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CSEWG 2020, Online

Partial and differential (α,n) cross section measurements on boron, carbon, and oxygen isotopes

This research was supported by the National Science Foundation through Grant No. Phys-2011890, and the Joint Institute for Nuclear Astrophysics through Grant No. PHY-1430152 (JINA Center for the Evolution of the Elements).

A brief introductions to the state of (α,n) reactions in the literature

- Many of the high energy resolution (α,n) measurements were made at ORNL in the 60's and 70's using a flat efficiency graphite-sphere neutron counter.
- These are all **TOTAL** cross section measurements

PHYSICAL REVIEW VOLUME 128, NUMBER 1 OCTOBER 1, 1962

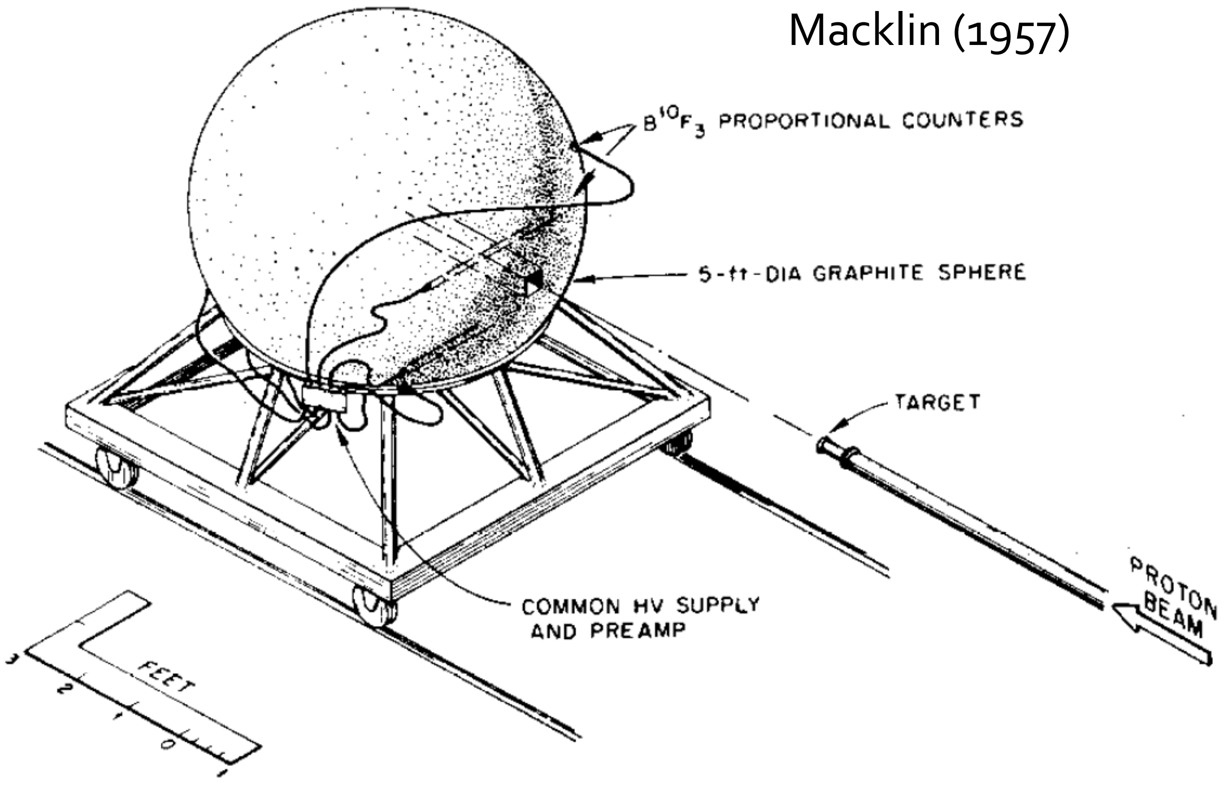
Level Structure in Ne^{22} and Si^{30} from the Reactions $O^{18}(\alpha,n)Ne^{21}$ and $Mg^{26}(\alpha,n)Si^{29}$

J. K. Bair and H. B. Willard
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received April 6, 1962; revised manuscript received June 20, 1962)

PHYSICAL REVIEW C VOLUME 7, NUMBER 4 APRIL 1973

Total Neutron Yield from the Reactions $^{13}C(\alpha,n)^{16}O$ and $^{17,18}O(\alpha,n)^{20,21}Ne$†

J. K. Bair
Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37830
and
F. X. Haas
Mound Laboratory, Miamisburg, Ohio
(Received 20 November 1972)



Macklin (1957)

A brief introductions to the state of (α,n) reactions in the literature

- In the 70's several differential and partial cross section measurements were made by Van der Zwan and Geiger at Chalk River
  - Stilbene crystals
  - Spectrum Unfolding
  - Partial and differential

2.A.1

Nuclear Physics A152 (1970) 481–494; © North-Holland Publishing Co., Amsterdam

THE ^{9}Be(α, n)^{12}C CROSS SECTION BETWEEN 1.5 AND 7.8 MeV

L. VAN DER ZWAN and K. W. GEIGER
Division of Physics, National Research Council, Ottawa 7, Canada

1.E.1: 2.A.1

Nuclear Physics A180 (1972) 615—624; © North-Holland Publishing Co., Amsterdam

THE ^{7}Li(α, n)^{10}B DIFFERENTIAL CROSS SECTION FOR α-ENERGIES OF UP TO 8 MeV

L. VAN DER ZWAN and K. W. GEIGER
Division of Physics, National Research Council, Ottawa K1A 0S1, Canada

1.E.1: 2.B

Nuclear Physics A216 (1973) 188–198; © North-Holland Publishing Co., Amsterdam

THE ^{10}B(α, n) ^{13}N,^{13}N* CROSS SECTION FOR α-ENERGIES FROM 1.0 TO 5 MeV

L. VAN DER ZWAN and K. W. GEIGER
Division of Physics, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0S1

1.E.1: 2.B

Nuclear Physics A246 (1975) 93–103; © North-Holland Publishing Co., Amsterdam

THE ^{11}B(α, n)^{14}N CROSS SECTION FOR α-ENERGIES UP TO 8 MeV

L. VAN DER ZWAN and K. W. GEIGER
Division of Physics, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0S1

1.E.1: 2.B

Nuclear Physics A284 (1977) 189–198; © North-Holland Publishing Co., Amsterdam

ENERGY LEVELS IN ^{23}Na FROM THE ^{19}F(α, n)^{22}Na REACTION

L. VAN DER ZWAN and K. W. GEIGER
Division of Physics, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0S1

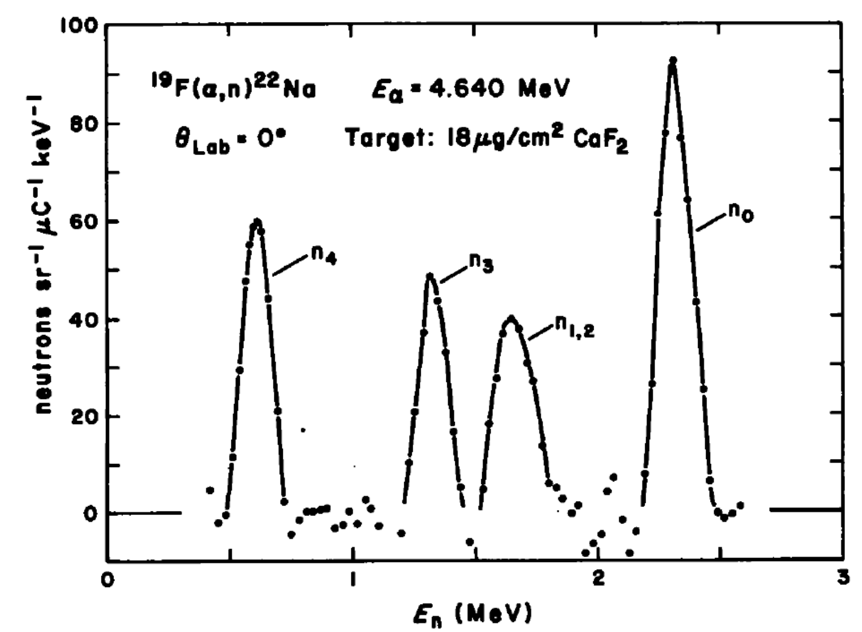
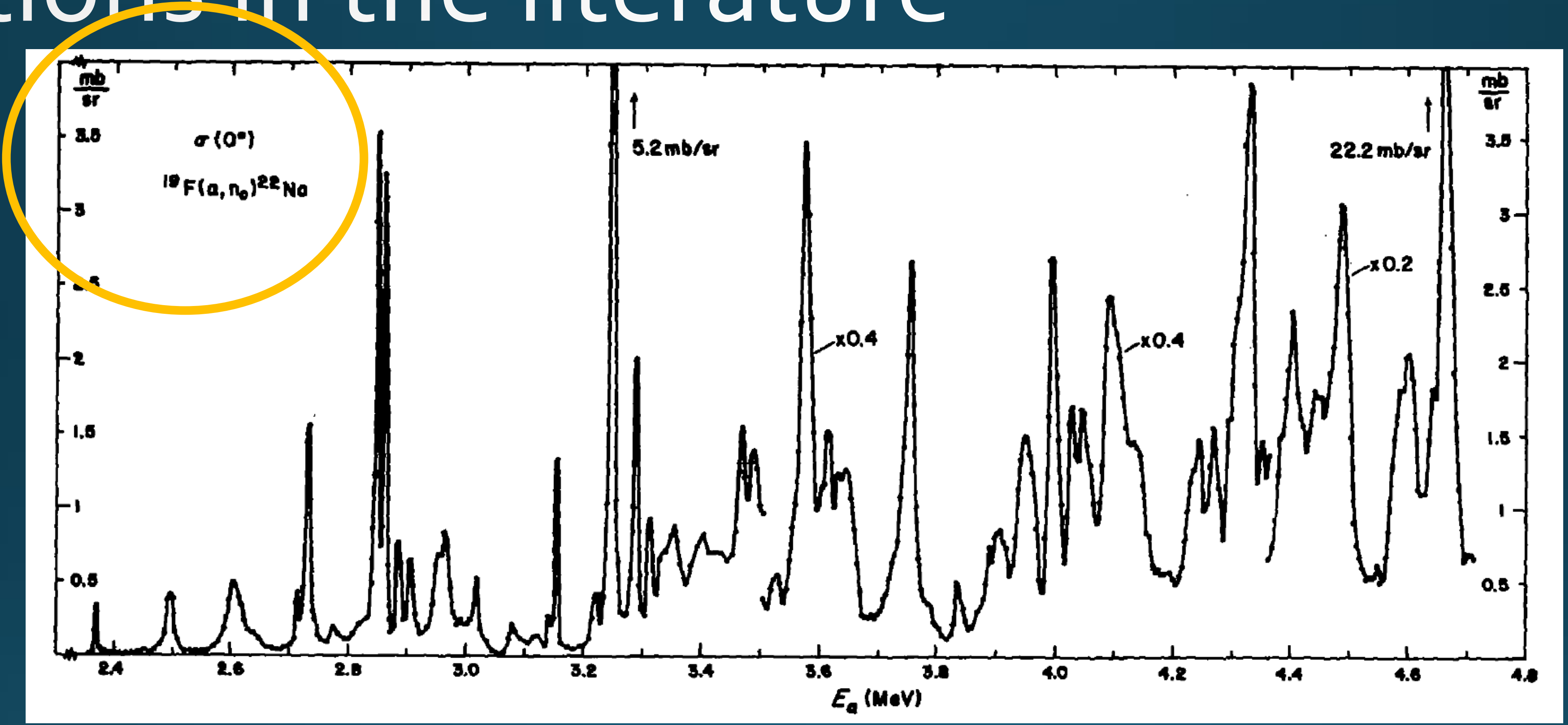


Fig. 1. Neutron spectrum from a ^{19}F target obtained with a stilbene scintillator.

