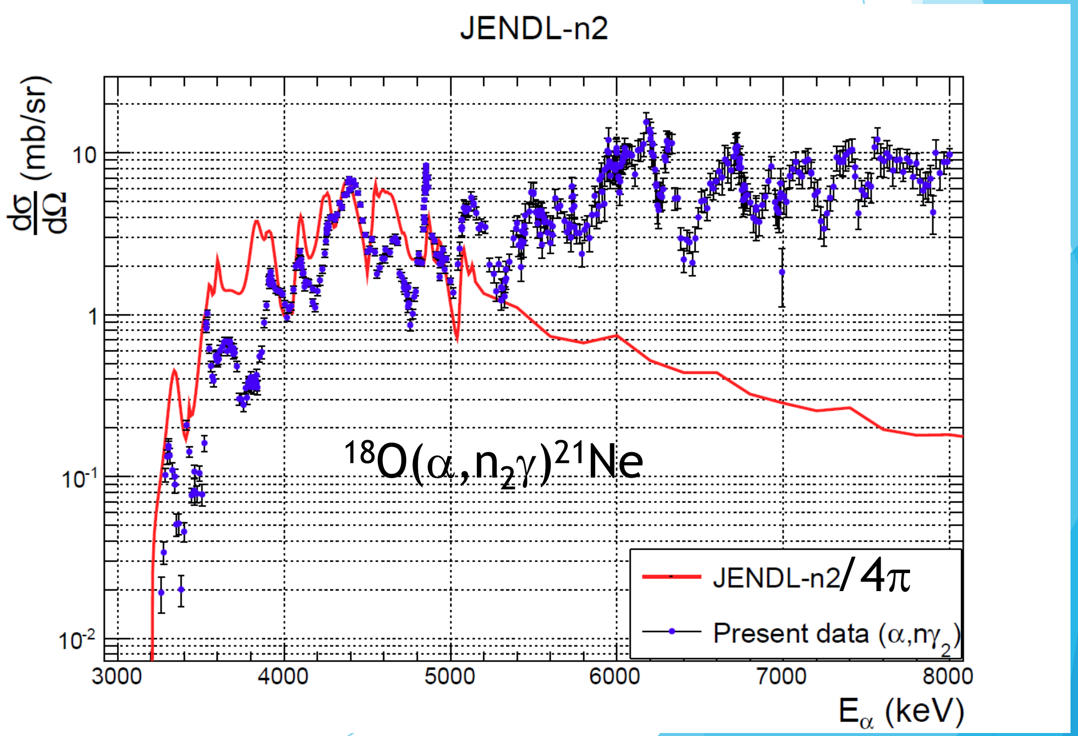


(α,n_1)
$^{13}C(\alpha,n)^{16}O$
Cross Section (barns)
10^{-1}
10^{-2}
4.0
4.5
5.0
5.5
6.0
6.5
Laboratory Energy (MeV)
Davis et al. (1963), n_0
Bair and Haas (1973), n_{total}
Harissopulos et al. (2005), n_{total}
Giorginis et al. (2007), n_0
ENDF/B VI (JENDL)
ENDF/B VII.1
ENDF/B VIII
Febbraro et al. (2020), n_0
Brandenburg et al., n_{total}
ND (Dec 2020), n_0

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

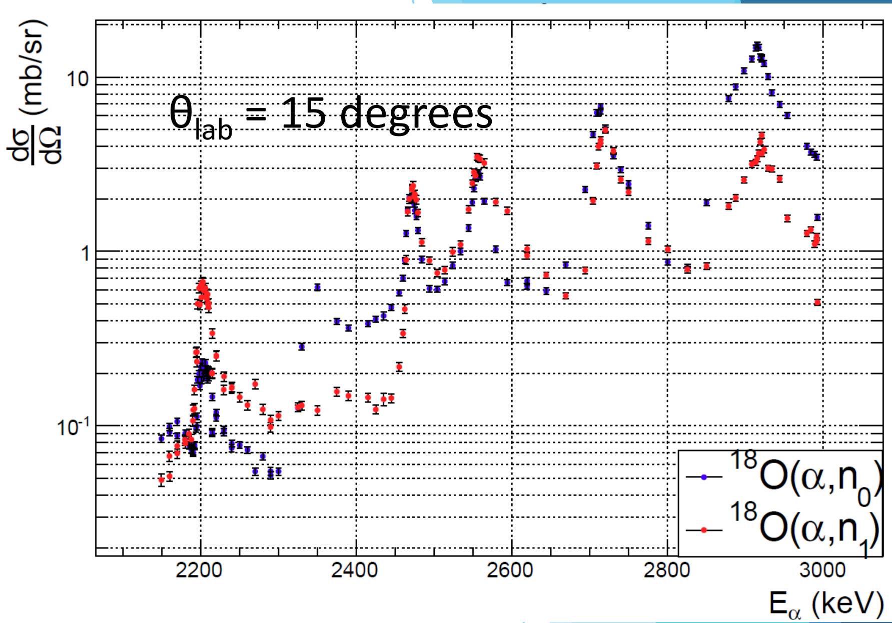
- Rebbeca Toomey (Rutgers)
- PhD work
- ODeSA array + HPGe at 125 degrees

