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

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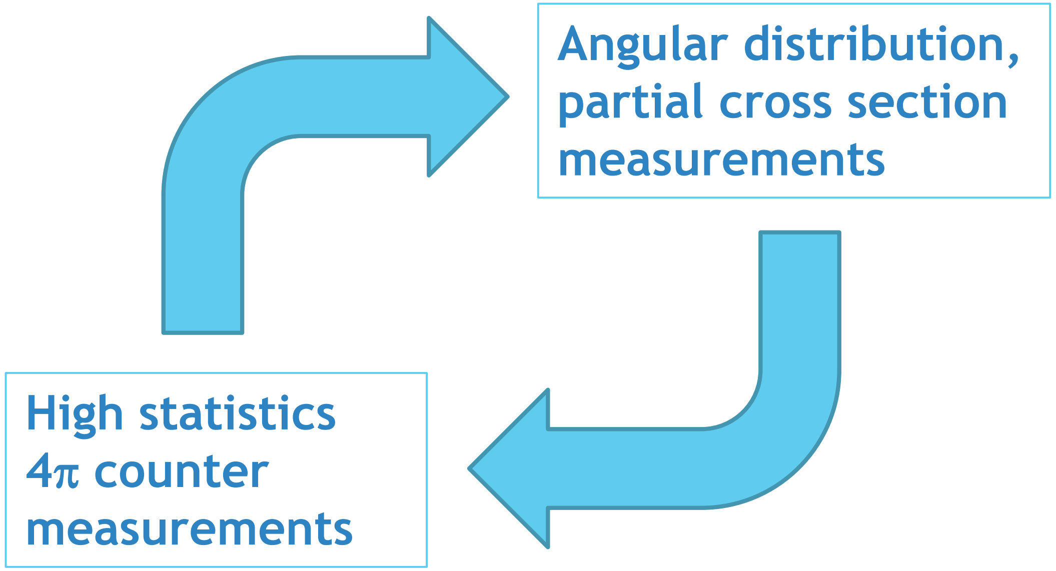
Motivations

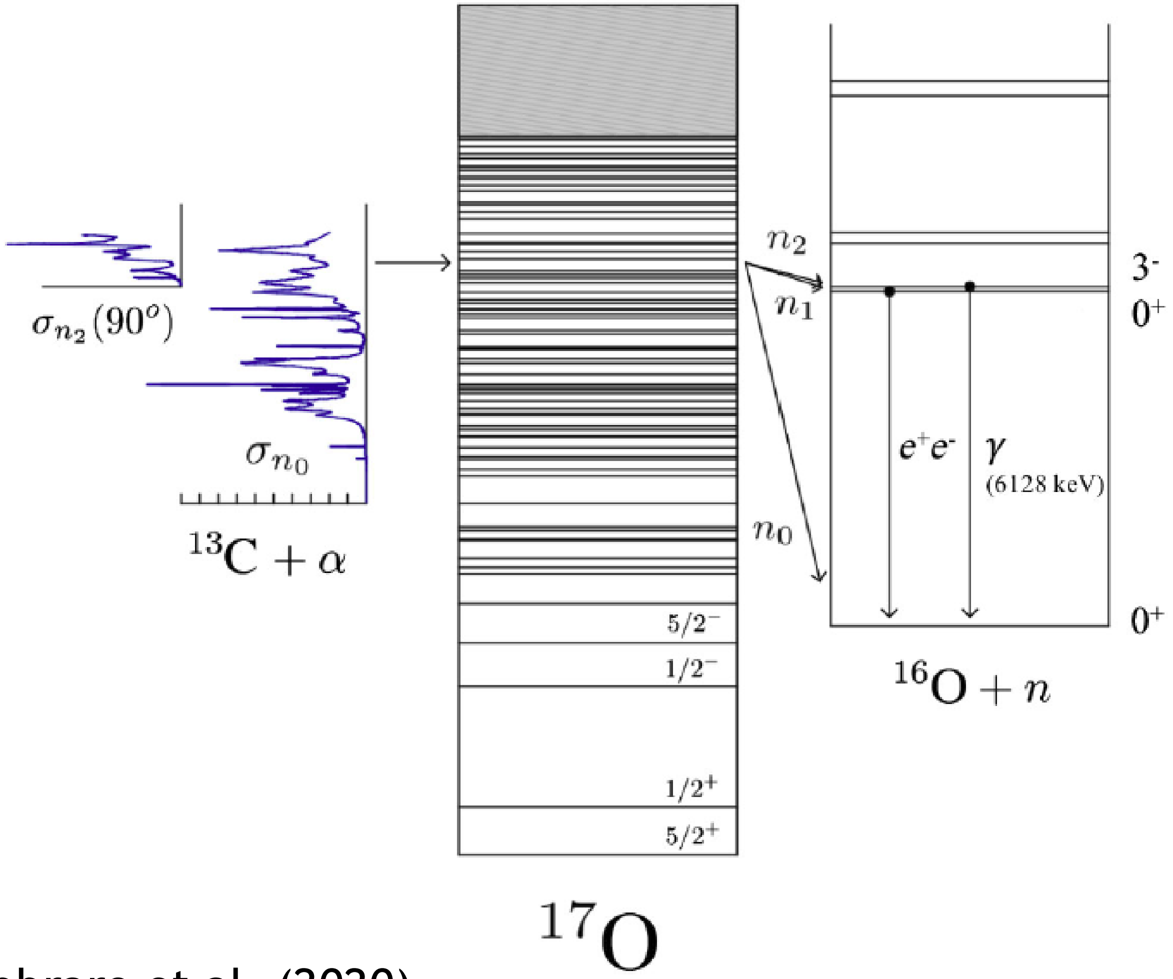
- Large mass detectors for neutrino and dark matter detection (e.g. CDMS, DUNE, KamLAND)
  - Actinides and light elements (carbon, oxygen, etc.) are hard to completely remove from setups
  - Actinide decays → up to 9 MeV α-particles → (α,n) on light nuclei in the environment
- Neutron applications
  - Sources4c modernization
  - ^{19}F, ^{18}O, ^{17}O, $^{13}C(\alpha,n)$ reactions
  - For example, data evaluation of the ^{17}O system, $^{16}O(n,\alpha_0)^{13}C$ (See Mark Paris' talk on Wednesday at 15:20 and Thursday at 13:55 EST.)
- Nuclear Astrophysics
  - (main) *s*-process neutron source: $^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$, $^{17}O(\alpha,n)^{20}Ne$, $^{18}O(\alpha,n)^{21}Ne$, $^{25}Mg(\alpha,n)^{28}Si$, $^{26}Mg(\alpha,n)^{29}Si$
  - First stars: $^{10,11}B(\alpha,n)^{13,14}N$
  - 100 keV to a few MeV
- See (Paraskevi) Vivian Dimitriou's talk on Wednesday at 15:40 EST