Van der Zwan and Geiger (1977)

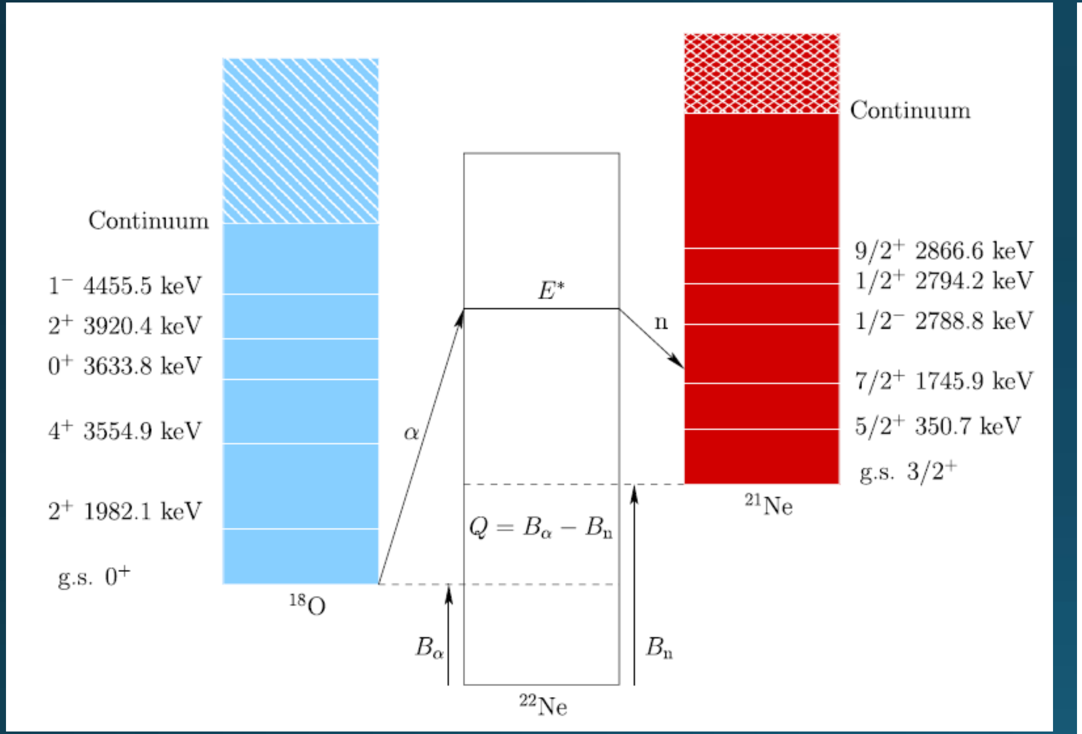
A brief introductions to the state of (α,n) reactions in the literature

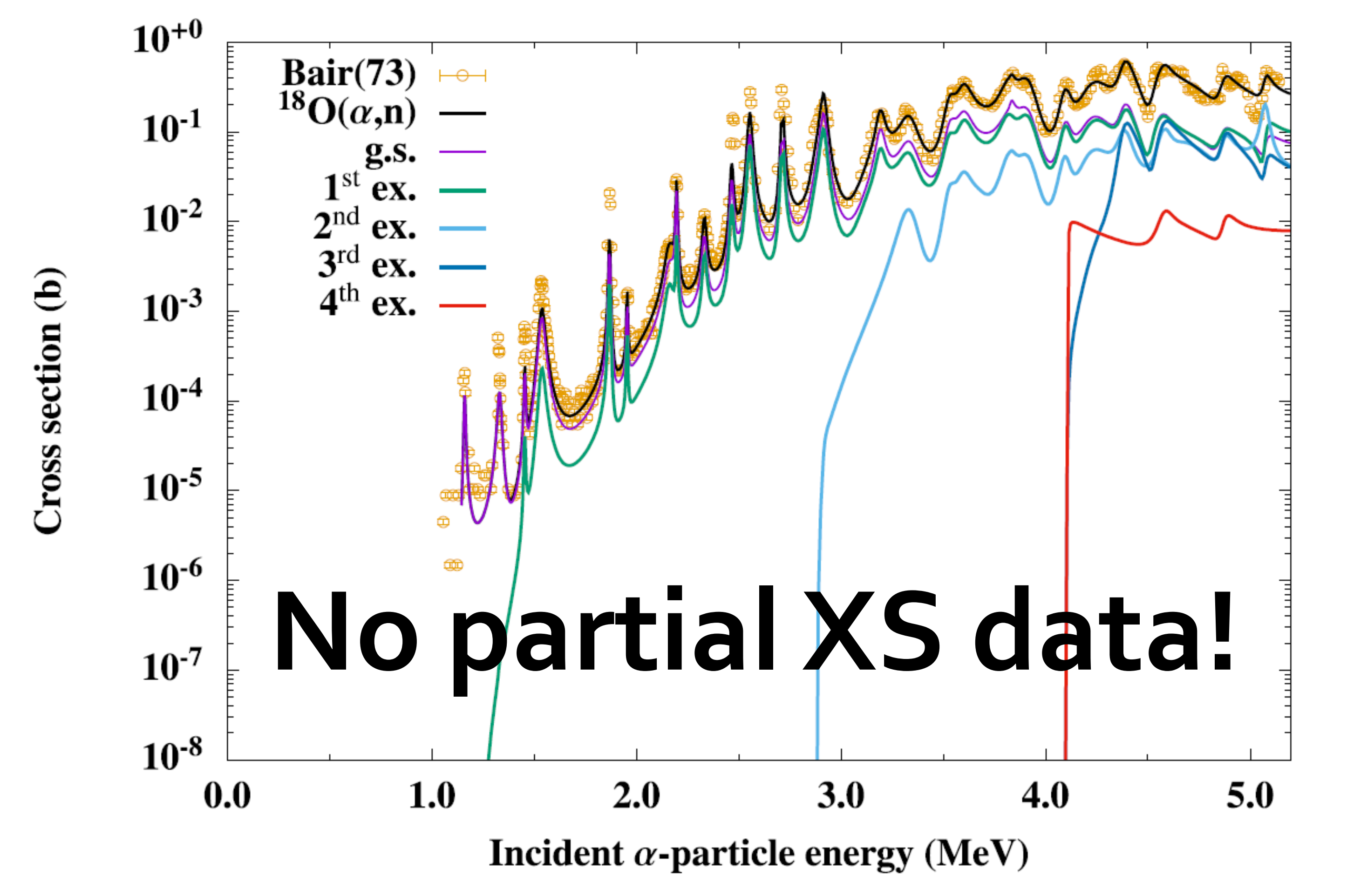


- Limited angular coverage
- Can't convert to angle integrated cross section
- Are usually not used in the compilations

Partial Cross Sections

Pigni *et al.* (2020)

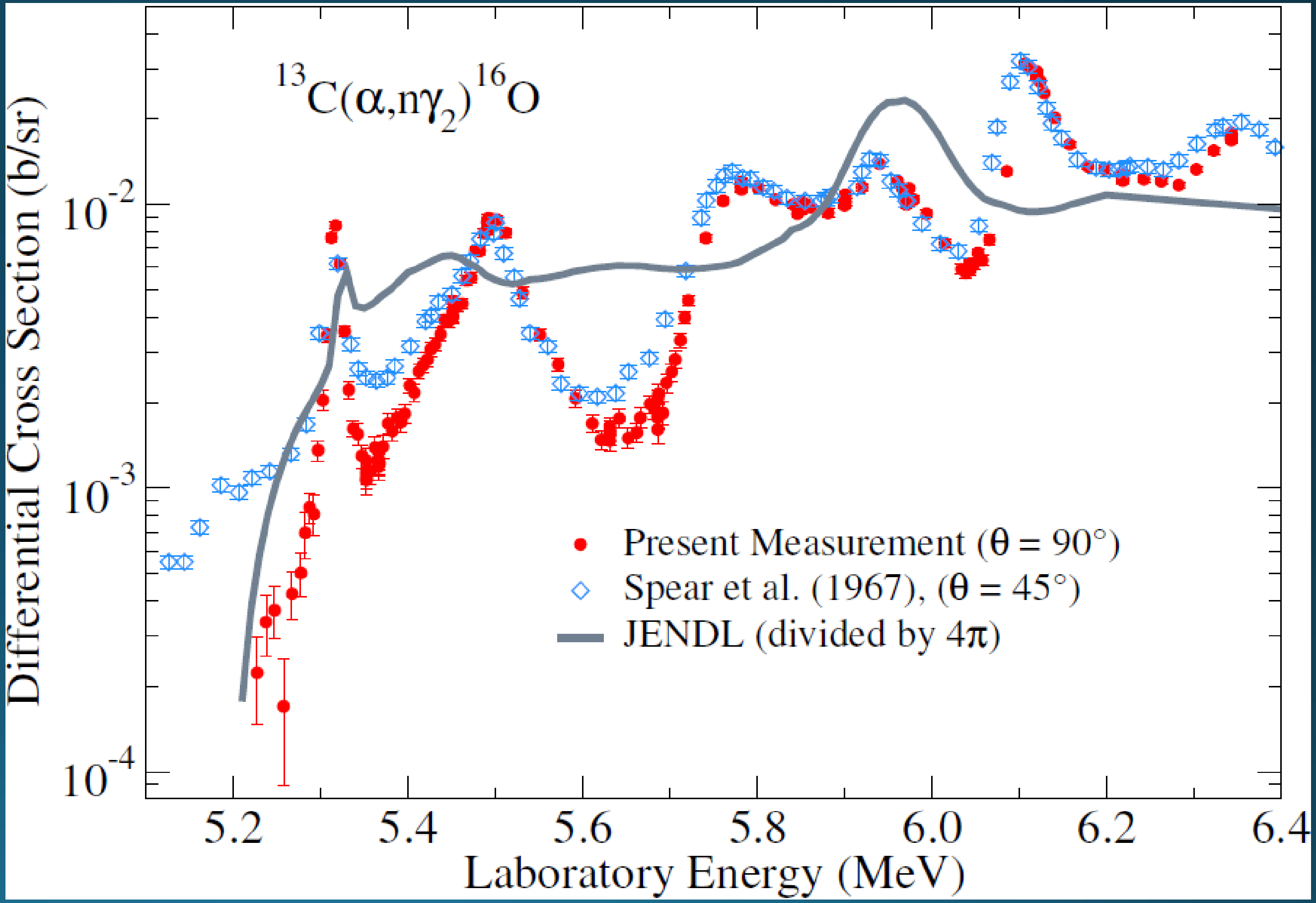




Partial cross sections in the evaluations are based on statistical model calculations, which are not very accurate (order of magnitude).

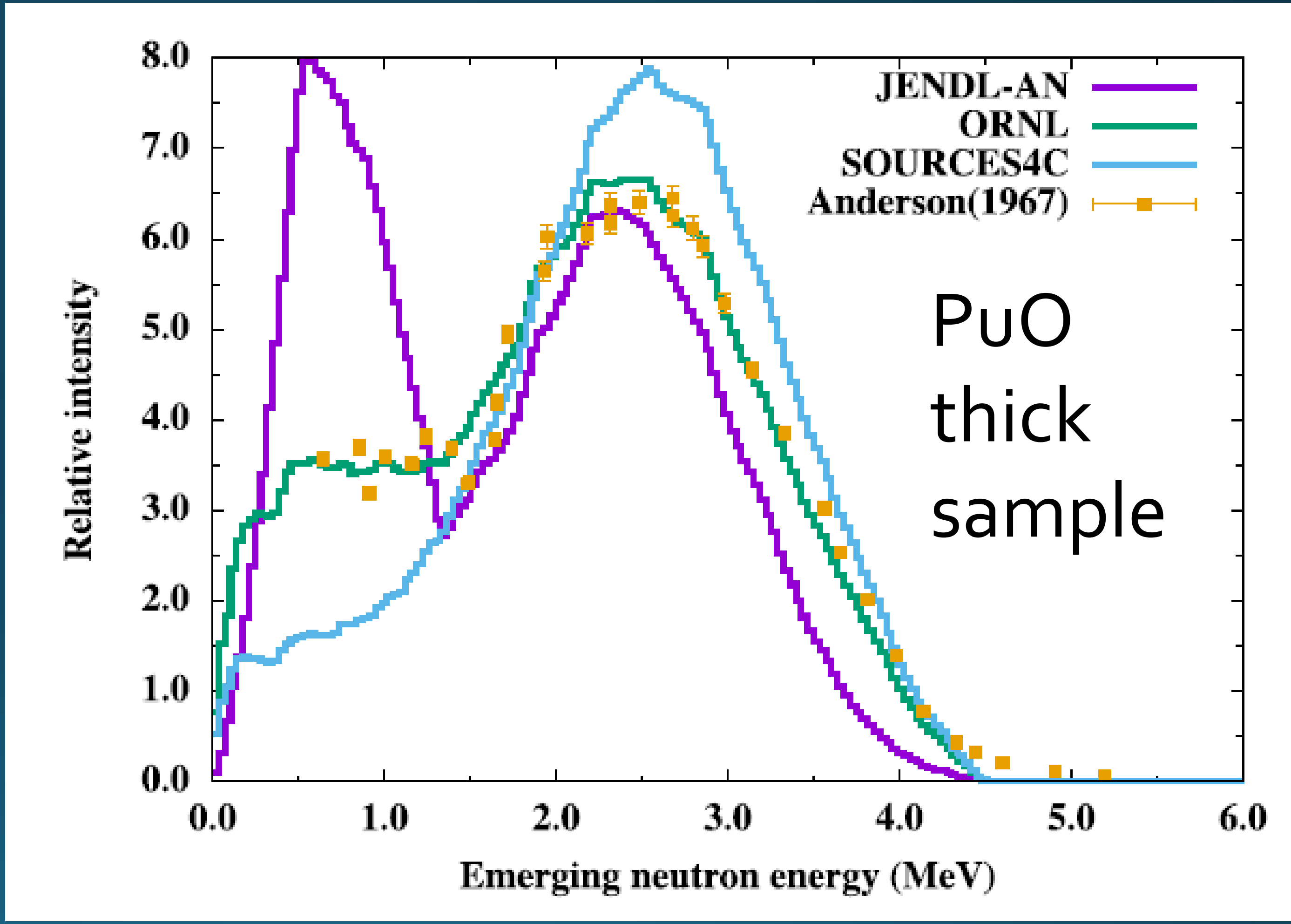
How are these partial cross section estimated in the compilations?