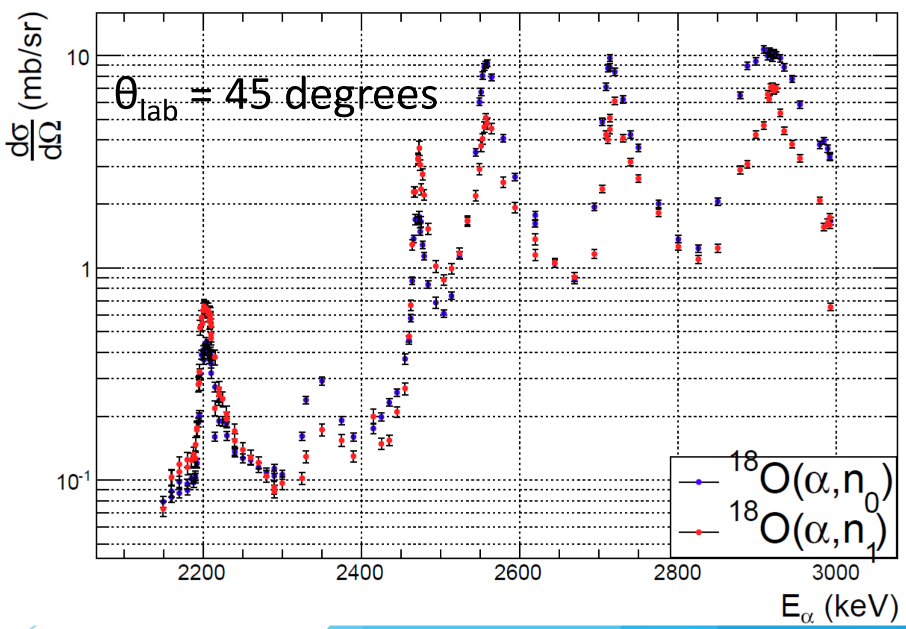




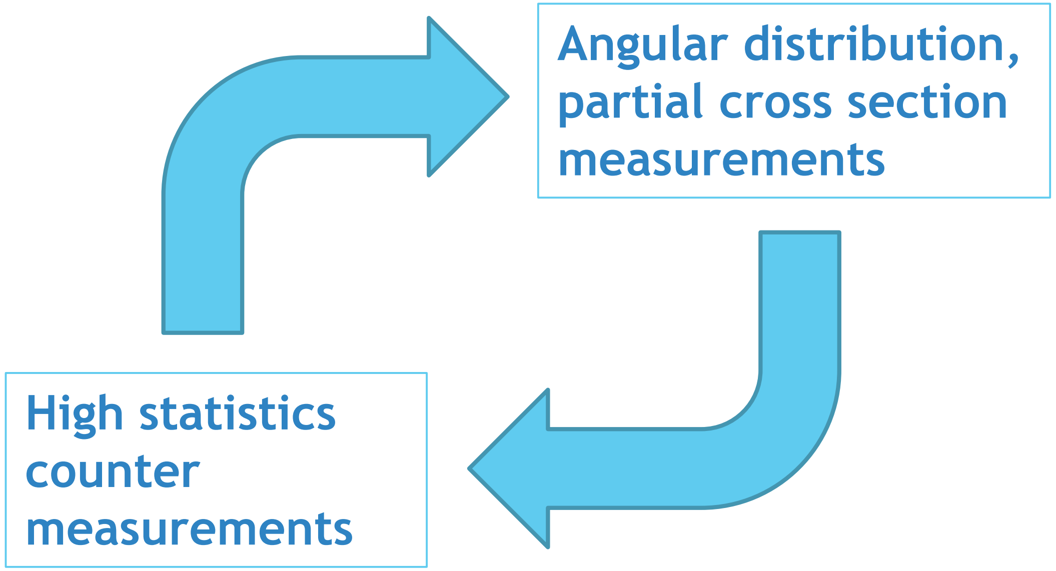
$^{18}O(\alpha,n)^{21}Ne$: Latest results!

- First n_0 and n_1 partial cross section measurements!
- n_0 and n_1 populate the same levels with very similar branchings at these energies
- Still have a lot of data to analyze.
  - 10 Angles at each energy (sometimes 20)
  - Data extend up to 8 MeV
- Quality of ODeSA measured response matrix is poorer at higher energies.
- Headed to LANL in November to make improved measurements!



