$^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ at the University of Notre Dame

James deBoer

The University of Notre Dame

Nuclear Reaction Rates for the s-process, February 22-23 2024

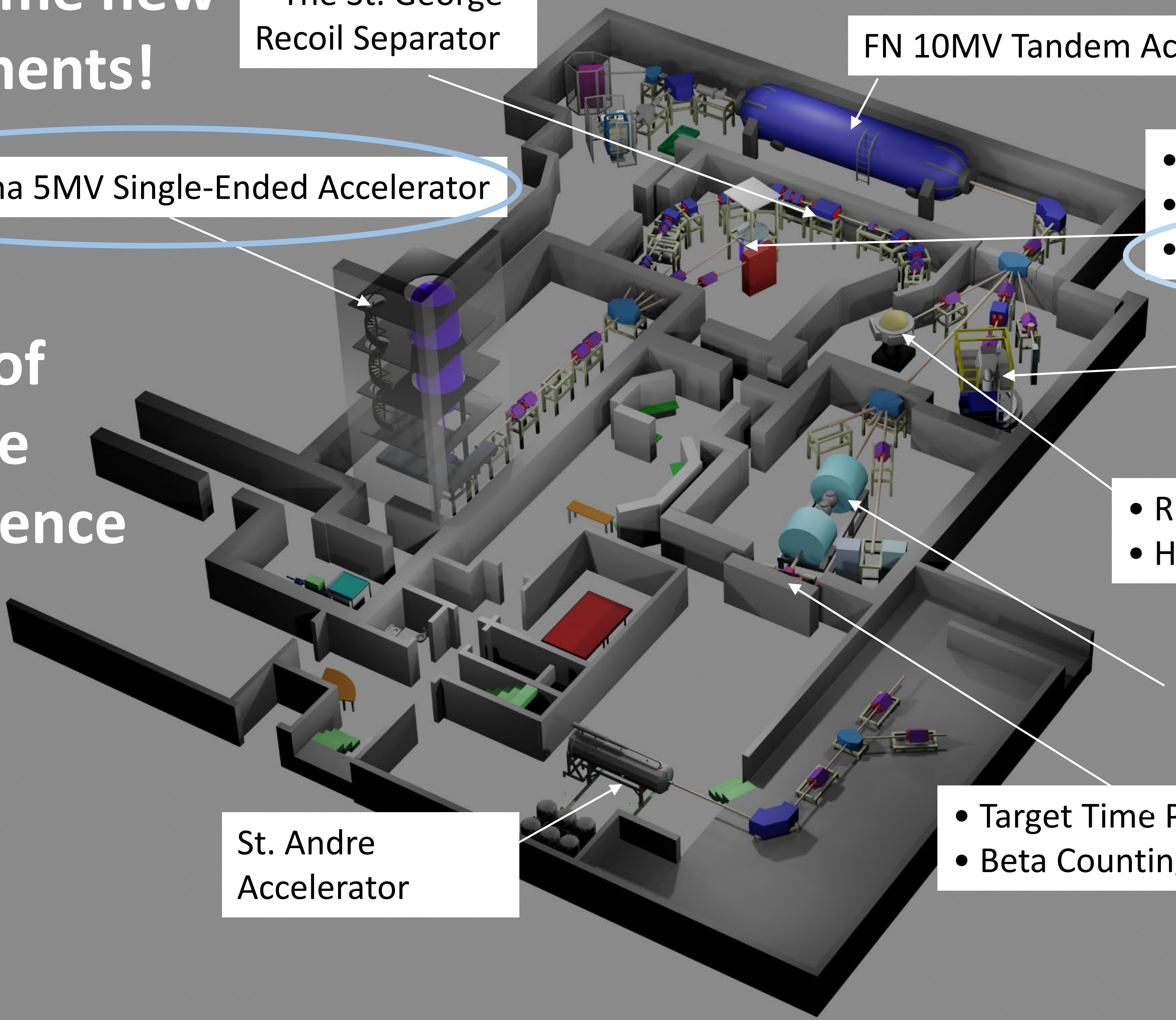
UNIVERSITY OF NOTRE DAME

IReNA

International Research Network for Nuclear Astrophysics

Lets do some new measurements!

University of Notre Dame Nuclear Science Laboratory



- The St. George Recoil Separator

FN 10MV Tandem Accelerator

- Santa Ana 5MV Single-Ended Accelerator

- GEORGINA
- RHINO
- 5U Solid Target Line

- Accelerator Mass Spectror

- R2D2
- Hector

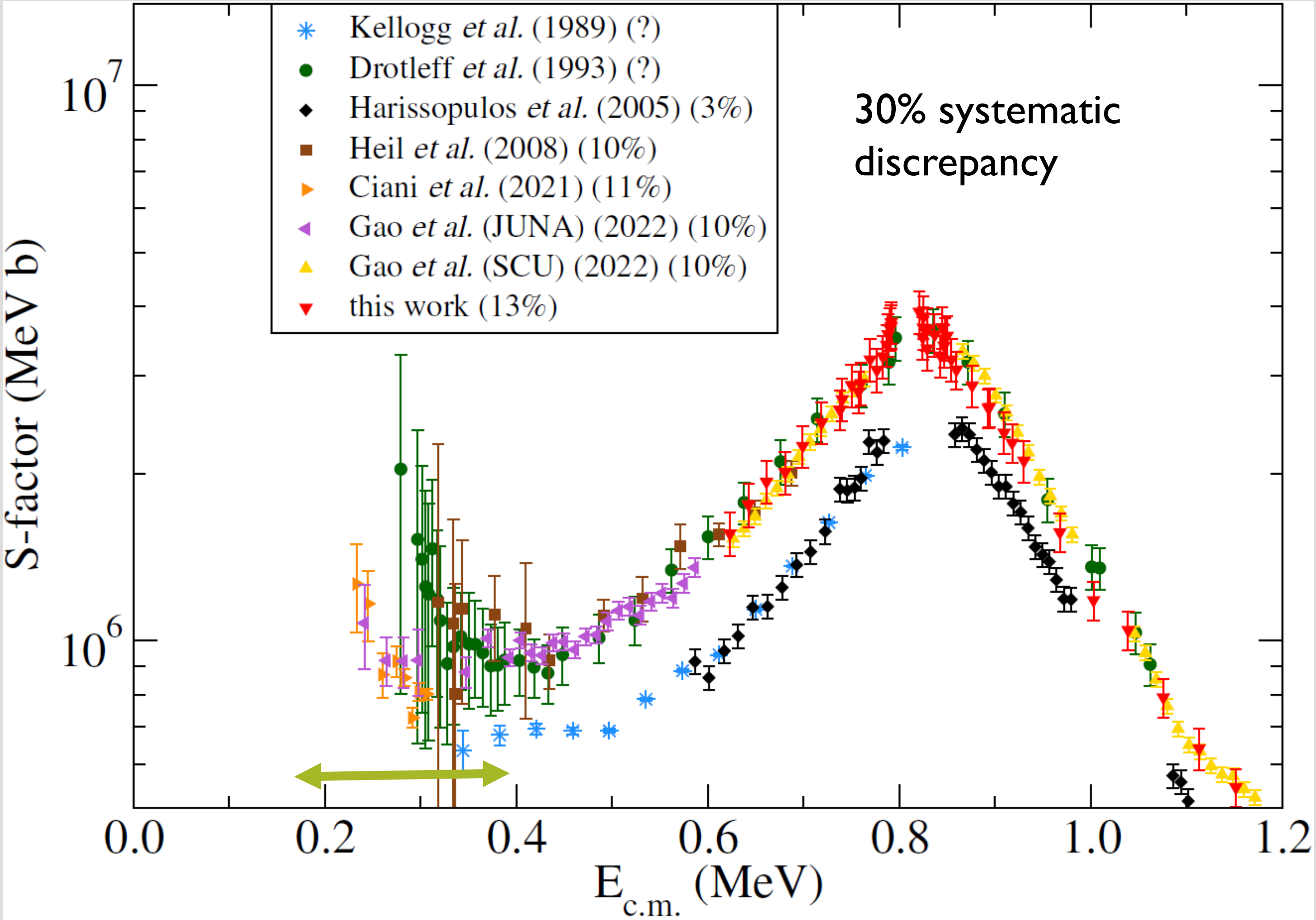
- TWINSOL

- Target Time Projection Chamber
- Beta Counting Station

St. Andre Accelerator

S-FACTOR DATA AT LOW ENERGY

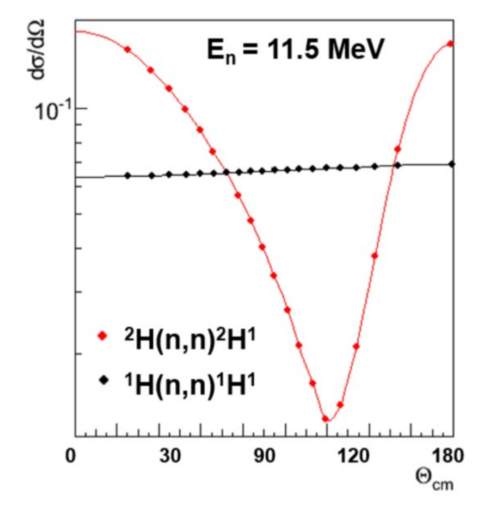
- Almost all angle integrated data measured using 4π neutron moderator counters
- High efficiency for low count rate experiments
- Yields are still sensitive to the underlying neutron angular distributions, which are usually unknown!
- Angular distribution data, even at higher energies, can complement the angle integrated data.

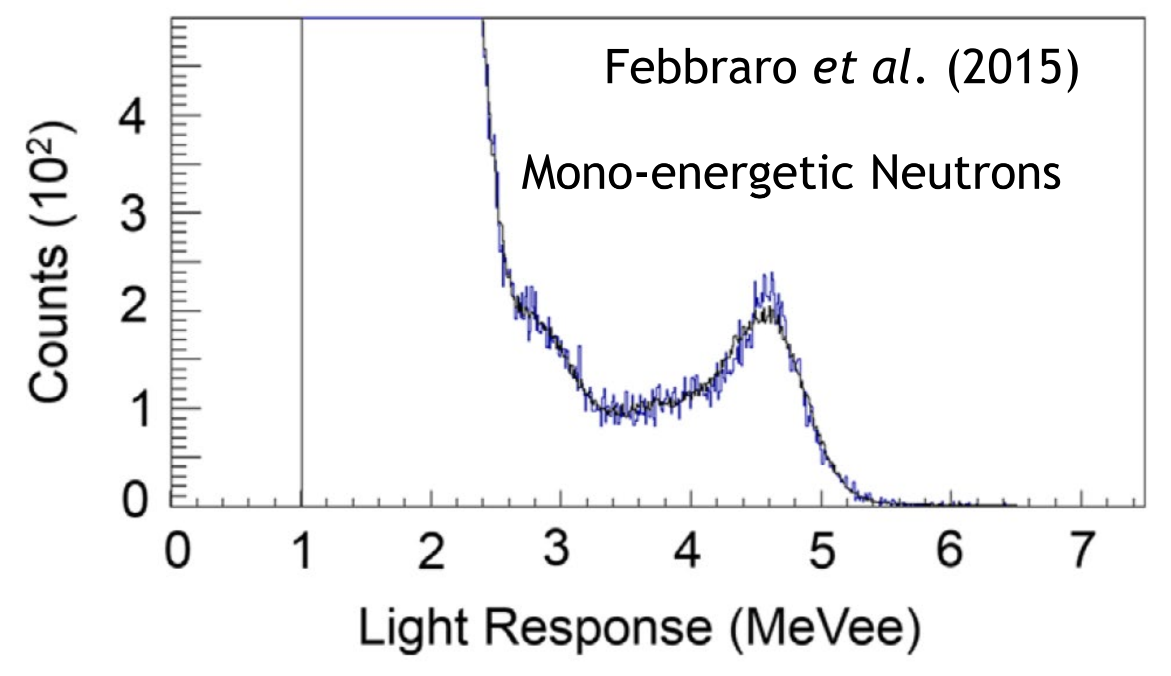


30% systematic discrepancy

Deuterated Liquid Scintillators

- Some immediate intrinsic energy sensitivity because of the high energy cutoff of the light response spectrum (no time of flight needed)
- Intrinsic efficiency of about 20% for 1 MeV neutrons
- Spectrum has a peak from the n(d,d)n angular distribution
- Relatively inexpensive
- Can be purchased commercially from Eljen





Febbraro *et al.* (2015)

Mono-energetic Neutrons

My favorite spectrum unfolding example

- target
  - 94% ^{10}B
  - 6% ^{11}B
  - Trace amounts of ^{13}C build up
  - Thick Ta backing (no background)

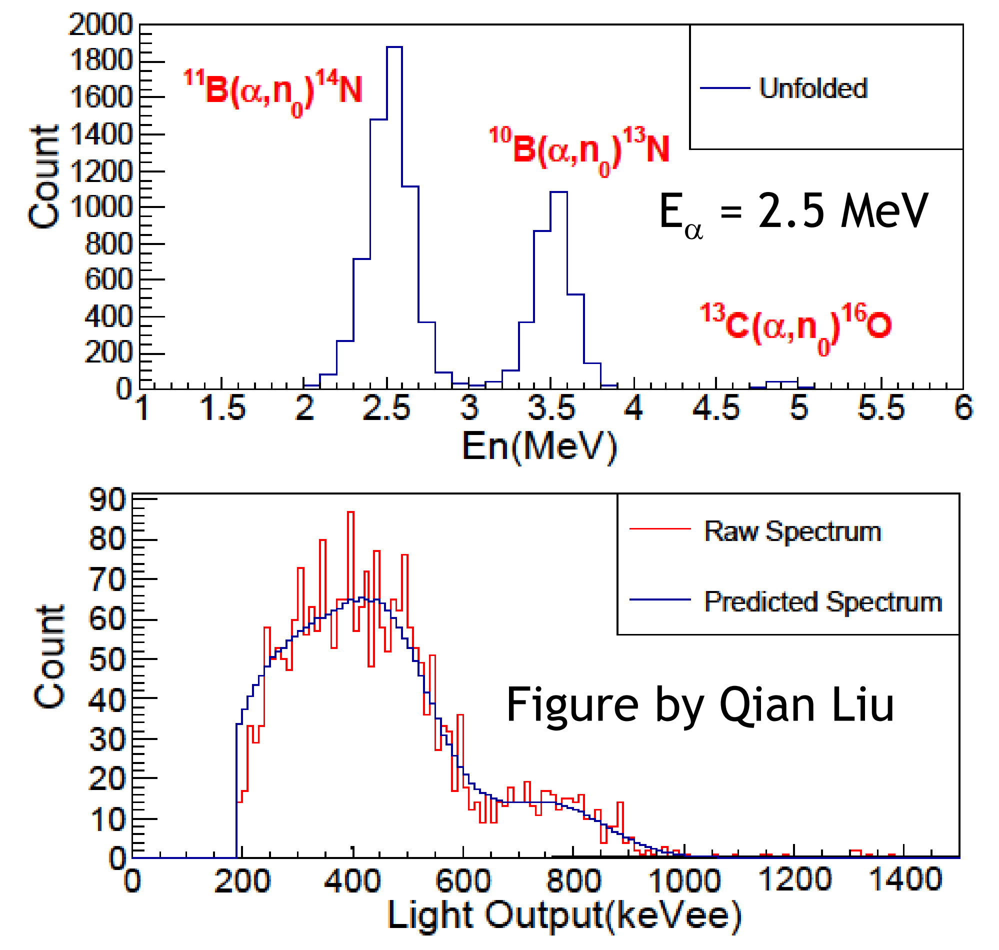
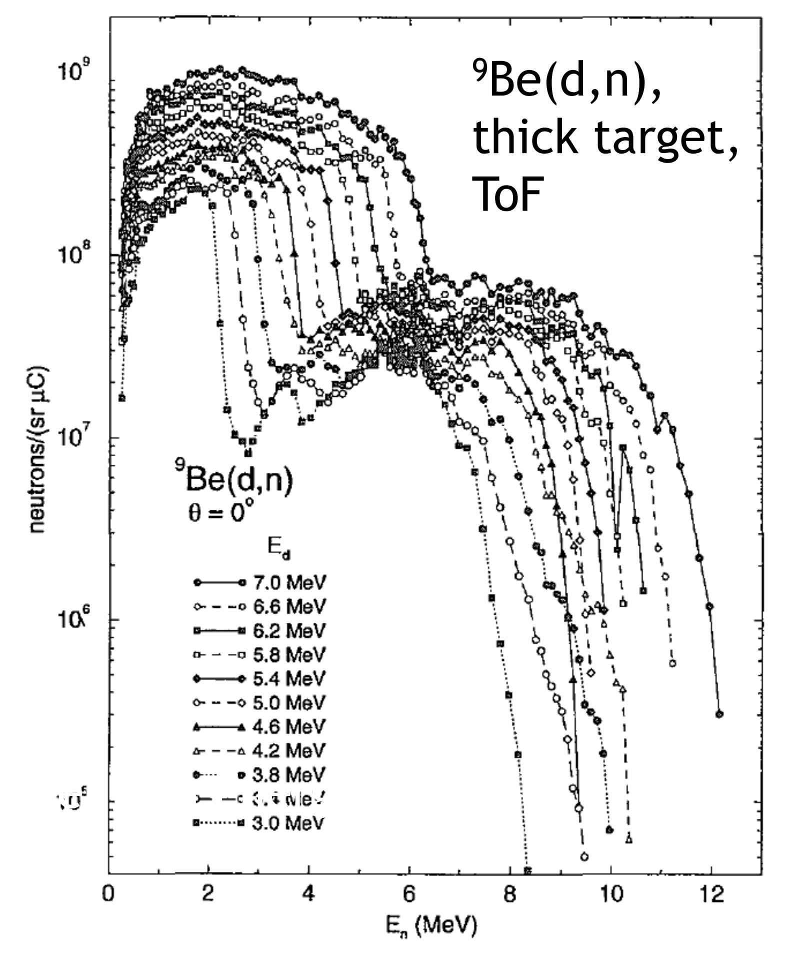


Figure by Qian Liu

The price of spectrum unfolding: mapping out the detector response

- Have to create a detector response matrix that has the evolution of the light response spectrum as a function of mono-energetic neutron energy
- Accomplished with time-of-flight and a well known reaction spectrum
- Ohio University, Edwards Lab



^{9}Be(d,n), thick target, ToF

Massey *et al.* (2002)

Response Matrix

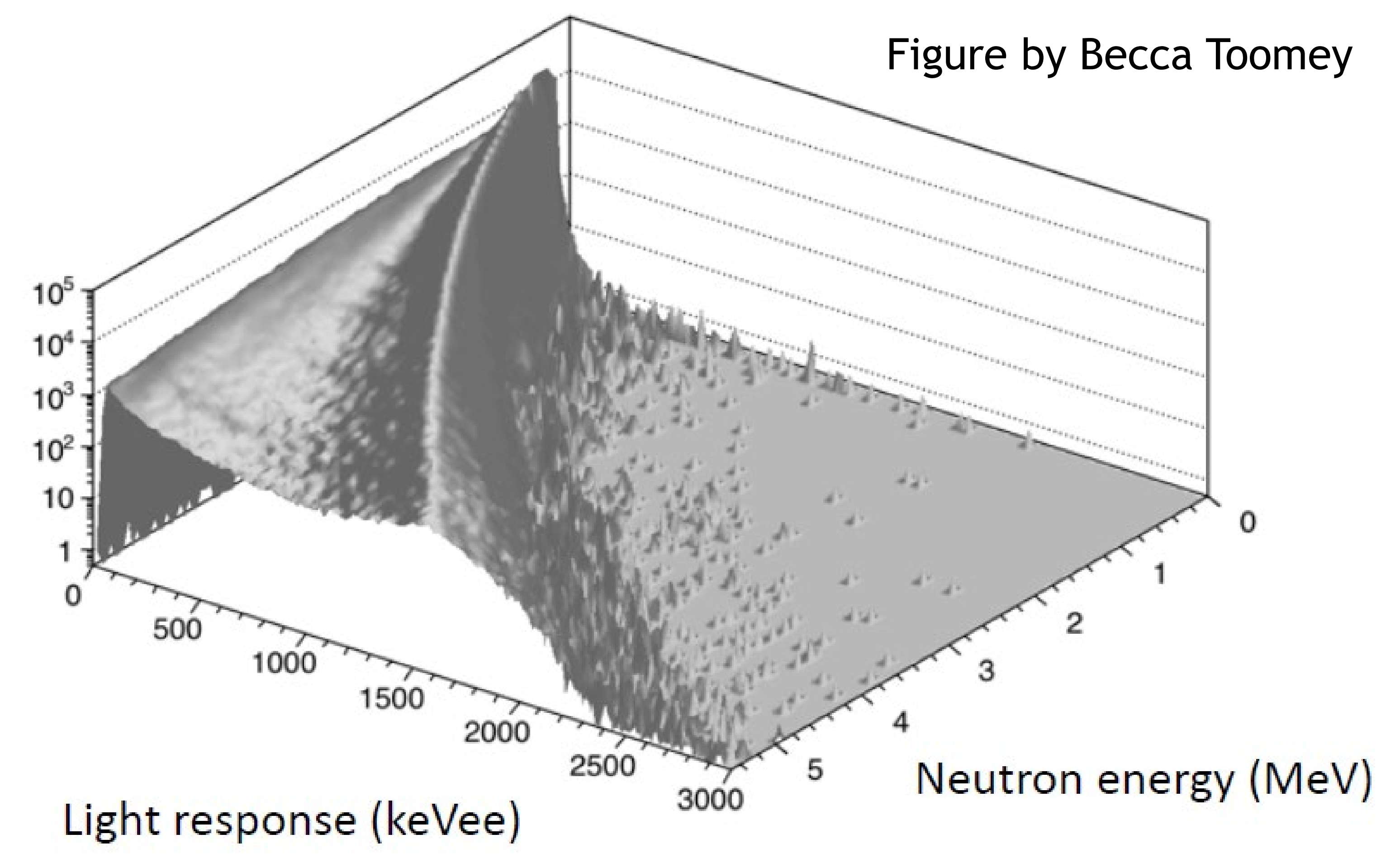
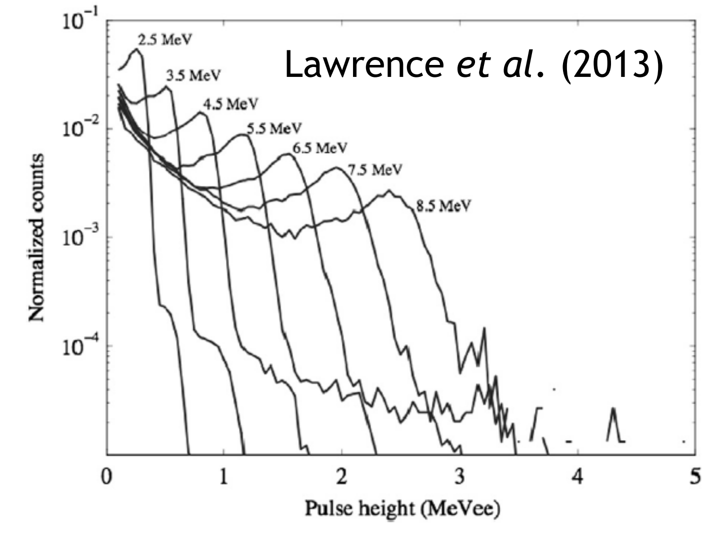


Figure by Becca Toomey

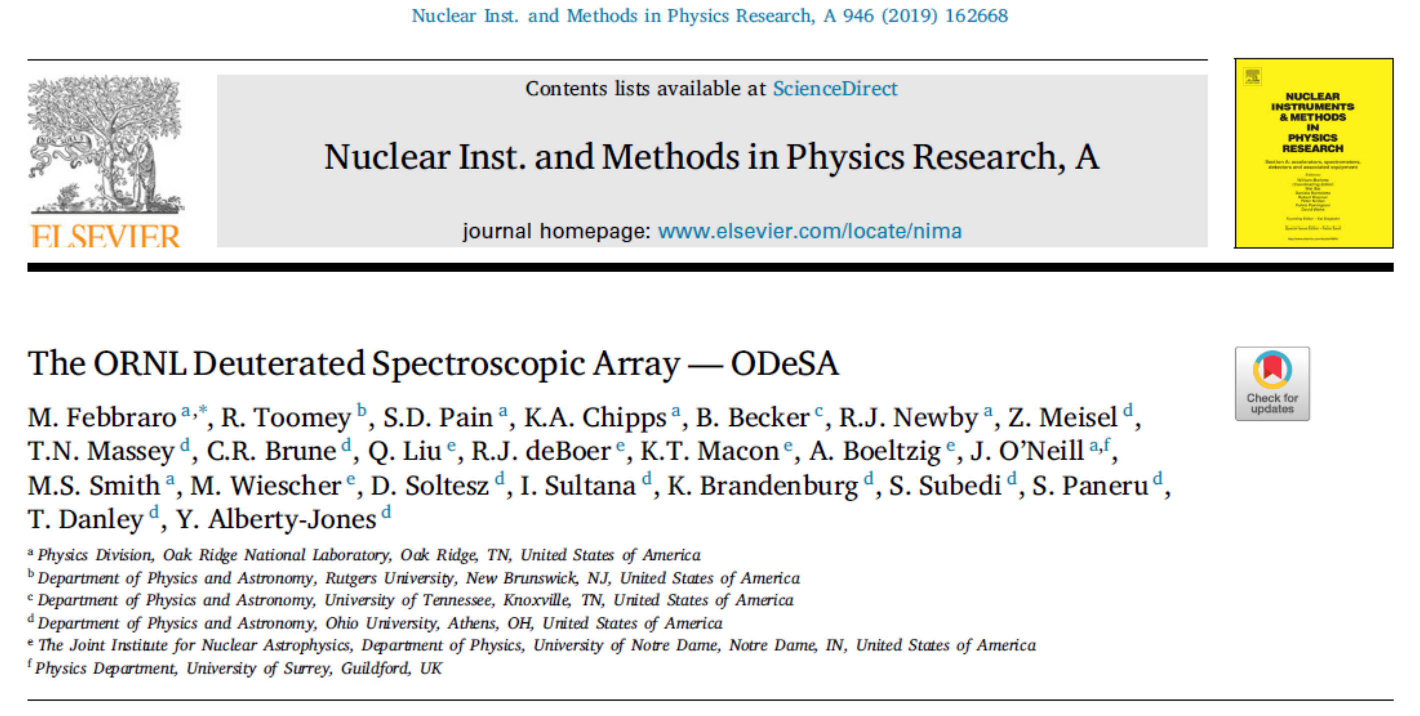
Gives detector light response as a function of incident mono-energetic neutron energy



Lawrence *et al.* (2013)

Fig. 10. Seven columns from the measured response matrix for a 3 × 2-in. EJ315 detector, corresponding to normalized pulse-height spectra from quasi-mono-energetic neutron spectra.

