Report on U.S. Experimental Activities

WPEC 2021

Yaron DANON

CSEWG measurements committee chair, on behalf of CSEWG

Rensselaer Polytechnic Institute, Troy, NY 12180, USA

WPEC, May 13, 2021, via Webex

Introduction

- **This update is based on presentations during the November 2020 CSEWG meeting.**
- **A link to full presentations:**

  https://indico.bnl.gov/event/7233/timetable/#20201130.detailed

- **Reports from different laboratories:**

1. Updates on nuclear data experiments at LANSCE – I, Hye Young Lee (**LANL**)
2. Updates on nuclear data experiments at LANSCE – II, Keegan Kelly (**LANL**)
3. New UML capability for measurements of nuclear data – capture gammas from Mn-56, Marian Jandel (**UML**)
4. Neutron-induced neutron emission from U-235 and Pu-239, Kumar Mohindroo, (**RPI**)
5. Hf(n,tot) Measurement in the High Energy Region at the RPI LINAC, (**NNL/RPI**)
6. Berkeley Nuclear Data Measurements Program, Jonathan Morrell, (**UCB**)
7. University of Kentucky Accelerator Laboratory Activities, Jeffrey Vanhoy, (**UKAL**)
8. YHx data measured at the SNS, Chris Chapman, (**ORNL**)
9. Partial and differential (α,n) cross section measurements on boron, carbon, and oxygen isotopes, James deBoer (**UND**)

This report represents only part of the U.S. nuclear data activity.

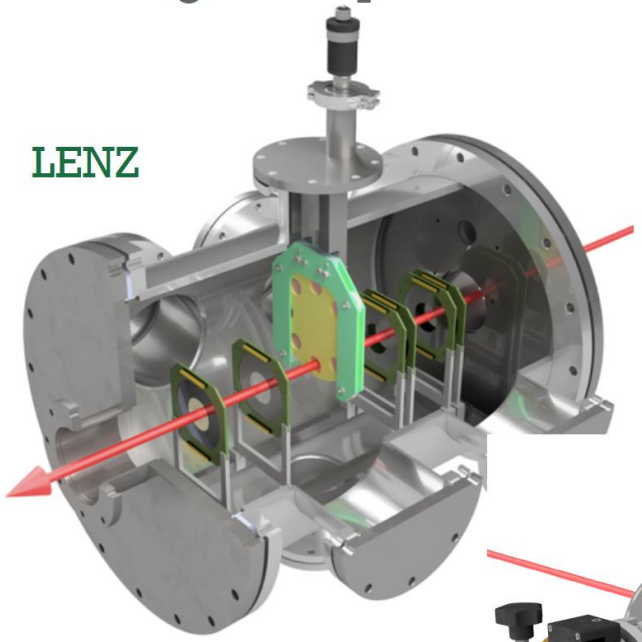
Los Alamos National Laboratory

- **LANL experimental updates on LENZ and DICER in FY20. (LANL)**
  - ^{56}Fe(n,α) LENZ data analysis
  - Diamond data- ^{12,13}C(n,z) reaction
  - ^{56,58,59,60}Ni(n,z) LENZ measurements and data analysis
  - DICER update (neutron transmission with mm size beam)
- **Scattering Analysis with the Chi-Nu Liquid Scintillators**

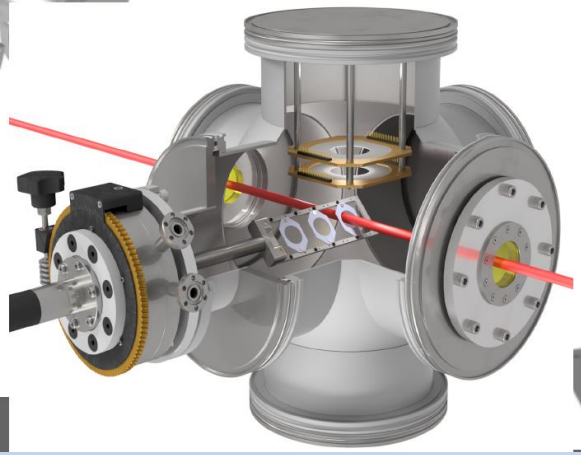
Contents

- Double differential cross sections on ^{54}Fe(n,p) and ^{56}Fe(n,α)
- Validation of neutron induced reactions on ^{nat}C, using an active target at 0.4 MeV < E_n < 22 MeV
- Progress report on ^{56,58,59,60}Ni(n,p) reaction studies at WNR
- Progress report on DICER project at Lujan Center