- Total cross section is measured
- Branching ratio is then calculated from a statistical model
- But **statistical models are not very accurate for light nuclei**!
  - Population of different resonances



The need for partial cross sections

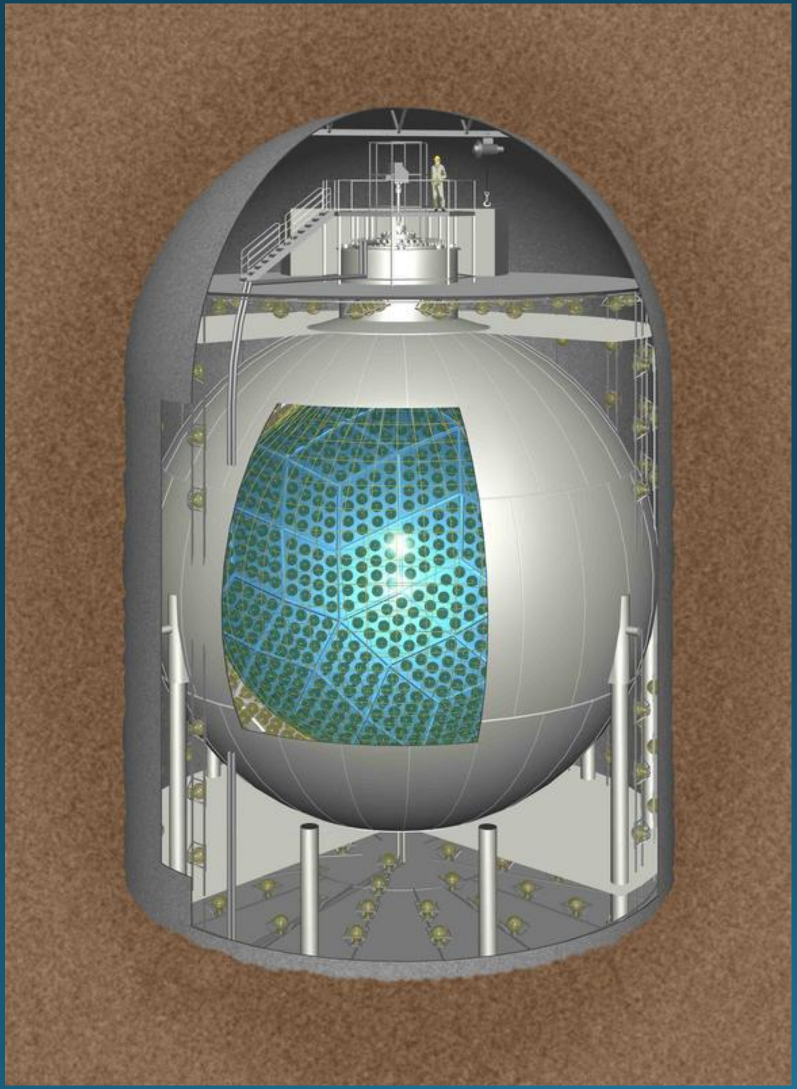
- Neutron energy spectrum for a Plutonium Oxide matrix
  - Pu decay produced neutrons up to about 9 MeV
- Use of partial $^{17,18}O(\alpha,n)$ cross sections from JENDL-AN give a very poor reproduction of the thick target data
- Need **partial cross sections**



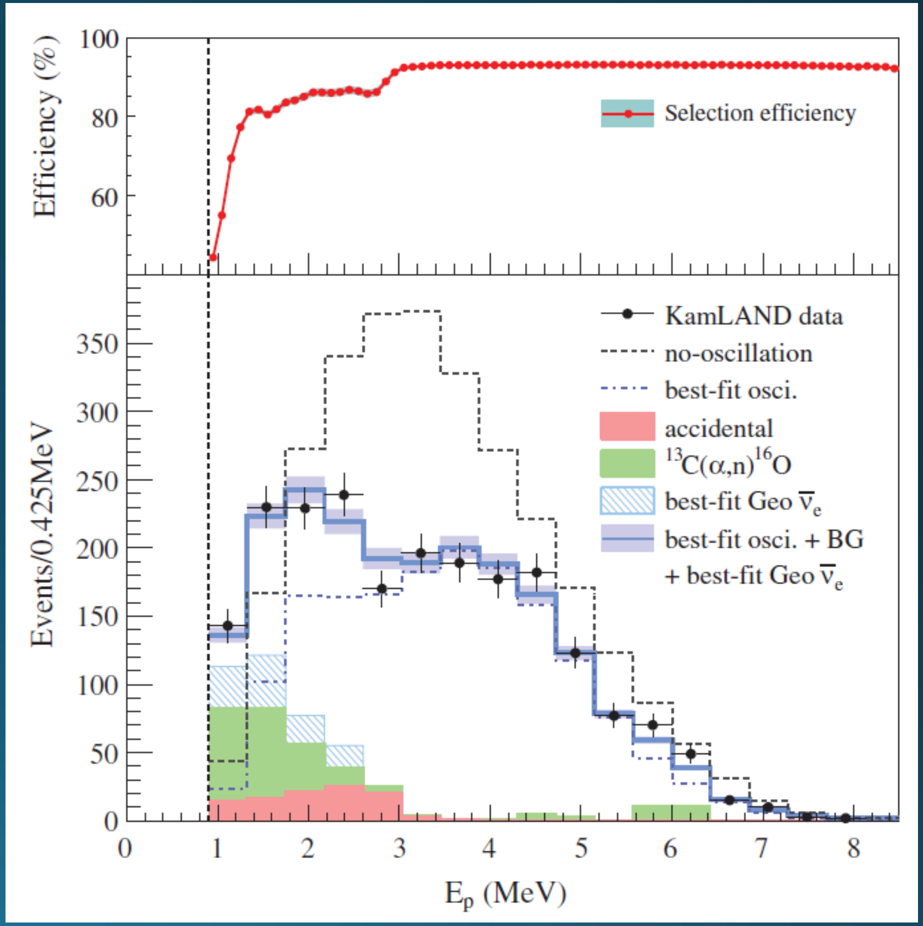
Pigni *et al.* (2020)

Background reactions in neutrino detectors

- Actinide decay chains produce α-particles up to 9 MeV (Radon→Po)
- $^{13}C(\alpha,n)^{16}O$ (KAMLAND), $^{17}O(\alpha,n)^{20}Ne$, $^{18}O(\alpha,n)^{21}Ne$ (SNO) act as a neutron background sources
- Need **partial cross sections** in order to simulate accurately



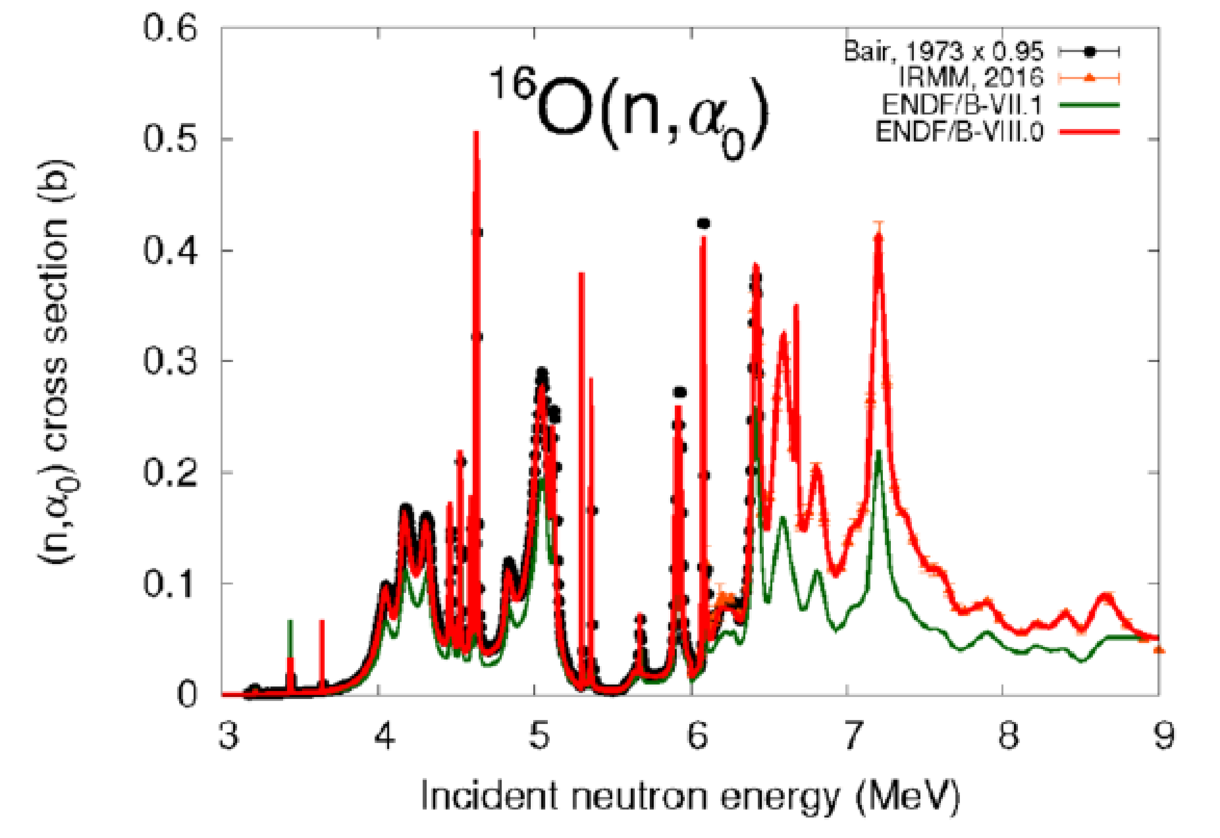
KAMLAND website

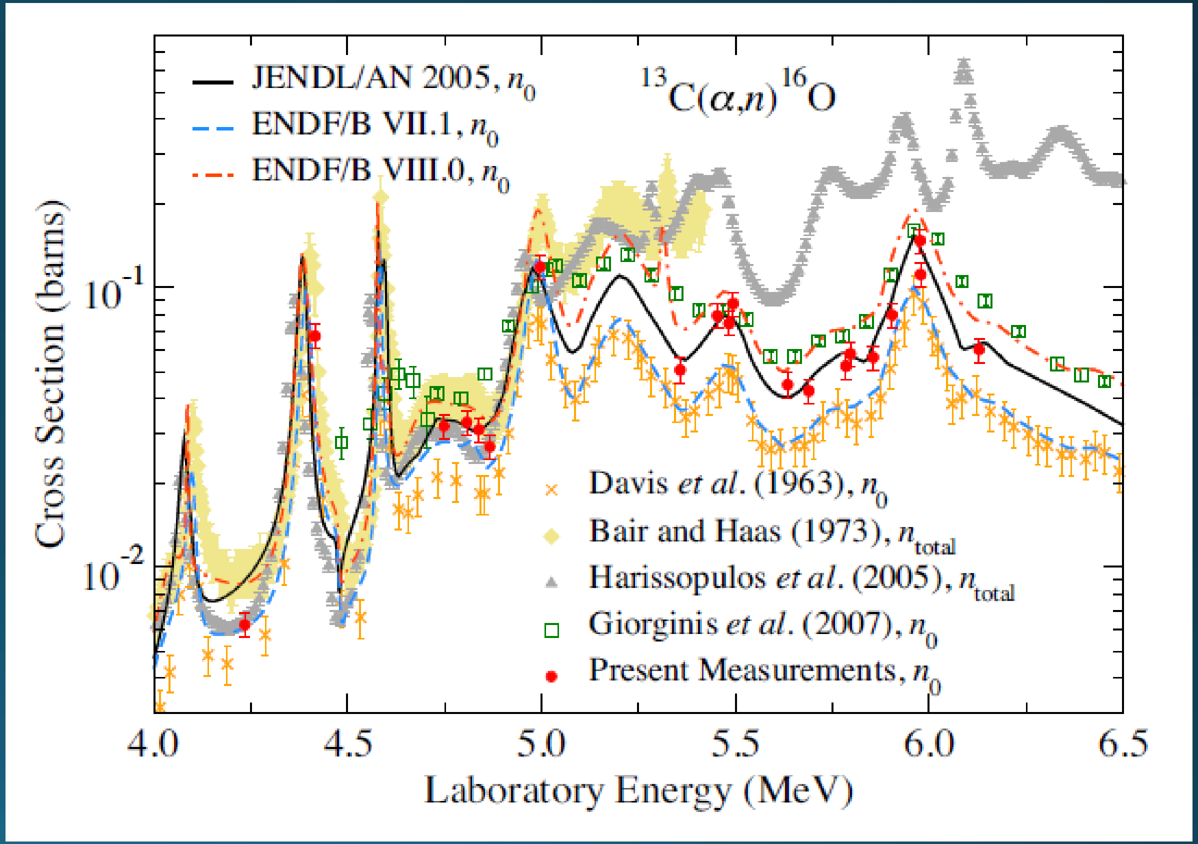


Gando *et al.* (2011)