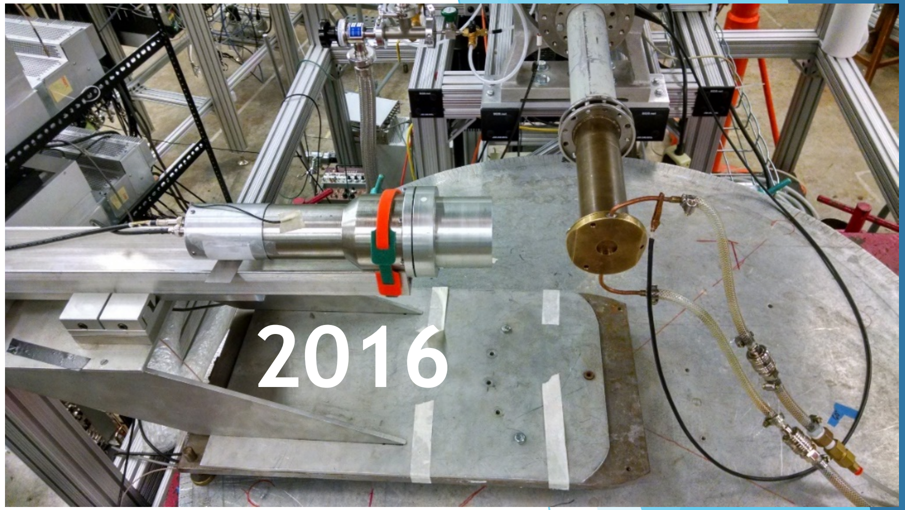


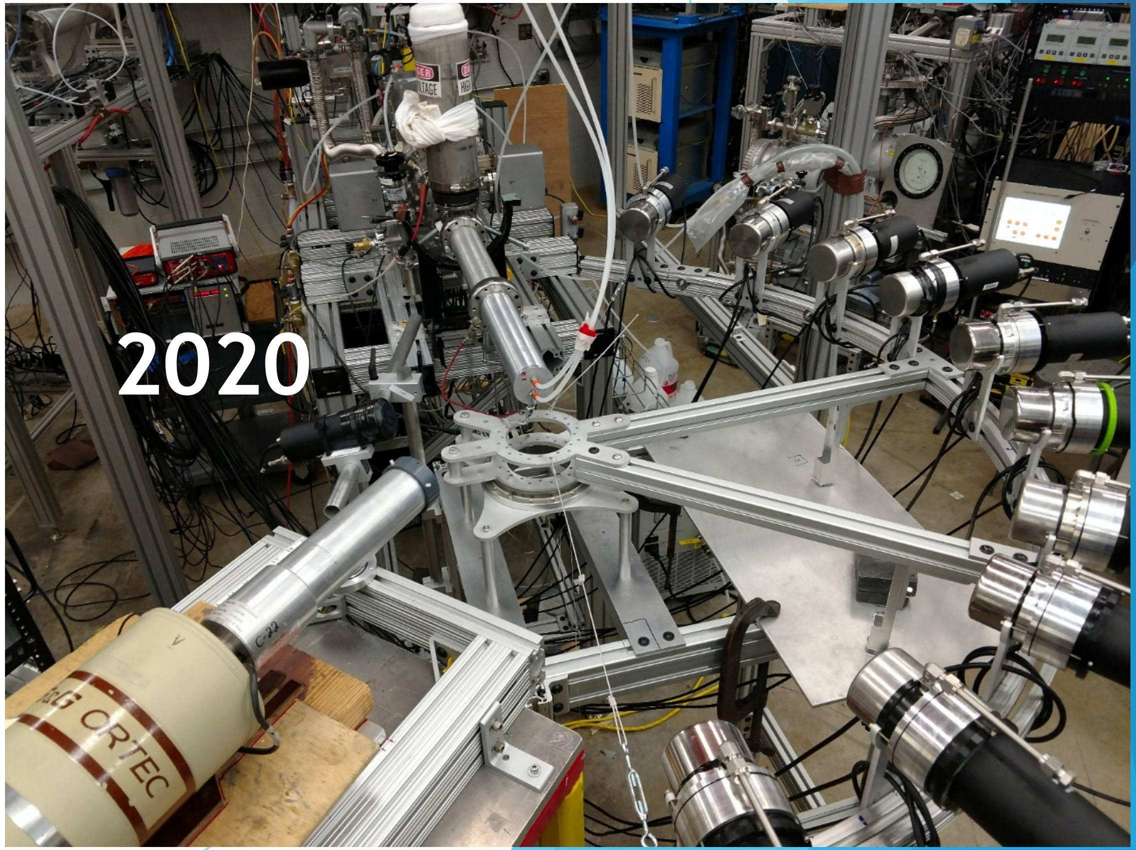
One way we can improve (α,n) type reactions