ODeSA – ORNL Deuterated Liquid Spectroscopic Array



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The ORNL Deuterated Spectroscopic Array — ODeSA

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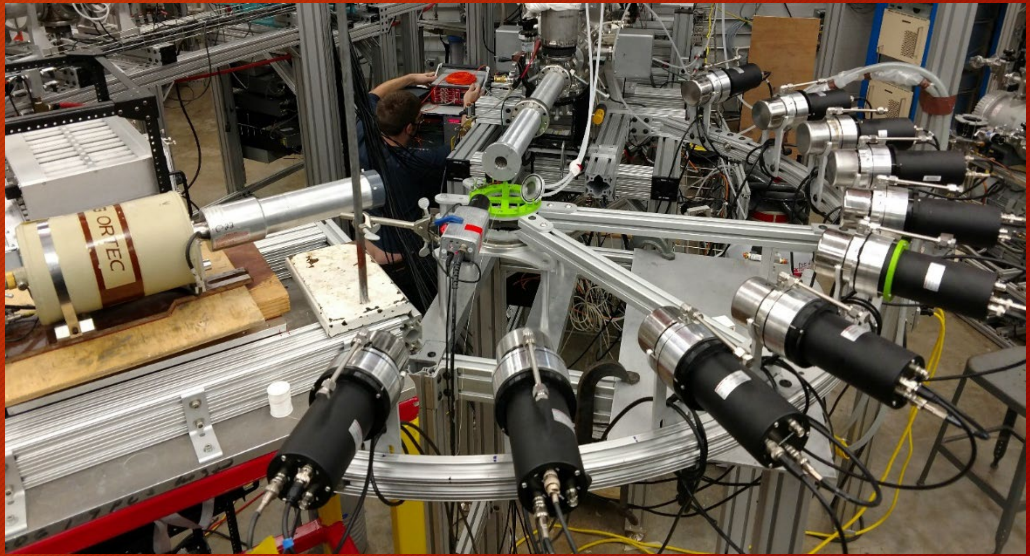
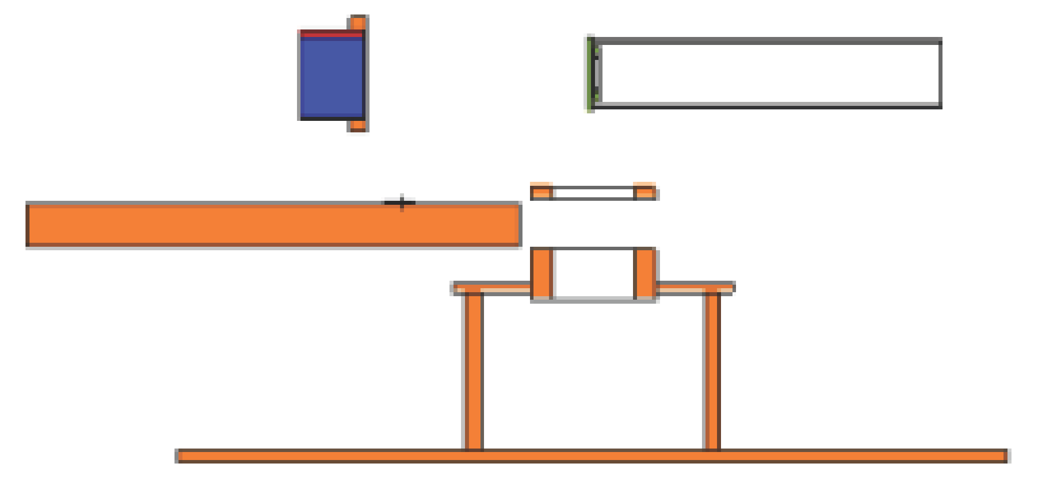
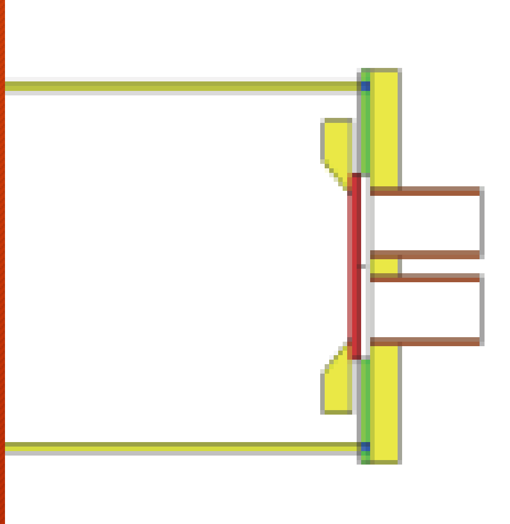


Models with MCNP: Geometric and neutron scattering corrections (very important!)

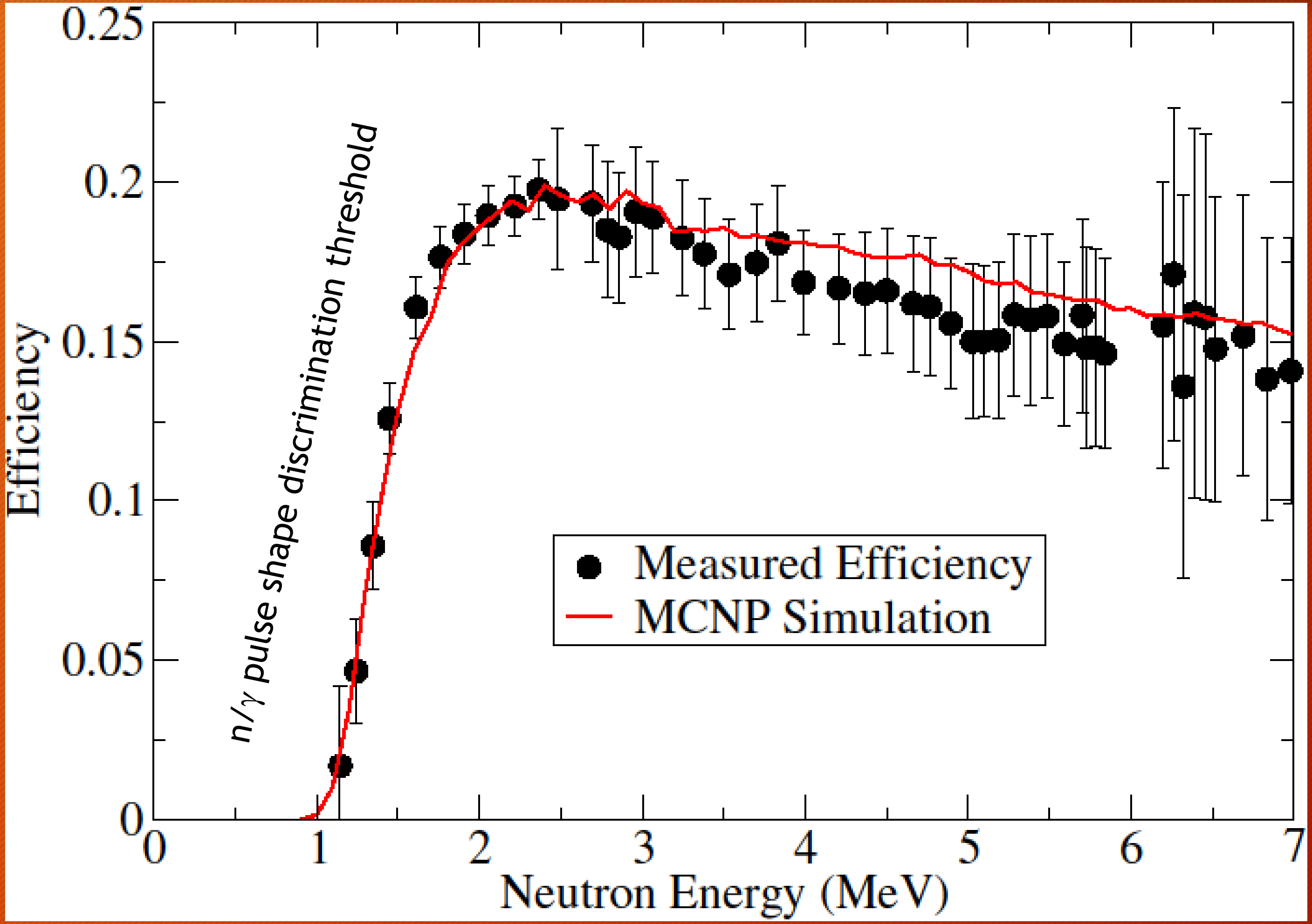


Setup pieces for MCNP simulation



Zoom in of target holder

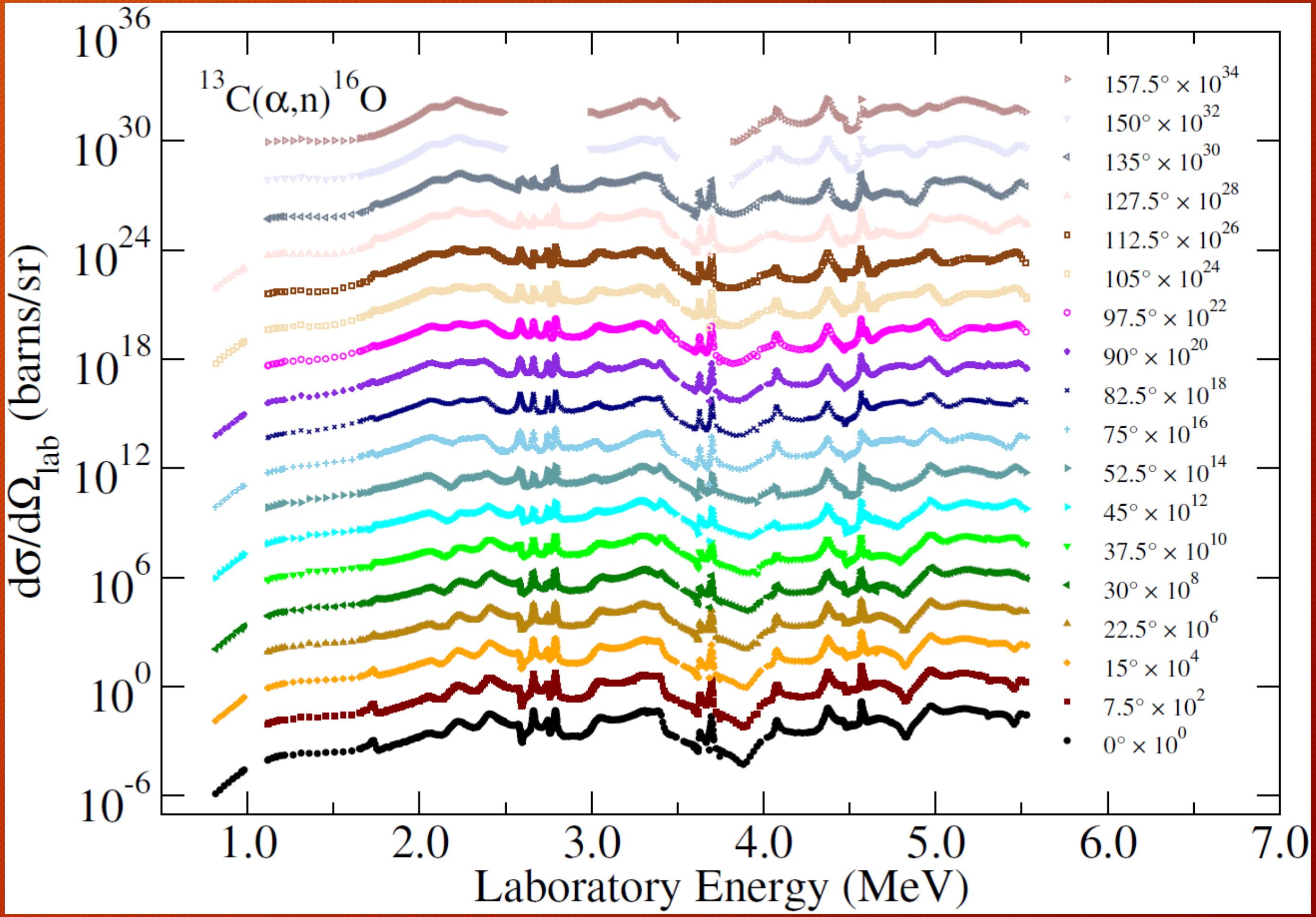
Intrinsic Efficiency of a deuterated liquid scintillator (ODeSA detector)



Using ^{9}Be(d,n) at OU

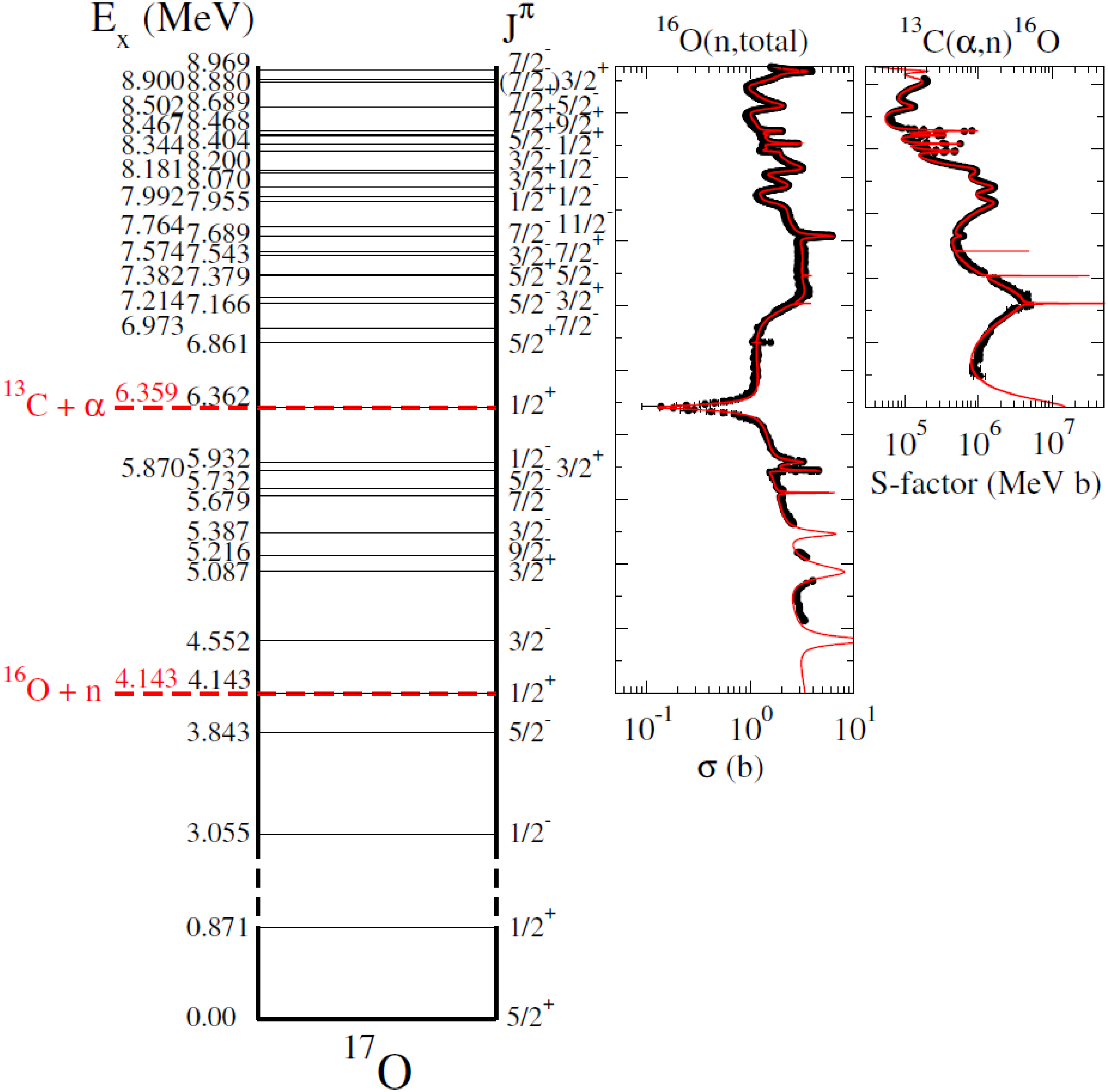
What about those $^{13}C(\alpha,n)^{16}O$ measurements?

- Measured the differential cross section at 18 angles from 0.8 to 6.5 MeV
- Thin target (5 to 10 ug/cm^2)
  - Made by Gyürky György at ATOMKI
  - Energy loss ranges between 5 and 20 keV
- Over 700 different energies
- By far the most detailed mapping of the differential cross section in energy



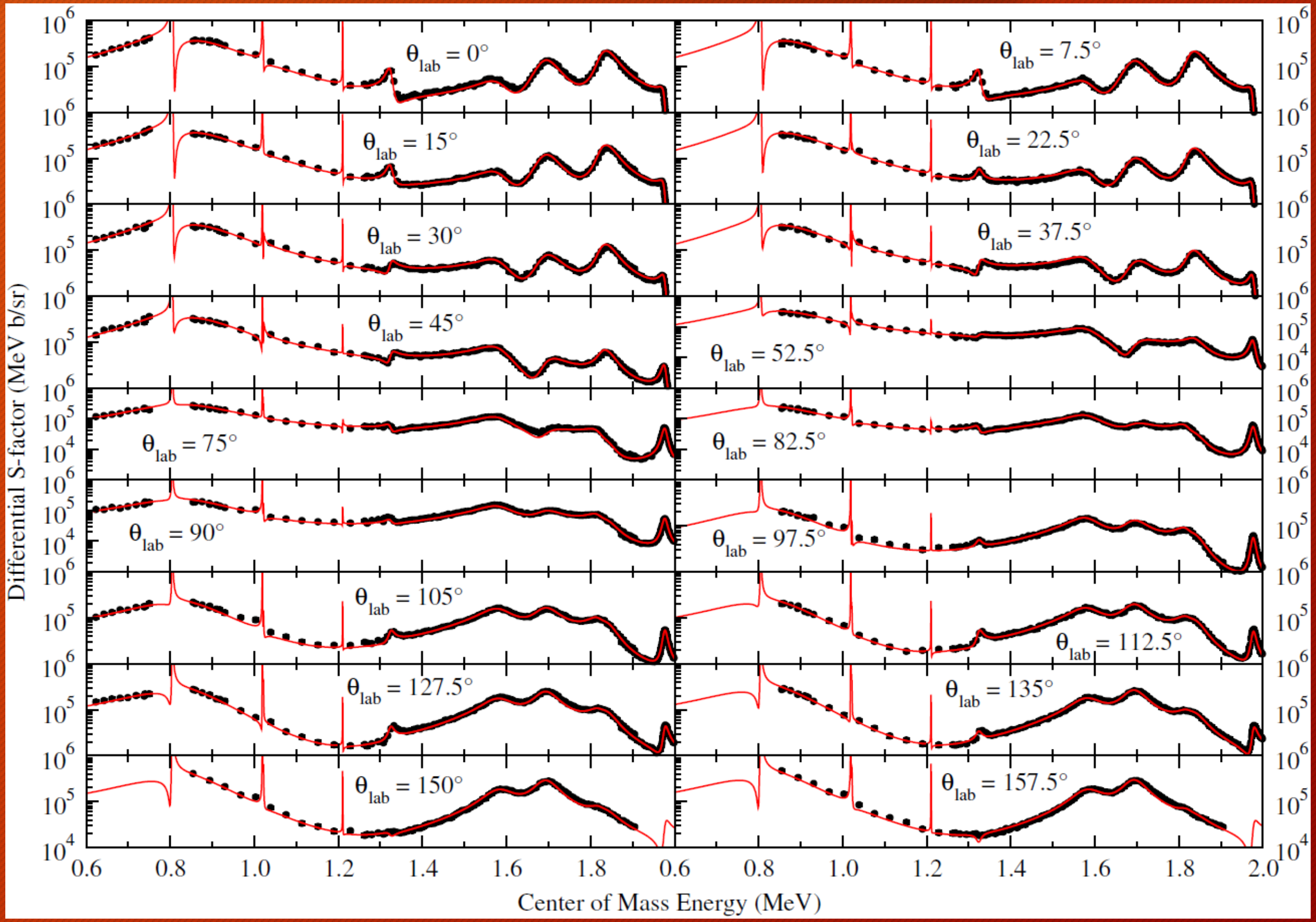
R-matrix fit at low energy

- Nuclear astrophysics application
- Used the LANL fit as a starting point and then fit to our new data from 0.8 up to 3.3 MeV



Low Energy ND data fit

- Simultaneous fit of the 18 angles we measured
- Looks good!
- Had to just change one J^{π} assignment from LANL fit



Multi parameter fitting and uncertainty analysis

Current procedure

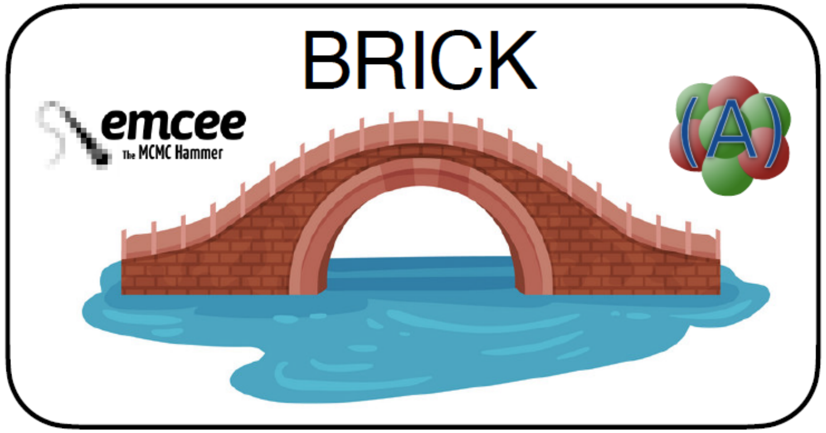
- Perform first fits using traditional χ^2 minimization routine and fits “by hand”

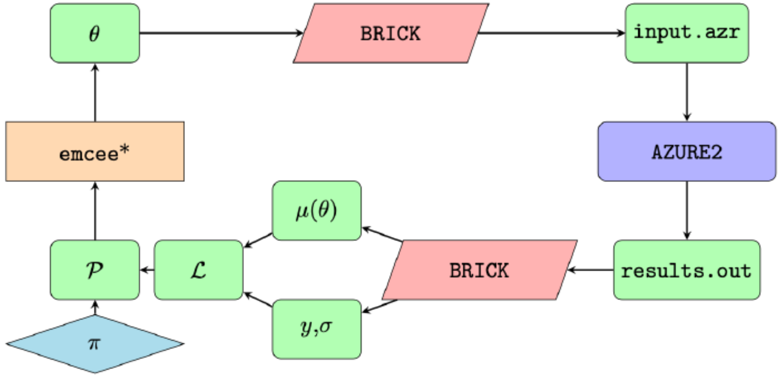
Refine the fit using a Bayesian method and then sample the parameter space using a Markov Chain Monte Carlo sampler to obtain the uncertainty

The MCMC takes a lot of computation time

- For AZURE2, a python wrapper called **BRICK** (pip install brick-james) has been developed using the MCMC routine emcee
- Definitely a big step forward, but we can do better

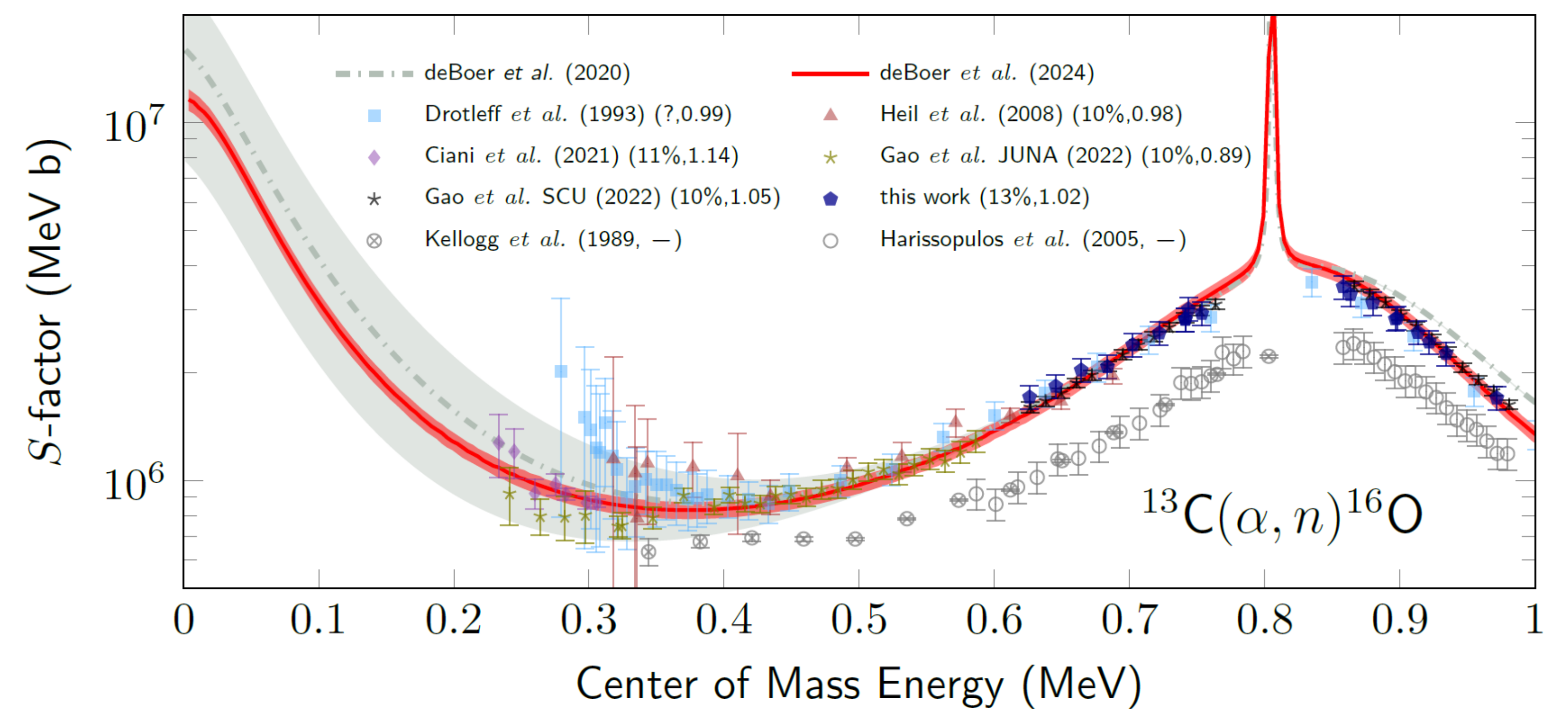
Machine learning algorithms to do R-matrix fits are being investigated





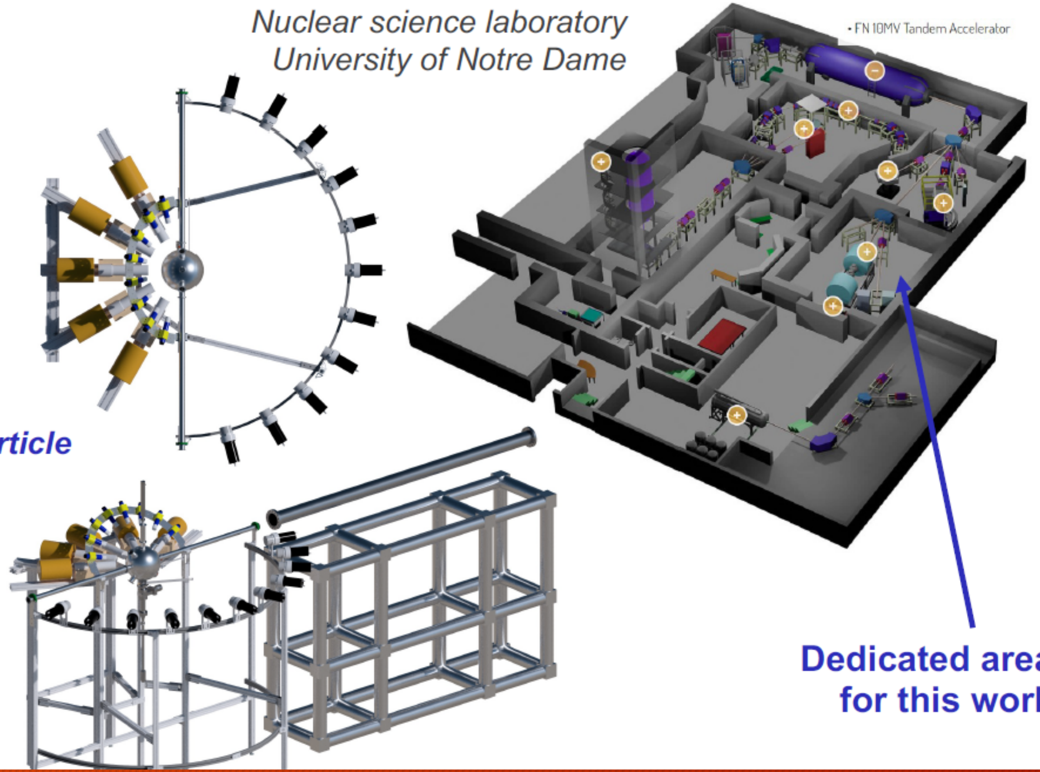
Focused on low energy extrapolation

- Astrophysics
  - s-process nucleosynthesis
  - T = 0.2 GK
  - About 0.17 to 0.4 MeV
- Some data inconsistencies
  - Seem to now be largely resolved
- BRICK MCMC uncertainty estimation
- 5% at these energies