LENZ

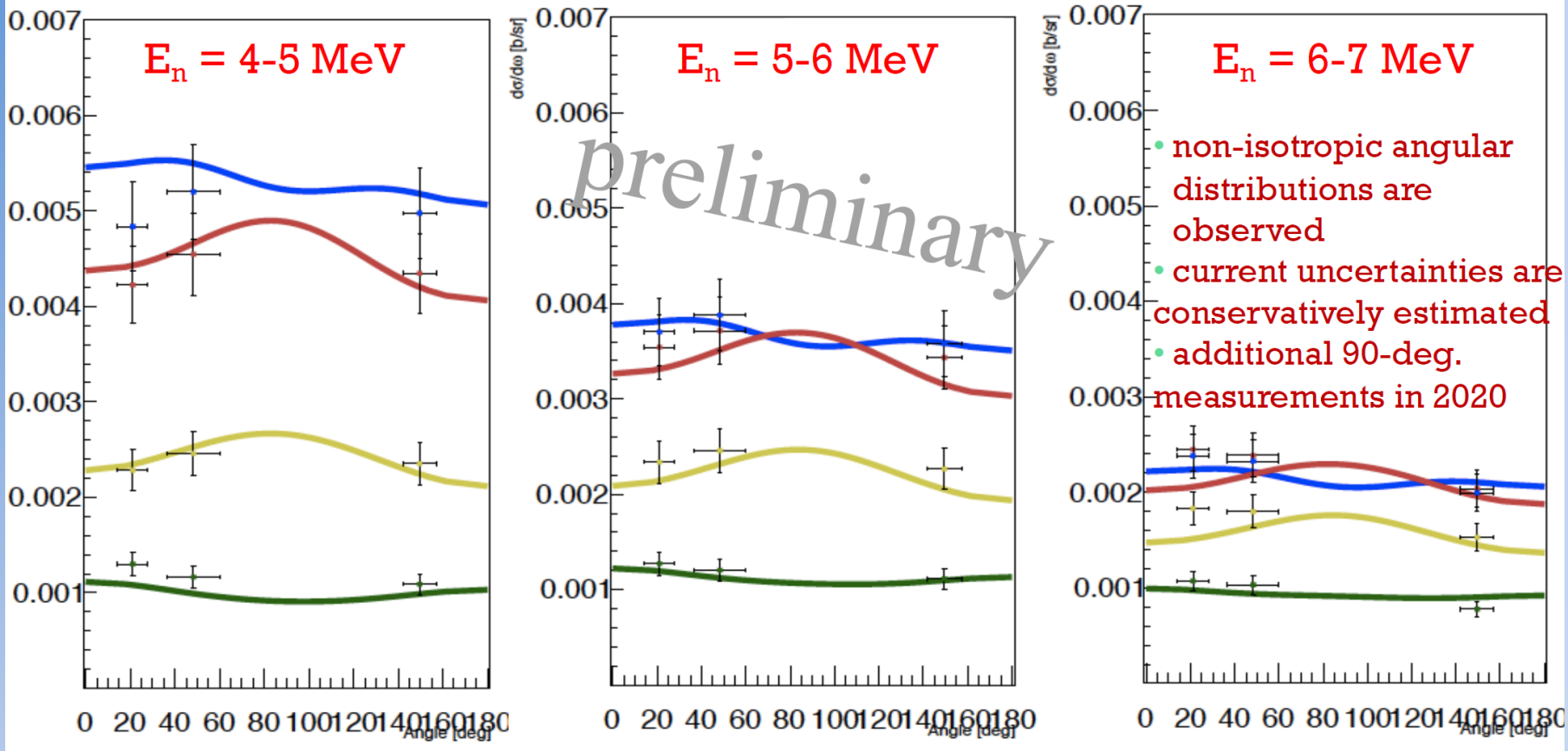


ALSOLENZ:
around 90-deg.
measurement



hotLENZ:
radioactive nucleus
measurement

^{54}Fe(n,p) angular distributions ($d\sigma/d\Omega$ (b/sr) vs. θ_{lab} (deg))