Neutron Data Evaluation

Detailed balance





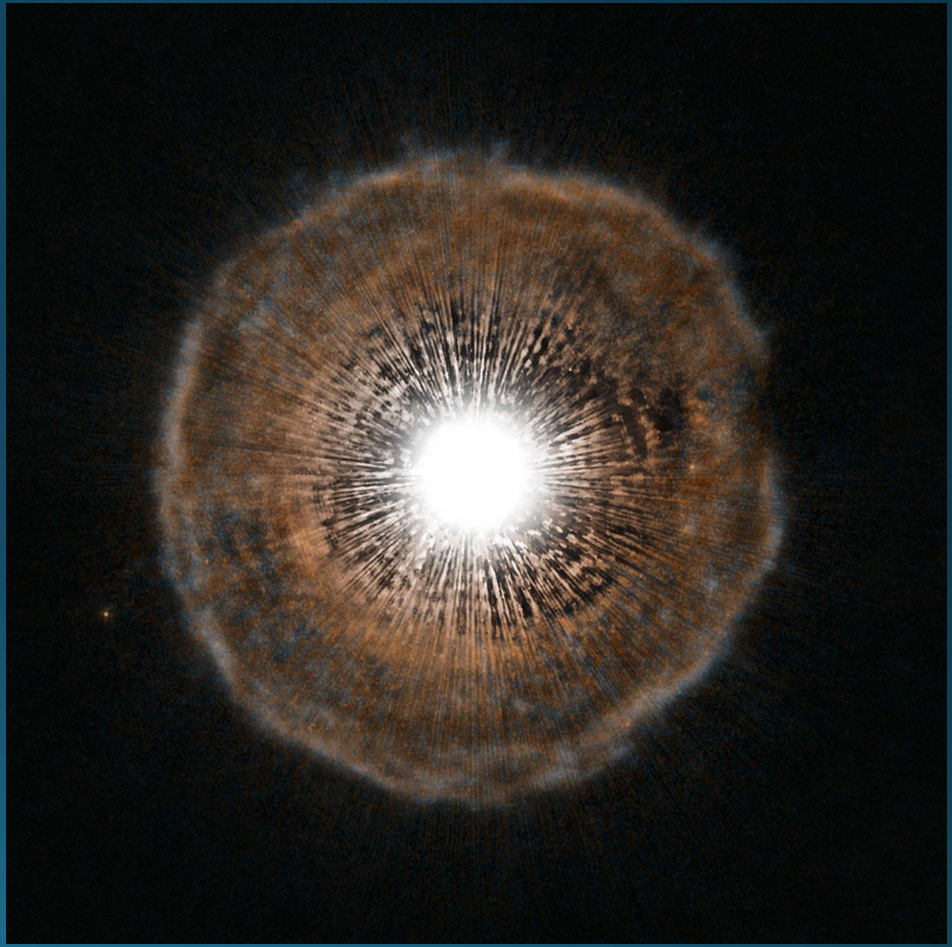
ENDF/B VIII, Brown et al. (2018)

Febbraro et al. (2020)

Need ground state partial cross section

Nuclear Astrophysics

- First star nucleosynthesis: $^{10}B(\alpha,n)^{13}N$, $^{11}B(\alpha,n)^{14}N$
- Primary *s*-process reactions: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$
- Secondary *s*-process reactions: $^{17}O(\alpha,n)^{20}Ne$, $^{18}O(\alpha,n)^{21}Ne$, $^{25}Mg(\alpha,n)^{28}Si$, $^{26}Mg(\alpha,n)^{29}Si$



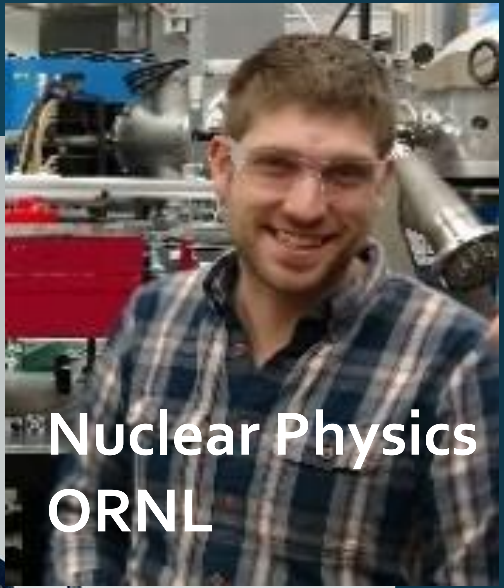
The Red Giant, U Cam, ESA/NASA

How can we get this data in an efficient and cost effective way?

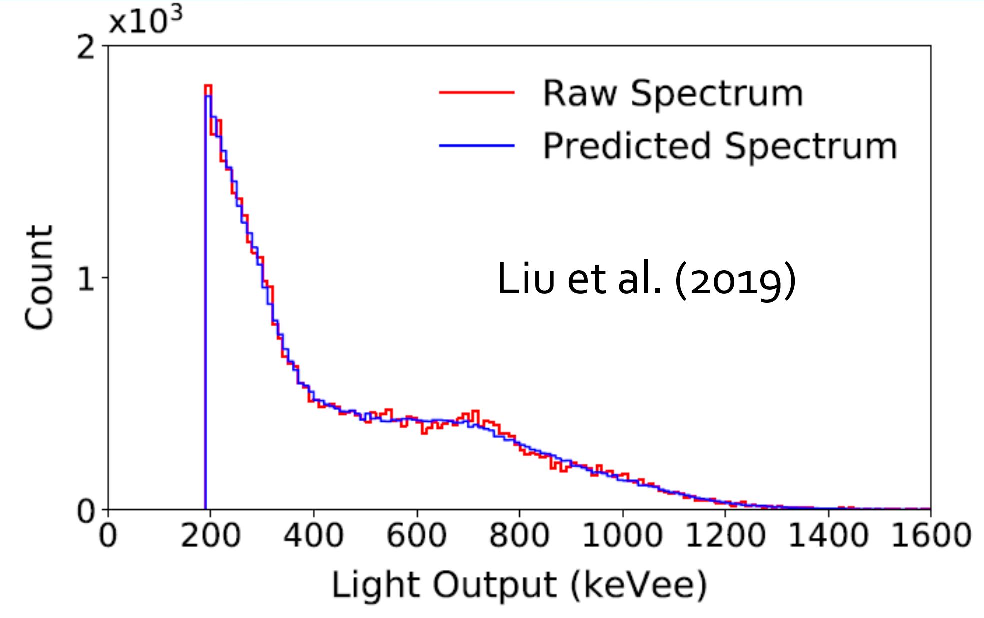
- The ORNL Deuterated Spectroscopic Array --- ODeSA
  - High efficiency, cost effective detector
- High beam current, good energy resolution accelerator
  - Santa Ana Accelerator --- University of Notre Dame
- Up front hurdles: calibration (response matrix) and unfolding algorithms
- 1 to 2 weeks of beam time, full differential and partial cross sections can be measured
- Data analysis is main time component (1-2 years of dedicated graduate student work)

Febbraro et al. (2019)

Michael Febbraro



Spectrum Unfolding



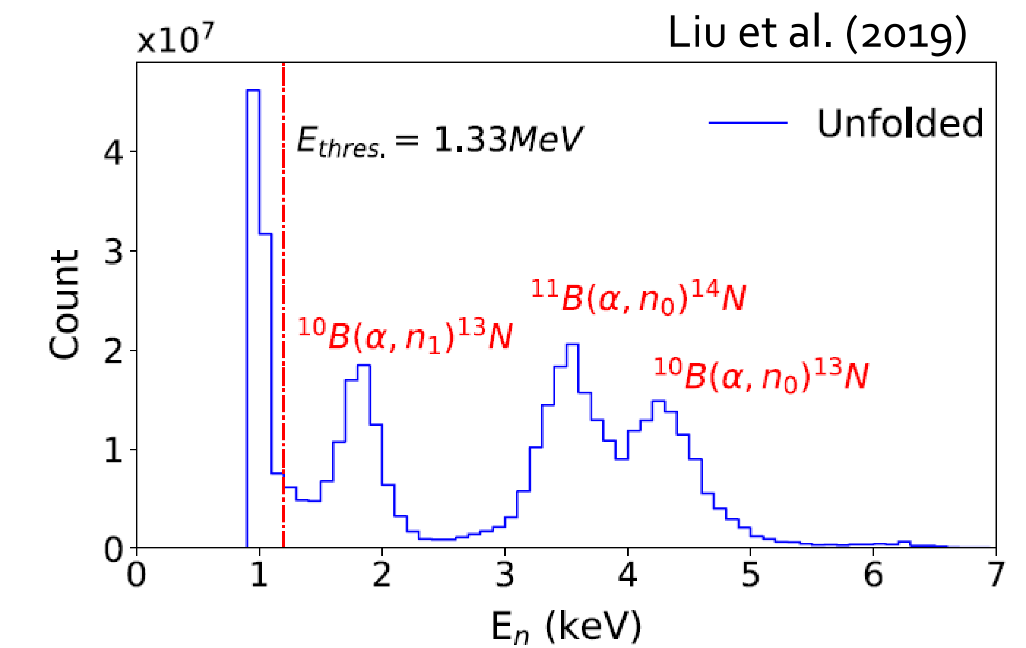
Light output spectrum

+

Maximum Likelihood

=

Neutron Energy Spectrum



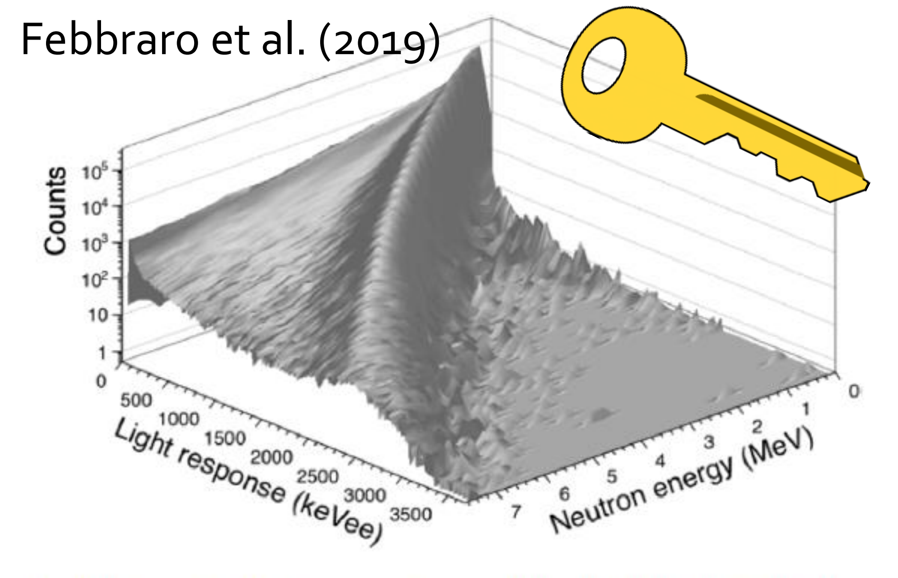


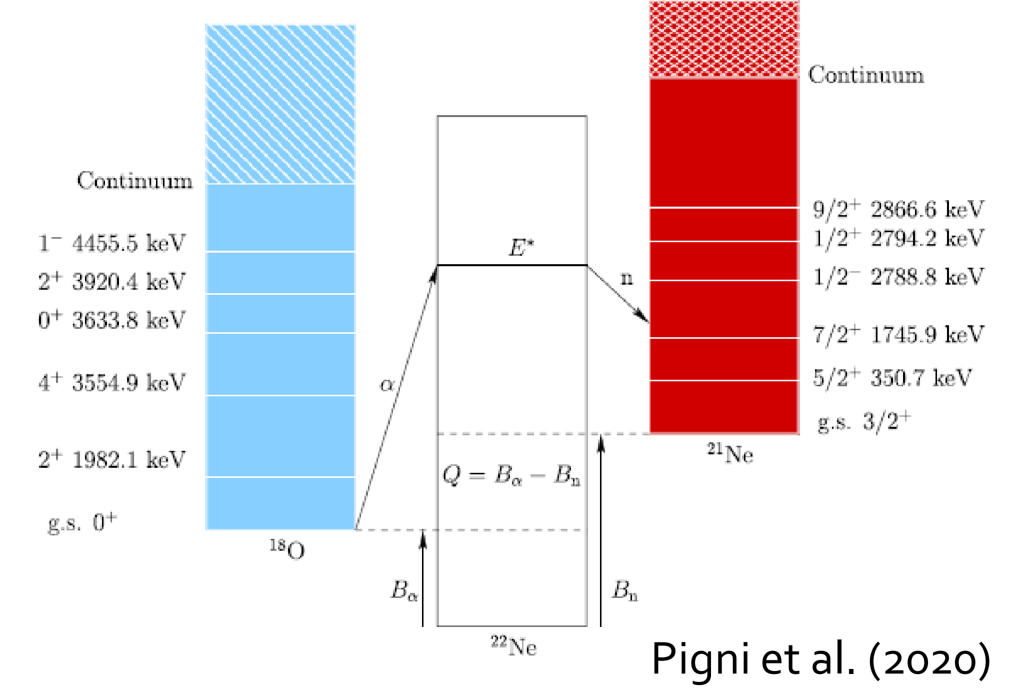
Fig. 9. Response matrix generated using a broad energy neutron source from a thick target $^{27}Al(d,n)$ reaction at E_d = 7.44 MeV [12].