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



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



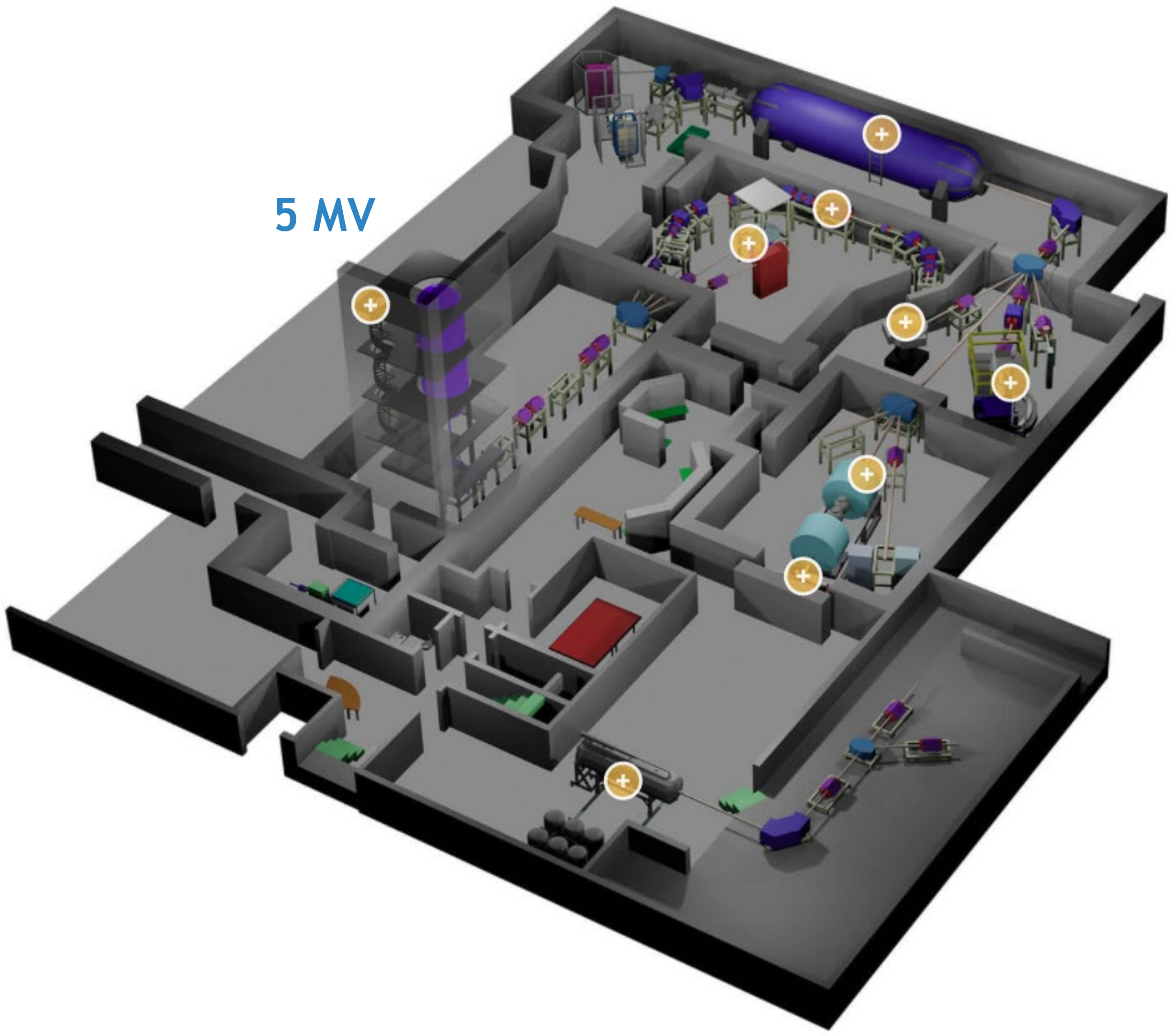
Febbraro et al. (2020)

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

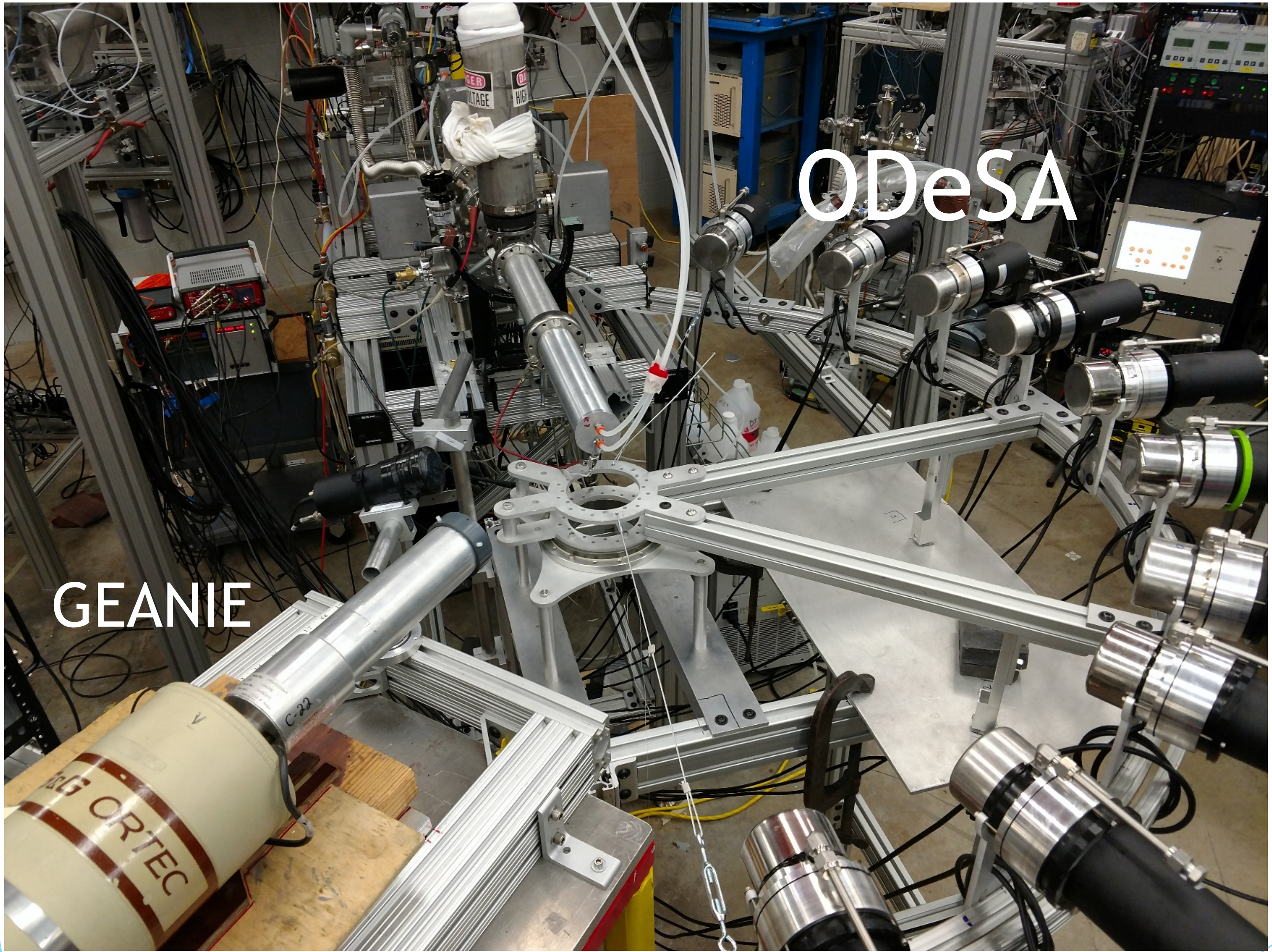
Nuclear Science Laboratory (NSL) at the University of Notre Dame

- isnap.nd.edu

- 5 MV single ended accelerator
  - dc alpha beam, alphas from 300 keV up to 9 MeV
  - up to 100 uA of beam on target
  - Usually using 10 uA for these studies
  - Energy resolution of better than 1 keV, energy uncertainty of less than 10 keV