- non-isotropic angular distributions are observed
- current uncertainties are conservatively estimated
- additional 90-deg. measurements in 2020

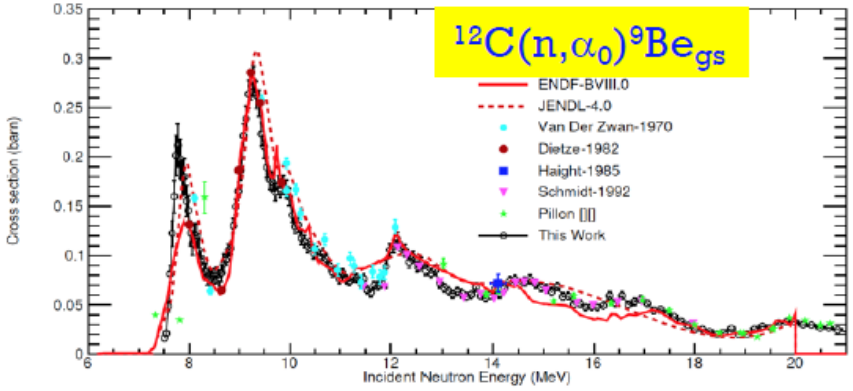
-dots are LENZ measurements

-Solid lines show newly calculated angular distributions, where Legendre coefficients are explicitly calculated. Details of this work will be presented by H.I. Kim in Evaluation Session.

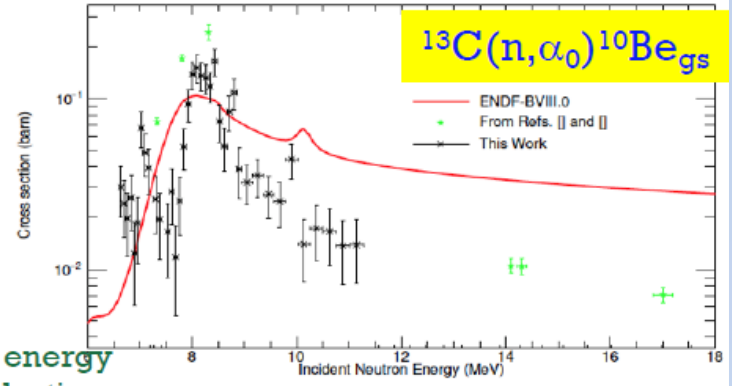
Red: (n,p_0), Blue: (n,p_1), Yellow: (n,p_2), Green: (n,p_3)

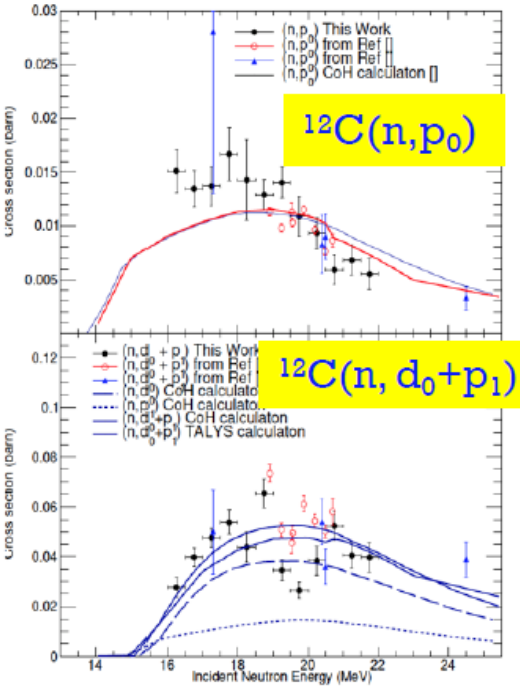
Diamond data- $^{12,13}C(n,z)$ reaction evaluation