The future of (α,n) measurements at ND (E_α = 2 to 8 MeV)

- Dedicated beamline at the University of Notre Dame Nuclear Science Laboratory for the life of the project!
  - FN beamline
- Full suite of detectors
  - Deuterated scintillator arrays → ***Neutron***
  - GENIE n-type HPGe → ***Gamma***
  - Silicon detectors → ***Charge particle***
- Dedicated target fabrication and characterization
  - Apparatus for enriched ^{12}C foil production
  - Air-free metallic lithium handling
  - Isotopically enriched ^{13}C, ^{10}B, ^{11}B, ^{7}Li



Nuclear science laboratory
University of Notre Dame

Dedicated area for this work

Sponsor – NNSA DNN NA22
PM – LTC David Matters
TA – Dr Elizabeth Heckmaier

NNSA National Nuclear Security Administration

OAK RIDGE National Laboratory

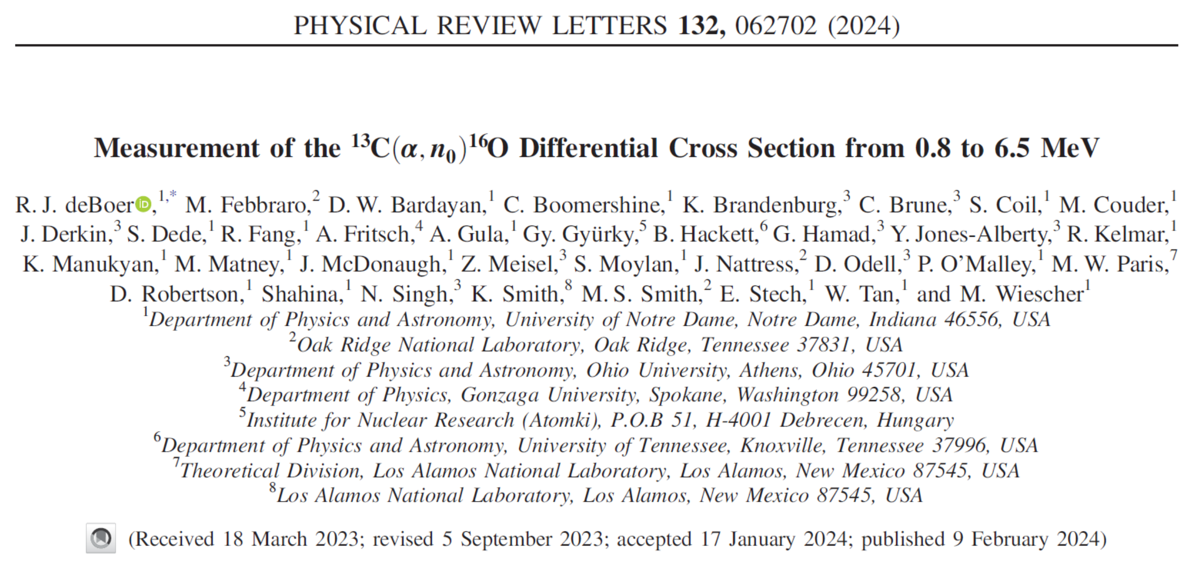
Los Alamos NATIONAL LABORATORY

UNIVERSITY OF NOTRE DAME

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

^{7}Li(a,n), ^{10}B(a,n), ^{11}B(a,n), ^{13}C(a,n), ^{19}F(a,n)

Collaborators



PHYSICAL REVIEW LETTERS **132,** 062702 (2024)

Measurement of the $^{13}C(\alpha, n_0)^{16}O$ Differential Cross Section from 0.8 to 6.5 MeV

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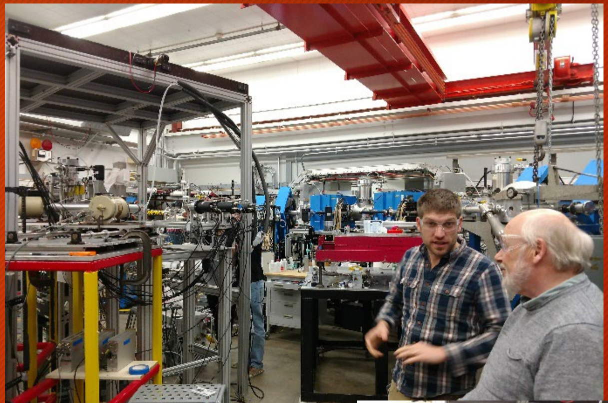
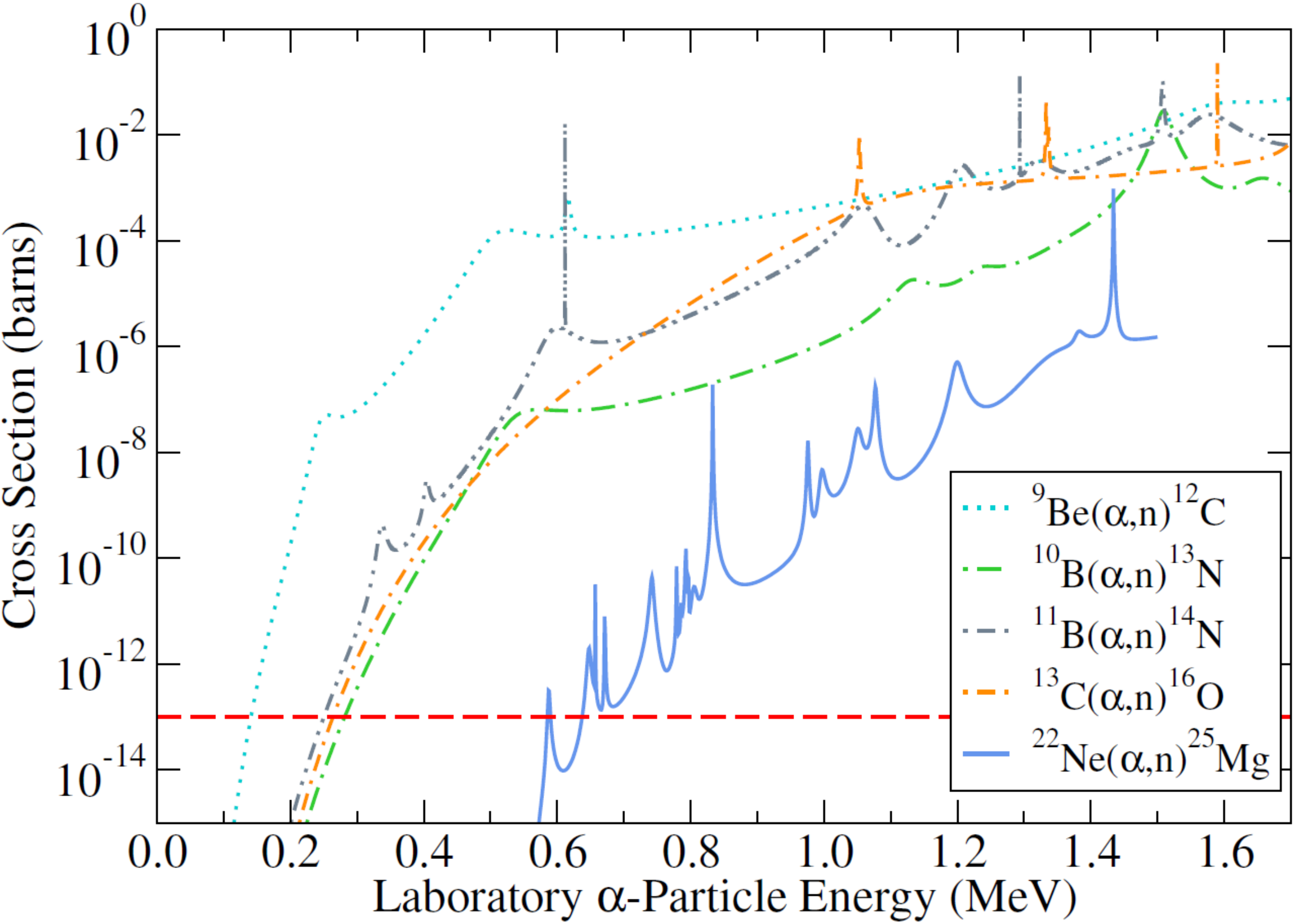
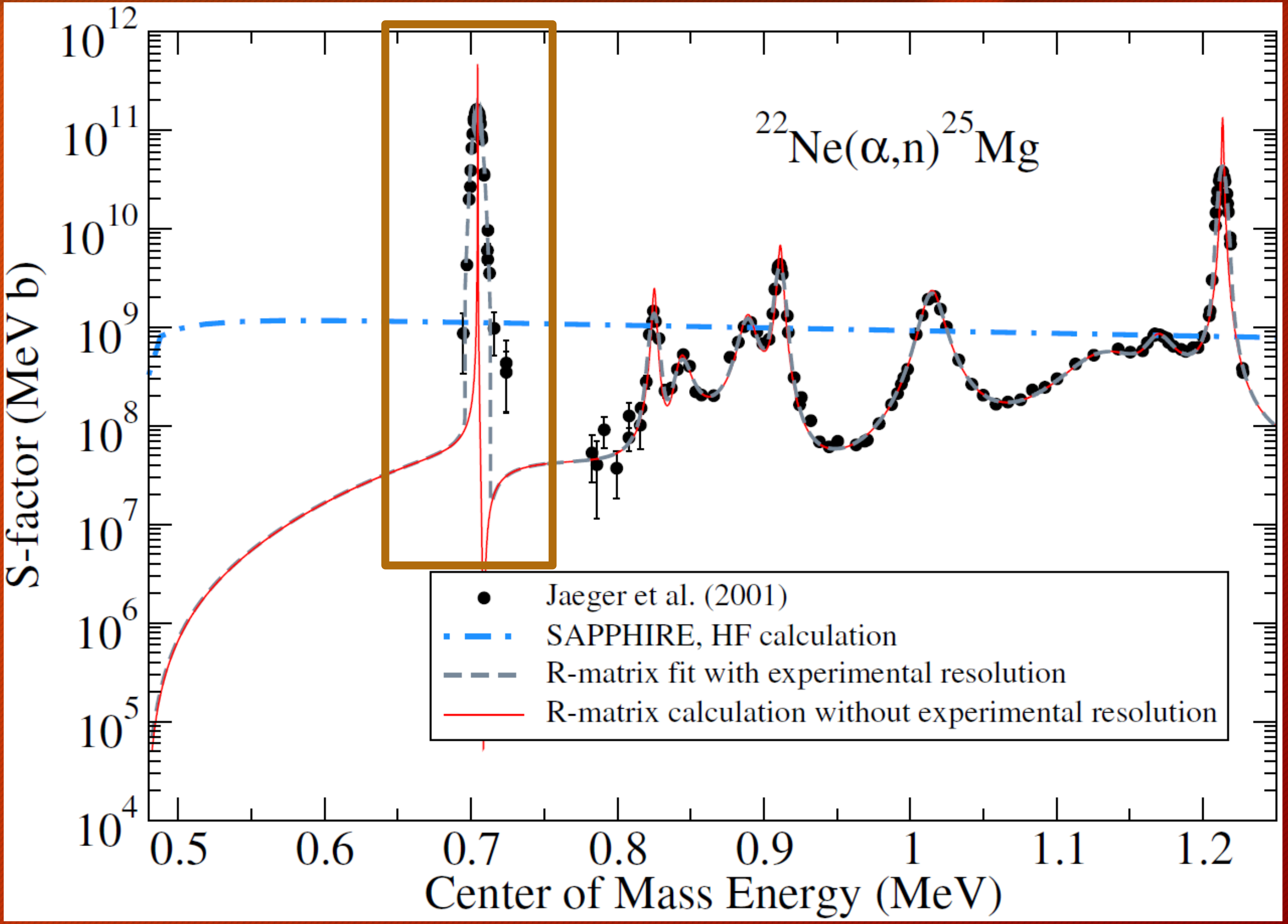


The merciless Coulomb barrier



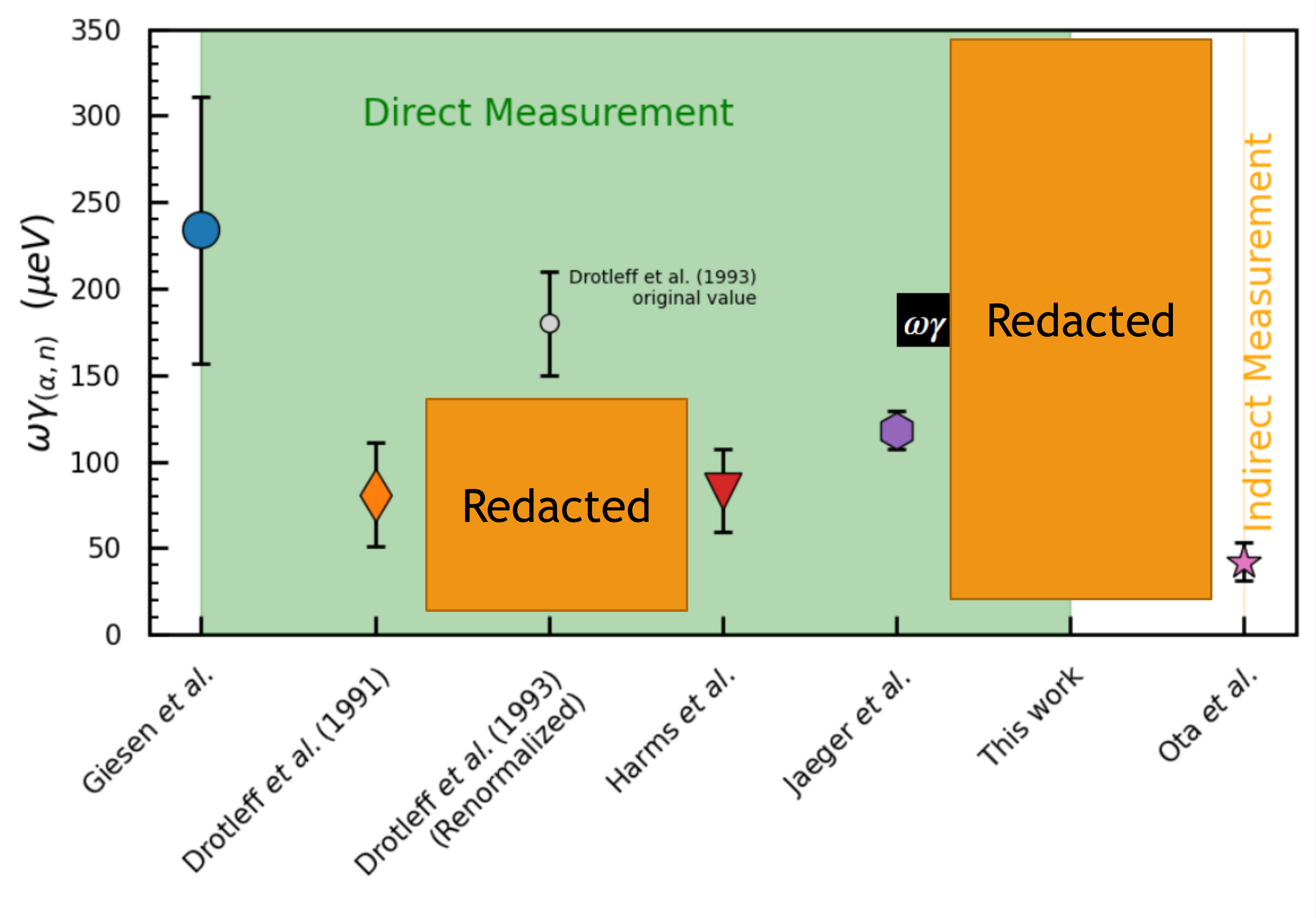
The low energy $^{22}Ne(\alpha,n)^{25}Mg$ S-factor

- Negative Q-value of -0.478 MeV
- Main resonance at helium burning temperatures (about 0.3 GK) is at 830 keV (or 702 keV cm frame)
- There is still some uncertainty in its strength however



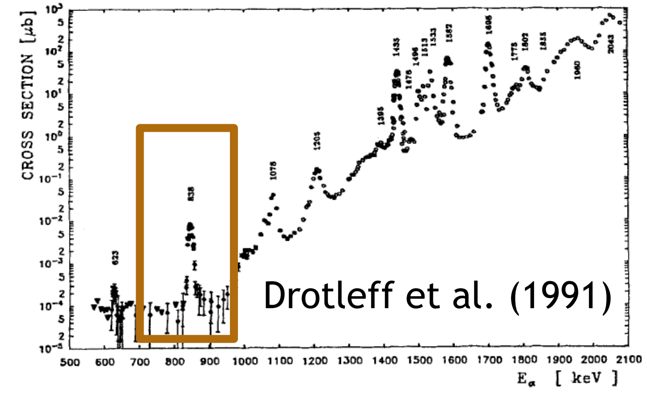
$^{22}Ne(\alpha,n)^{25}Mg$, 830 keV resonance strength

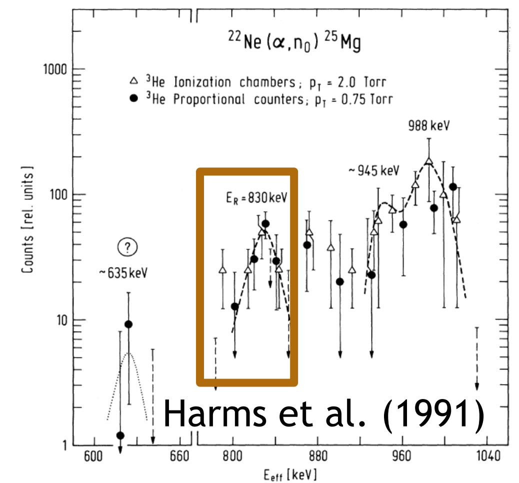
- See recent reviews by Adsley *et al.* (2021) and Wiescher *et al.* (2023)
- Shamelessly stolen several of these slides from Michael's graduate student Shahina

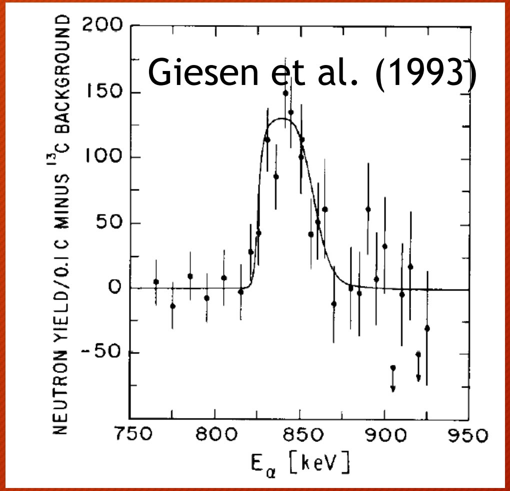


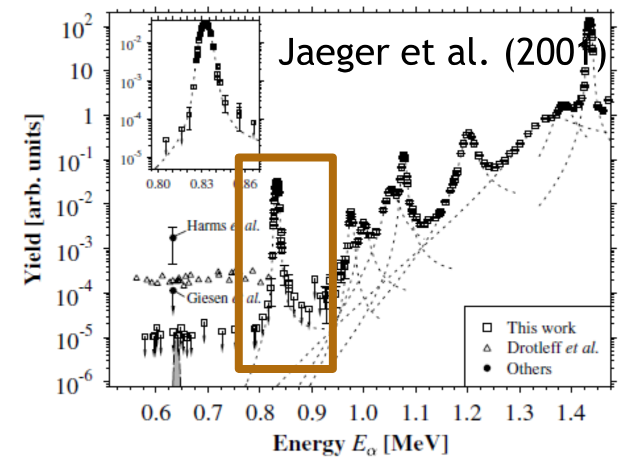
Quick review of past measurements

- Drotleff *et al.* (1991)
  - Gas target with a neutron counter
  - $\omega\gamma_{(\alpha,n)}$ = 80(30) ueV
- Harms et al. (1991)
  - Gas target with ^{3}He spectrometers
  - $\omega\gamma_{(\alpha,n)}$ = 83(24) ueV
- Giesen *et al.* (1993)
  - Solid beam-stop target with a neutron counter
  - Background signal was 75% of yield on the resonance
  - $\omega\gamma_{(\alpha,n)}$ = 234(77) ueV
- Drotleff *et al.* (1993)
  - Astro paper
  - $\omega\gamma_{(\alpha,n)}$ = 180(30) ueV!
  - Renormalized to the strength to the 1580 keV resonance
- Jaeger *et al.* (2001)
  - Gas target using a neutron counter
  - $\omega\gamma_{(\alpha,n)}$ = 118(11) ueV!


Drotleff et al. (1991)

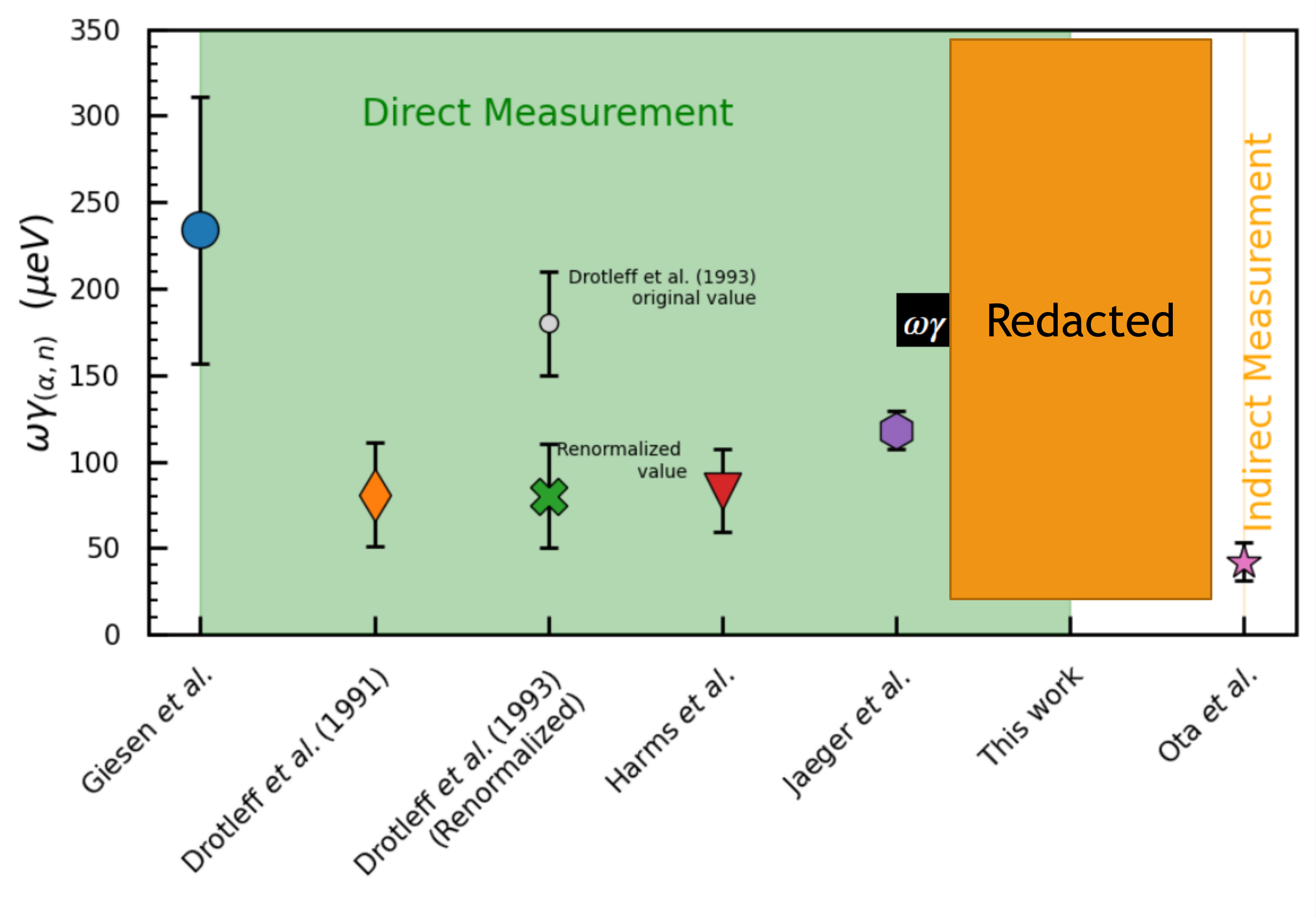

Harms et al. (1991)


Giesen et al. (1993)


Jaeger et al. (2001)

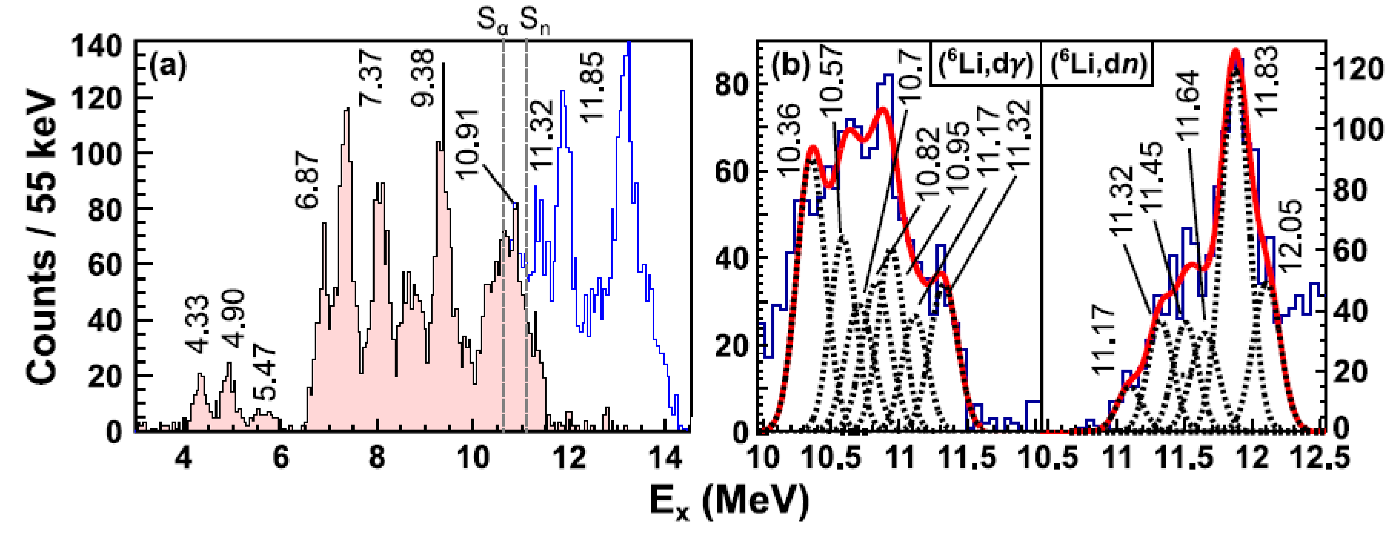
Drotleff renormalization

- 1580 keV resonance strength
    - Wolke et al. (1989): 1360 (200) ueV
    - Harms et al. (1991): 1270 (200) ueV
    - Drotleff thesis: 2900(300) ueV