Dec 2020 setup, ND 5U "solid target" line

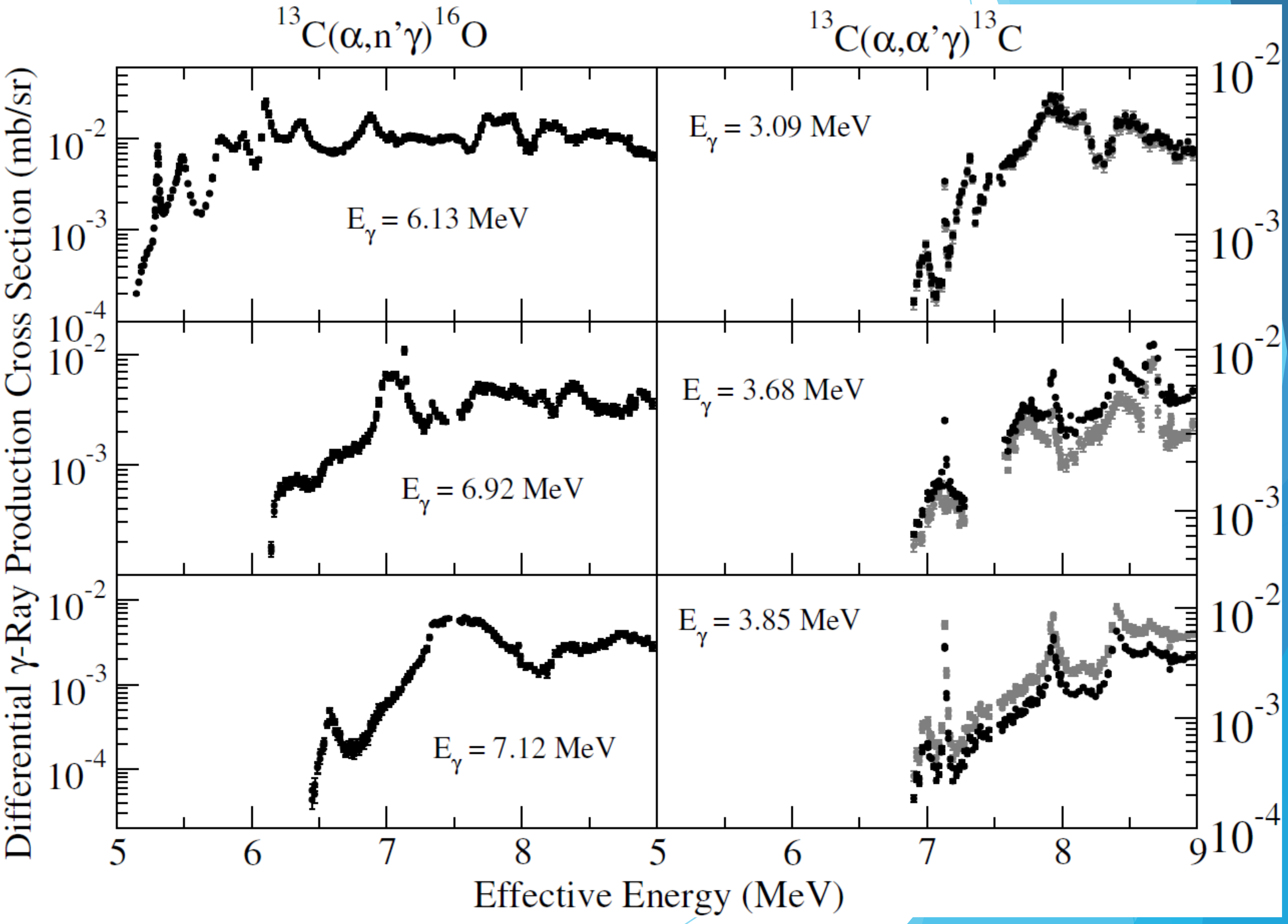


Febbraro et al. (2019)

Michael Febbraro

New measurements (Dec 2020)

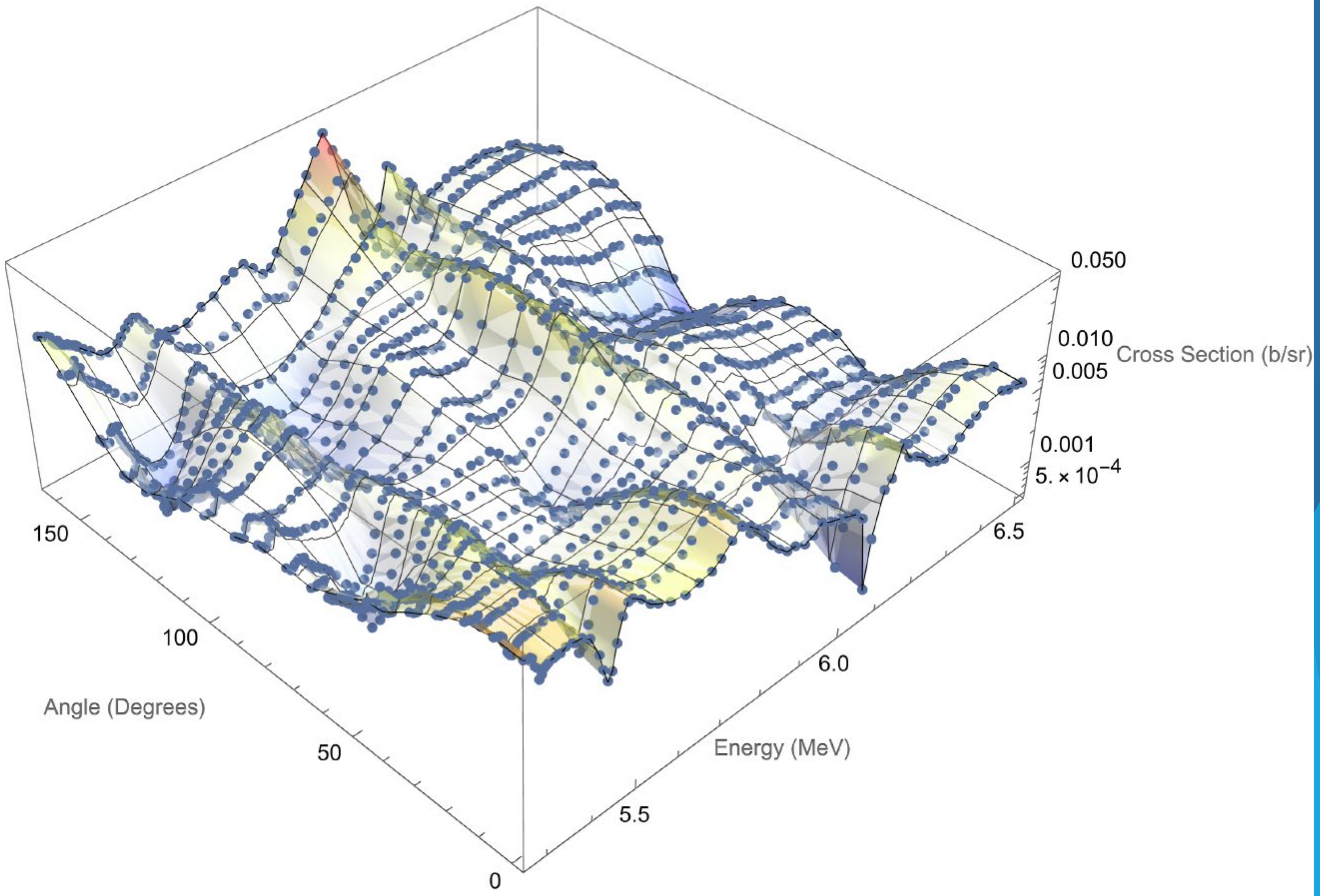
- $^{13}C(\alpha,n\gamma)$ using GEANIE HPGe @ 45 degrees
- First measurements of $^{13}C(\alpha,\alpha\gamma)^{13}C$
- Could separate 6.92 and 7.12 MeV transitions with HPGe
- Only previous measurement was by



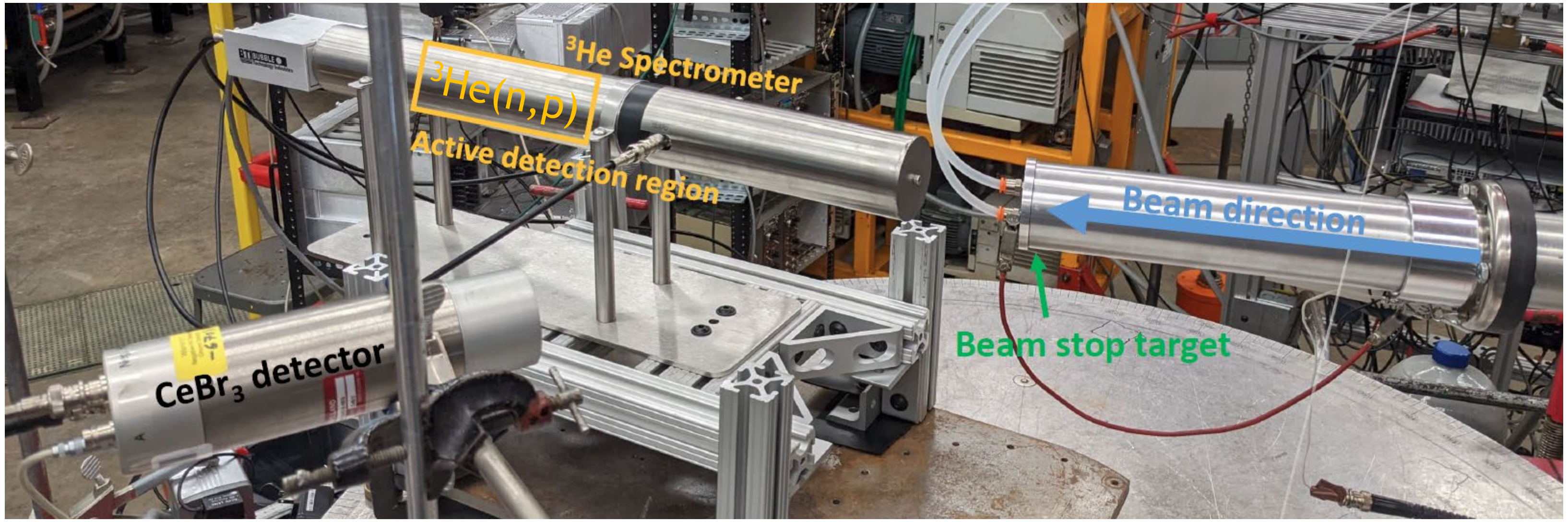
$^{13}C(\alpha,n_0)$ angular distributions from ODeSA measurements