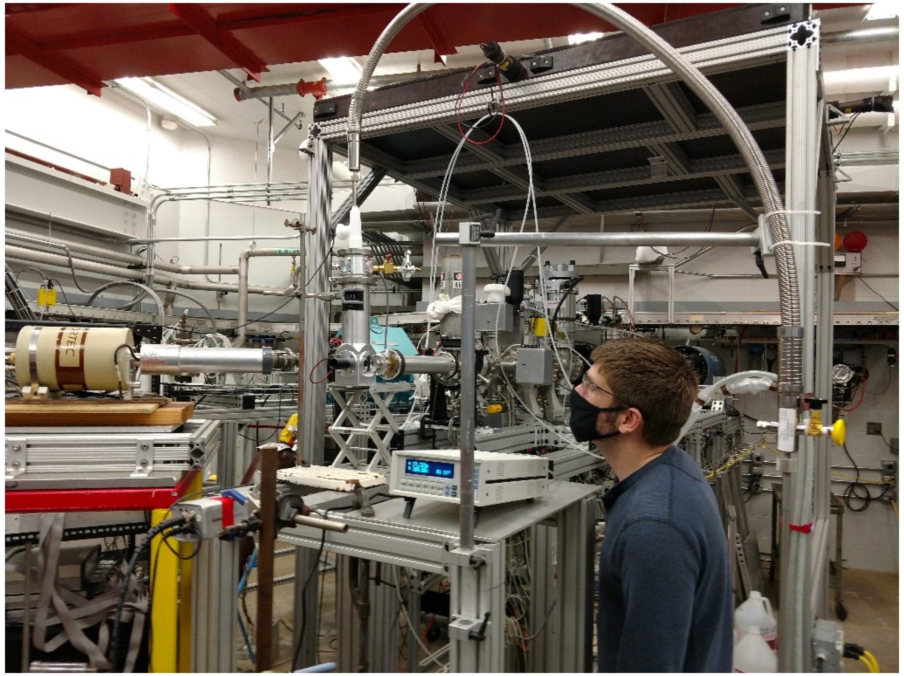
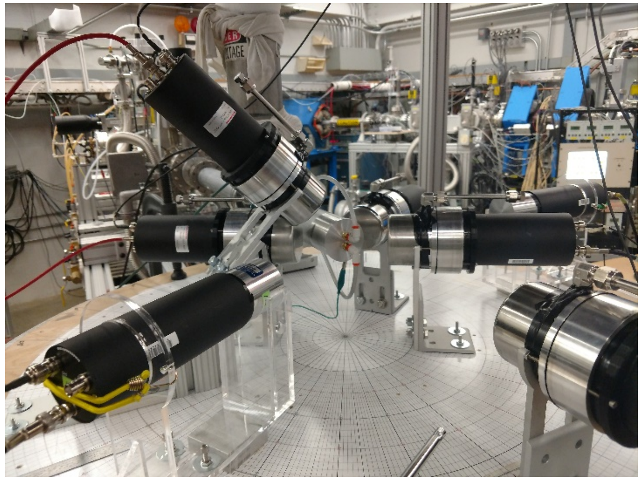
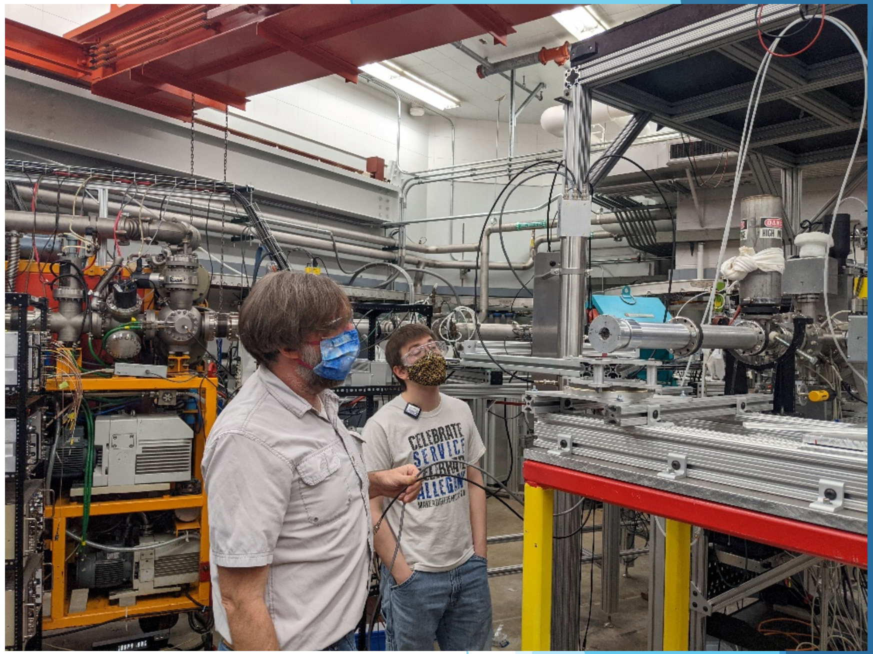