Indirect measurements

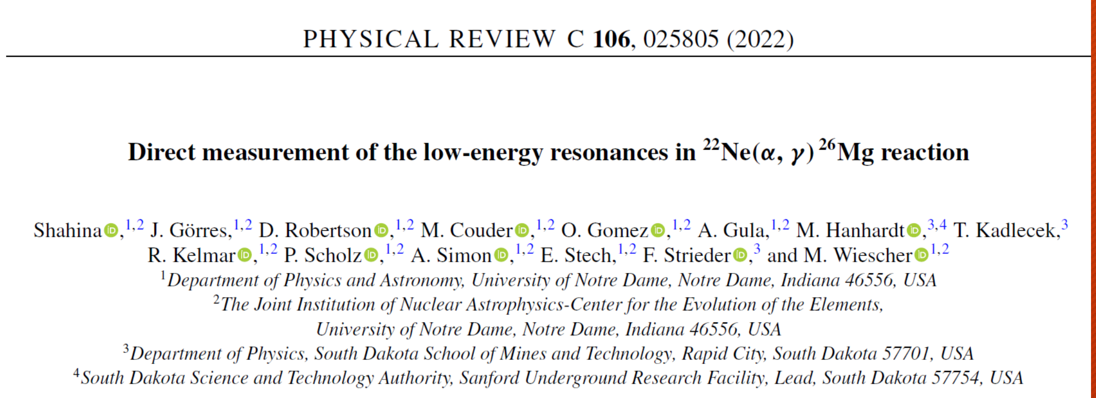
- Ota *et al.* (2020)
  - ^{22}Ne(^{6}Li,d)^{26}Mg transfer
  - n/γ = 1.14(26)
  - Where as direct measurements imply n/γ of about 3
- Jayatissa *et al.* (2020)
  - ^{22}Ne(^{6}Li,d)^{26}Mg
  - Γ_α = 13 ueV (if $J^\pi = 1^-$)
  - $\omega\gamma_{(\alpha,n)}$ = 42(11) ueV



Ota *et al.* (2020)

A simple setup

- 2 inch by 2 inch stilbene detector from Oak Ridge (Jason Nattress)
- Deeply implanted (200 keV) ^{22}Ne target (in tantalum), same target type used for recent ^{22}Ne(α,γ)^{26}Mg 830 keV resonance strength measurement



PHYSICAL REVIEW C **106**, 025805 (2022)

Direct measurement of the low-energy resonances in ^{22}Ne(α, γ)^{26}Mg reaction

Shahina,[1,2] J. Görres,[1,2] D. Robertson,[1,2] M. Couder,[1,2] O. Gomez,[1,2] A. Gula,[1,2] M. Hanhardt,[3,4] T. Kadlecek,[3]
R. Kelmar,[1,2] P. Scholz,[1,2] A. Simon,[1,2] E. Stech,[1,2] F. Strieder,[3] and M. Wiescher[1,2]
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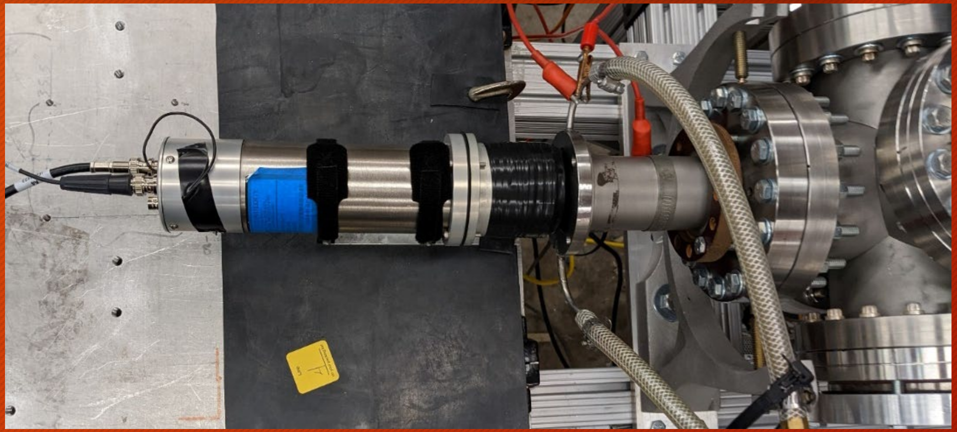
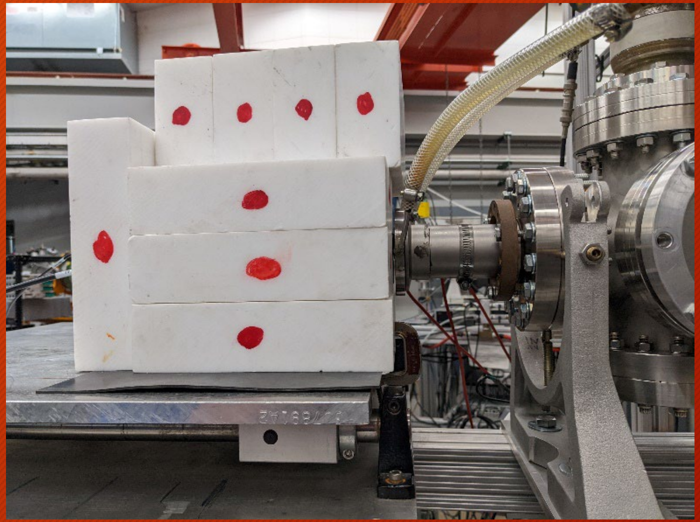
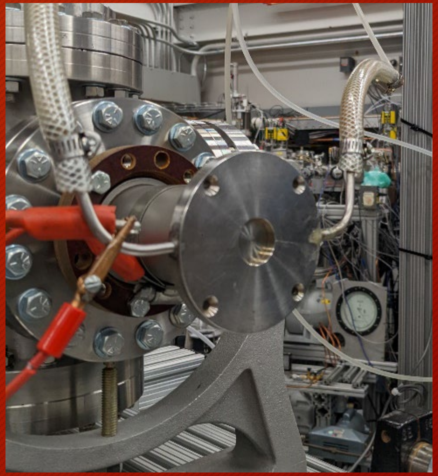
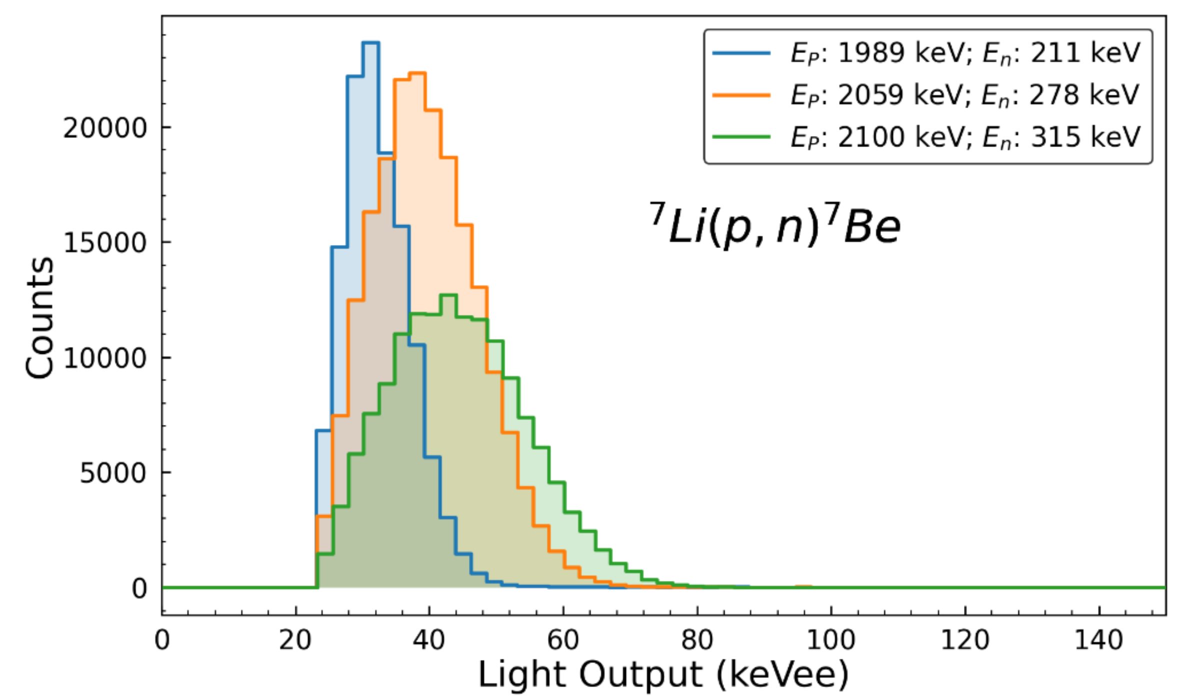






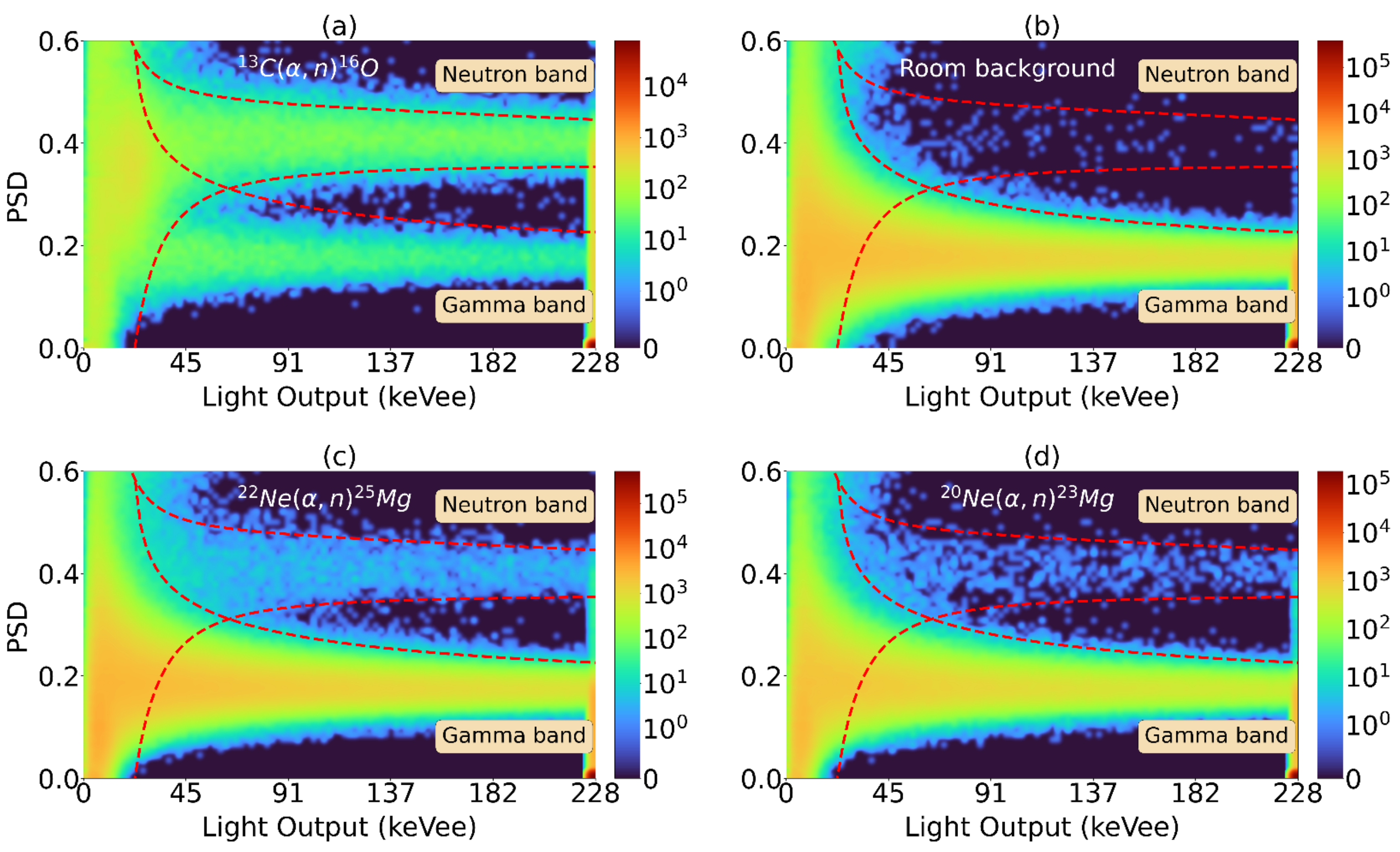
Detector characterization

- We used the ^{7}Li(p,n)^{7}Be reaction to characterize the light response of the detector at low energy
- Neutron energy on the 830 keV resonance is about 280 keV at 0 degrees



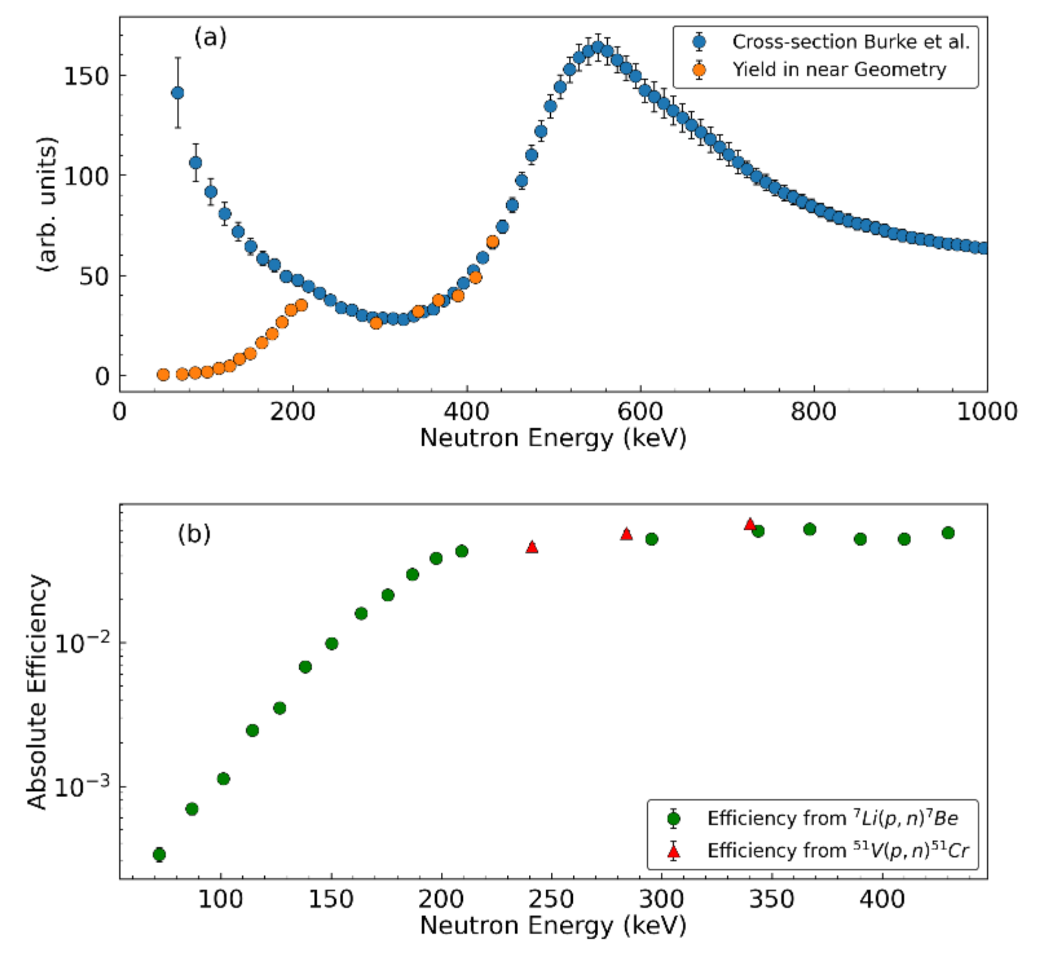
Discrimination between neutrons and gamma rays

- Pulse shape discrimination (PSD) between neutrons and gamma rays determines the low energy efficiency cutoff



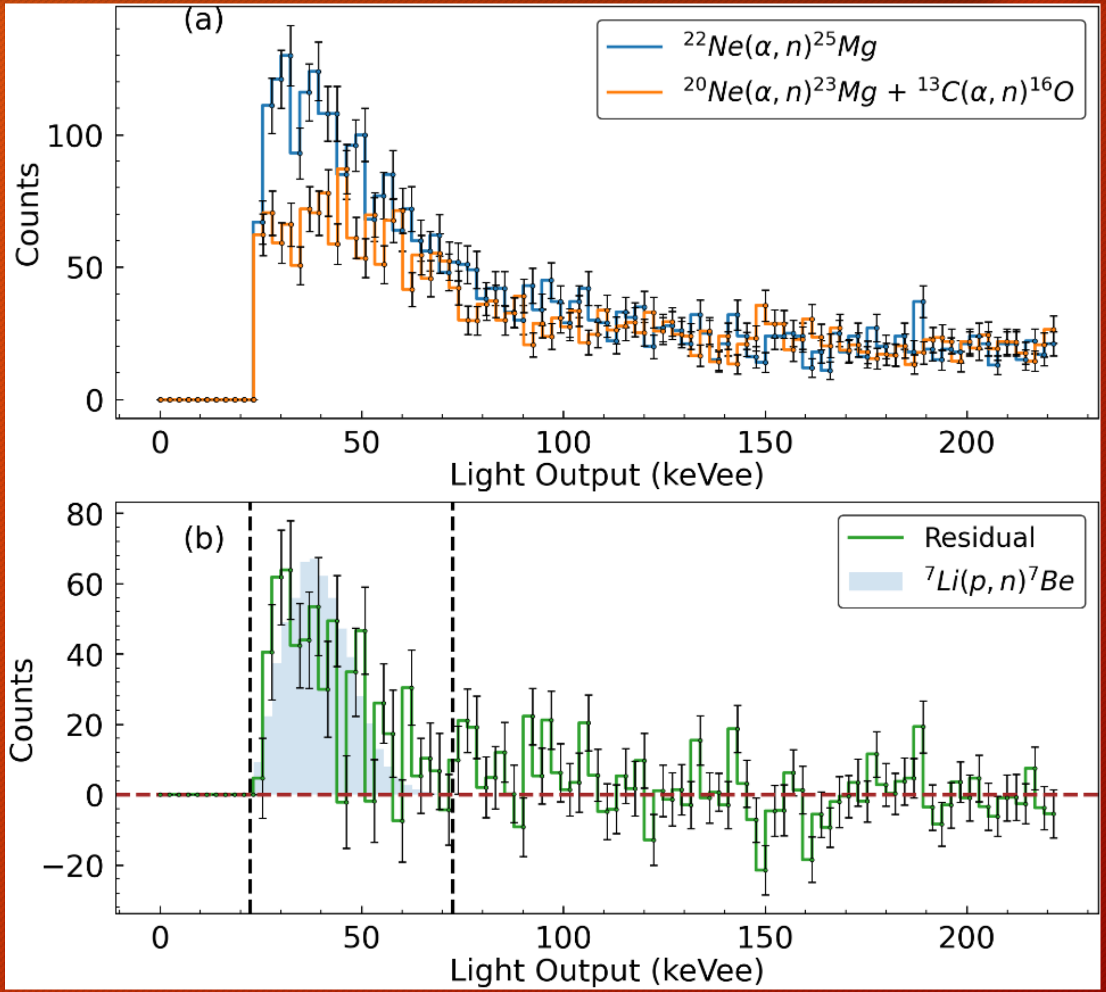
Efficiency

- ^{7}Li(p,n)^{7}Be yield at zero degrees compared to cross section measurements
- The efficiency using ^{7}Li(p,n)^{7}Be and ^{51}V(p,n)^{51}Cr activation
- Plot doesn’t have close geometry correction
- When this is applied, at 280 keV, we get 0.0588(34) and 0.0572(37) for our efficiency for neutrons coming from the 830 keV resonance in the ^{22}Ne(α,n)^{25}Mg reaction



Background subtraction

- Here’s the spectrum that we get from the stilbene detector
- We see a lot of background from natural background and beam induced $^{13}C(\alpha,n)^{16}O$
- However, the $^{13}C(\alpha,n)^{16}O$ background produces counts at high light output (Q = +2.2 MeV), thus we have a way to discriminate based on energy
- The shape of the residual signal is consistent with what we measured using the $^7Li(p,n)^7Be$ reaction



Our result

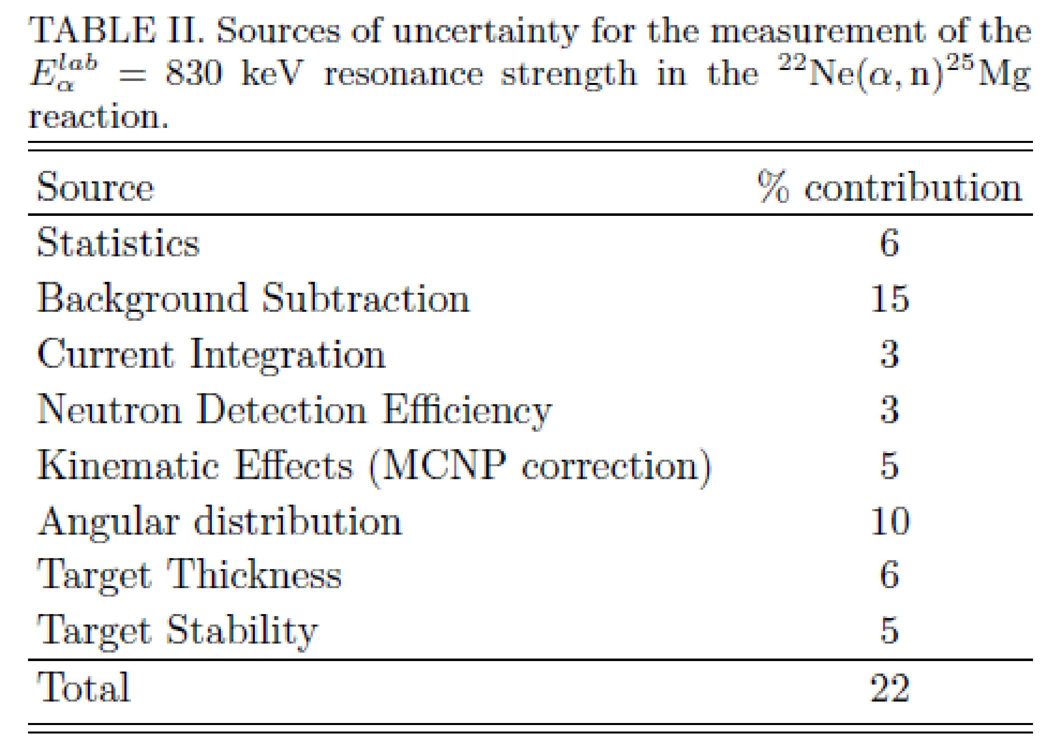
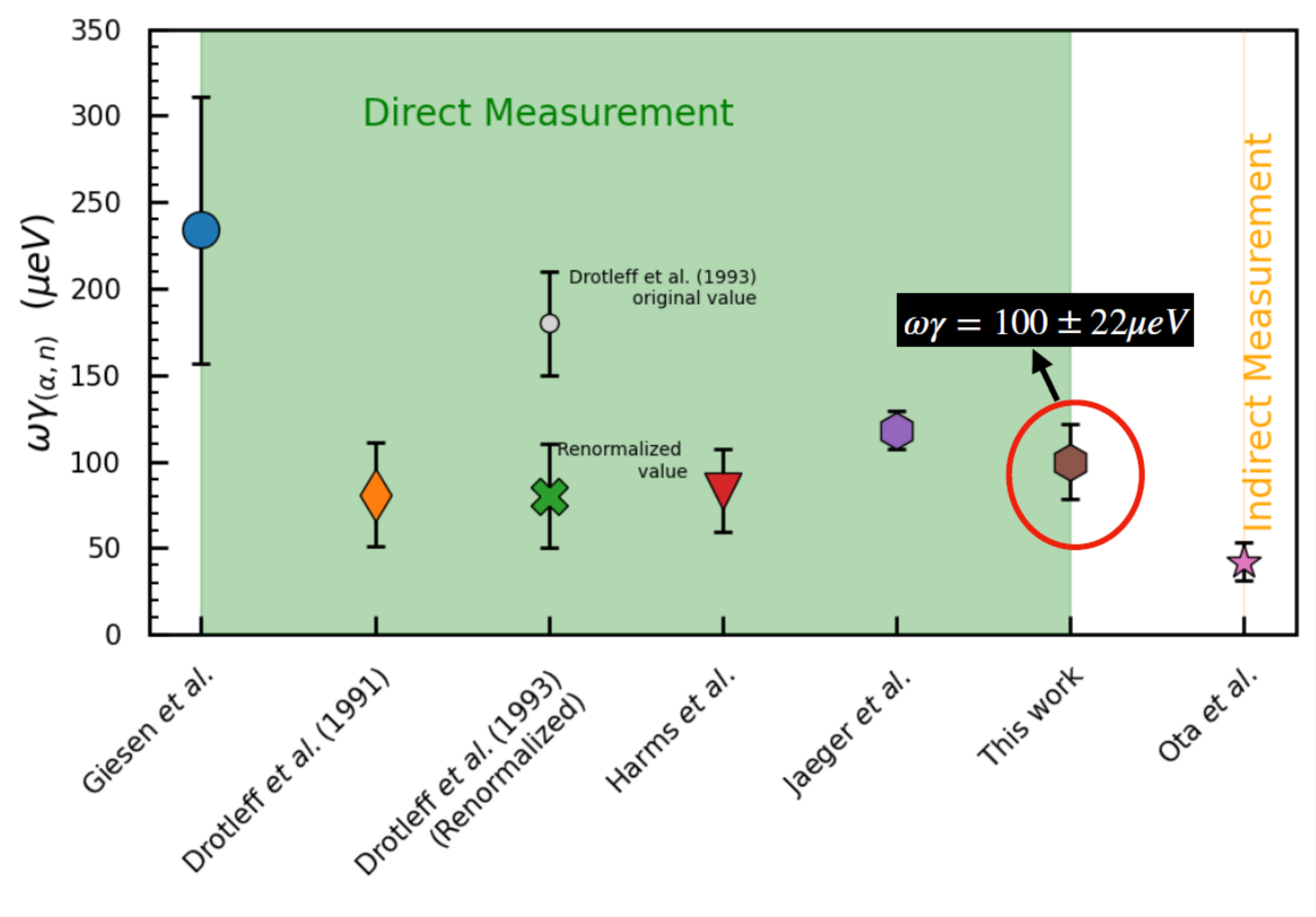


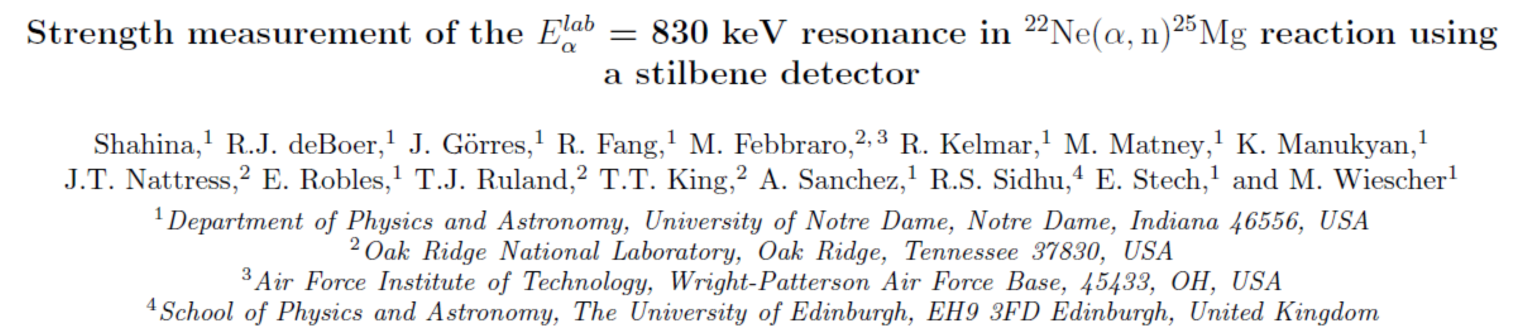
TABLE II. Sources of uncertainty for the measurement of the $E_{\alpha}^{lab} = 830$ keV resonance strength in the $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ reaction.