- About 20 keV energy steps
- 20 point angular distributions
- Uncertainties are usually about 5% (unfolding dominated)

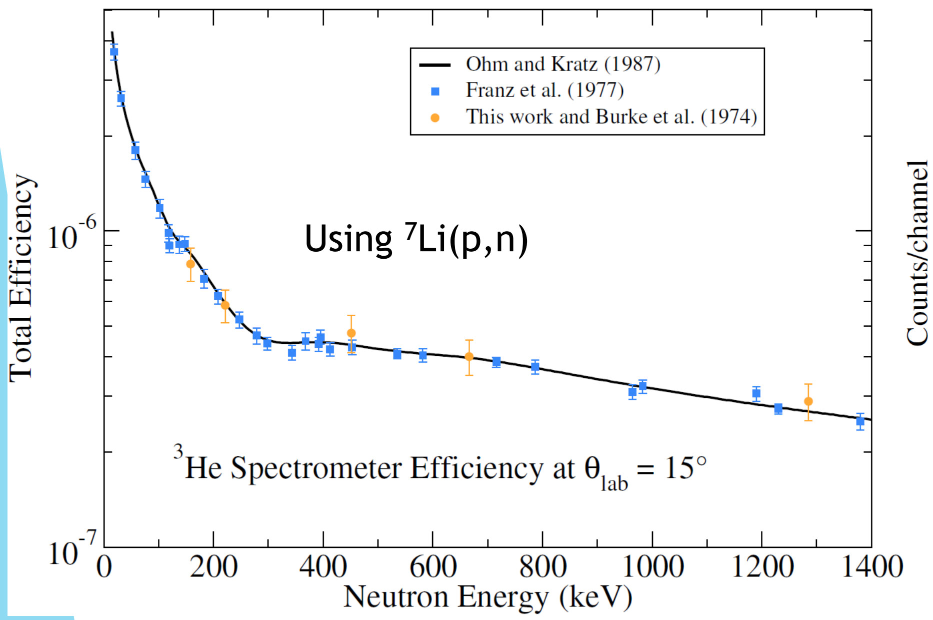
- Measurements actually go up to 9 MeV, but our current measured detector response only allows us to go up to 6.5 MeV

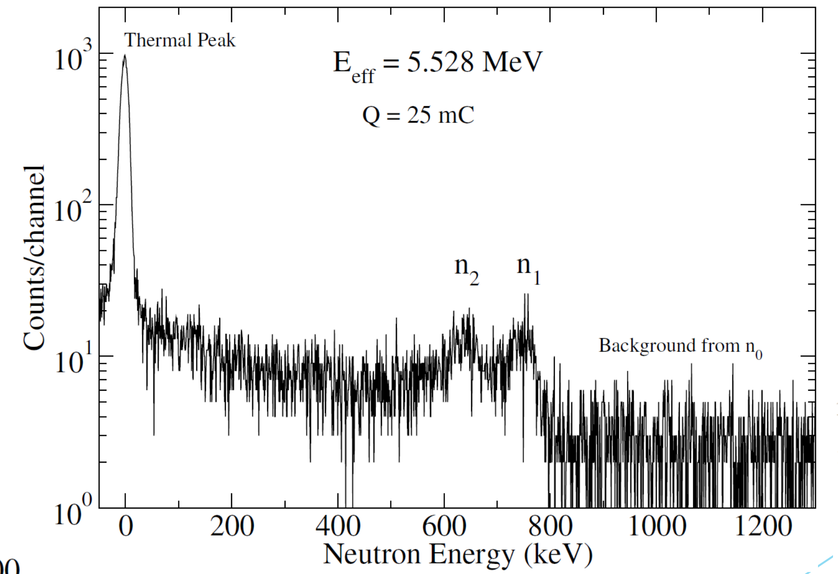


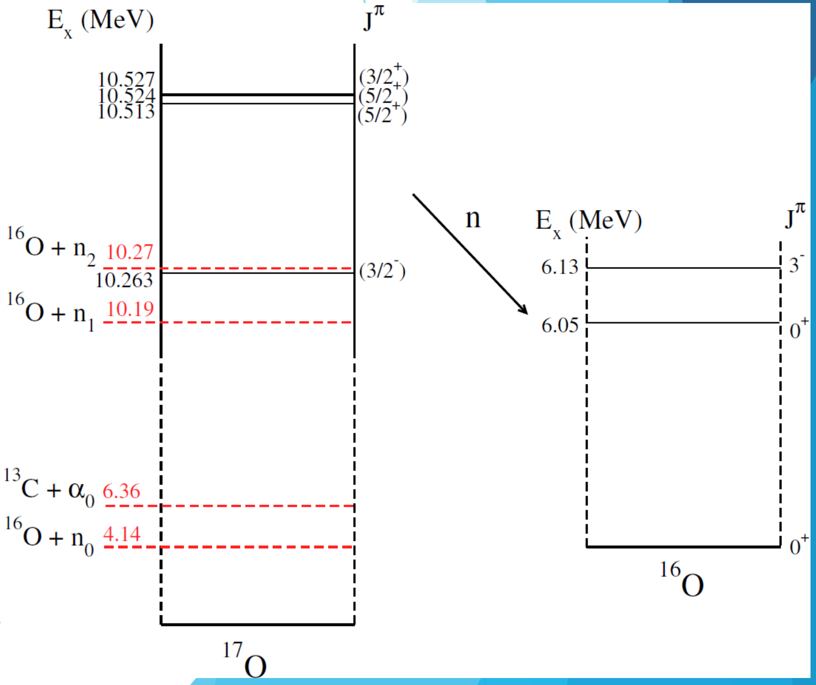
$^{13}C(\alpha,n_1)$ measurements, Feb 2021