Response matrix

Calibrations preformed at the **Edwards Accelerator Laboratory** at OU

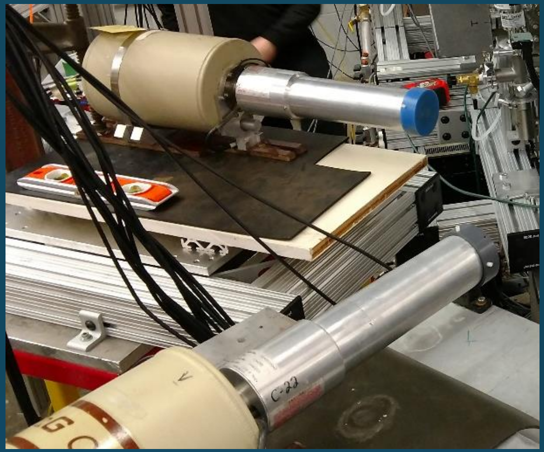
Secondary γ-ray angular distributions

- Provides a complementary method of measuring many excited state reactions



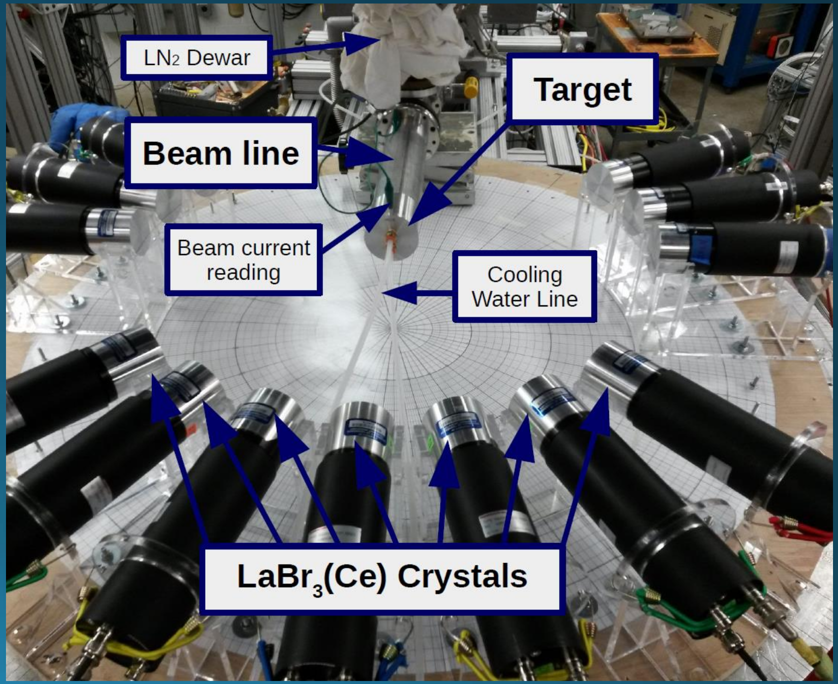
Pigni et al. (2020)

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).



GEANIE HPGe detectors on loan from LANL **Aaron Couture**

HAGRiD array of $LaBr_3$ detectors from **Kate Jones** at UTK



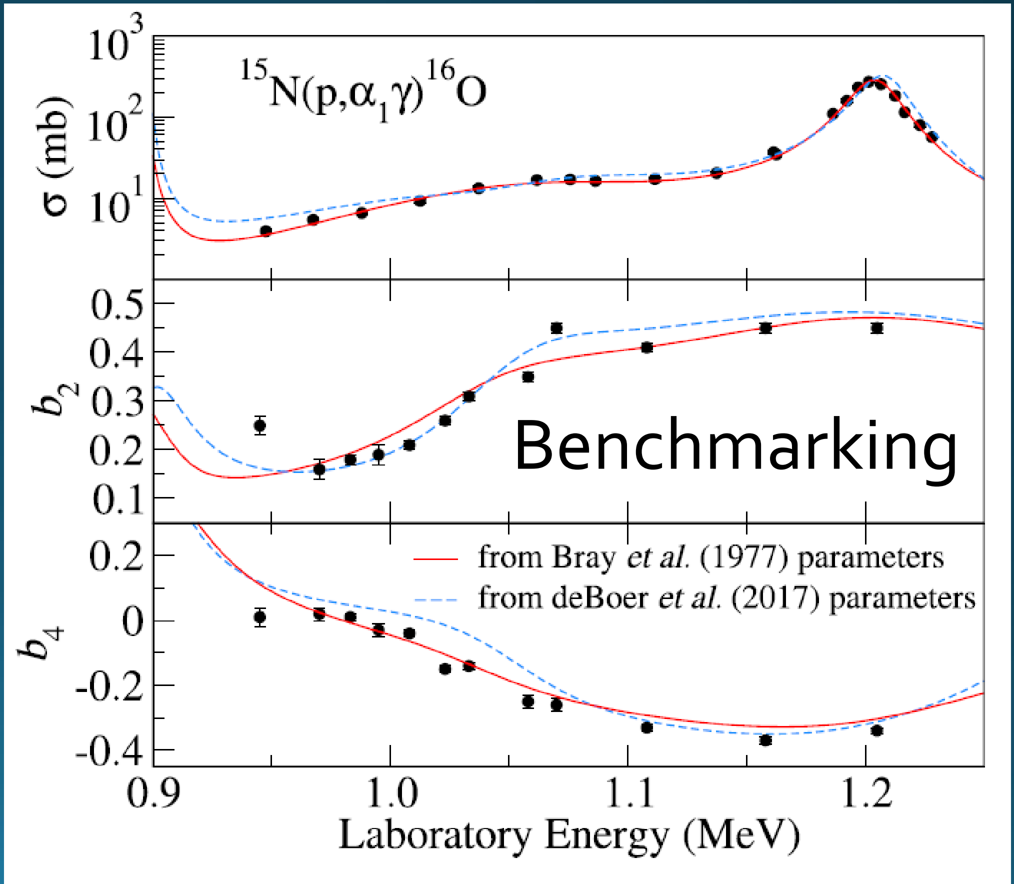
Secondary γ-ray decays from the partial-wave T matrix with an R-matrix application to $^{15}N(p, \alpha_1\gamma)\,^{12}C$

Carl R. Brune *
Edwards Accelerator Laboratory, Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA

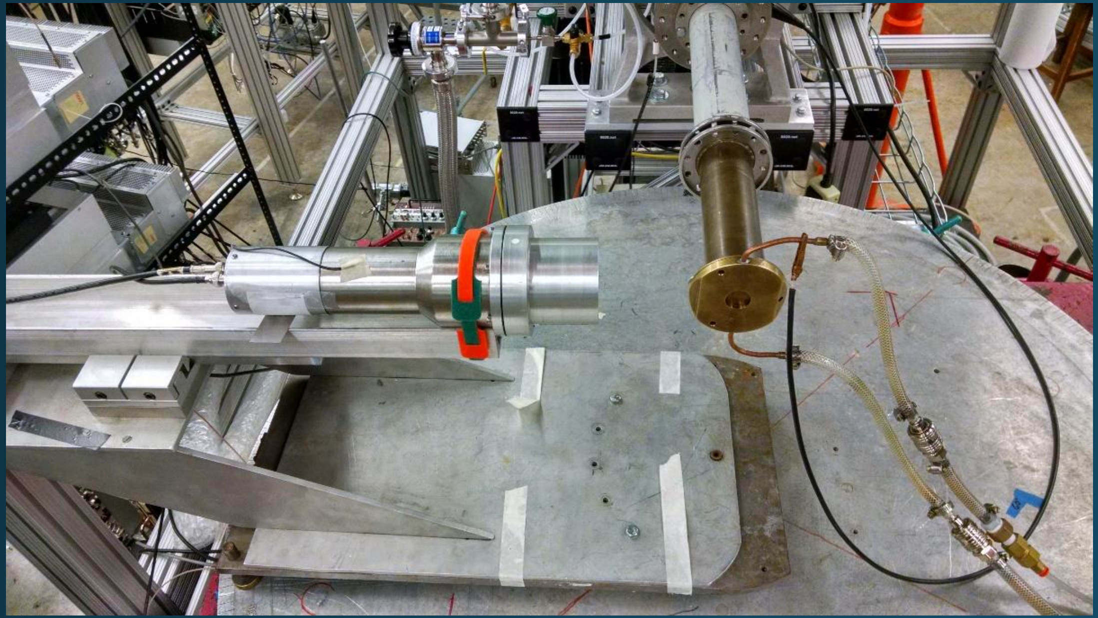
R. James deBoer †
The Joint Institute for Nuclear Astrophysics, Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA

- $^{13}C(\alpha,n\gamma)^{16}O$
- $^{17}O(\alpha,n\gamma)^{20}Ne$
- $^{18}O(\alpha,n\gamma)^{21}Ne$
- $^{25}Mg(\alpha,n\gamma)^{28}Si$