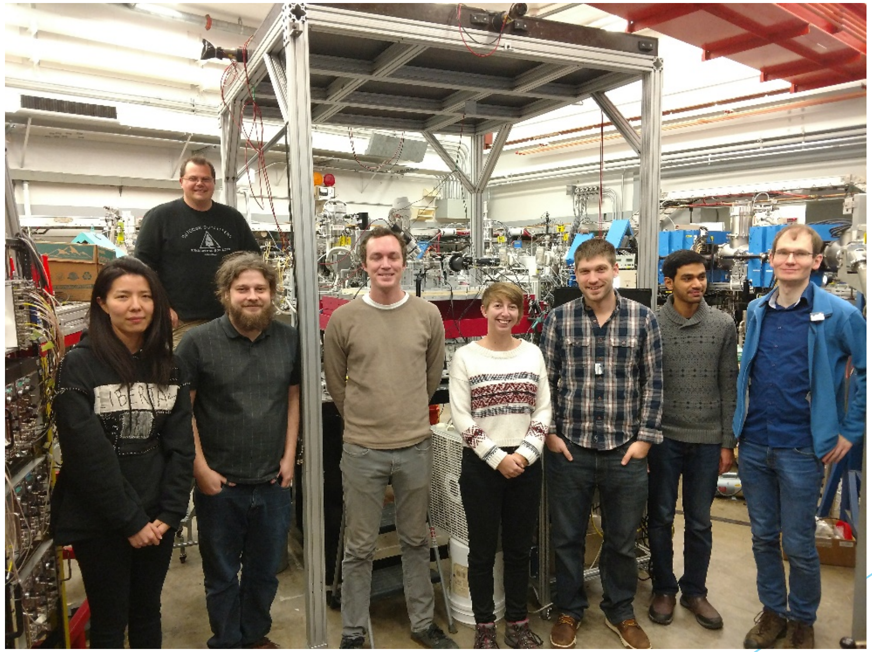
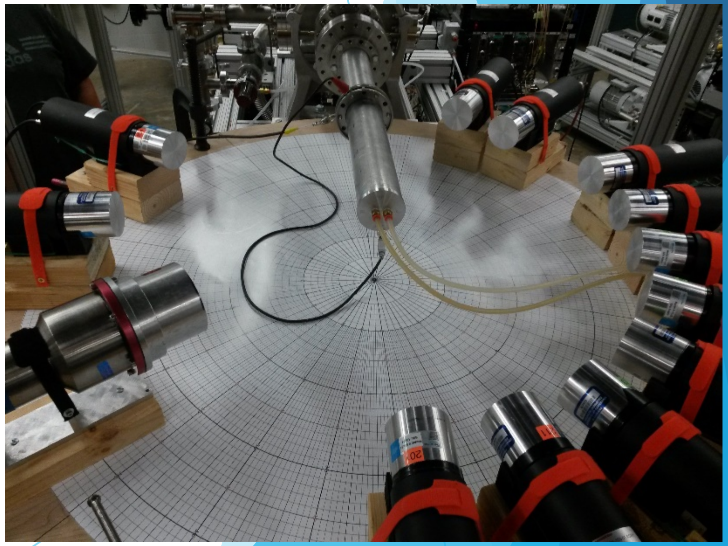
Summary and Foreword

- We've measured $^{13}C(\alpha,n_0)$, $^{13}C(\alpha,n_2\gamma)$, $^{13}C(\alpha,n_3\gamma)$, and $^{13}C(\alpha,n_4\gamma)$ in the higher energy range (5 to 9 MeV) and $^{13}C(\alpha,n_1)$ from 5 to 6 MeV
- Future work
  - Measure detailed angular distributions of $^{13}C(\alpha,n_0)$ from about 1 to 5 MeV (in two weeks)
  - Measure ODeSA response matrix up to 20 MeV at LANSCE (done last week!)
  - Expand (α,n_1) measurements from 6 to 9 MeV





Collaborators

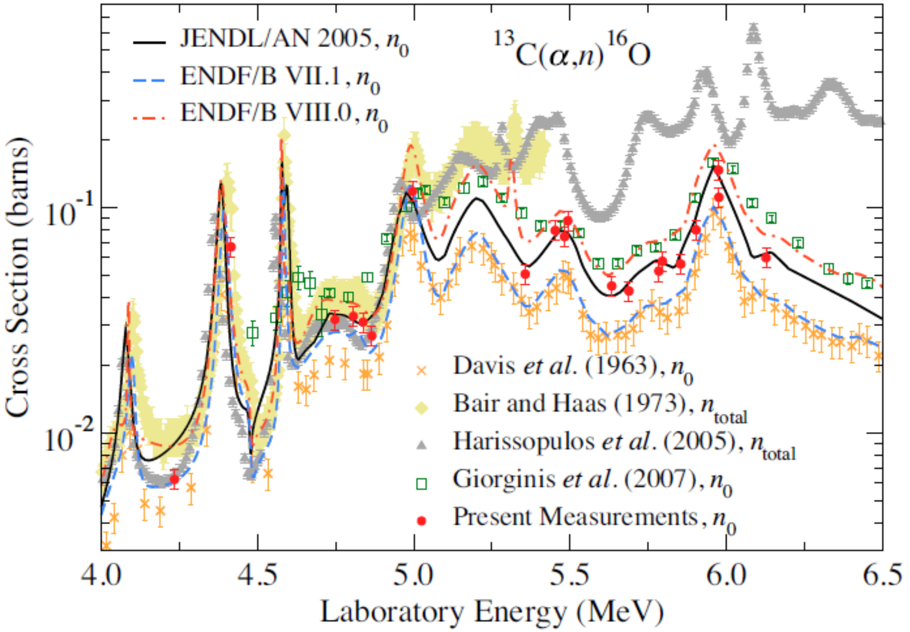
- UND
  - Manuel Couder
  - Kachatur Manukyan
  - Ed Stech
  - Dan Robertson
  - Wanpang Tan
  - **Michael Wiescher**
  - August Gula
  - Rebeka Kelmar
  - Shahina Shahina
  - + many other ND grad student shifters
- ORNL
  - **Michael Febbraro**
  - Michael Smith
  - Toby King
  - Jason Nattress
  - Marco Pigni
- OU
  - Carl Brune
  - Zach Meisel
  - Daniel Phillips
  - Kristyn Brandenburg
  - **Daniel Odell**
- ATOMKI
  - György Gyürky
- HZDR
  - Axel Boeltzig
- LSU
  - Kevin Macon
- Rutgers
  - Rebecca Toomey
- LANL
  - Aaron Couture
  - Hye Young Lee
  - Karl Smith
- UTK
  - Kate Jones