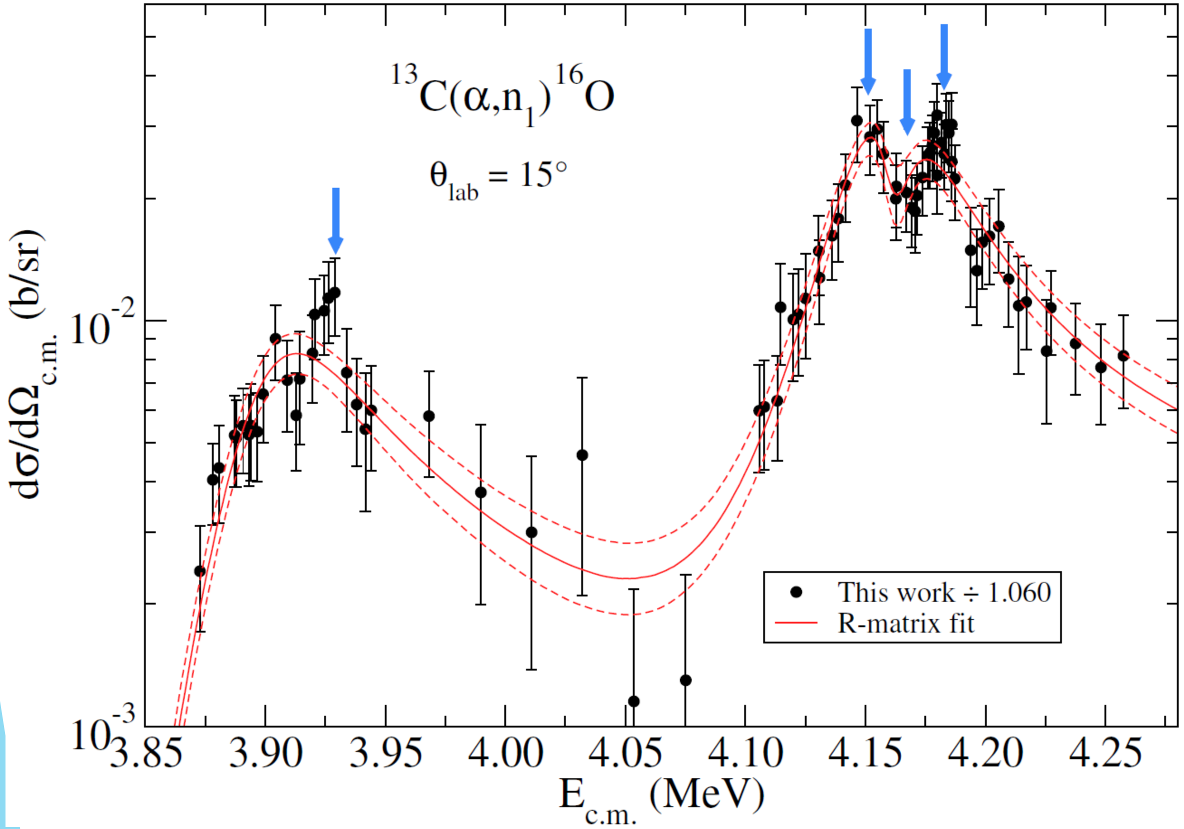
- Michael Wiescher
- ND 5U accelerator
- DC alpha beam
- 10 ug/cm^2 ^{13}C target (György Gyürky)
- 30 uA on target
- 30 minute runs
- Typically a few hundred counts

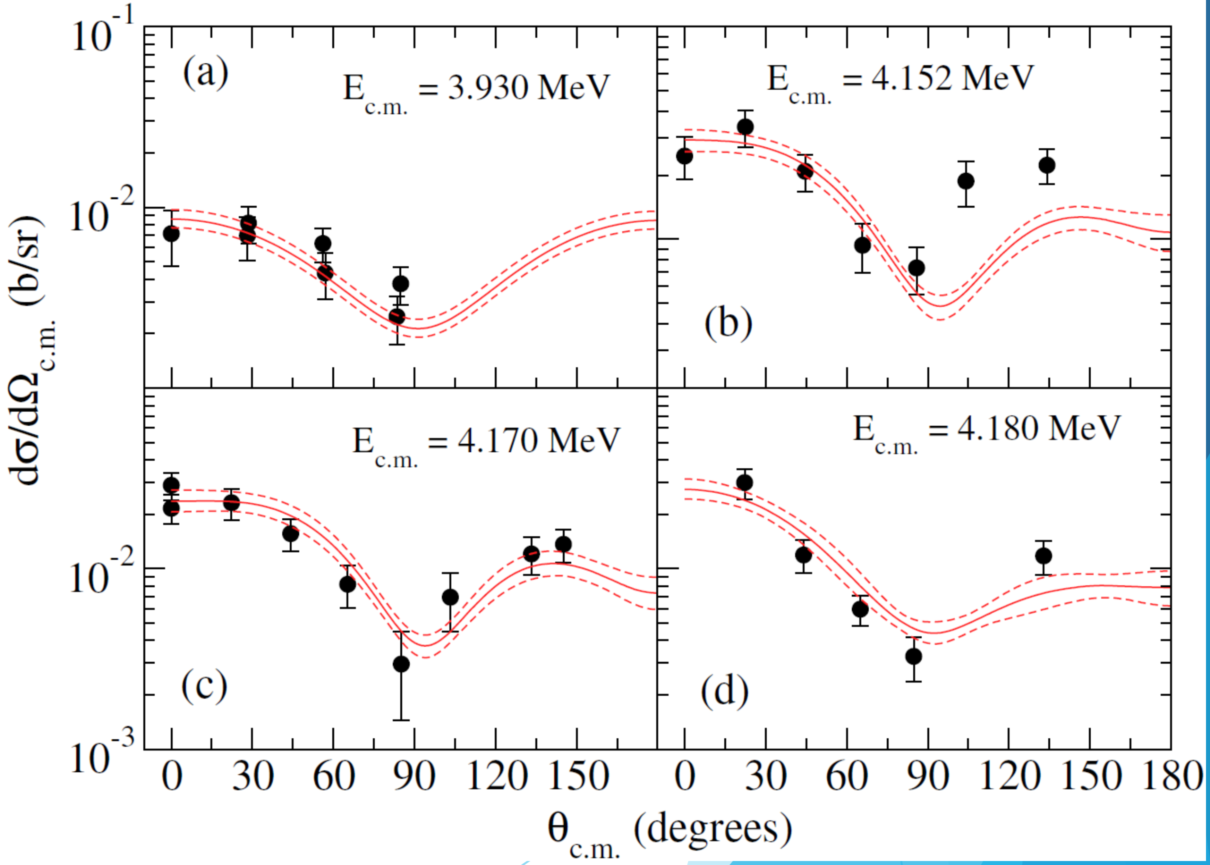




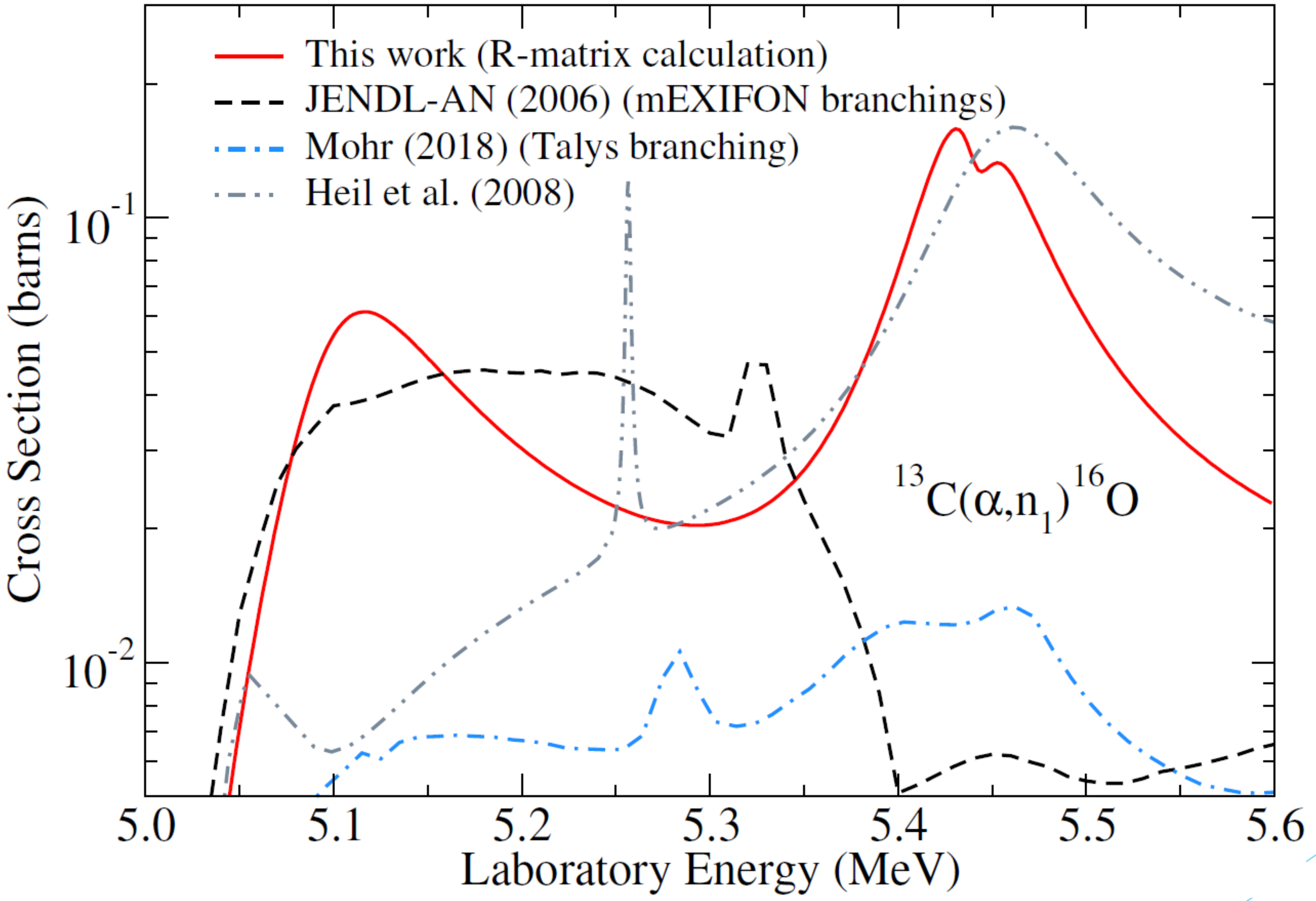


First measurement of $^{13}C(\alpha,n_1)$ cross section (plus MCMC analysis)