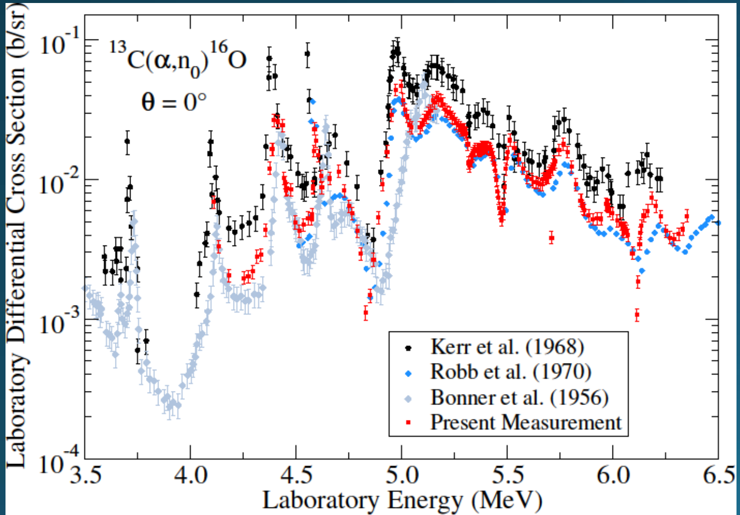
AZURE2
R-matrix code
azure.nd.edu

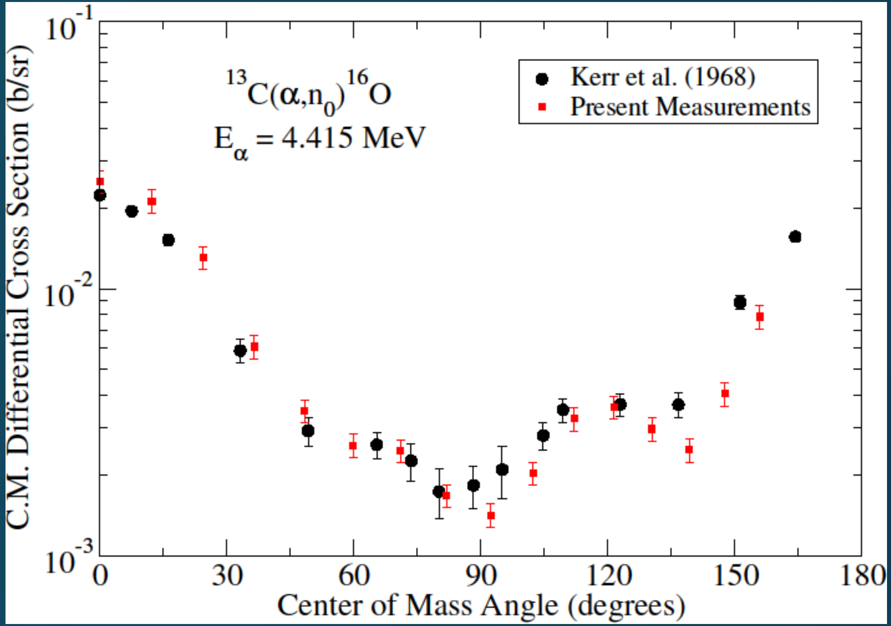


$^{13}C(\alpha,n)^{16}O$



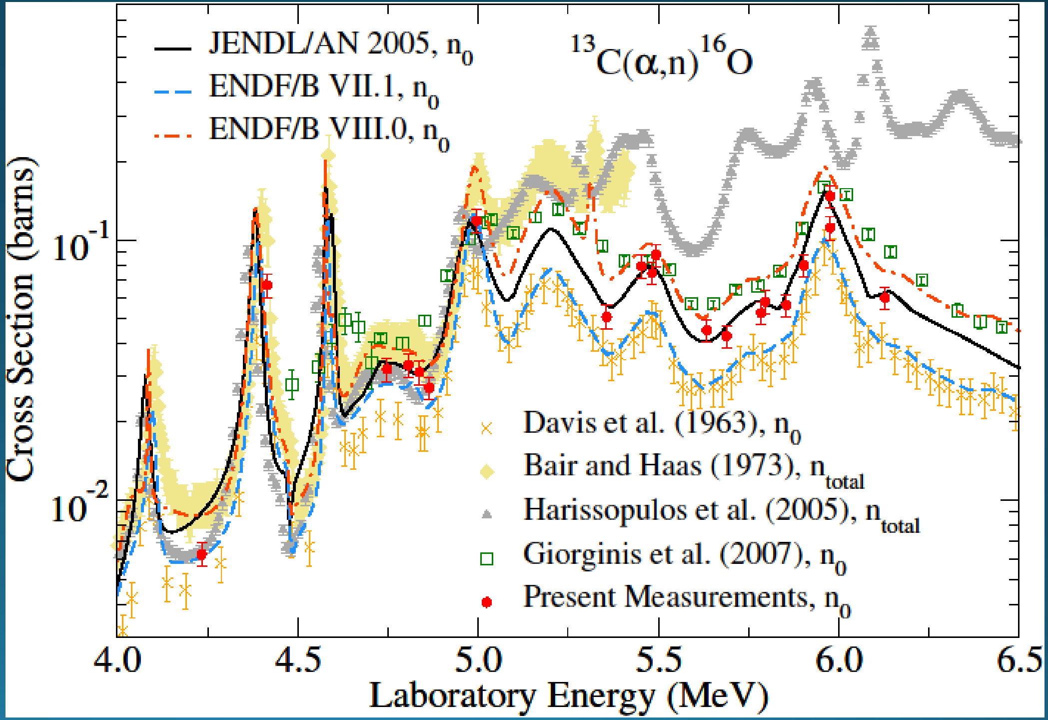
2016 setup



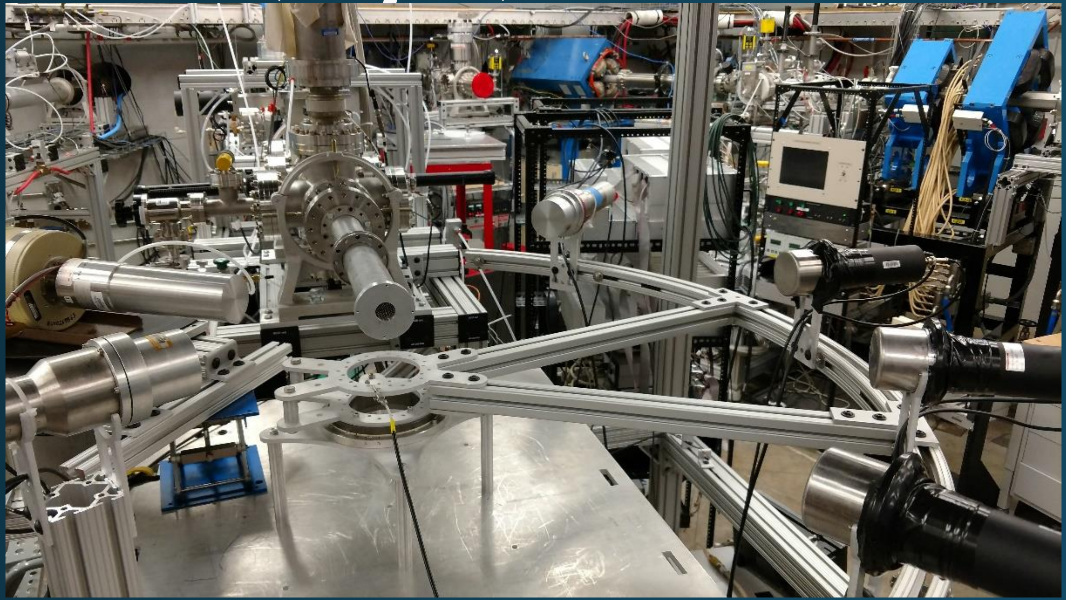


20, 16 point angular distributions

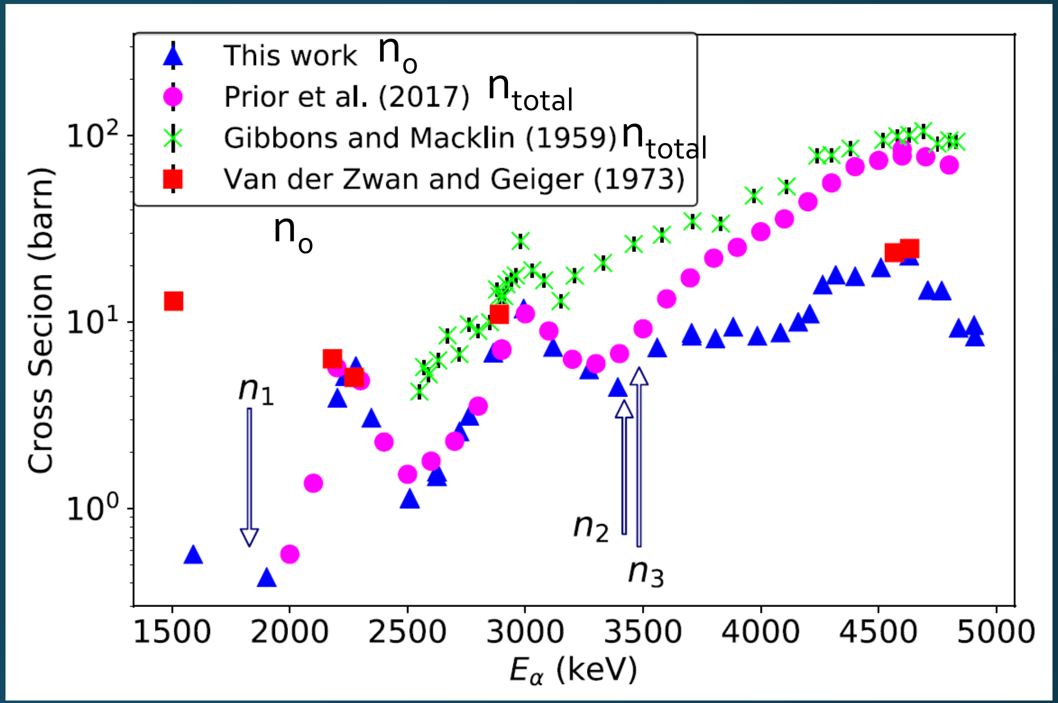
Febbraro et al. (2020)

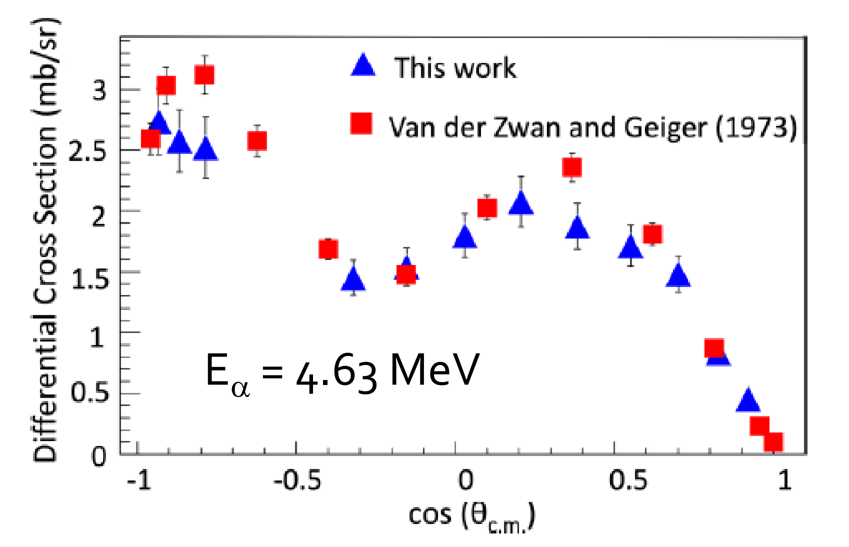


$^{10}B(\alpha,n)^{13}N$

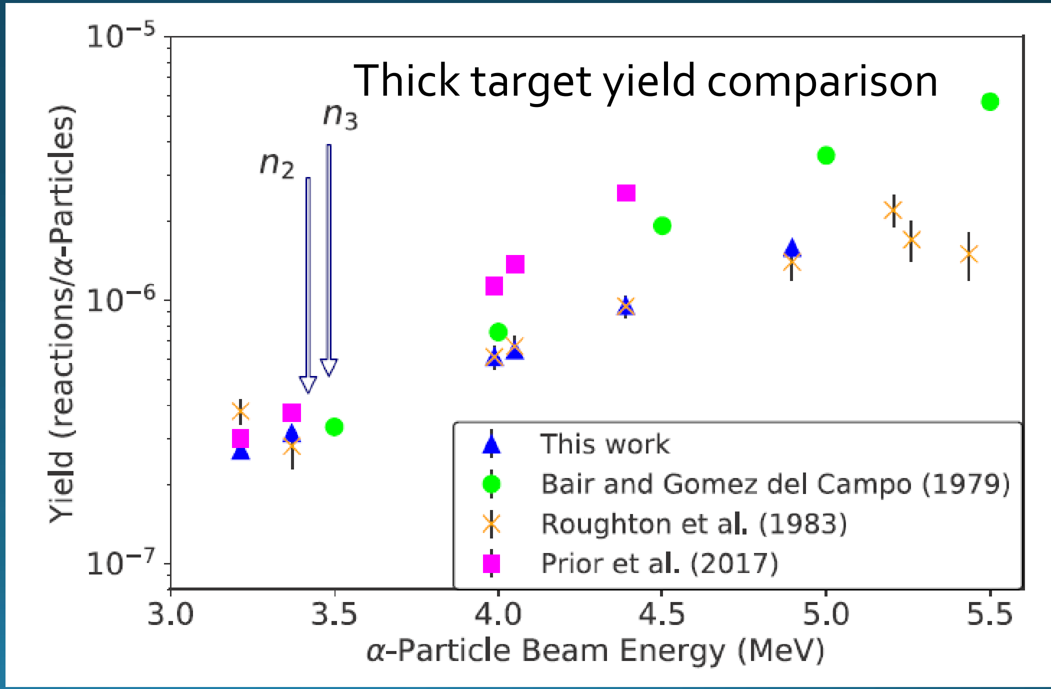


2017 Setup



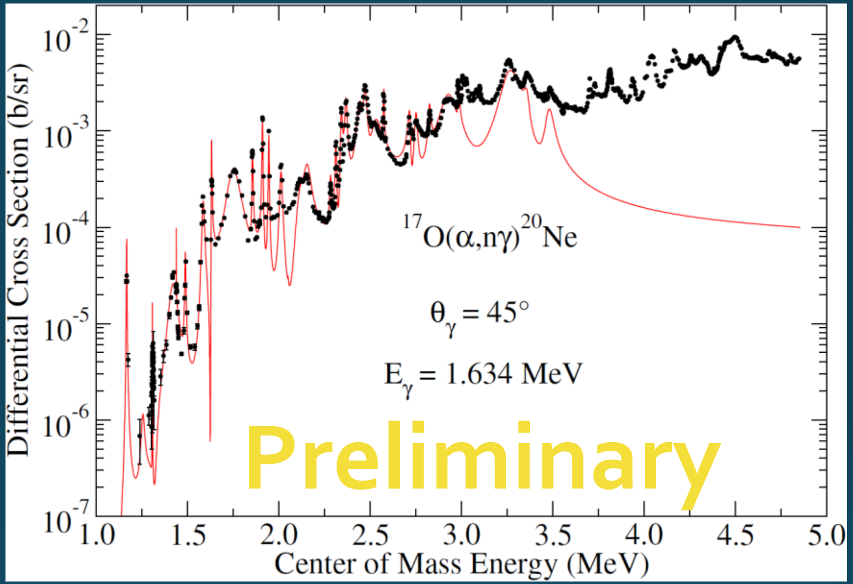


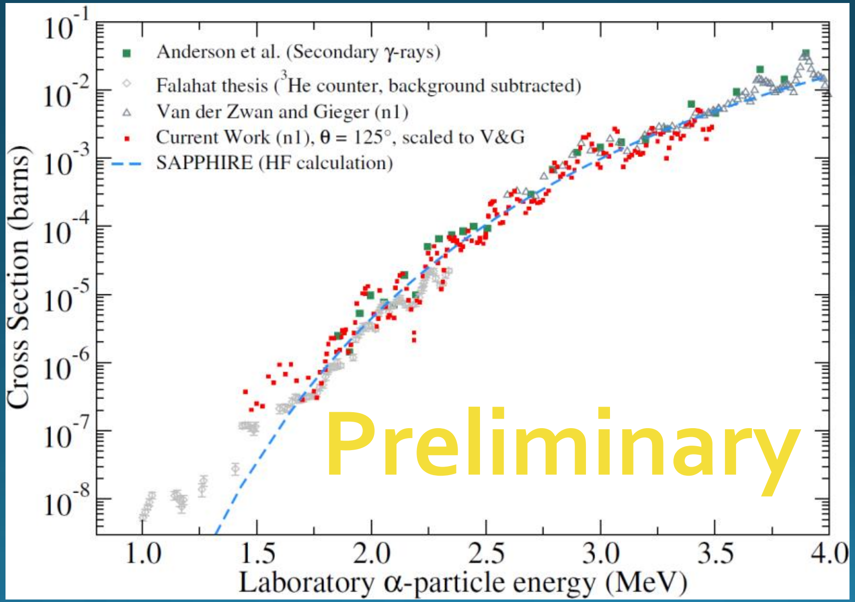
Liu et al. (2019)