Source	% contribution
Statistics	6
Background Subtraction	15
Current Integration	3
Neutron Detection Efficiency	3
Kinematic Effects (MCNP correction)	5
Angular distribution	10
Target Thickness	6
Target Stability	5
Total	22



$\omega\gamma = 100 \pm 22\mu eV$

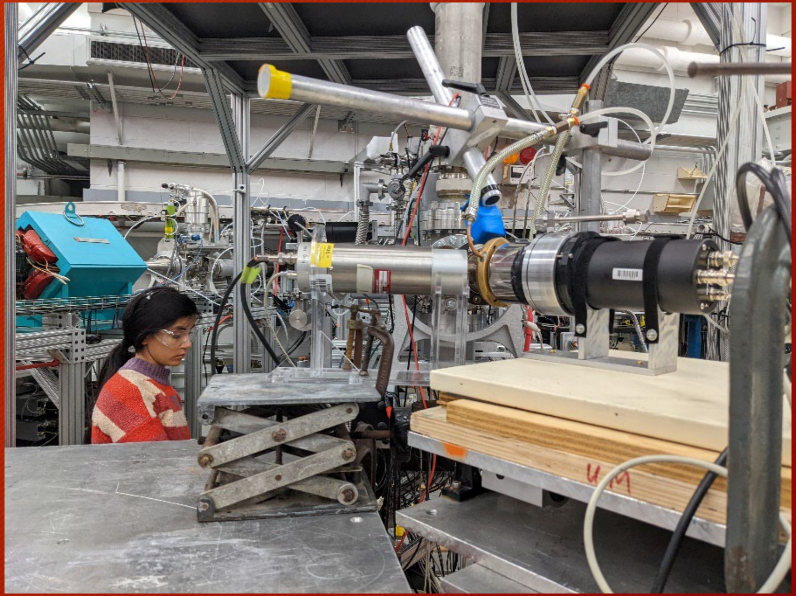
Collaborators



Strength measurement of the $E_\alpha^{lab} = 830$ keV resonance in $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ reaction using a stilbene detector

Shahina,[1] R.J. deBoer,[1] J. Görres,[1] R. Fang,[1] M. Febbraro,[2,3] R. Kelmar,[1] M. Matney,[1] K. Manukyan,[1]
J.T. Nattress,[2] E. Robles,[1] T.J. Ruland,[2] T.T. King,[2] A. Sanchez,[1] R.S. Sidhu,[4] E. Stech,[1] and M. Wiescher[1]
[1] *Department of Physics and Astronomy, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2] *Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA*
[3] *Air Force Institute of Technology, Wright-Patterson Air Force Base, 45433, OH, USA*
[4] *School of Physics and Astronomy, The University of Edinburgh, EH9 3FD Edinburgh, United Kingdom*

Submitted to PRC



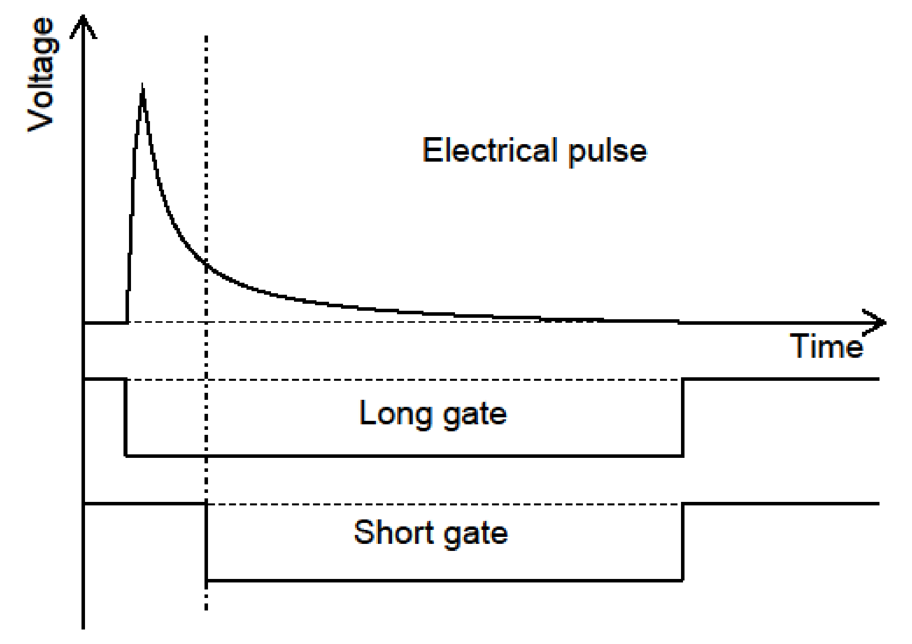
EDINBURGH AZURE2 *R*-MATRIX WORKSHOP

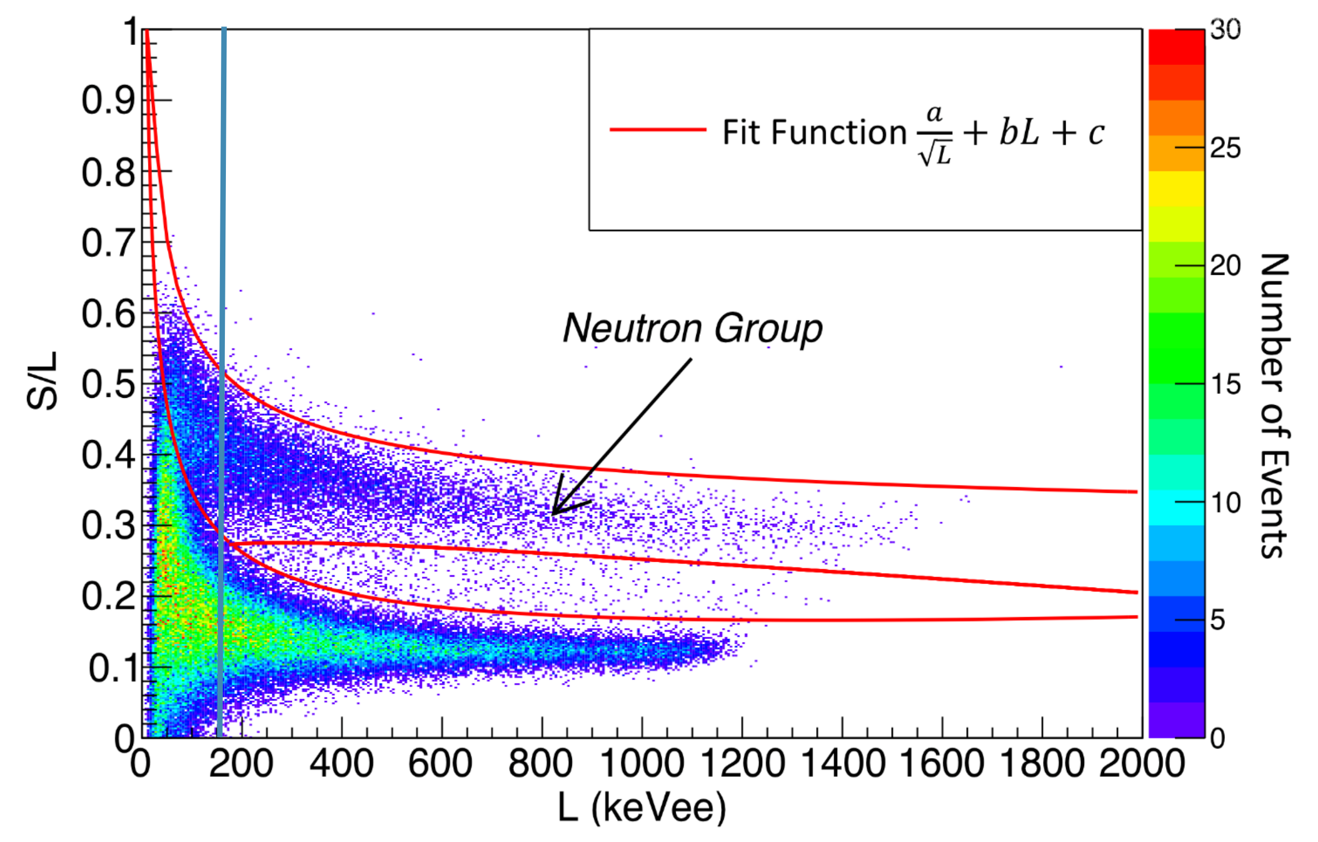
- A workshop dedicated to learning how to use the AZURE2 *R*-matrix code
- Local organizer: Marialiusa Aliotta
- Introductory theory by Carl Brune
- I will go through a series of hands on examples
- June 2024, University of Edinburgh
- https://indico.ph.ed.ac.uk/event/274/
- Scotch

azure.nd.edu

BACKUP SLIDES

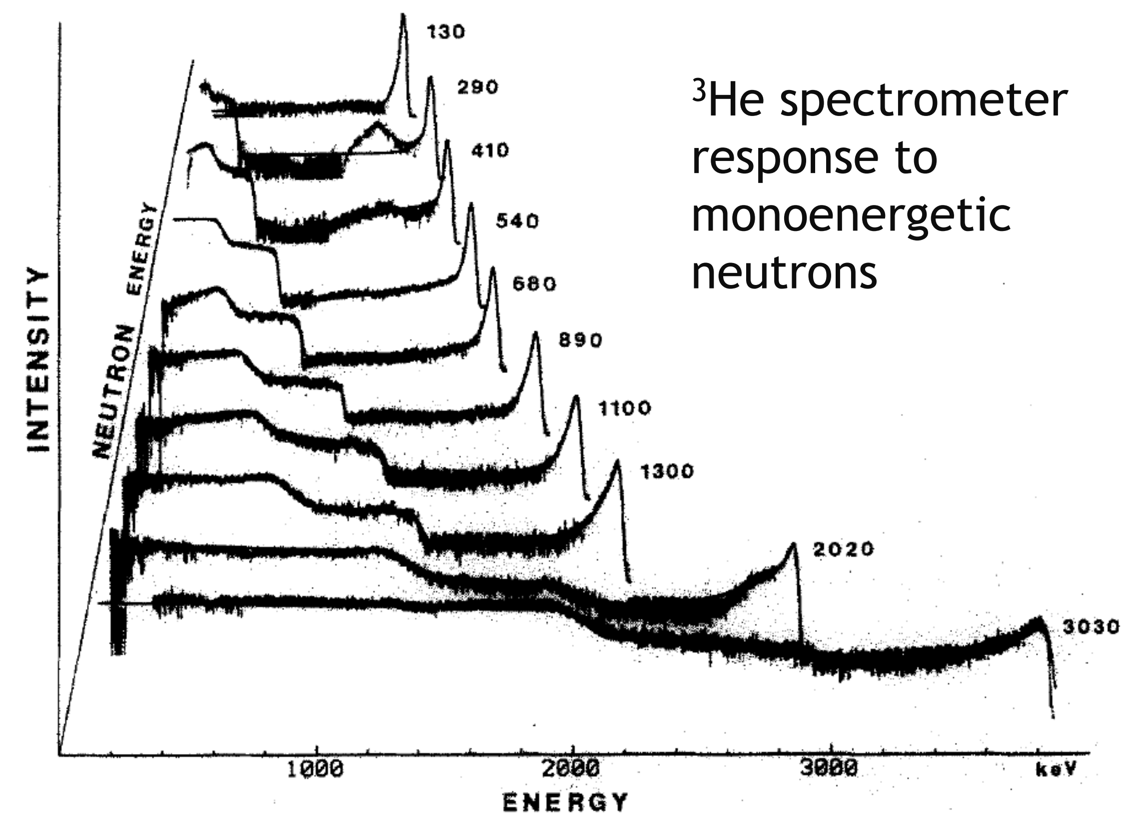
PULSE SHAPE DISCRIMINATION N/Γ





What does it take to do neutron spectroscopy?

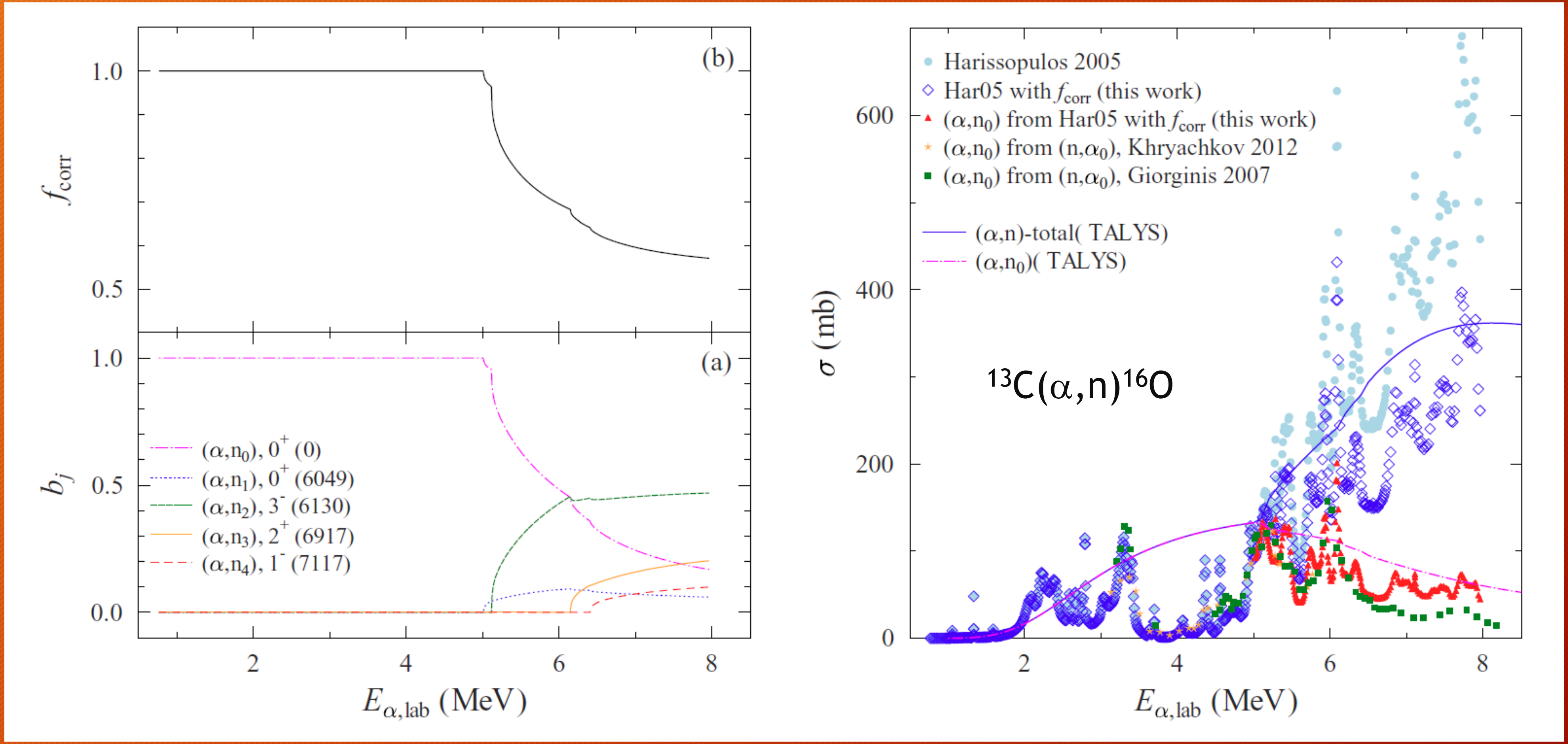
- Time of flight
  - Accelerator system needs a beam that is bunched with sufficient timing
    - This is available on a lot of tandem and cyclotron accelerator system
- Detectors with intrinsic neutron energy sensitivity
  - ^{3}He spectrometer, Lithium Glass
    - Efficiency is poor (10^{-4})
    - Expensive (One ^{3}He spectrometer is like $30k)



^{3}He spectrometer response to monoenergetic neutrons

Beimer *et al.* (1985)

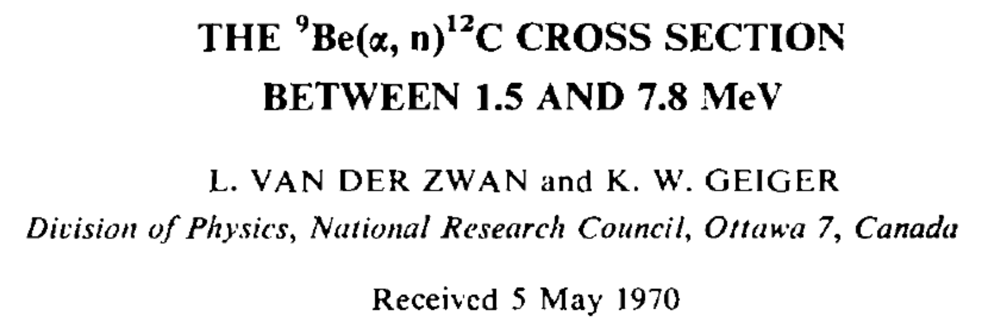
Recently illustrated by Mohr (2018)



P. Mohr (2018)

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

- There isn’t much that hasn’t been tried before
- But often old techniques need to be revised in light of improved technology
- Van der Zwan and Geiger used stilbene detectors for neutron spectroscopy throughout the 1970’s



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

Received 5 May 1970

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

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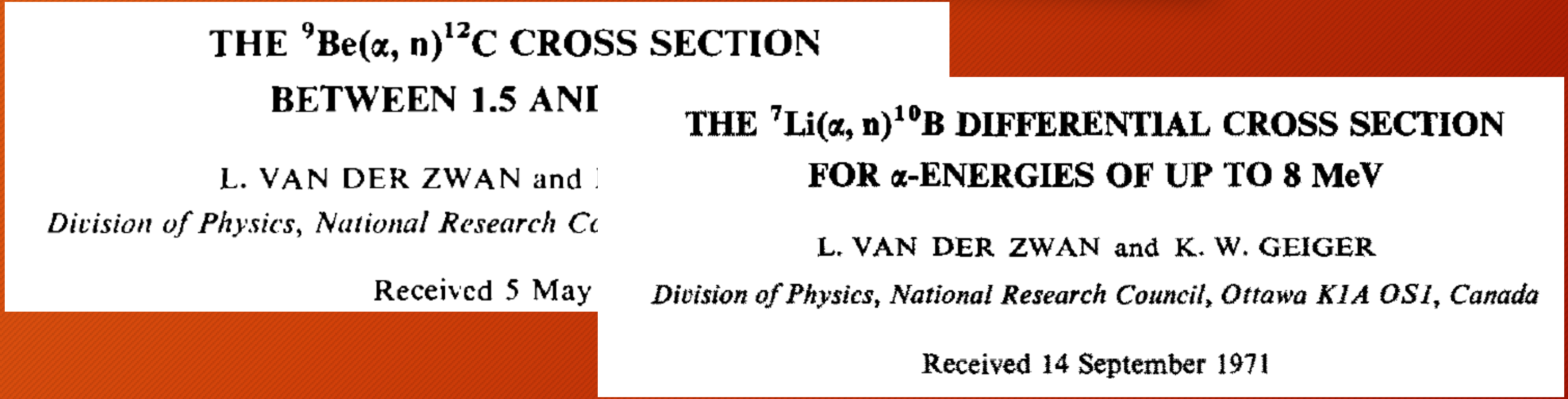

THE ^{9}Be(α, n)^{12}C CROSS SECTION

BETWEEN 1.5 AN

L. VAN DER ZWAN and

Division of Physics, National Research C

Received 5 May

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 OS1, Canada

Received 14 September 1971

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

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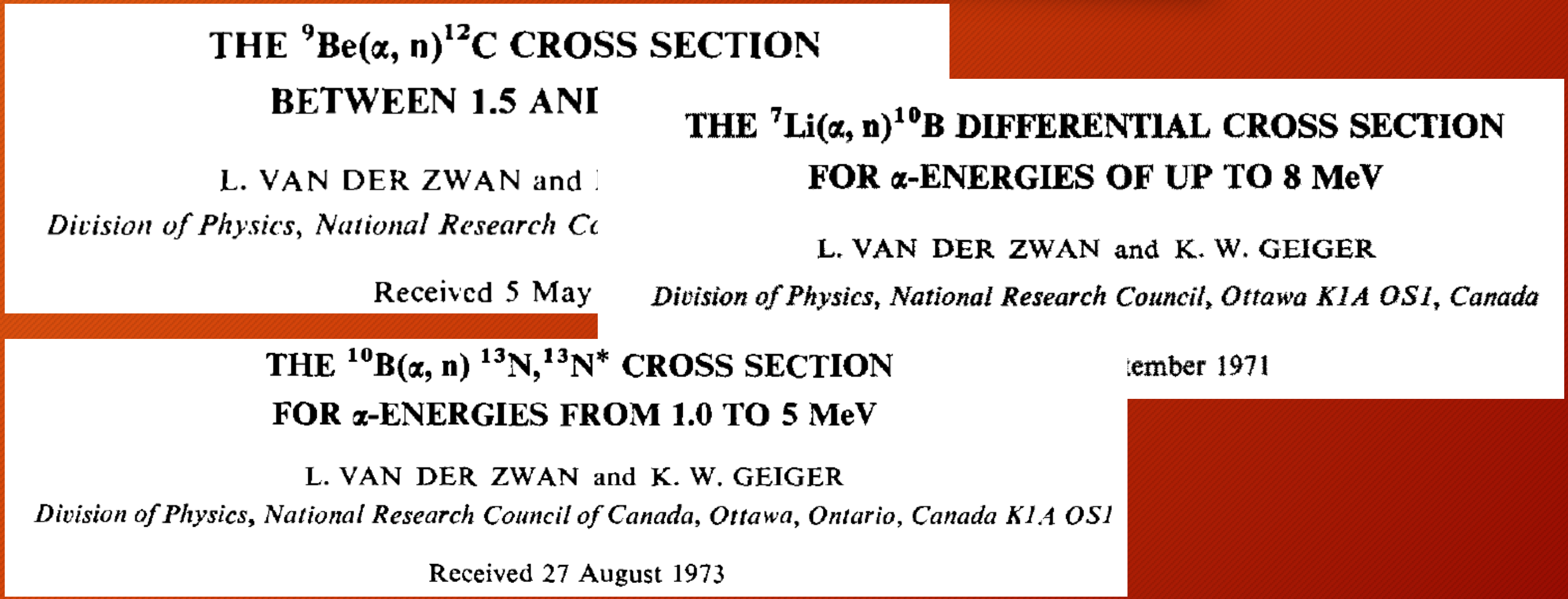

THE ^{9}Be(α, n)^{12}C CROSS SECTION

BETWEEN 1.5 AN

L. VAN DER ZWAN and

Division of Physics, National Research C

Received 5 May

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 OS1, Canada

tember 1971

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 OS1

Received 27 August 1973

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

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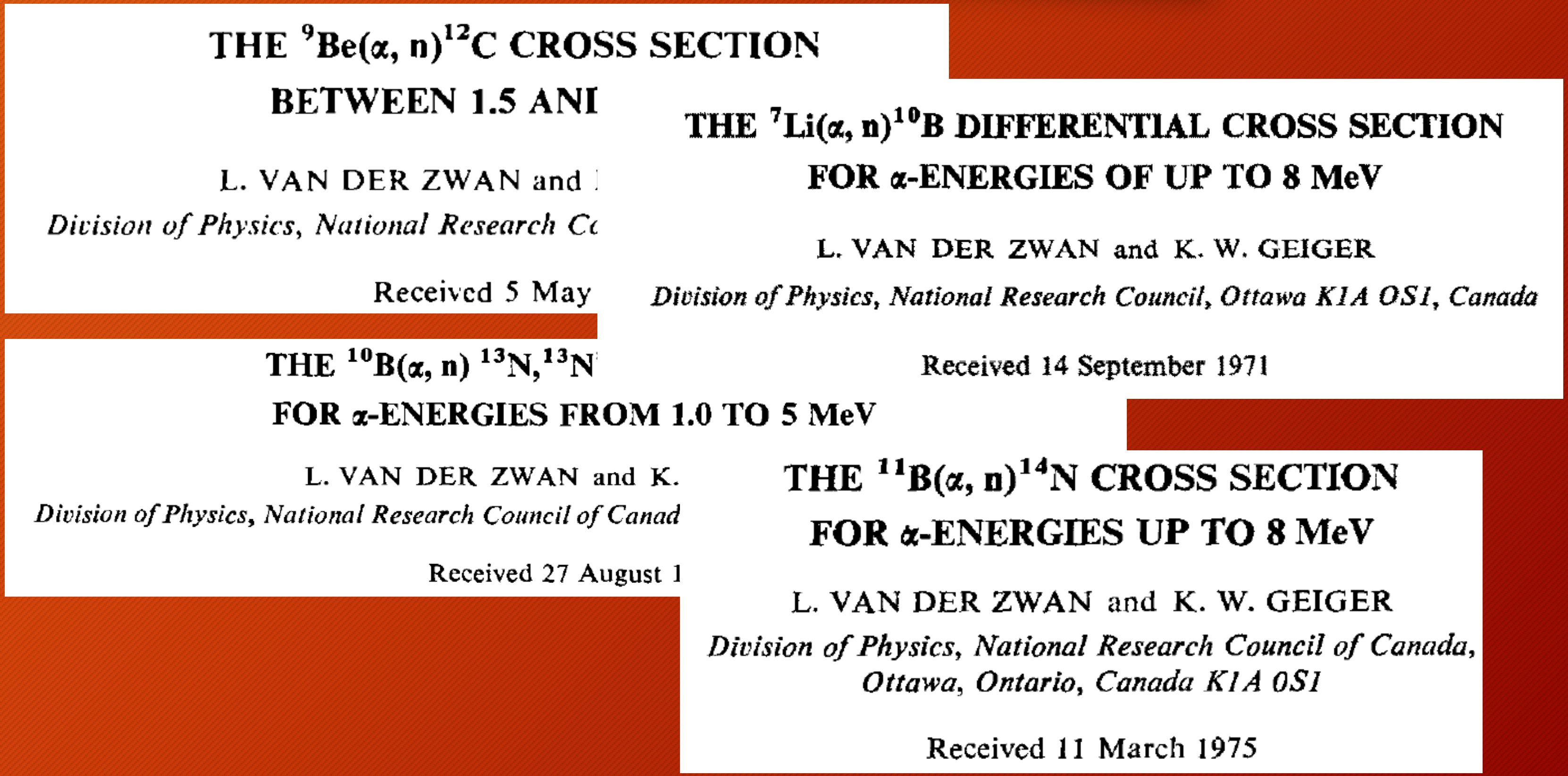