Comparison with evaluations

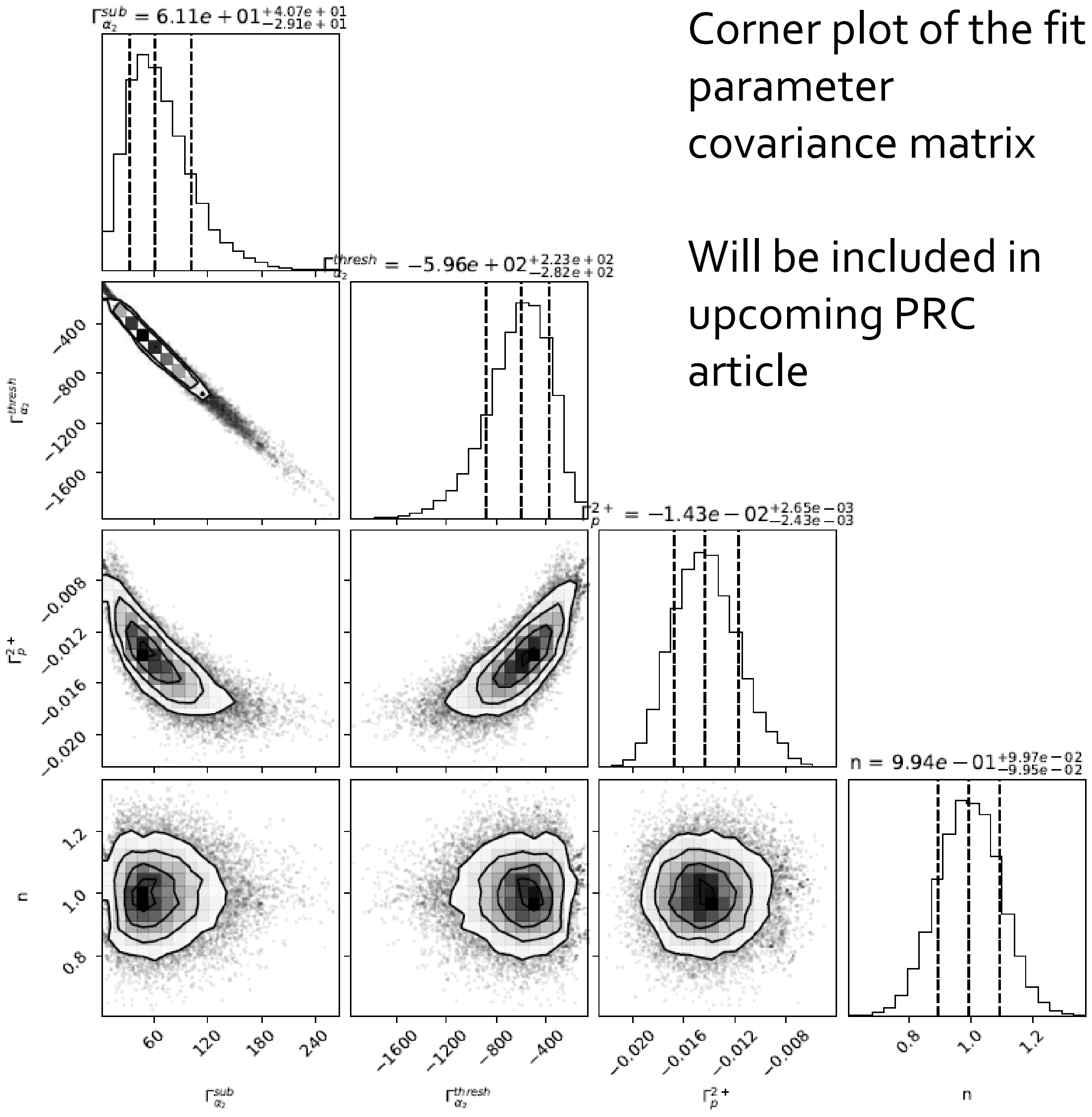


Thanks to Marco Pigni for SAMMY calculations of Heil's R-matrix fit!