IAEA *R*-matrix and light element data workshops

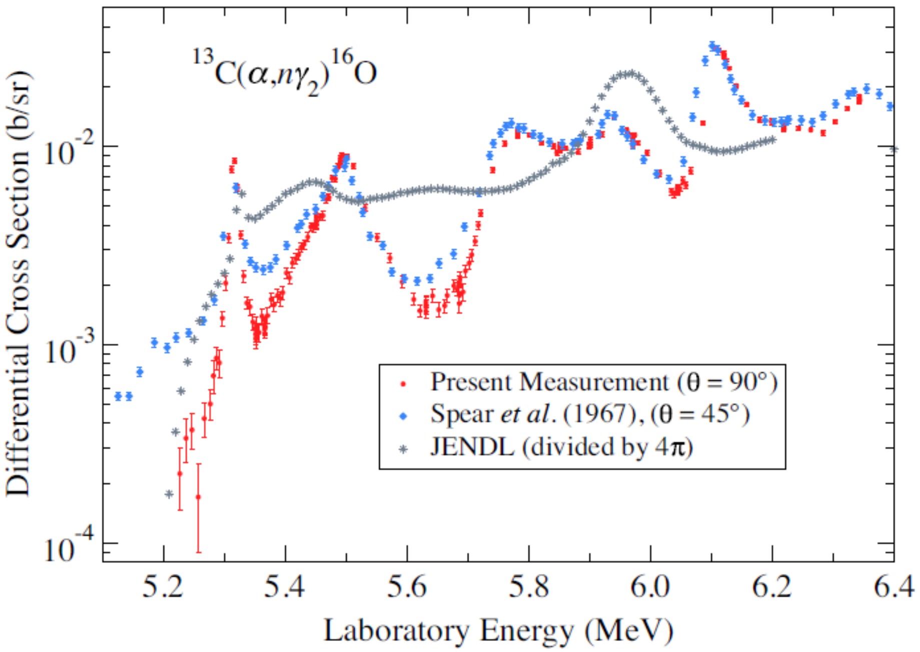
- Vivian Dimitriou
- Ian Thompson

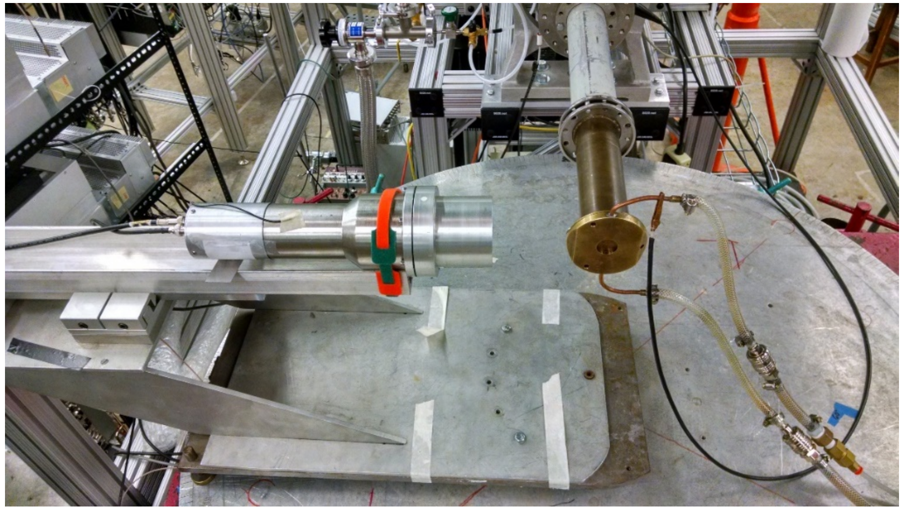