THE ^{9}Be(α, n)^{12}C CROSS SECTION
BETWEEN 1.5 AN

L. VAN DER ZWAN and
Division of Physics, National Research C

Received 5 May

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

Received 14 September 1971

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

L. VAN DER ZWAN and K.
Division of Physics, National Research Council of Canad

Received 27 August 1

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

Received 11 March 1975

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

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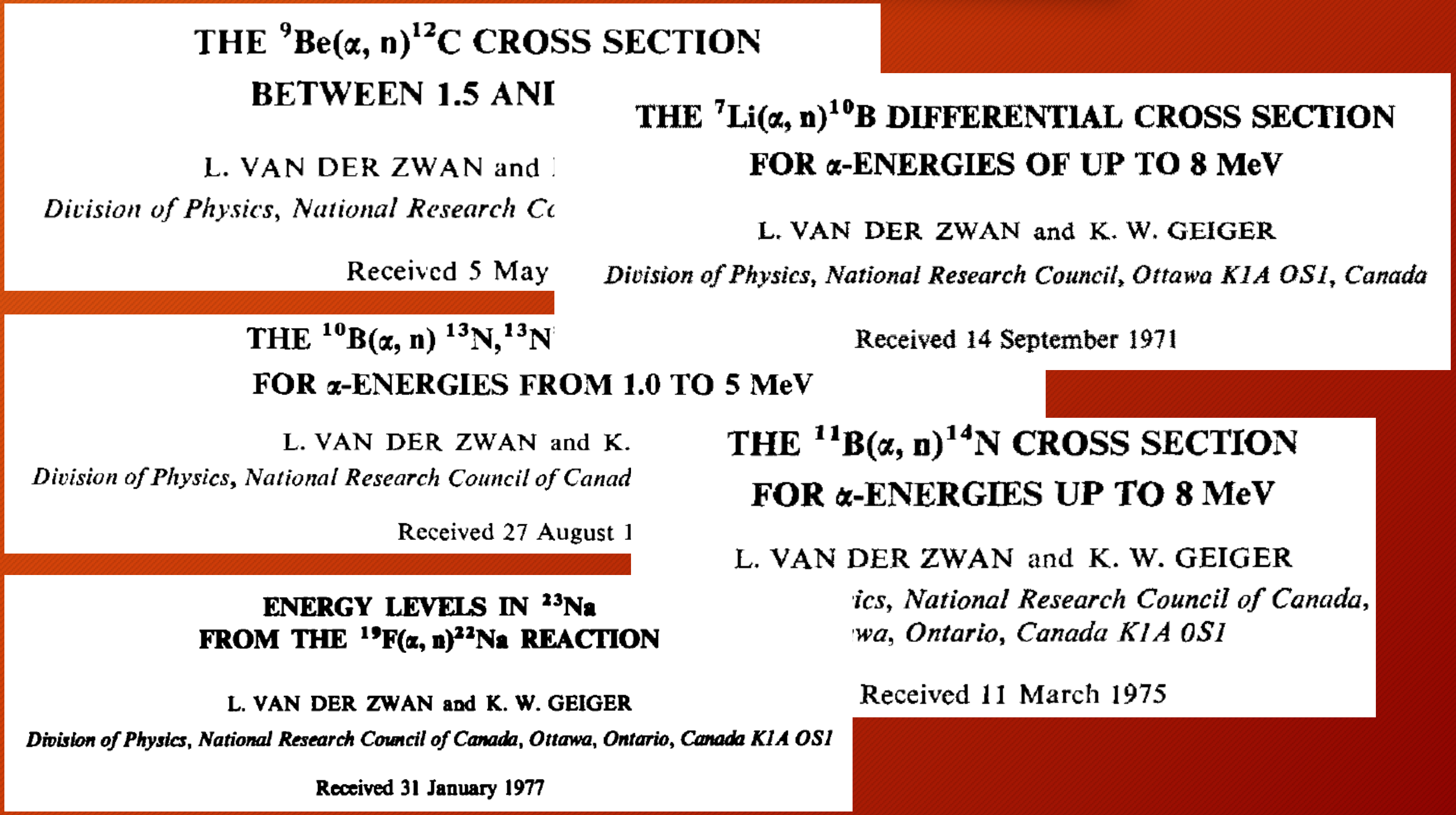

THE ^{9}Be(α, n)^{12}C CROSS SECTION
BETWEEN 1.5 AN

L. VAN DER ZWAN and
Division of Physics, National Research C

Received 5 May

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 OS1, Canada

Received 14 September 1971

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

L. VAN DER ZWAN and K.
Division of Physics, National Research Council of Canad

Received 27 August 1

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

L. VAN DER ZWAN and K. W. GEIGER
ics, National Research Council of Canada,
wa, Ontario, Canada K1A 0S1

Received 11 March 1975

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 OS1

Received 31 January 1977

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

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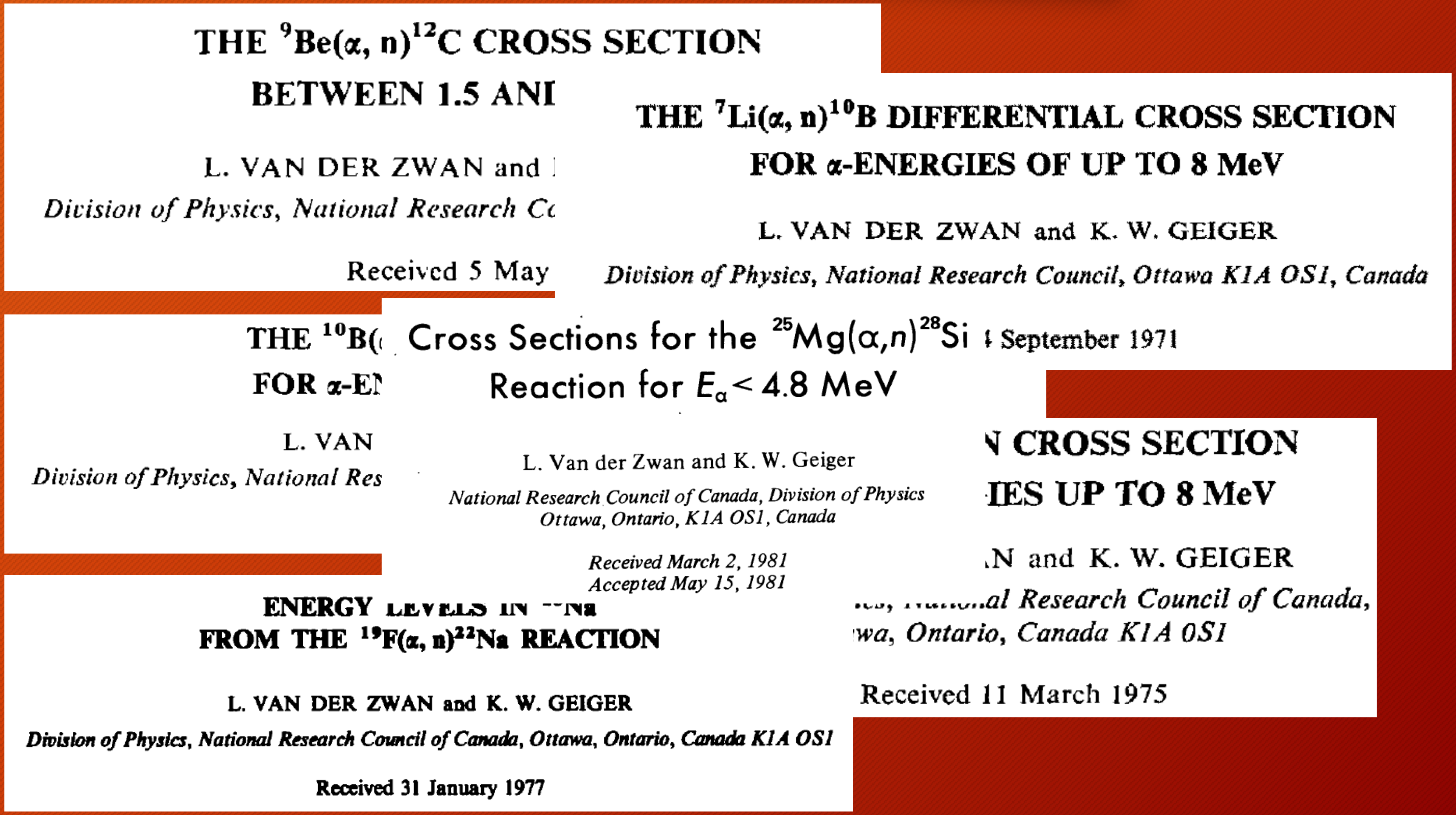


THE ^{9}Be(α, n)^{12}C CROSS SECTION
BETWEEN 1.5 AN
L. VAN DER ZWAN and
Division of Physics, National Research C
Received 5 May

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
September 1971

THE ^{10}B(
FOR α-E
L. VAN
Division of Physics, National Res

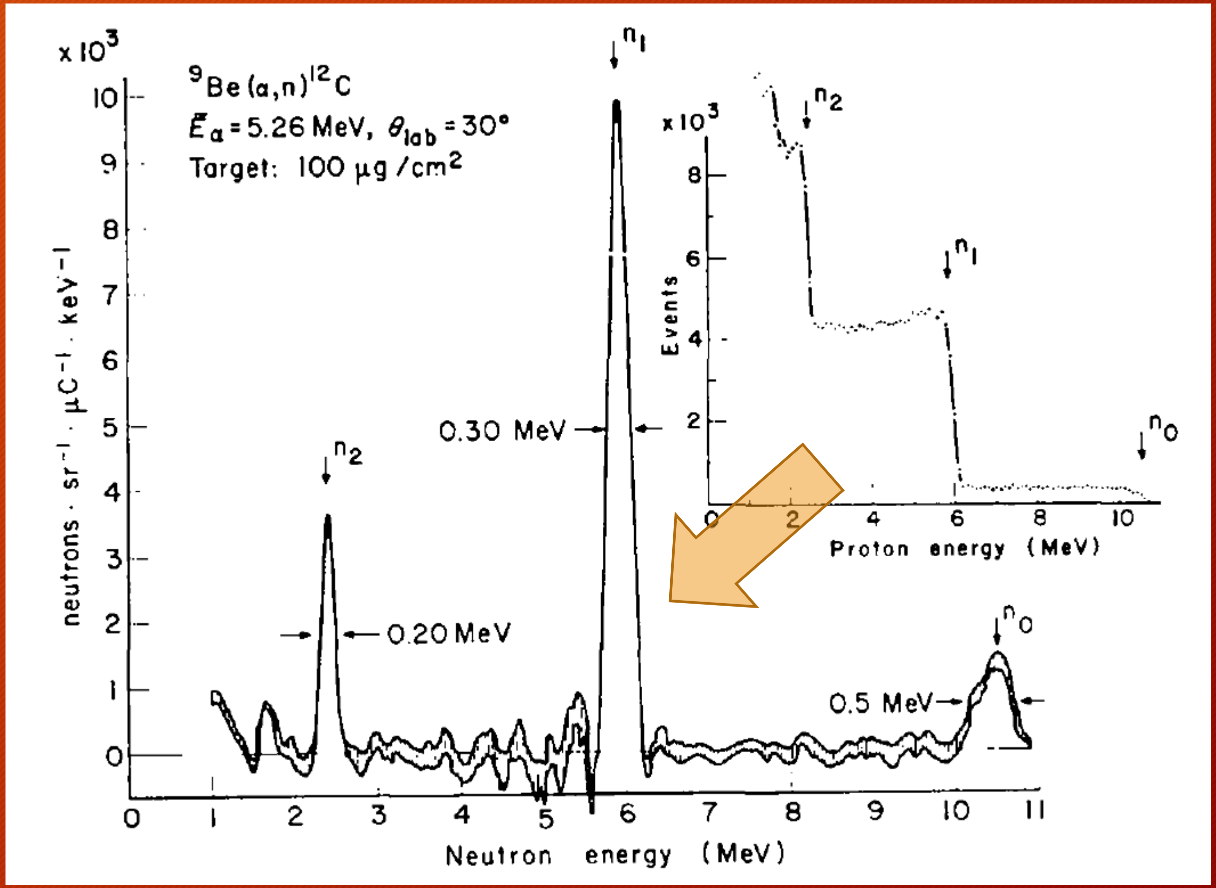
Cross Sections for the ^{25}Mg(α,n)^{28}Si
Reaction for $E_\alpha < 4.8$ MeV
L. Van der Zwan and K. W. Geiger
National Research Council of Canada, Division of Physics
Ottawa, Ontario, K1A 0S1, Canada
Received March 2, 1981
Accepted May 15, 1981

N CROSS SECTION
IES UP TO 8 MeV
N and K. W. GEIGER
al Research Council of Canada,
wa, Ontario, Canada K1A 0S1
Received 11 March 1975

ENERGY LEVELS IN 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
Received 31 January 1977

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

- Light response spectrum in a stilbene detector looks like step functions
- This can be numerically differentiated to obtain full energy peaks



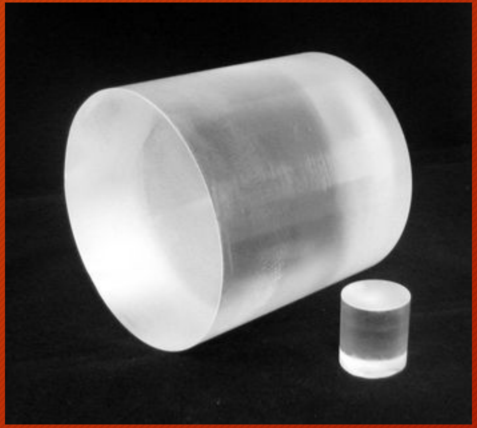
A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

- Why wasn’t this technique used more broadly?
  - Stilbene detectors were expensive and fragile
  - Differentiation analysis was very time consuming in the 1970’s?
  - Maybe there were questions about the reliability of the technique?

- These complications show in the data
  - Usually only a zero degree excitation function with angular distributions at only a few select energies
  - This gives a lot of information, but since reaction cross sections were not ever given, most of this data has never made it into the compilations ☹

A different approach: Deuterated Liquid and Stilbene Crystal Scintillators

- 30 years later…
  - The cost of stilbene crystals has come down somewhat
  - Still hard to get unfortunately, not many manufacturers
  - Some progress in increasing crystal size (up to about 2 inch by 2 inch)
  - Spectrum differentiation has been replaced by spectrum unfolding



Inrad Optics

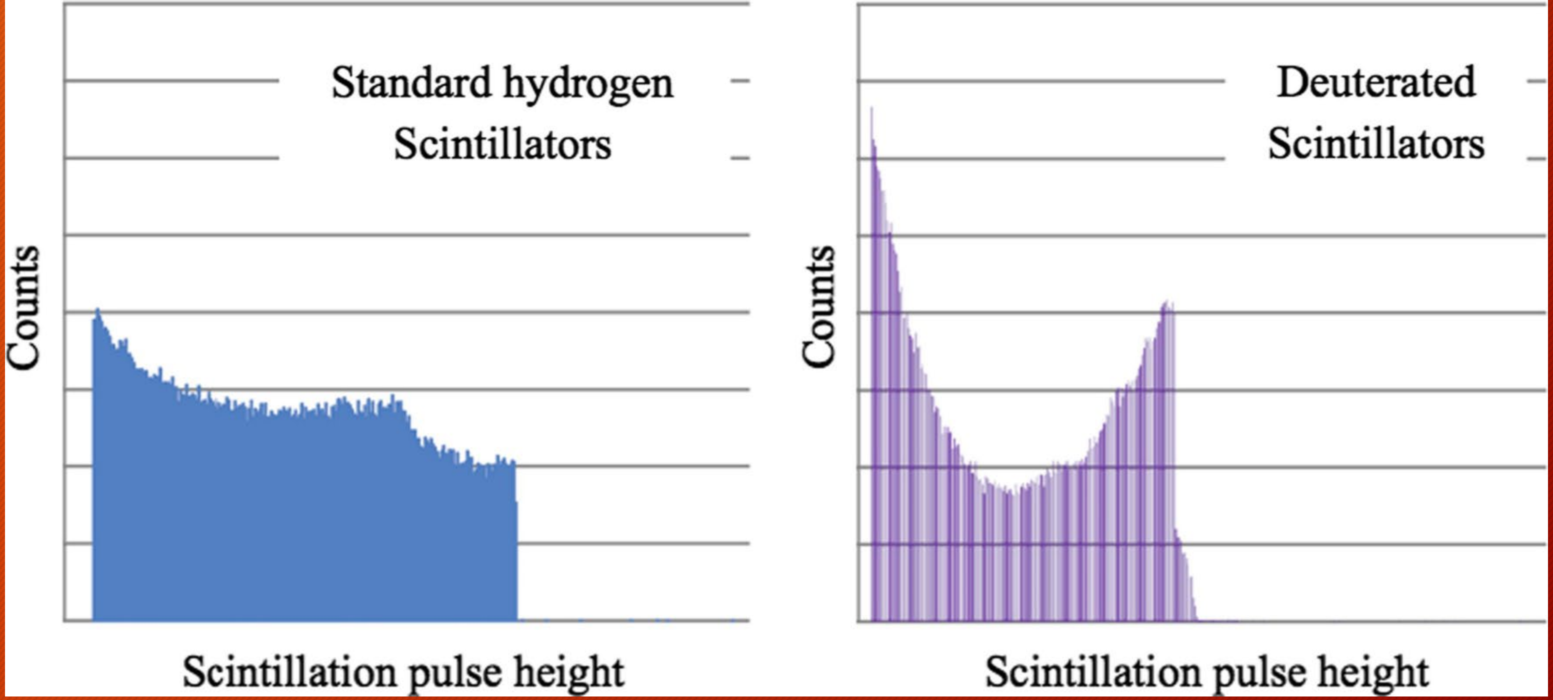
Liquid Scintillators vs stilbene

- Less expensive than stilbene
- More durable than stilbene
- Liquid itself is often hazardous, but when professionally sealed there is no issue
- A bit poorer resolution and higher threshold for neutron/γ-ray discrimination
- Used for many years, often in conjunction with the time of flight technique
- Spectra can also be unfolded

Brookhaven National Laboratory: Instrumentation Division

Liquid Scintillators: hydrogen vs deuterium

- Traditional liquid scintillators are hydrogen based
- Deuterium based scintillators are advantageous because they give more of a forward/backward peaked spectrum
- Greater sensitivity for an unfolding algorithm



Lawrence *et al*. (2013)

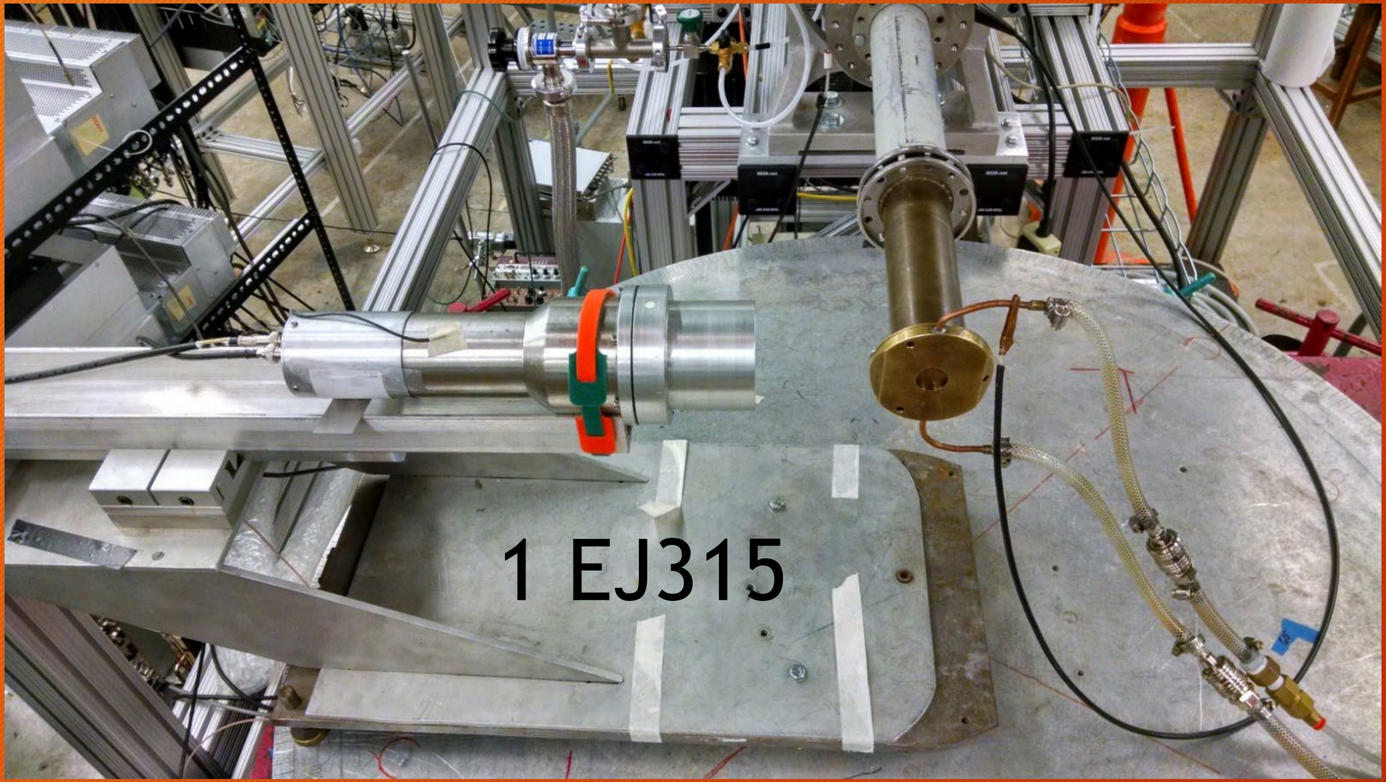
Deuterated Liquid Scintillators: readily available

- Eljen Technologies
  - Deuterated Benzene (C_6D_6)
  - Deuterated Xylene (C_8D_{10})
- Current detectors are C_6D_6 (EJ315)
  - Liquid is purified, giving better light output, giving lower energy PSD and better resolution

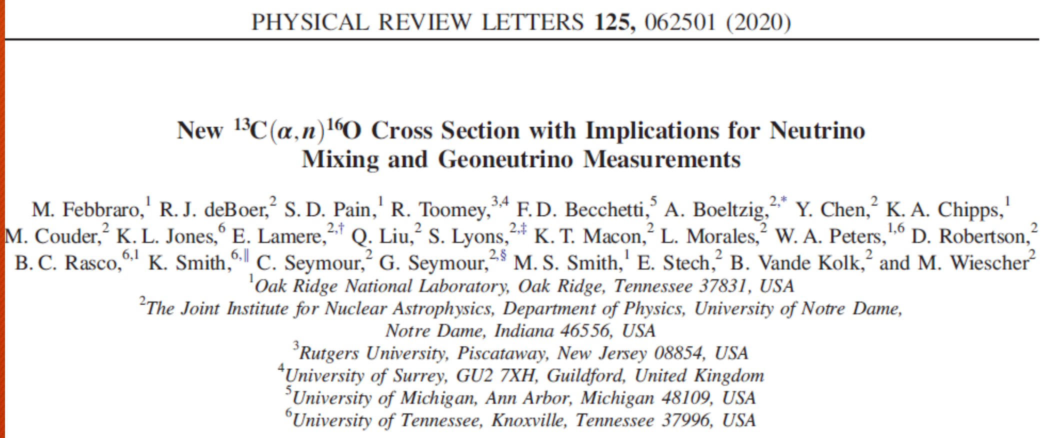
Eljen, EJ315

Mike Febbraro

Evolution of our setup: 2016



$^{13}C(\alpha,n)^{16}O$ measurements in 2016



PHYSICAL REVIEW LETTERS **125,** 062501 (2020)

New $^{13}C(\alpha,n)^{16}O$ Cross Section with Implications for Neutrino Mixing and Geoneutrino Measurements

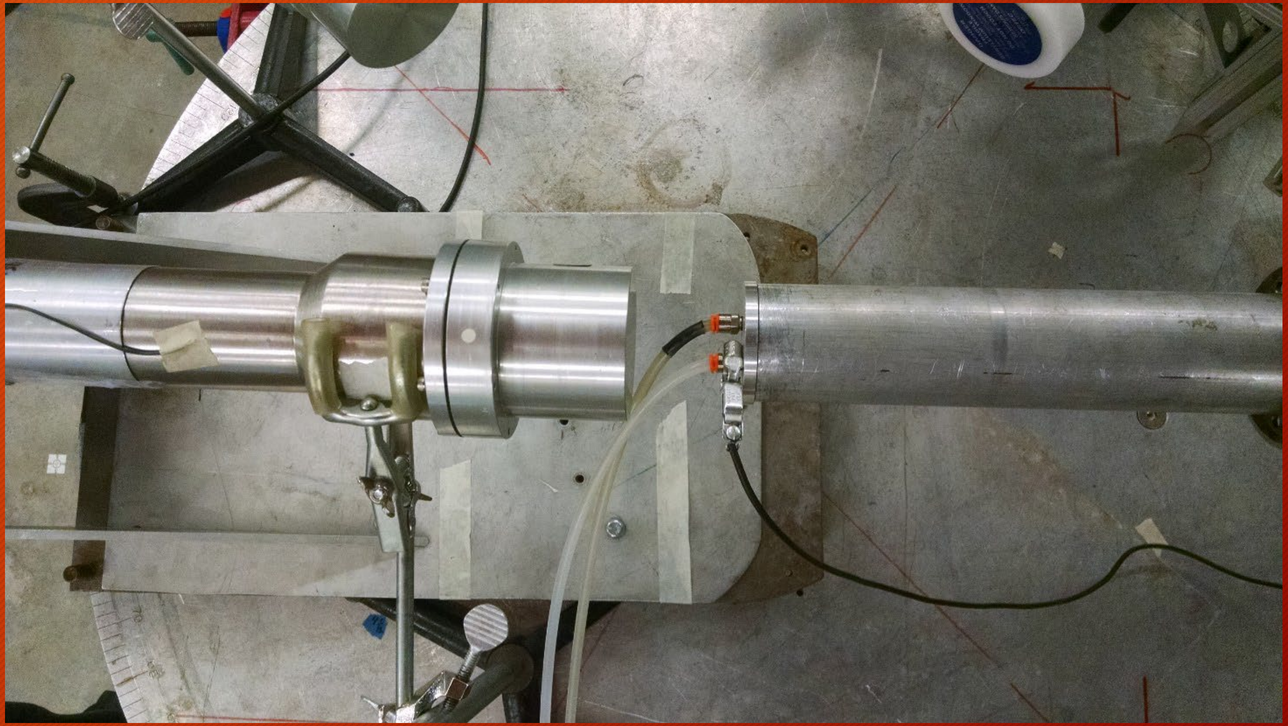
M. Febbraro,[1] R. J. deBoer,[2] S. D. Pain,[1] R. Toomey,[3,4] F. D. Becchetti,[5] A. Boeltzig,[2,*] Y. Chen,[2] K. A. Chipps,[1] M. Couder,[2] K. L. Jones,[6] E. Lamere,[2,†] Q. Liu,[2] S. Lyons,[2,‡] K. T. Macon,[2] L. Morales,[2] W. A. Peters,[1,6] D. Robertson,[2] B. C. Rasco,[6,1] K. Smith,[6,∥] C. Seymour,[2] G. Seymour,[2,§] M. S. Smith,[1] E. Stech,[2] B. Vande Kolk,[2] and M. Wiescher[2]

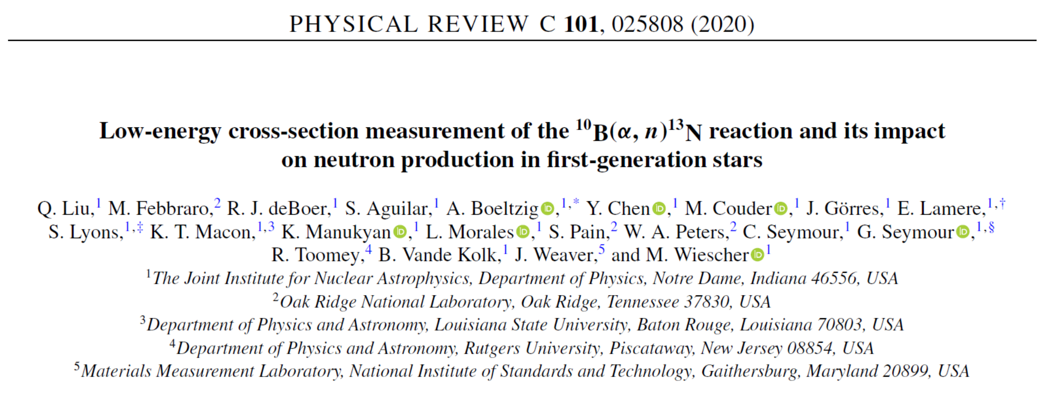
[1] *Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[2] *The Joint Institute for Nuclear Astrophysics, Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[3] *Rutgers University, Piscataway, New Jersey 08854, USA*
[4] *University of Surrey, GU2 7XH, Guildford, United Kingdom*
[5] *University of Michigan, Ann Arbor, Michigan 48109, USA*
[6] *University of Tennessee, Knoxville, Tennessee 37996, USA*