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

National Nuclear Security Administration

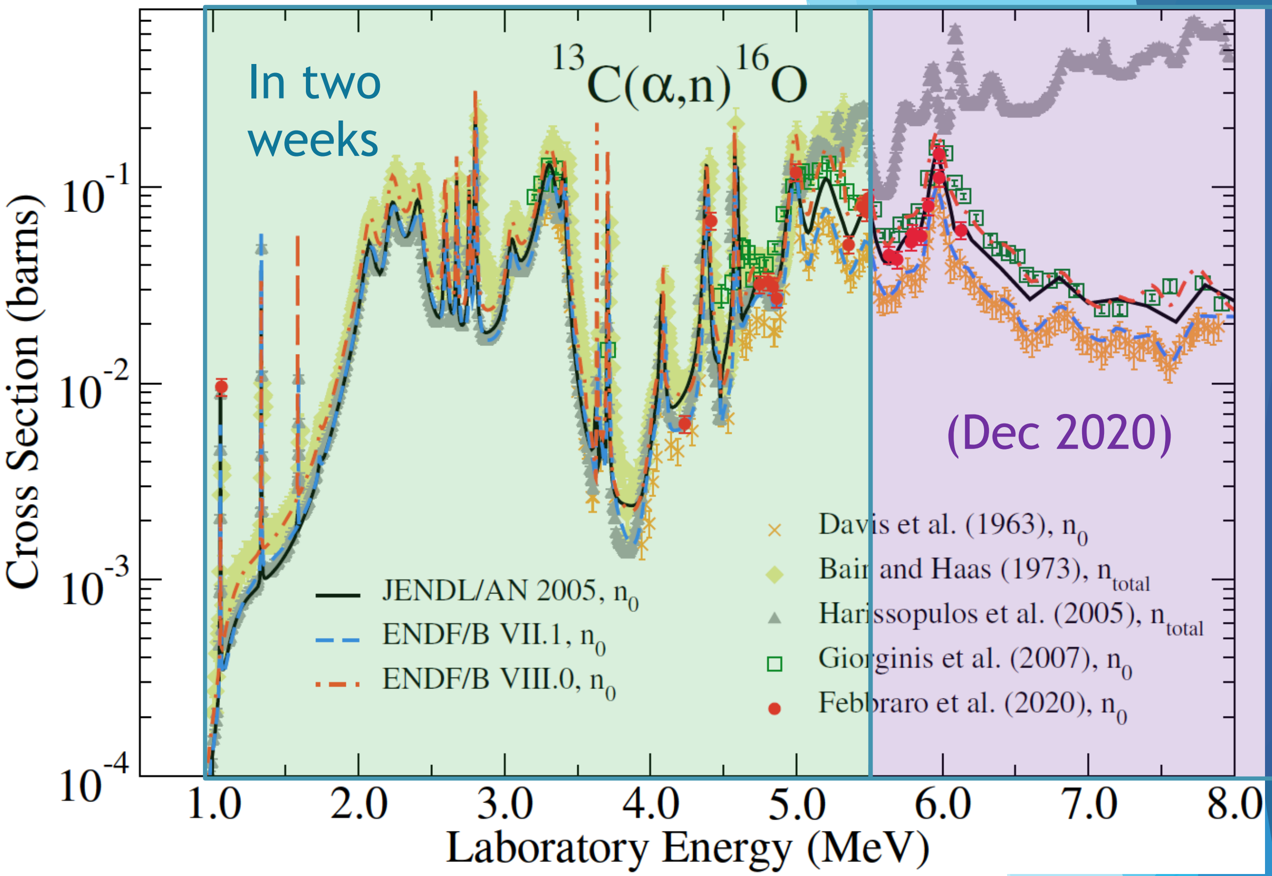


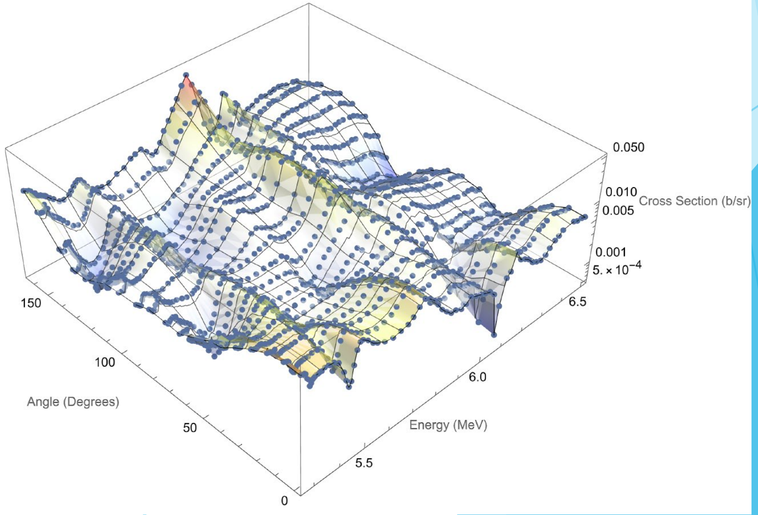
Corner plot of the fit parameter covariance matrix

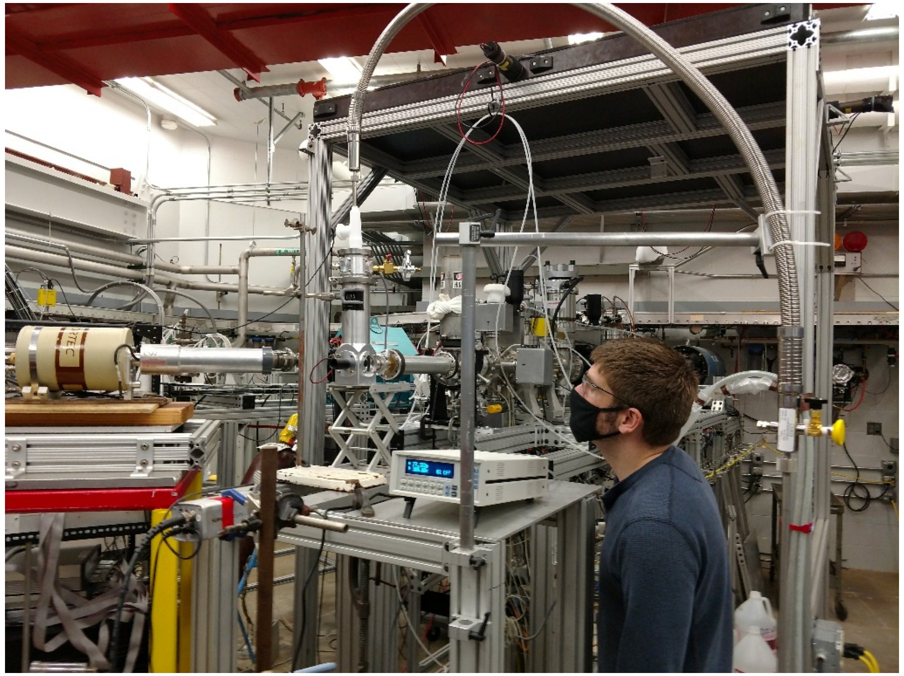
Will be included in upcoming PRC article

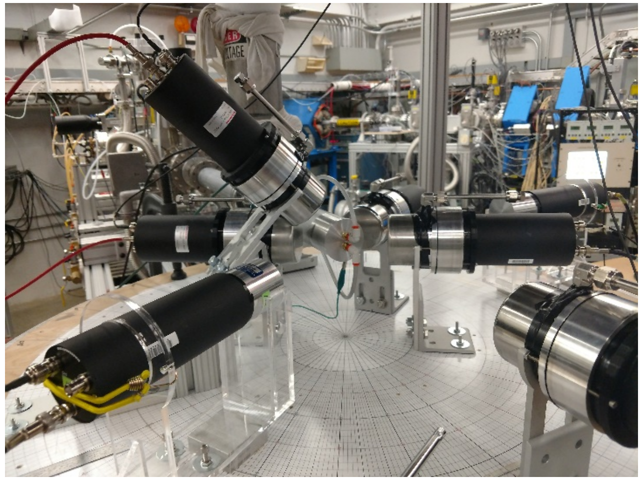
Summary and Foreword

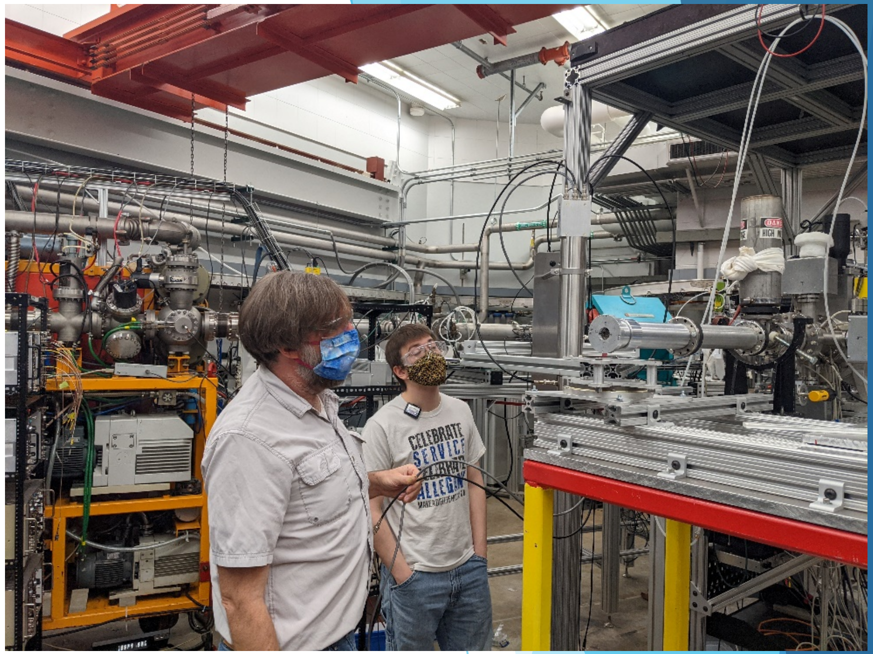
- We've measured $^{13}C(\alpha,n_0)$, $^{13}C(\alpha,n_2\gamma)$, $^{13}C(\alpha,n_3\gamma)$, and $^{13}C(\alpha,n_4\gamma)$ in the higher energy range (5 to 9 MeV) and $^{13}C(\alpha,n_1)$ from 5 to 6 MeV
- Future work
  - Measure detailed angular distributions of $^{13}C(\alpha,n_0)$ from about 1 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