$^{17}O(\alpha,n\gamma)^{20}Ne$ & $^{25}Mg(\alpha,n\gamma)^{28}Si$

2018, Secondary γ-ray angular distribution setup with HAGRiD

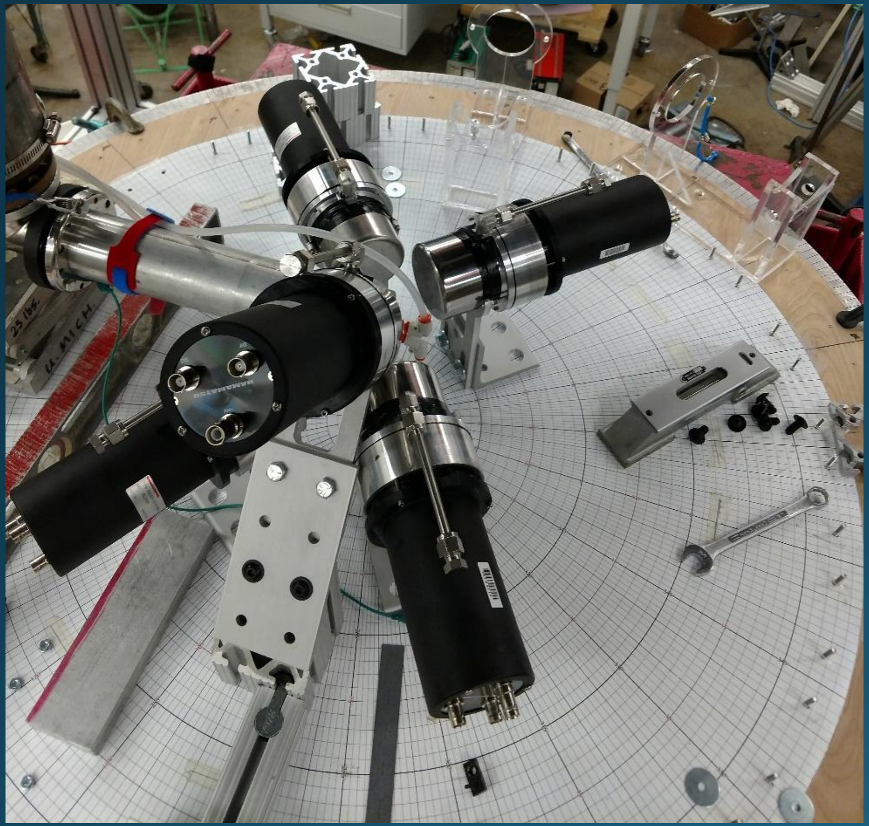




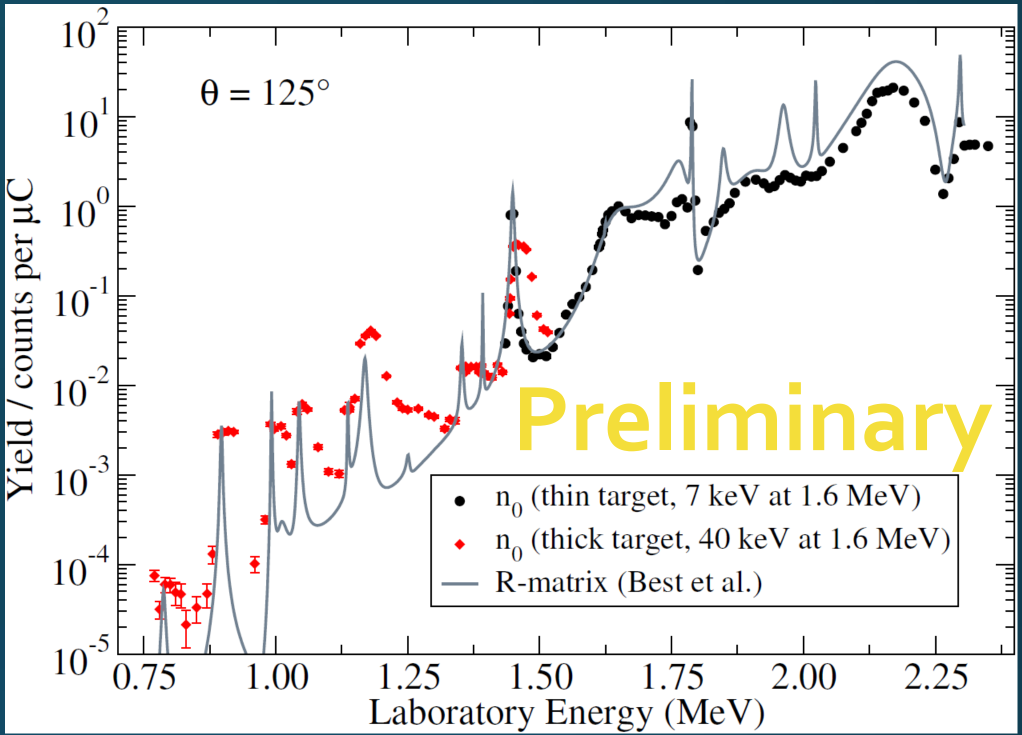
Kevin Macon

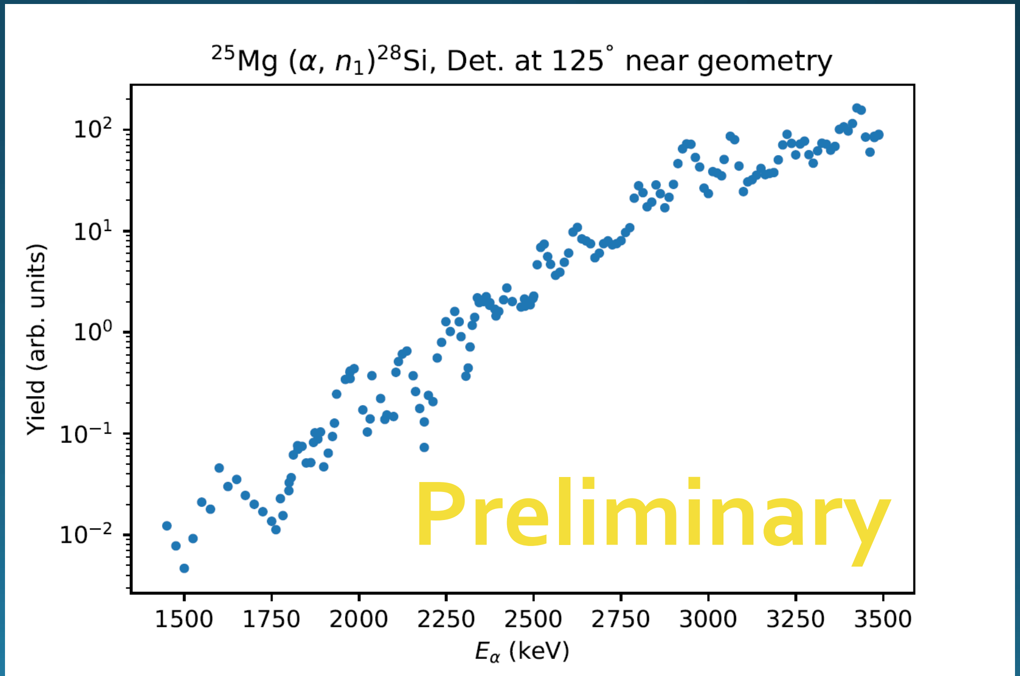
Shahina Shahina

$^{17}O(\alpha,n)^{20}Ne$ & $^{25}Mg(\alpha,n)^{28}Si$

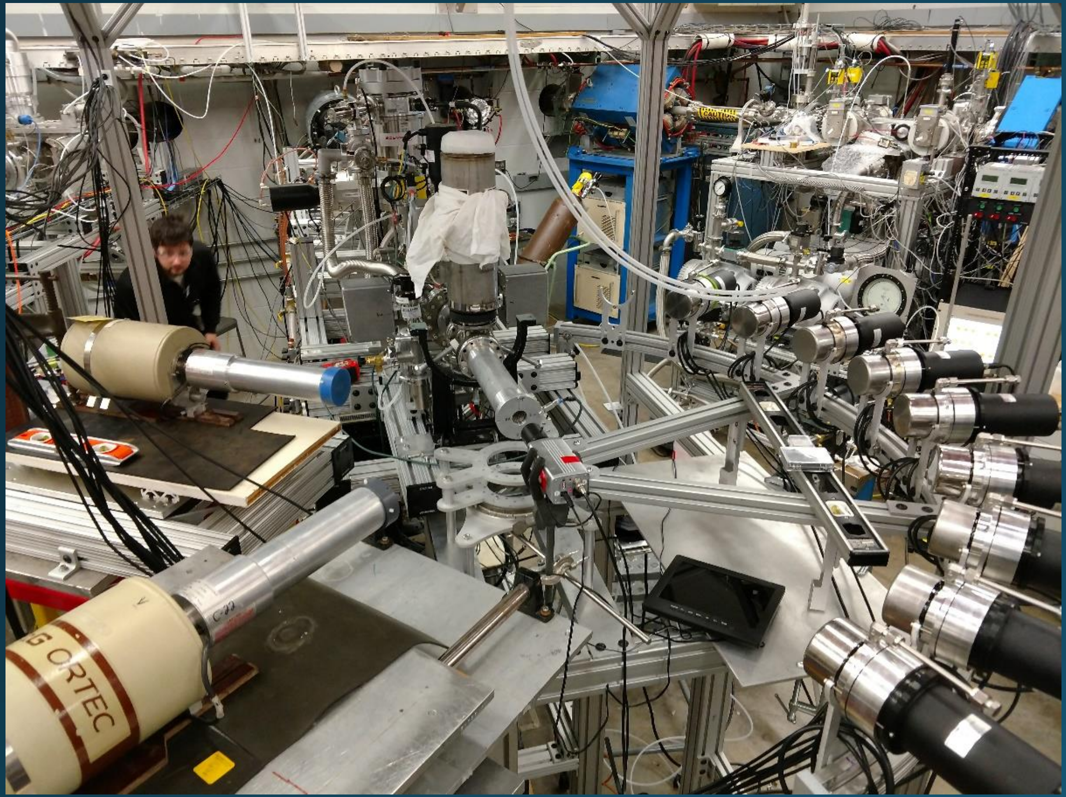


2018, Close geometry setup



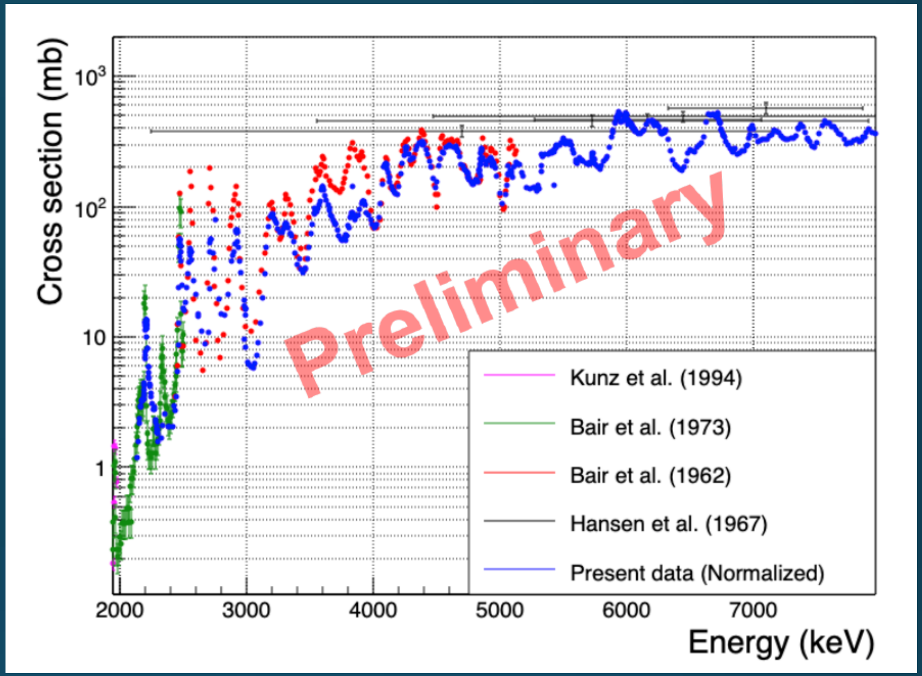


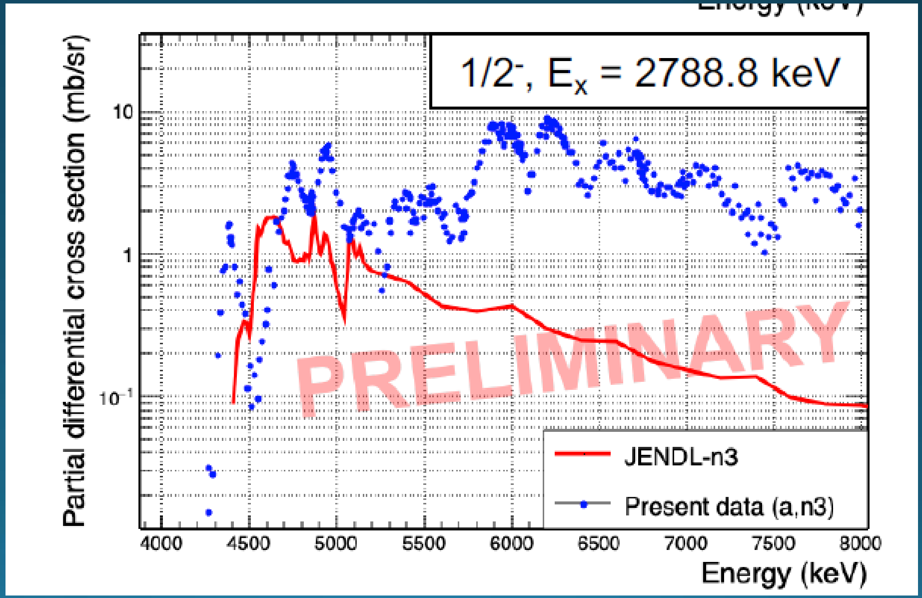
$^{18}O(\alpha,n)^{21}Ne$



2019 Setup

600 energy points at 10 or more angles from 2 to 8 MeV



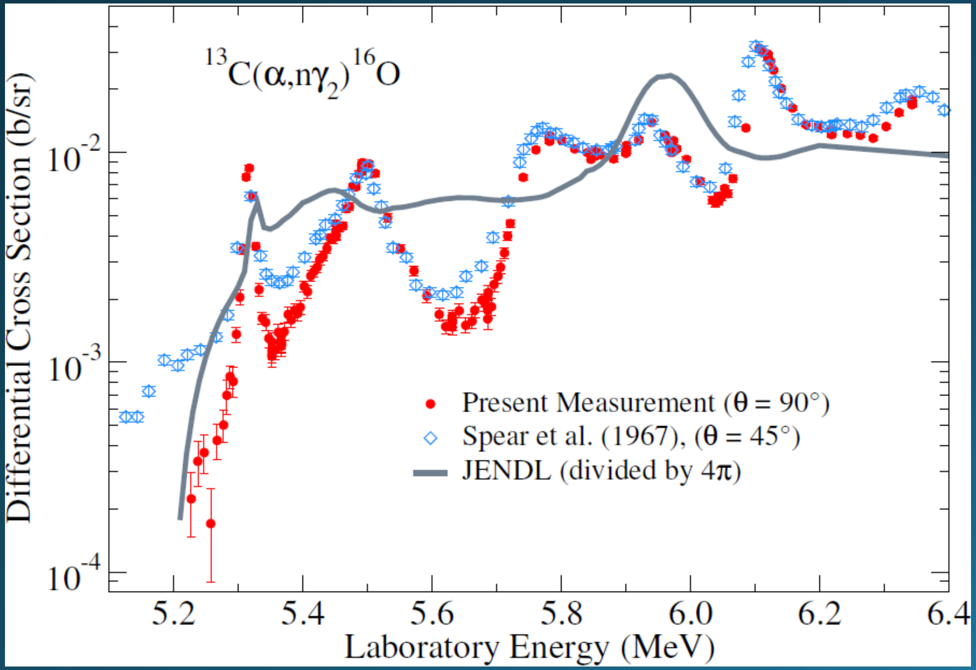


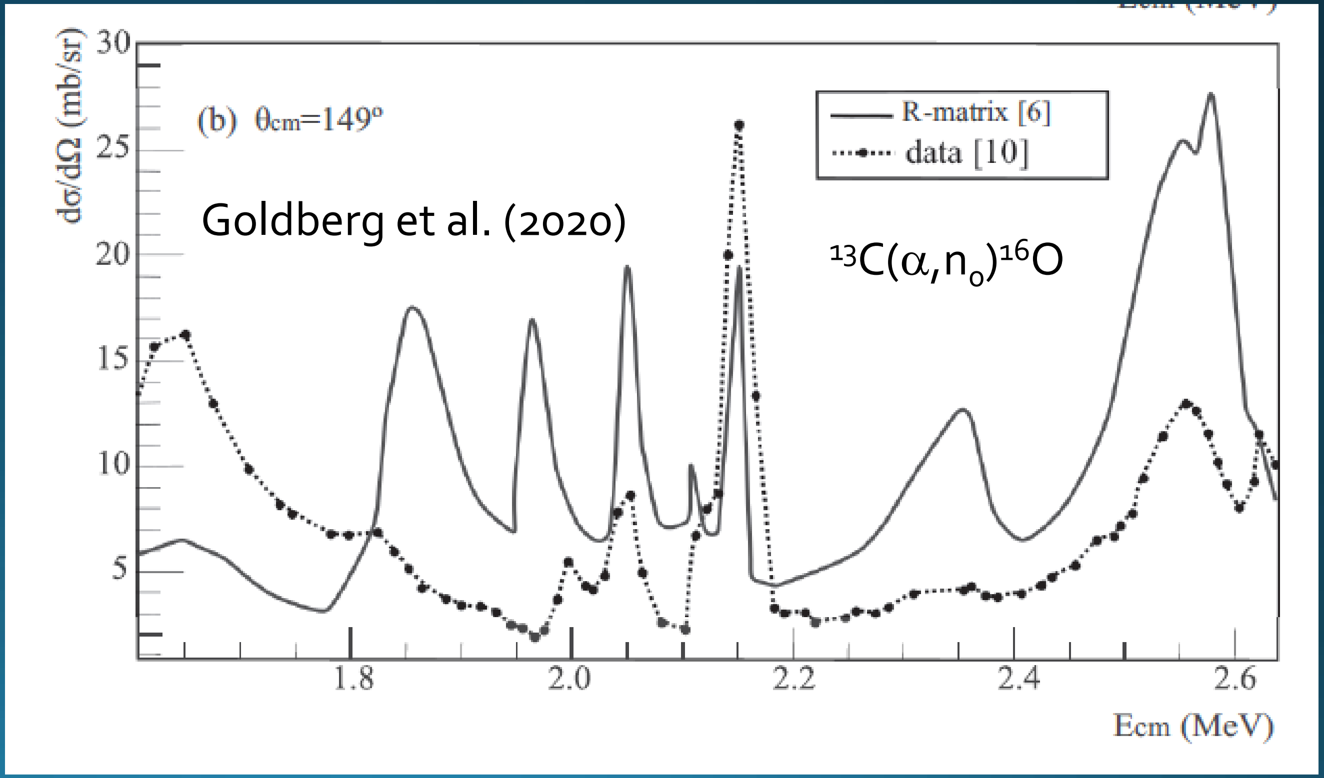
Becca Toomey (Rutgers)

GEANIE data

Measurement Expectations

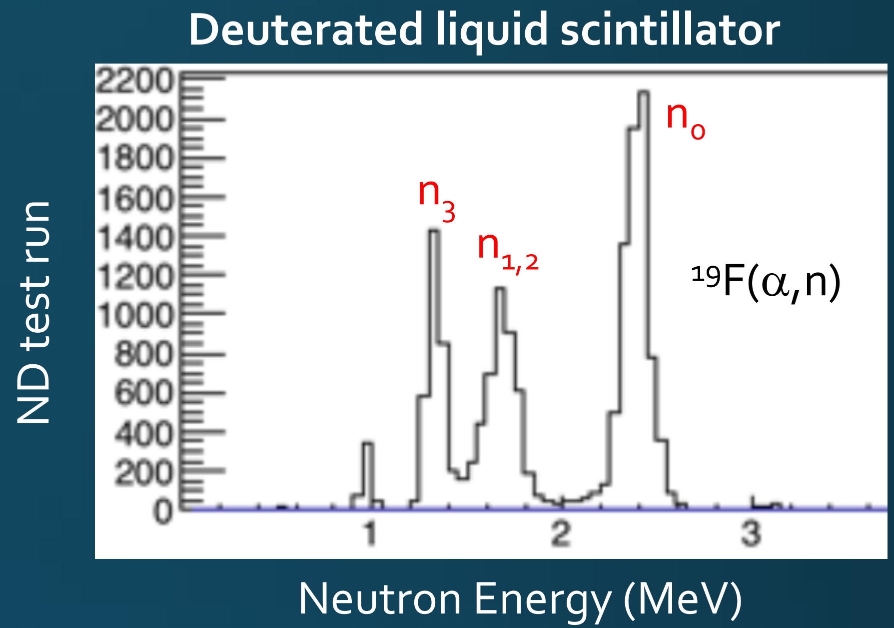
- Uncertainties
  - Target thickness usually dominates (as usual) --- 5 to 15% level
  - Efficiency uncertainty --- 10% level