- Critiques
  - Massive target holder
  - One detector
- Did it right
  - Waterlines out of the way
  - Brass is fine (not activated)

Evolution of our setup: 2017

- Critiques
  - Water lines… not the best idea
- Did it right
  - High efficiency in close geometry works well
  - Even for a light mass reaction like $^{10}B(\alpha,n)^{13}N$, kinematic broadening was not a problem





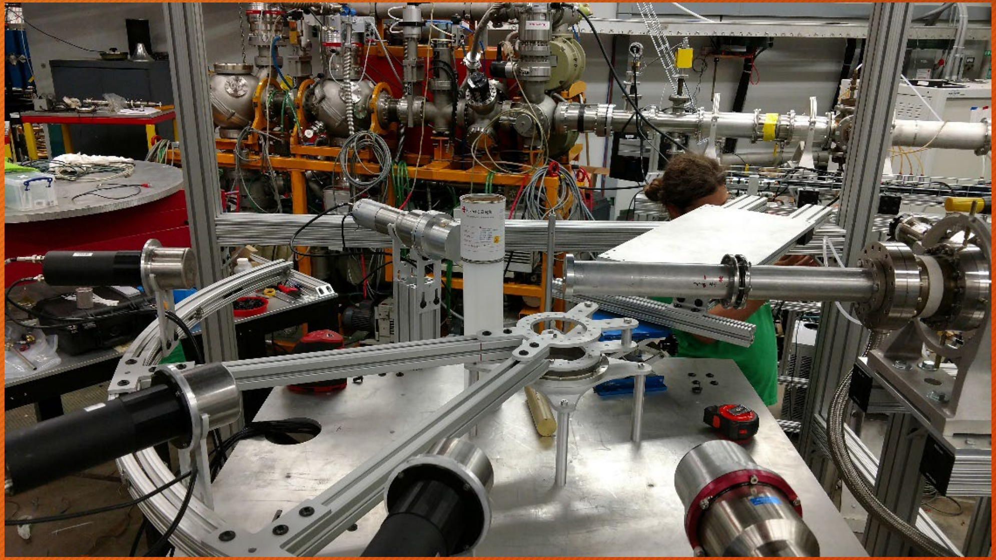
PHYSICAL REVIEW C **101**, 025808 (2020)

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]

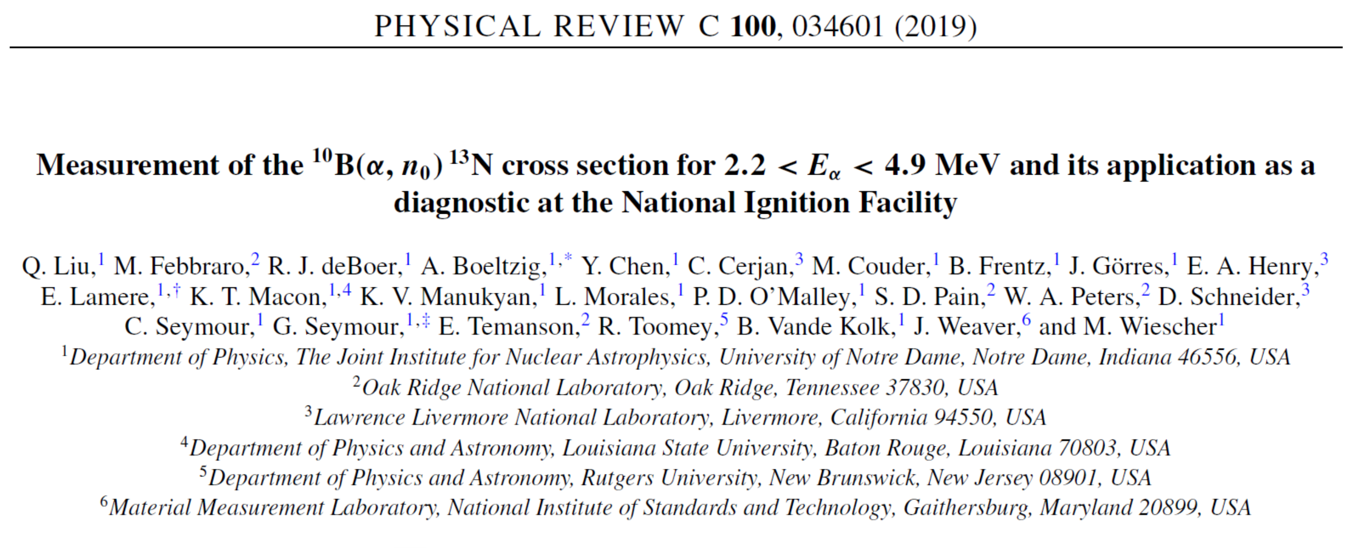
[1]*The Joint Institute for Nuclear Astrophysics, Department of Physics, Notre Dame, Indiana 46556, USA*
[2]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA*
[3]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[4]*Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA*
[5]*Materials Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*

Evolution of our setup: 2017



Far geometry setup for $^{10}B(\alpha,n)^{13}N$

- Critique
  - Water lines more in the way
- Did it right
  - Lower mass target holder
  - Rotatable table for more angular coverage



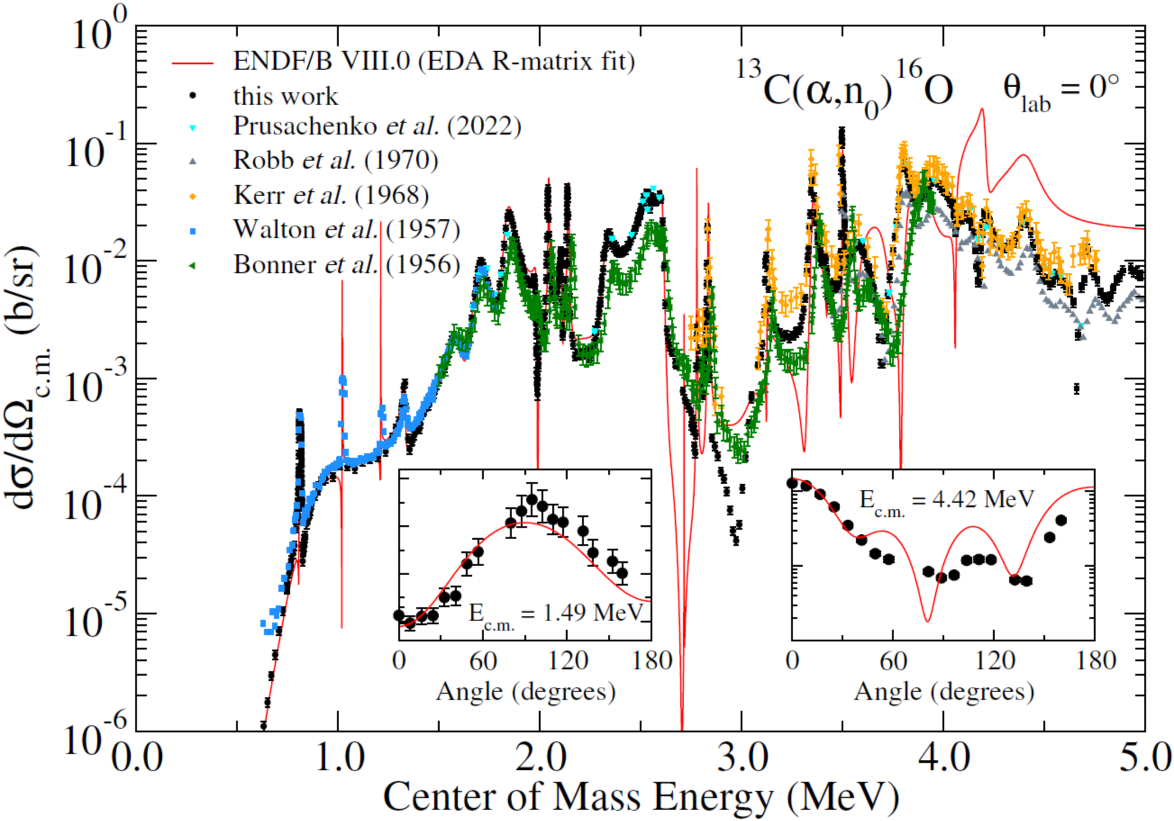
PHYSICAL REVIEW C **100**, 034601 (2019)

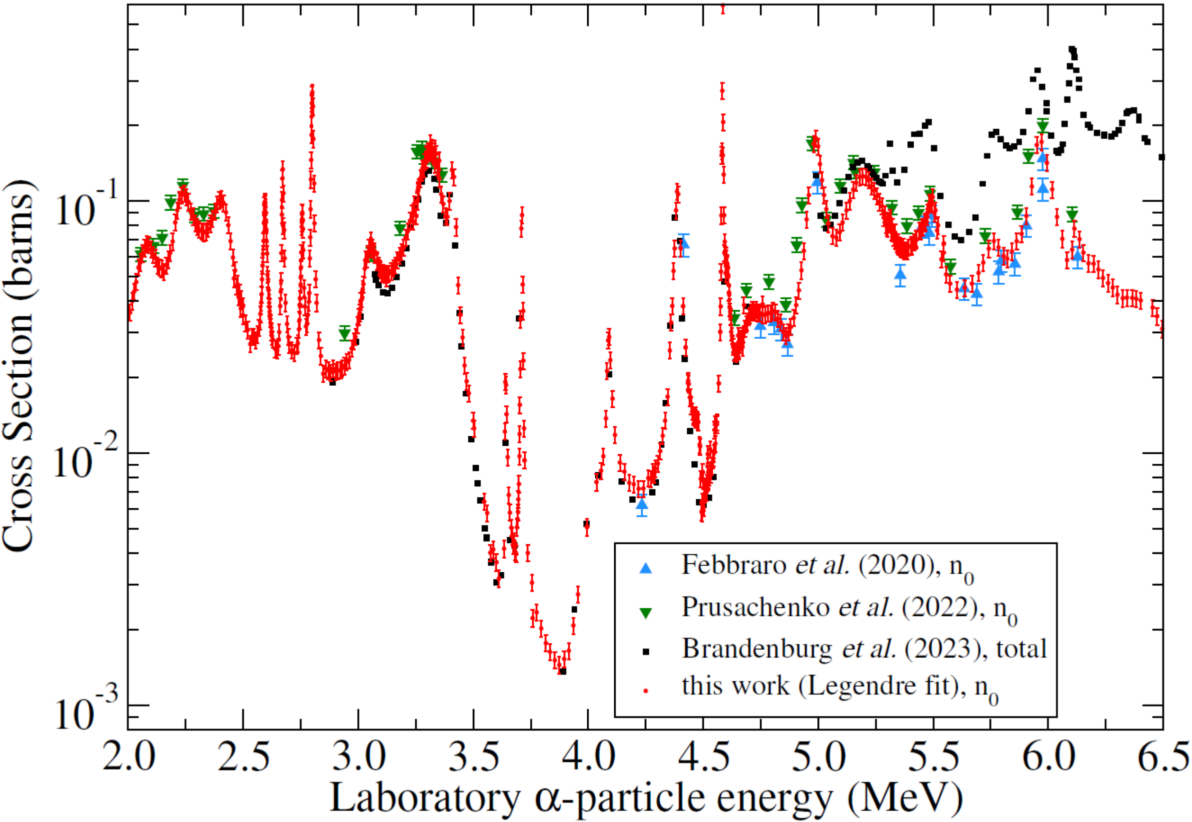
Measurement of the $^{10}B(\alpha, n_0)^{13}N$ cross section for $2.2 < E_\alpha < 4.9$ MeV and its application as a diagnostic at the National Ignition Facility

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]

[1] *Department of Physics, The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2] *Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA*
[3] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[4] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[5] *Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08901, USA*
[6] *Material Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*

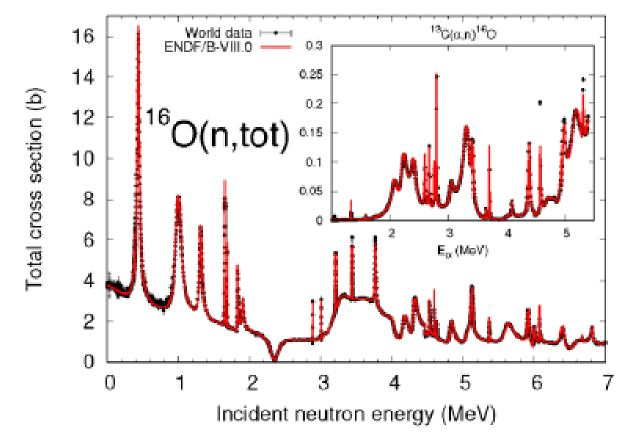
Comparisons to previous data

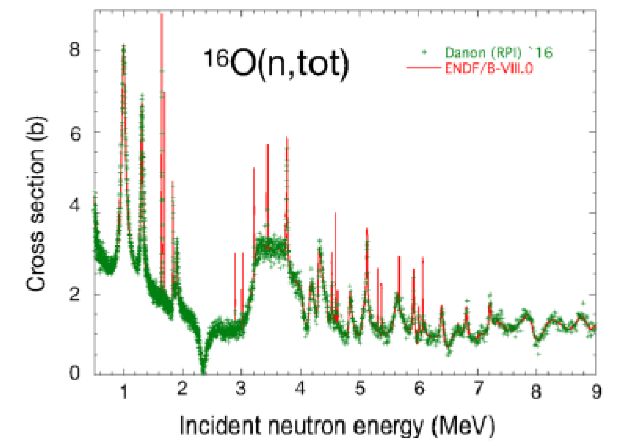


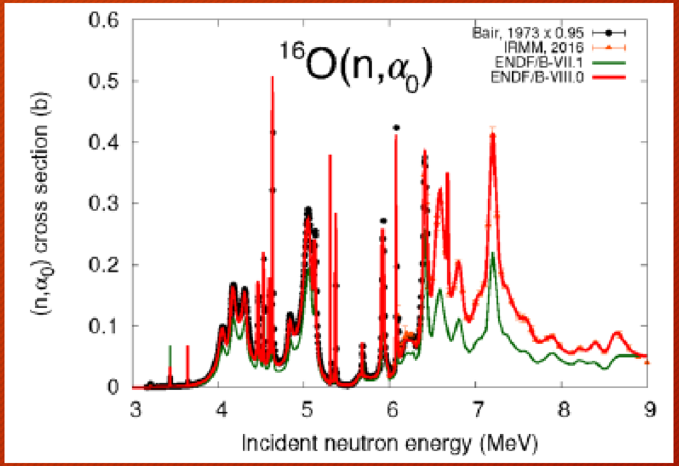


R-matrix fit

- Thanks to Mark Paris and Gerry Hale for supplying the resonance parameters for their R-matrix fit
  - ENDF/B VIII.0 version
- They have made the most comprehensive R-matrix fit by far
  - $^{16}O(n,total)$, $^{16}O(n,n)$, $^{16}O(n,n')$, $^{16}O(n,\alpha)$
  - $^{13}C(\alpha,\alpha)$, $^{13}C(\alpha,n)$
  - LOTS of data sets







Brown *et al.* (2018) (ENDF/B VIII.0)

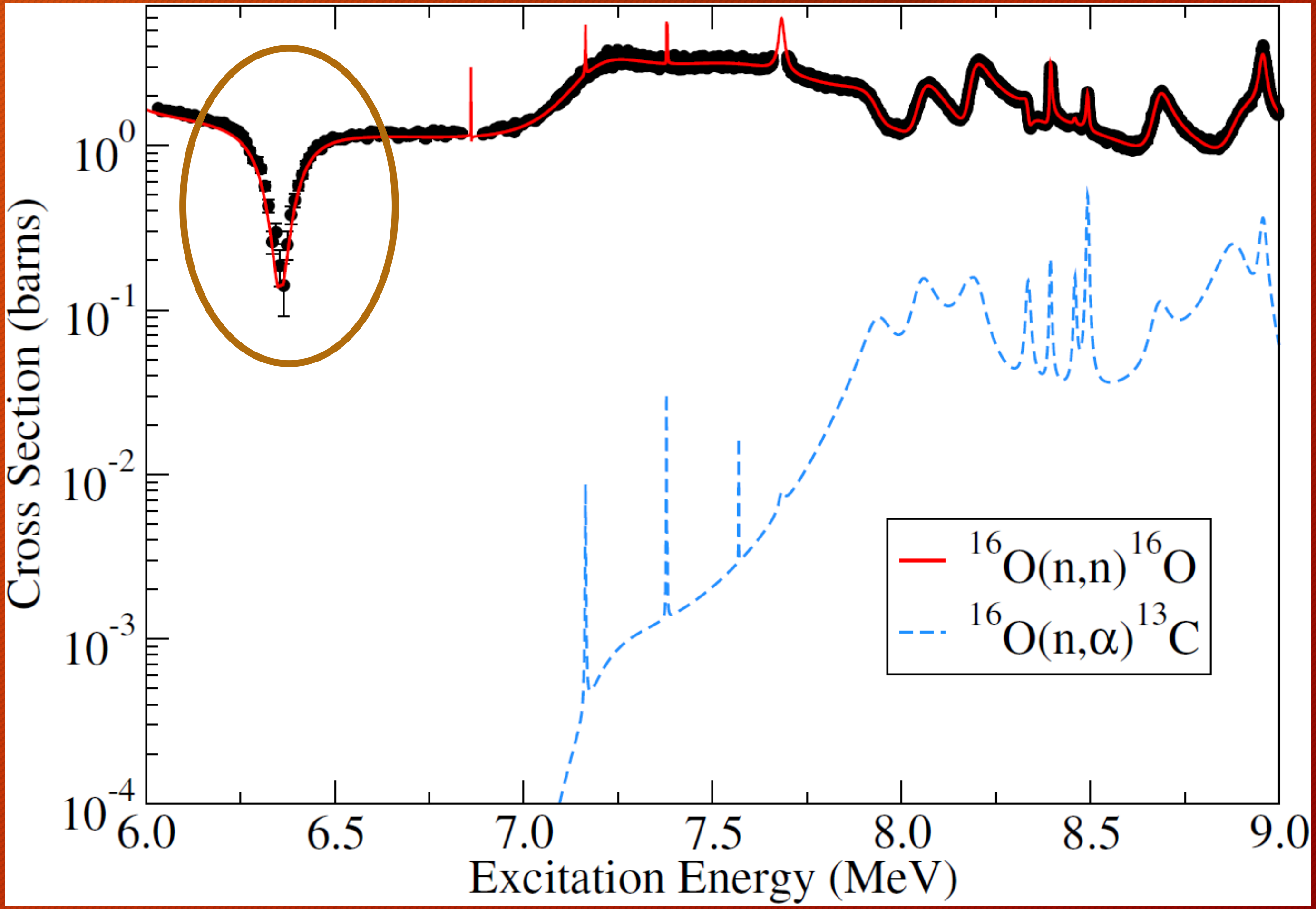
AZURE: An R-matrix code for Nuclear Astrophysics

Azuma *et al.* PRC **81**, 045805 (2010)

- Active code development by Dick Azuma from perhaps the mid ‘90s to 2010
- Became a collaboration sponsored by the Joint Institute for Nuclear Astrophysics (JINA)
- Several graduate students contributed to the code development
- AZURE2 code
  - Ethan Uberseder
  - 2012
  - azure.nd.edu

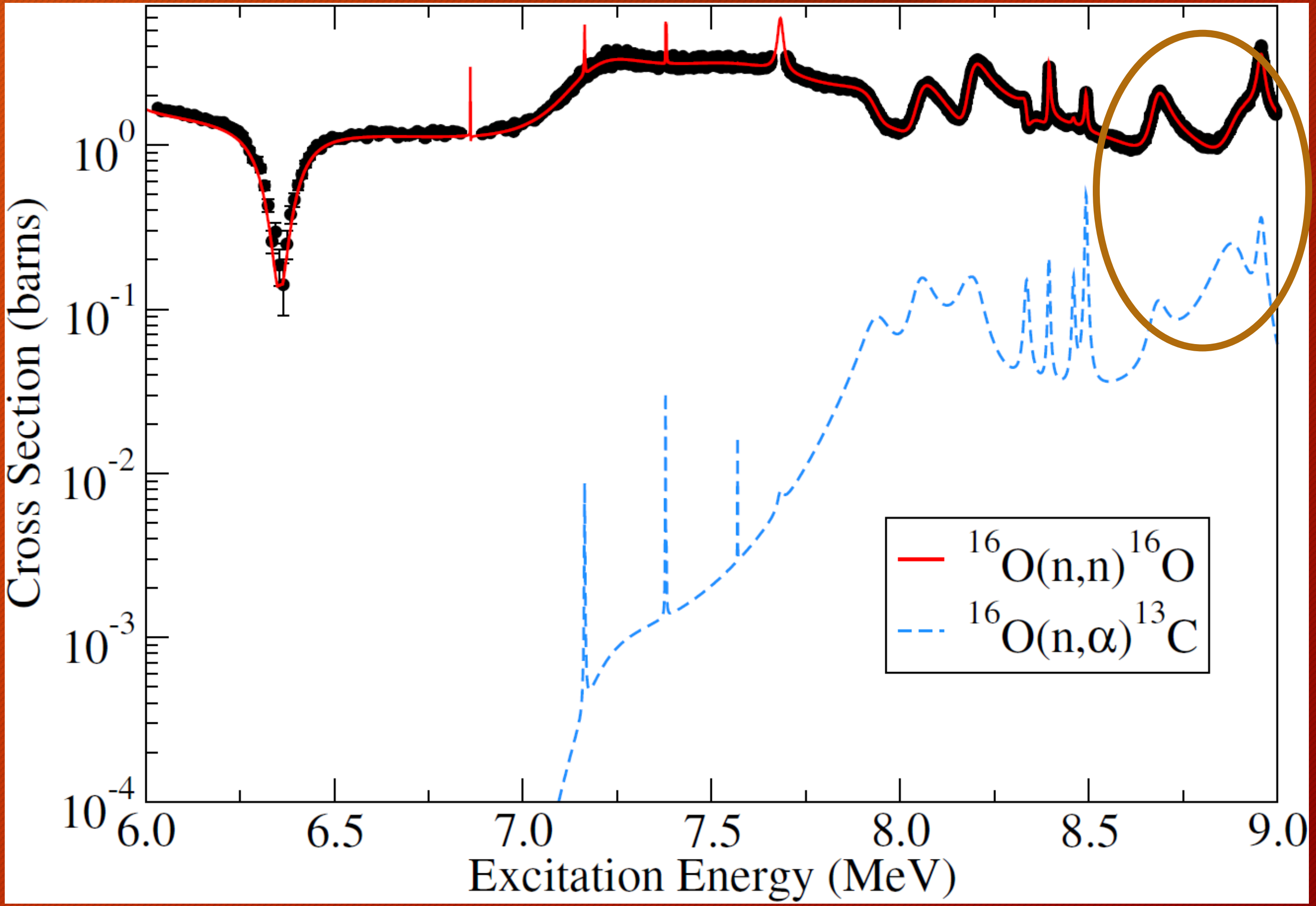
Special attention to the threshold state

- Its strength can be characterized by
    - excitation energy
    - Γ_n
    - Γ_α (or a ANC)
- Its neutron width and energy are constrained by ^{16}O(n,total) data



^{16}O(n,total) = ^{16}O(n,n)+^{16}O(n,α)

- There are resonances where the ^{16}O(n,α) cross section is up to 10% of the total
- Statistical uncertainties of the total cross section data is sub percent while the systematic uncertainty is about 5% (or less)
- Thus, the ^{16}O(n,total) data constrains the absolute scale of the ^{16}O(n,α) cross section



Special attention to the threshold state

- Its ANC has been measured several times with largely consistent results

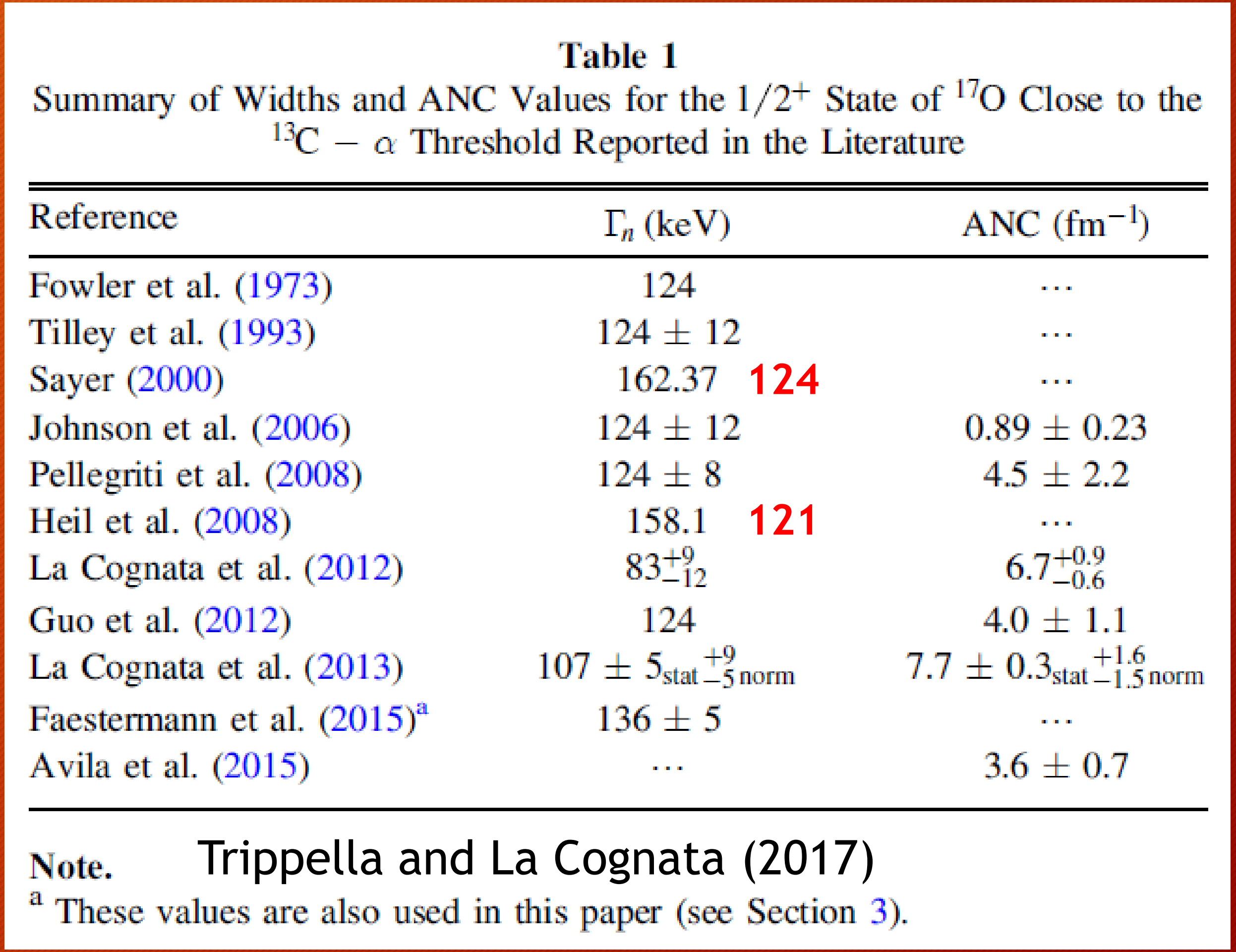


Table 1

Summary of Widths and ANC Values for the $1/2^+$ State of ^{17}O Close to the $^{13}\mathrm{C} - \alpha$ Threshold Reported in the Literature

Reference	Γ_n (keV)	ANC (fm^{-1})
Fowler et al. (1973)	124	⋯
Tilley et al. (1993)	124 ± 12	⋯
Sayer (2000)	162.37 124	⋯
Johnson et al. (2006)	124 ± 12	0.89 ± 0.23
Pellegriti et al. (2008)	124 ± 8	4.5 ± 2.2
Heil et al. (2008)	158.1 121	⋯
La Cognata et al. (2012)	83^{+9}_{-12}	$6.7^{+0.9}_{-0.6}$
Guo et al. (2012)	124	4.0 ± 1.1
La Cognata et al. (2013)	$107 \pm 5_{\mathrm{stat}}{}^{+9}_{-5}{}_{\mathrm{norm}}$	$7.7 \pm 0.3_{\mathrm{stat}}{}^{+1.6}_{-1.5}{}_{\mathrm{norm}}$
Faestermann et al. (2015)[a]	136 ± 5	⋯
Avila et al. (2015)	⋯	3.6 ± 0.7

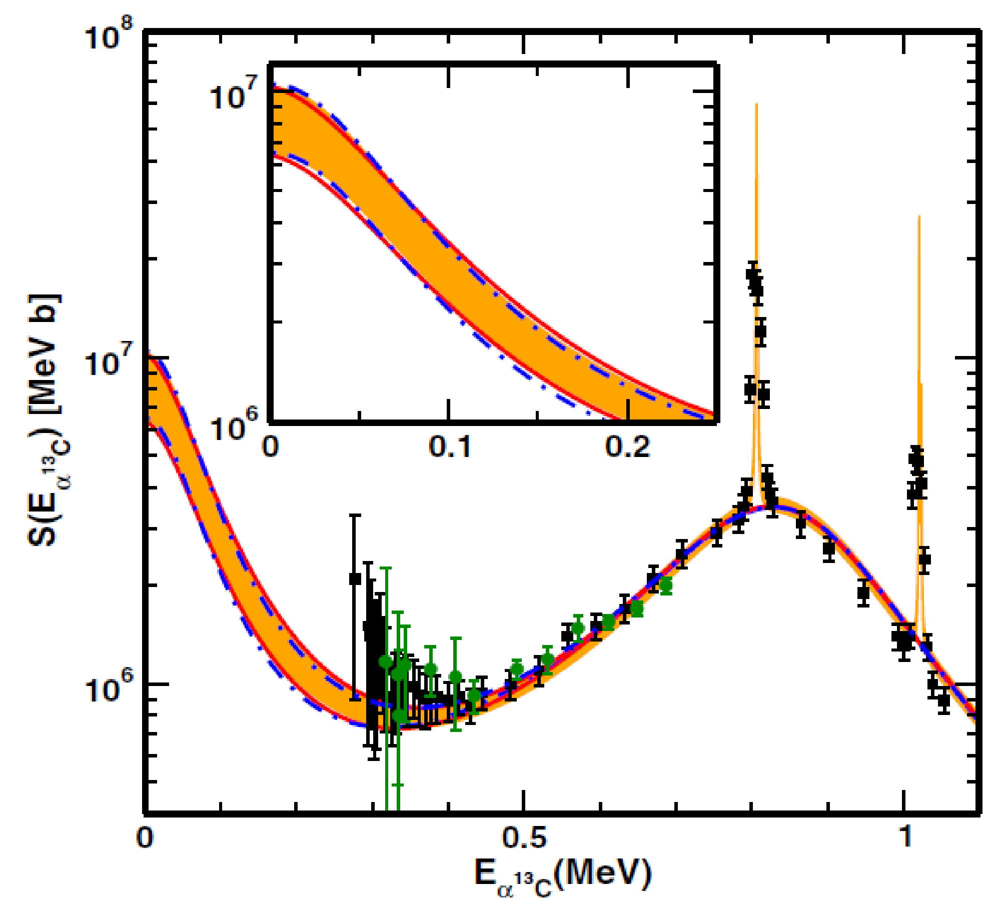
Note. Trippella and La Cognata (2017)

[a] These values are also used in this paper (see Section 3).