First measurements made back in 2016

$^{13}C(\alpha,n_0)$



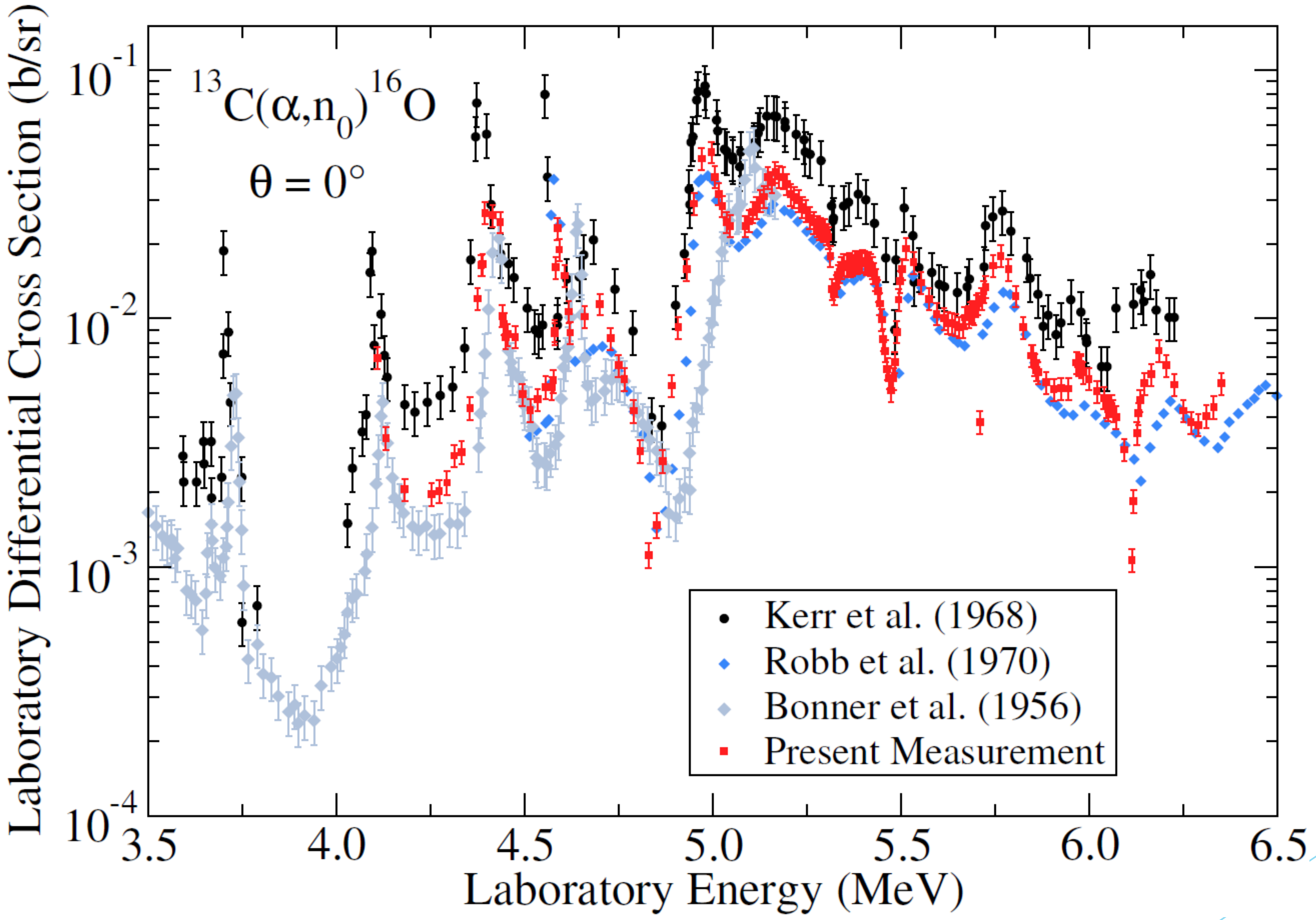
$^{13}C(\alpha,n_2)$





Febbraro et al. (2020)