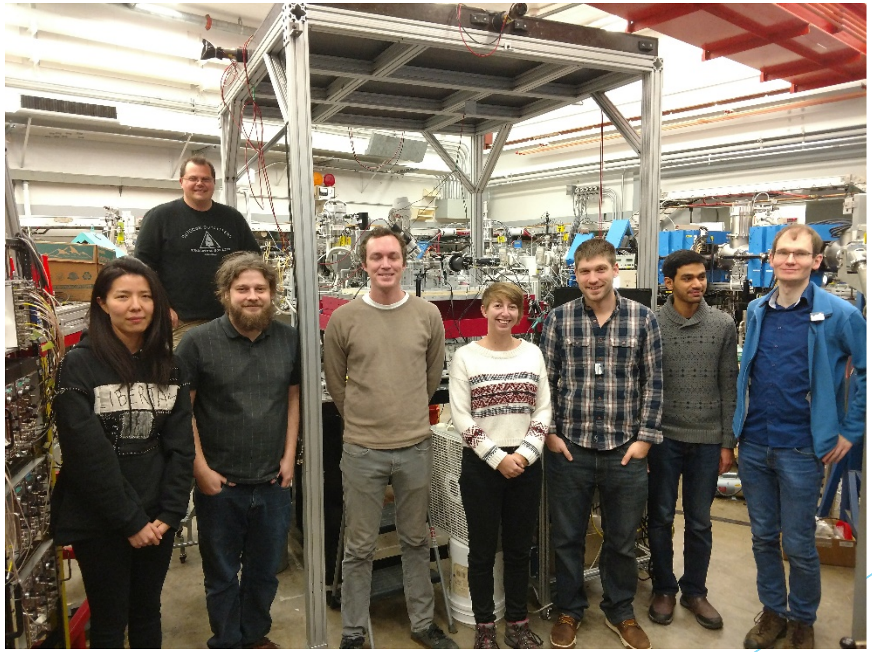


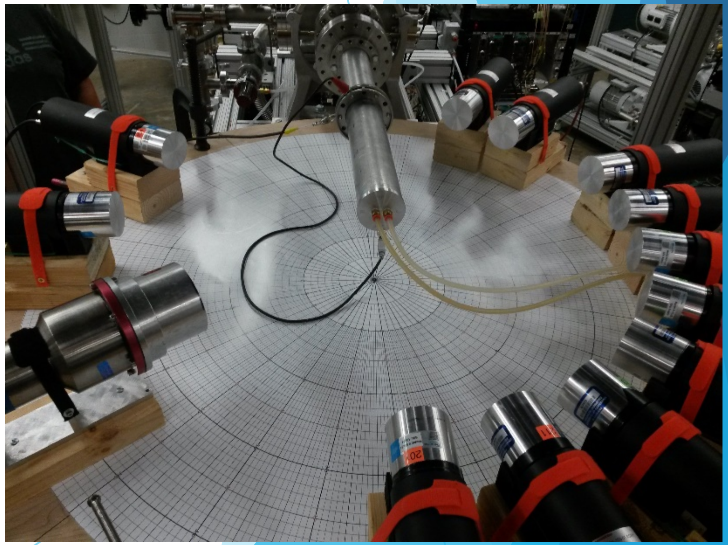








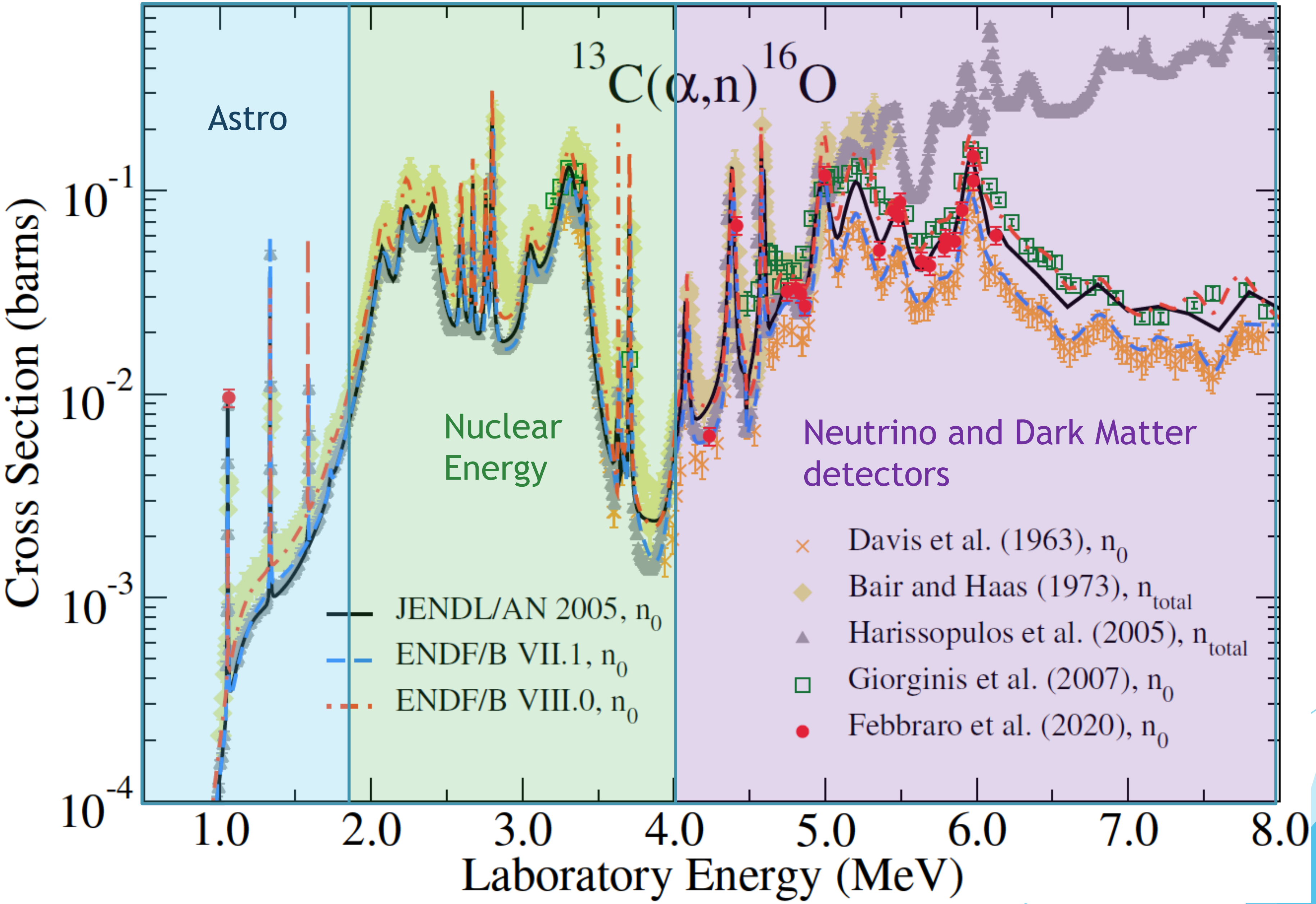




Collaborators

- 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

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



Measurement times ($$ or person power)

- neutron moderator counters
  - High yield (high efficiency, high beam currents)
  - No neutron energy information
  - Background subtraction is challenging
  - Angle integrated cross section
  - Efficiency depends on the neutron energy AND angular distributions
  - Efficiency (shape) must be obtained, largely, through simulation
  - High efficiency, high beam currents, very short measurement times

- Time-of-flight
  - low yield (far geometry, low beam currents)
  - Neutron spectroscopy, resolution depends on ToF distance and neutron energy
  - Backgrounds can much more easily identified
  - Partial, differential cross sections can be measured
  - Efficiency depends on the neutron energy, but neutron energy is now known
  - Efficiency (shape) must be obtained, largely, through simulation
  - ToF facilities have low beam intensity (100 nA), leading to long measurement times

- Spectrum unfolding
  - moderate yields (far geometric, high beam currents)
  - Neutron spectroscopy, dependent on quality of experimentally determined response matrix
  - Backgrounds can much more easily identified
  - Partial, differential cross sections can be measured
  - Efficiency depends on the neutron energy, but neutron energy is now known
  - Efficiency (shape) must be obtained, largely, through simulation
  - Higher beam intensities again possible, short measurement times

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 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 → $^{13}C(\alpha,n_2\gamma)$, $^{13}C(\alpha,n_{3+4}\gamma)$
  - $^{16}O(n,\alpha_0)^{13}C$ measurements give ground state cross section through detailed balance → $^{13}C(\alpha,n_0)$
    - New experiments at LANL
- Resolve the discrepancy with absolute normalization of cross section
  - Seems to be related to Carbon target structure or neutron detector efficiency
  - Probably best done using thick-target techniques or through heavy recoil detection of charged particles.