Threshold ANC

- Rough uncertainty range from ANC and THM measurements

- Reduced width amplitude comparison
  - Avila et al.: 0.541(57) MeV$^{1/2}$
  - This work: 0.539(16) MeV$^{1/2}$



Mukhamedzhanov *et al.* (2017)

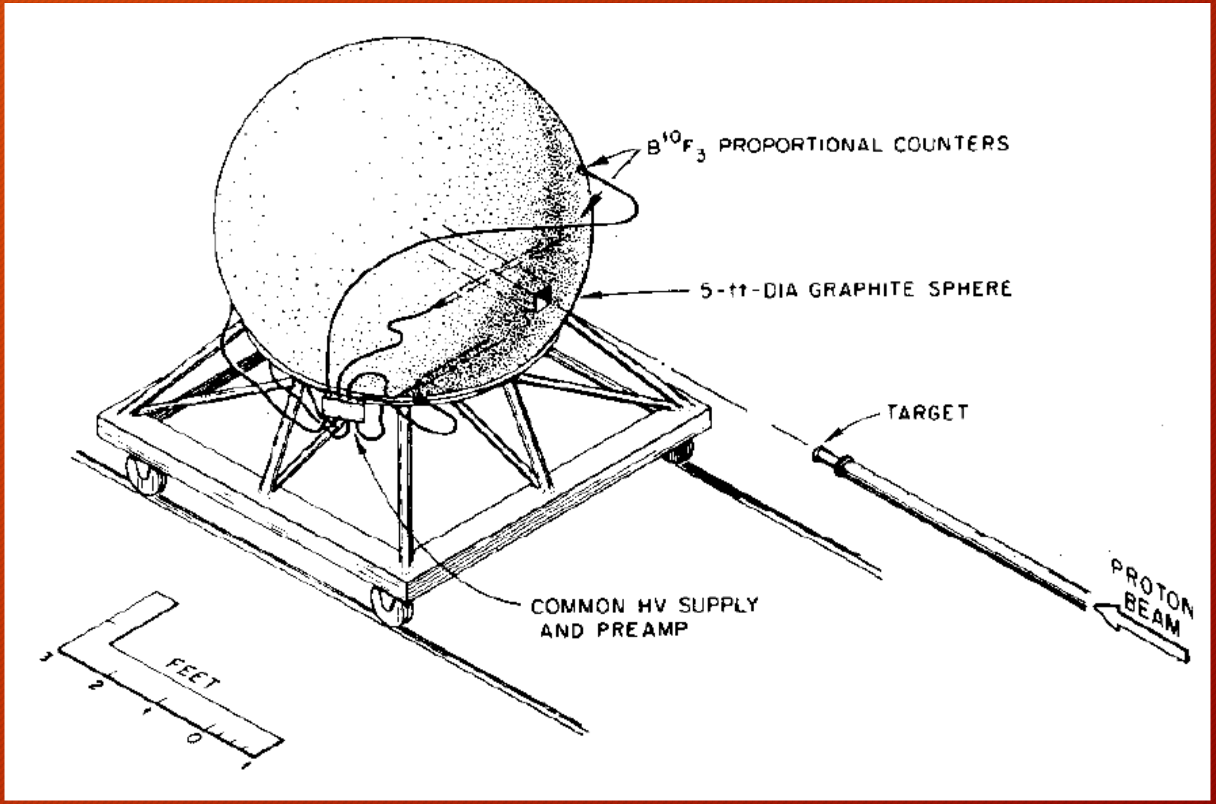
Is 5% crazy! (asks Grisha)

- It definitely doesn't include everything
- What assumptions were made?
  - The systematic uncertainties of each measurement are uncorrelated
  - The level structure is correct
  - There are still systematic differences between some of the data (just on a smaller level)
    - Absolute normalization of (n,total) data
  - *R*-matrix background contributions
  - Near threshold state level properties

- Why I think its not totally crazy
  - Several of the measurements are pretty independant
  - Level structure seems pretty well characterized
  - LANL fit goes to much higher energies and explicitly gives the strengths of higher energy levels
  - Constraint from neutron total cross section data
  - Asymptotic Normalization Coefficient (or reduced width amplitude) of the near threshold state found from transfer vs that found from the *R*-matrix fit is in excellent agreement

Previous Measurements: Moderator type detectors

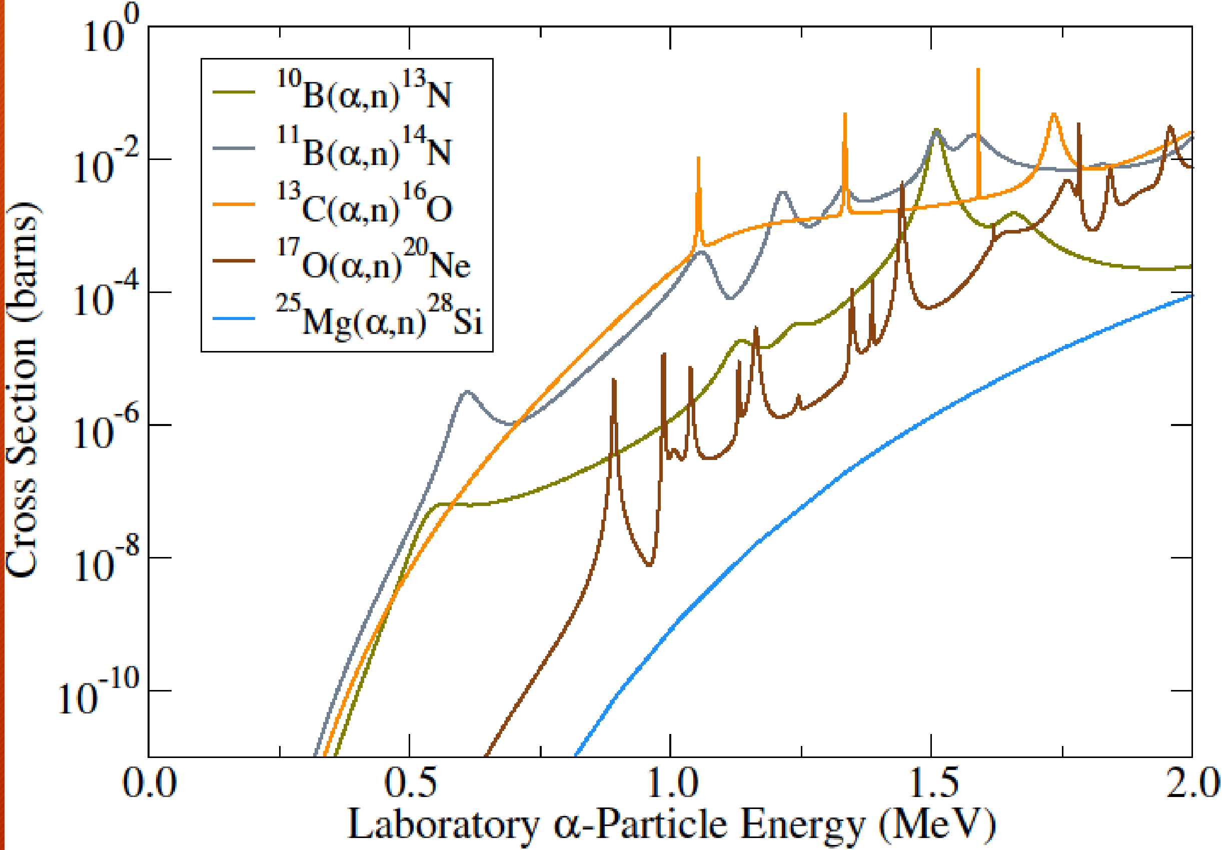
- Moderator
  - Target is placed at the center of a large neutron moderator material so that the fast neutrons from the reaction a slowed to thermal energies
  - Thermal neutrons are them capture in proportional counters that utilize reactions like ^{3}He(n,α) and ^{10}B(n,α) to create a detectable signal
  - Advantage
    - High Efficiency
    - can be almost 50%!
  - Disadvantage
    - No neutron energy information, just counts
    - Are you counting the neutrons that are actually from the reaction of interest or could you be getting background signals?



Macklin (1957)

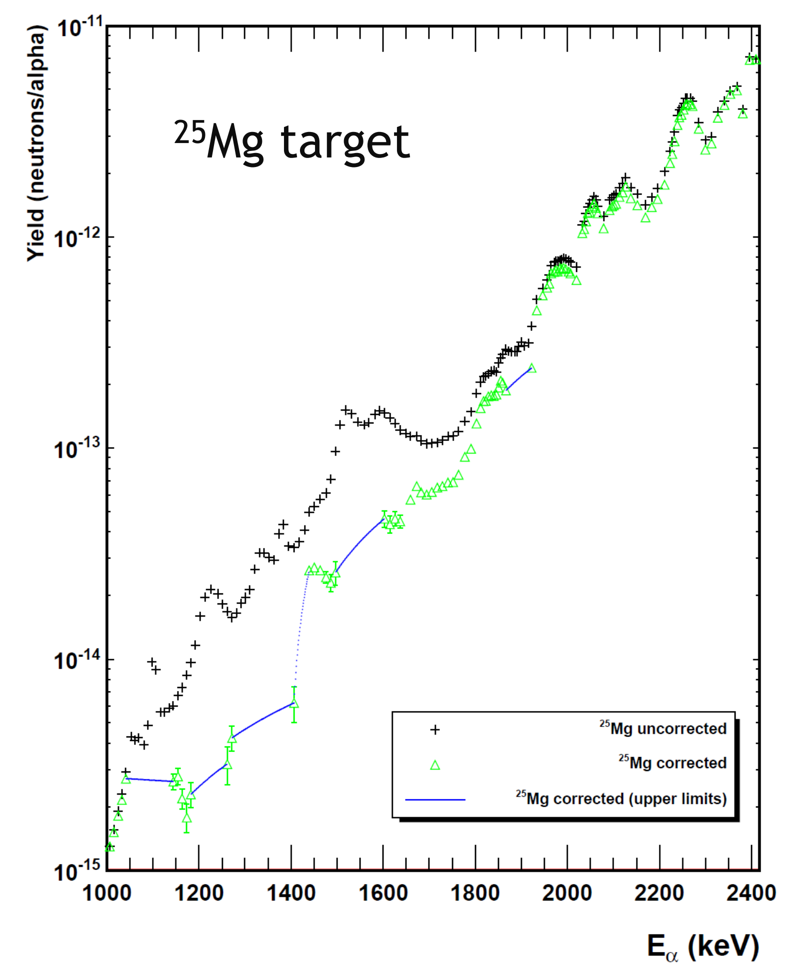
Background issues: The Coulomb barrier and trace light elements

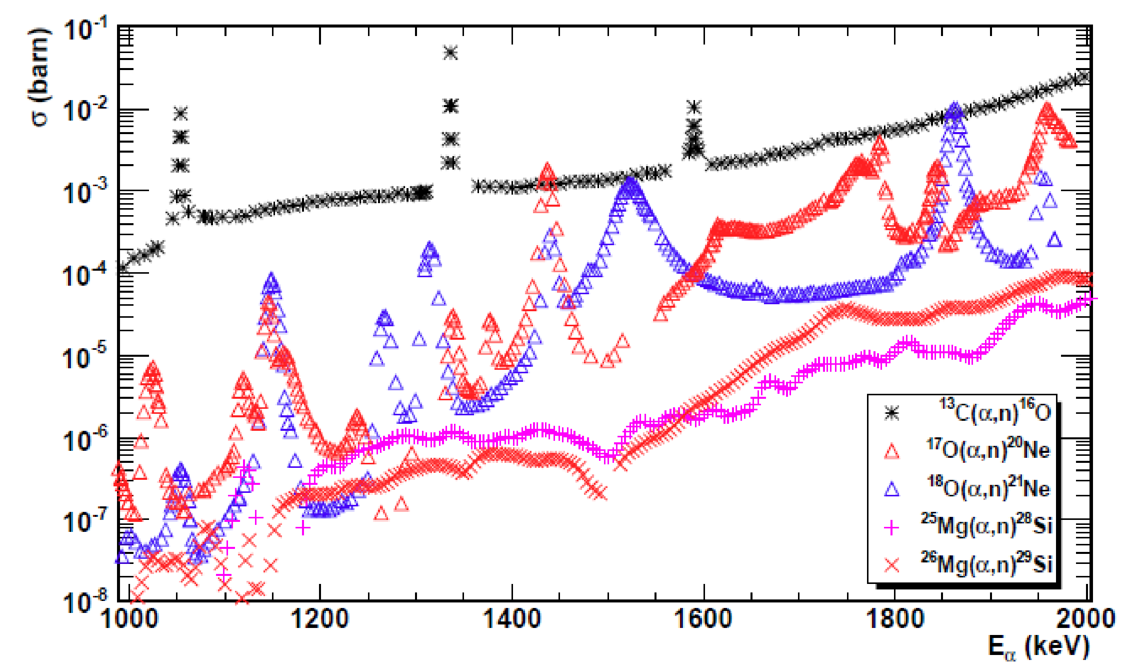
- It is very difficult to remove trace amounts of carbon, oxygen, and even boron from thin film type targets
- Many reactions of interest are positive Q-value, so it is often the case that excited final states can be populated
  - Must then know the branching ratio at each energy to apply the efficiency correction



Background issues: ^{25}Mg(α,n) with a ^{3}He counter

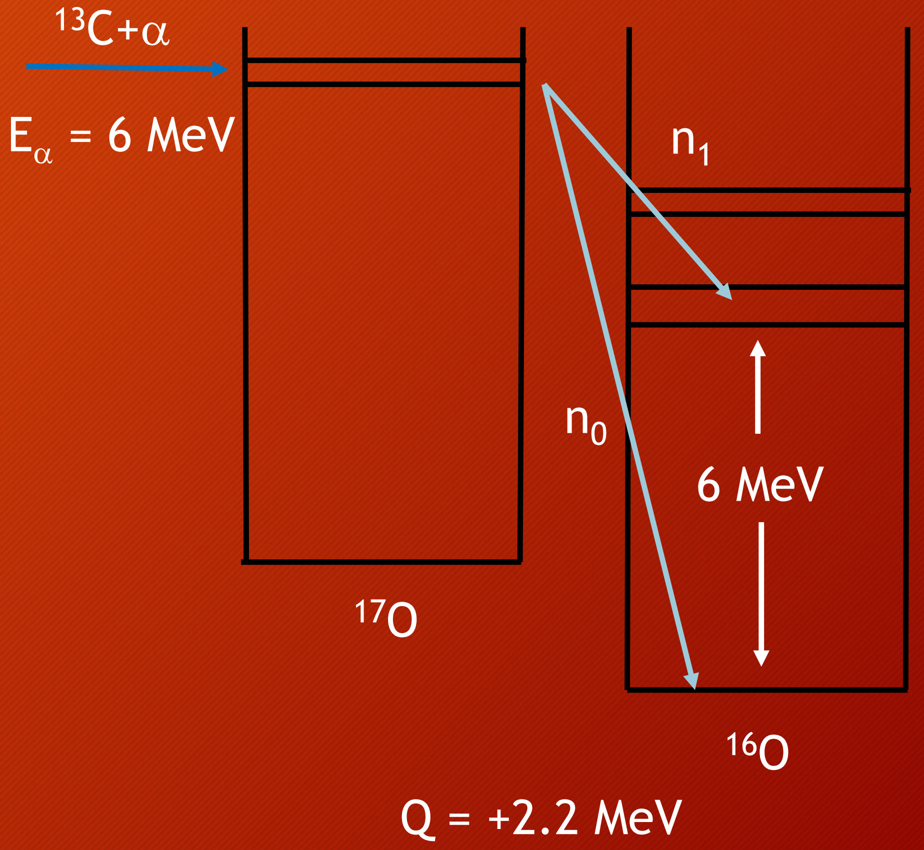
- Falahat thesis (Mainz)
- Measurements done at ND





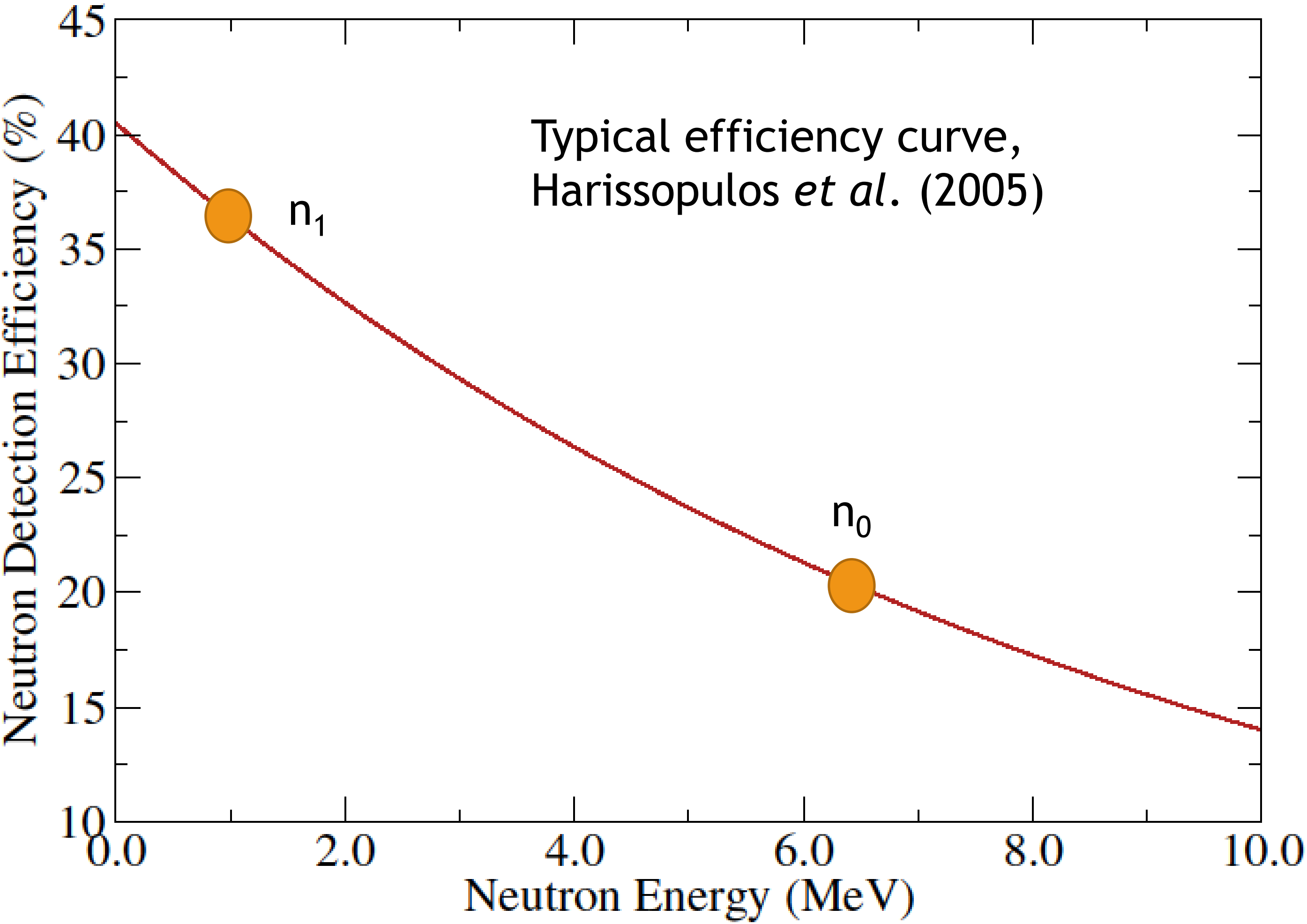
Efficiency and population of different final states

- A beam of 6 MeV alpha particles on a ^{13}C target
- Neutrons from the ground state transition (n_0) will have average energy of around 6.5 MeV
- Neutrons produced from the first excited state transition (n_1) will have an average energy of around 0.8 MeV



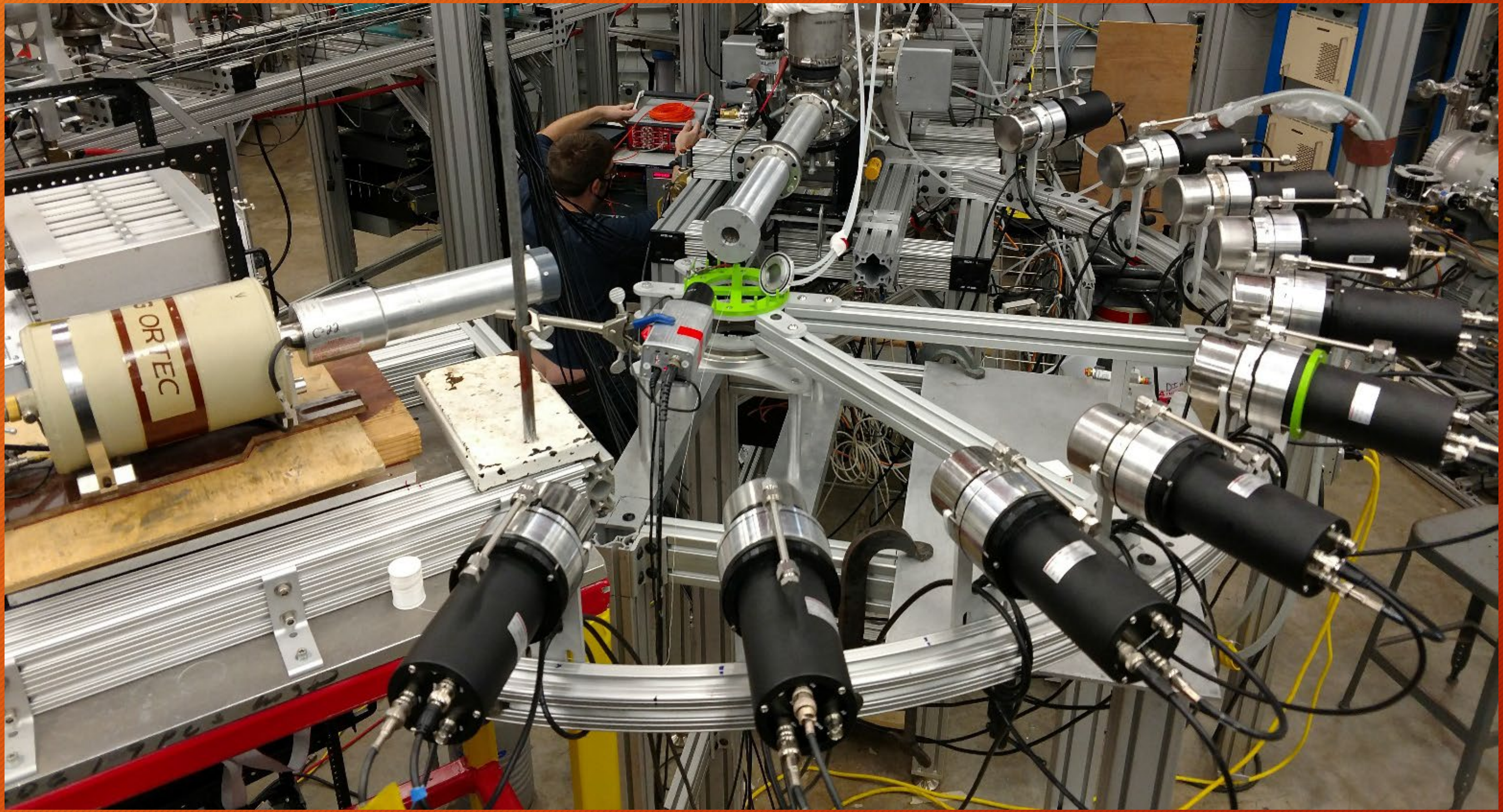
Which efficiency should be applied?

- Efficiency difference for n_0 and n_1 neutrons of about 17% absolute efficiency or a factor of 1.9 in observed yield!
- If using a counter types detector, you would already have to know the relative branching in order to calculate the cross section from the observed yield



Typical efficiency curve, Harissopulos *et al*. (2005)

$^{13}C(\alpha,n)^{16}O$ setup: 2020 & 2021



Setup planned for 2024

- Similar to 2023 version
  - Permanent setup
  - Robust frame and detector mounts
  - Reworked target ladder for targets always under vacuum