  - Relative angular distribution uncertainty --- 5% level
  - Unfolding uncertainty --- 5% level
  - Raw stats, usually no problem





What's next?

- $^{13}C(\alpha,n)^{16}O$, comprehensive measurement
- Radioactive Ion Beam measurements
- $^{19}F(\alpha,n)^{22}Na$?
- $^{9}Be(\alpha,n)^{12}C$?
- Higher mass range
- Proton induced reactions?



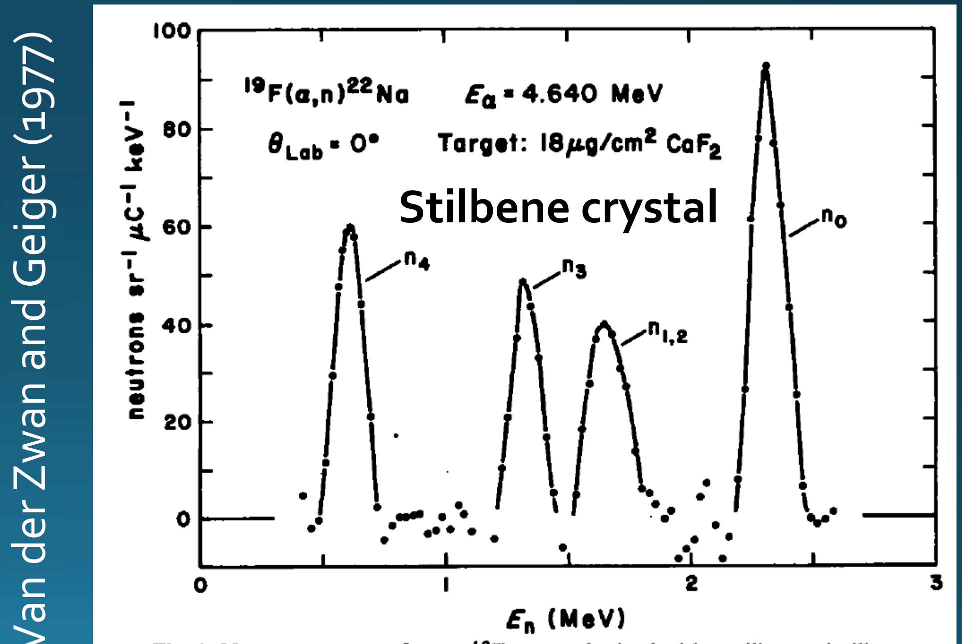


Fig. 1. Neutron spectrum from a ^{19}F target obtained with a stilbene scintillator.

Summary

- (α,n) cross sections on light elements are needed for a wide range of applications
- Past measurements are nearly all total cross sections. **Partial cross sections are needed!**

- A cost effective and efficient solution for (α,n) measurements
  - Deuterated liquid scintillators for prompt neutron detection
  - HPGe or $LaBr_3$ for secondary γ-ray detection
  - Notre Dame high current accelerator system (Santa Ana)