Unpublished data from 2016 run



Efforts at UND

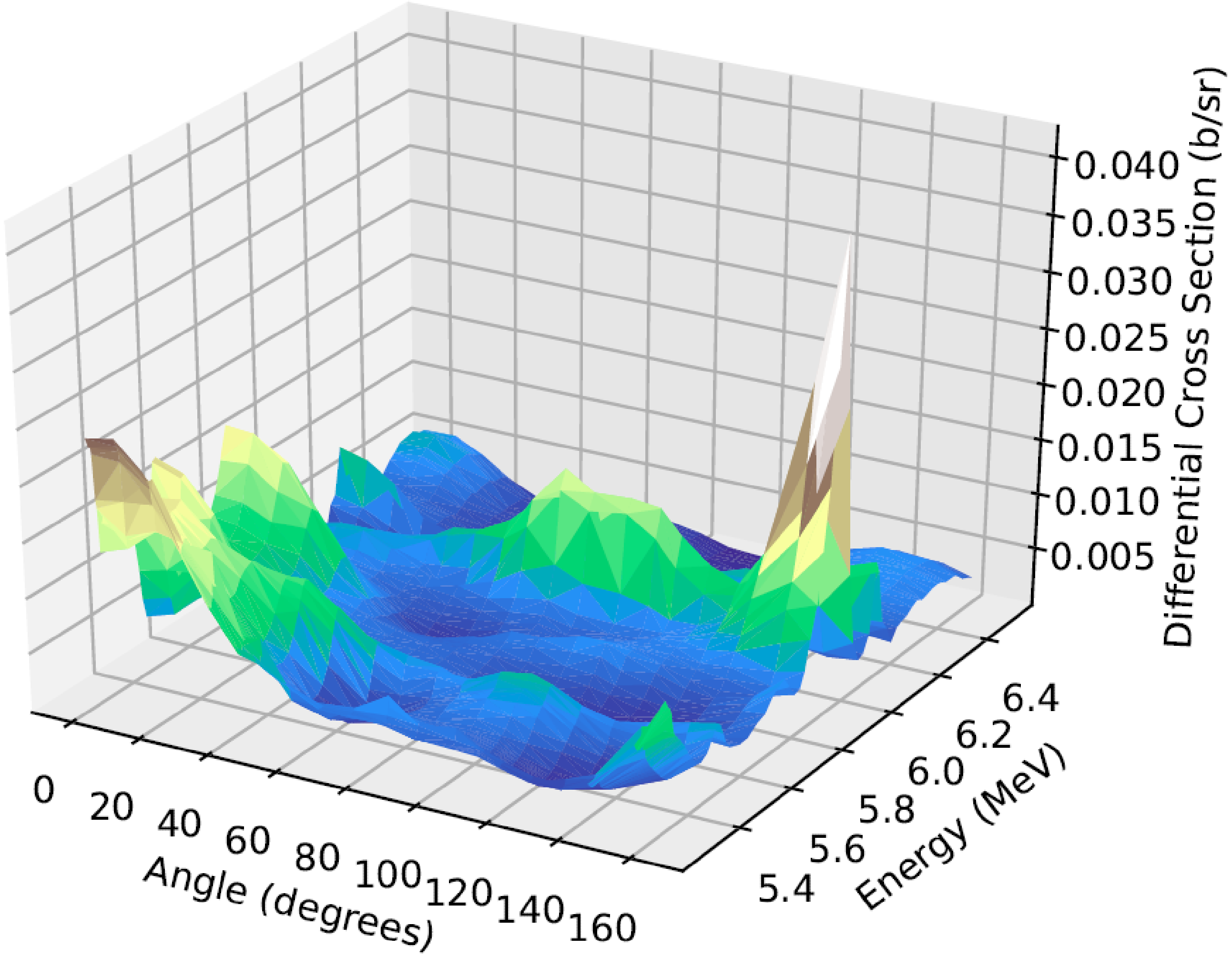
- Utilizing the **ODeSA array** of deuterated liquid scintillators from **Mike Febbraro** at ORNL
  - Intrinsic neutron spectroscopy, 200 keV resolution, 500 keV threshold
  - Make detailed angular distribution measurements across the entire range of interest (1 to 9 MeV)

- Utilizing **HAGRiD array** from **Kate Jones** at University of Tennessee at Knoxville and **GEANIE HPGe** detectors from **Aaron Couture** at LANL
  - Expand on the secondary γ-ray measurements of Spear et al. (1963) for $n_2\gamma$, $n_3\gamma$, and $n_4\gamma$ partial cross sections

- ^{3}He spectrometer at UND
  - Low efficiency, but excellent intrinsic neutron energy (30 keV) resolution and low threshold (<100 keV)
  - Efficiency becomes very low above 3 MeV

A quick review of past measurements (not comprehensive)

- 1963 --- Davis measures $^{16}O(n,\alpha)^{13}C$ **total reaction** cross section from 4 to 8 MeV
- 1963 --- Spear *et al.* measure $^{13}C(\alpha,n\gamma)^{16}O$ from 5 to 10 MeV using NaI
- 1968 --- Davids measures **total reaction** cross section from 0.475 to 0.7 MeV
  - Uses a stilbene crystal and psd
  - A thick 200 ug/cm^2 target was used
- 1973 --- Bair and Haas use a large 4π carbon sphere neutron moderator to measure the **total reaction** cross section from 1 to 5.5 MeV
  - Target thickness = 2 ug/cm^2, energy loss is a couple keV
  - Becomes the gold standard for many years
  - It's the backbone of the ENDF/B $^{16}O(n,\alpha)$ evaluation for many years
- 1993 --- Drotleff *et al.* measure the **total reaction** cross section from 570 to 2300 keV using a smaller polyethylene moderator
  - Very little experimental information is given
- 2005 --- Harissopulos *et al.* use a smaller polyethylene moderator to measure the **total reaction** cross section from 0.8 to 8 MeV
  - Target thickness = **20 ug/cm^2**, energy loss is 10's of keV
  - Throws a wrench in the ENDF/B-VII evaluation, resulting in a substantial change in the overall normalization



Differential Cross Section (b/sr)
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0 20 40 60 80 100 120 140 160
Angle (degrees)
5.4 5.6 5.8 6.0 6.2 6.4
Energy (MeV)