Black dots: LANSCE data

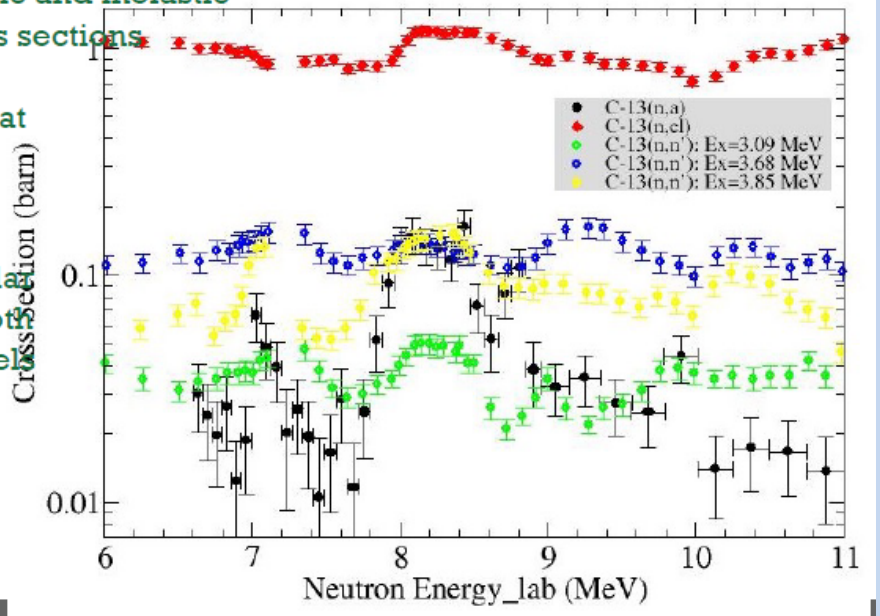


"Validation of neutron induced reactions on natural carbon using an active target at neutron energies from 0.4 to 22 MeV at LANSCE", S. A. Kuvin, H. Y. Lee, B. DiGiovine, A. Georgiadou, and D. Votaw, Phys. Rev. C (in preparation)





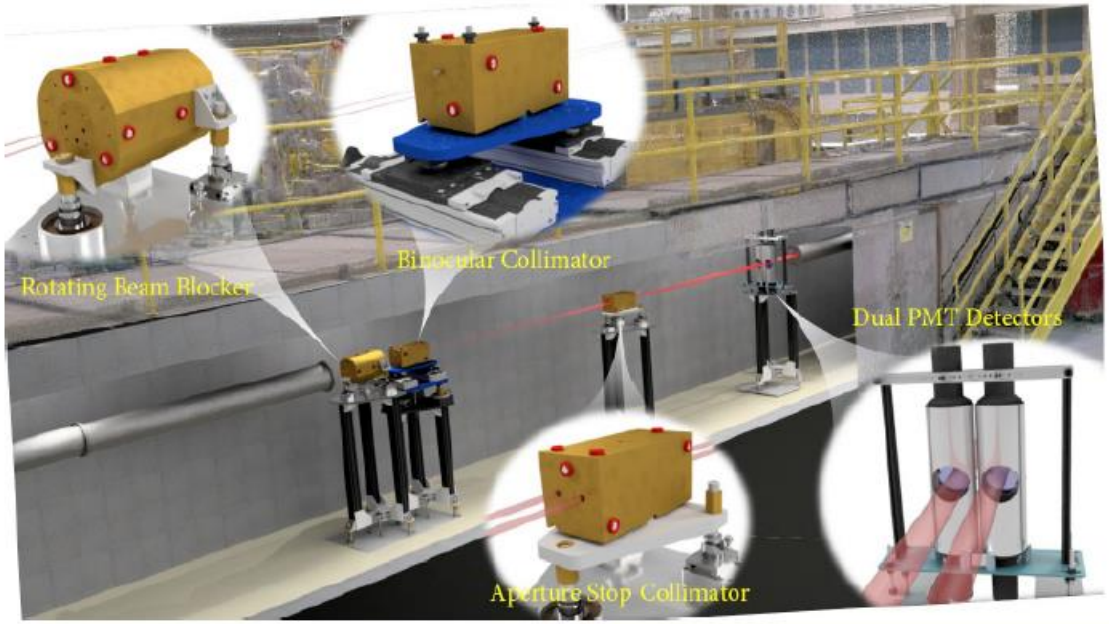
For the relevant LANSCE energy range, the elastic and inelastic scattering cross sections (Resler 1989 measurements at Ohio U.) are compared with the $^{13}C(n,\alpha_0)$. Presented similar structures in both reaction channels.

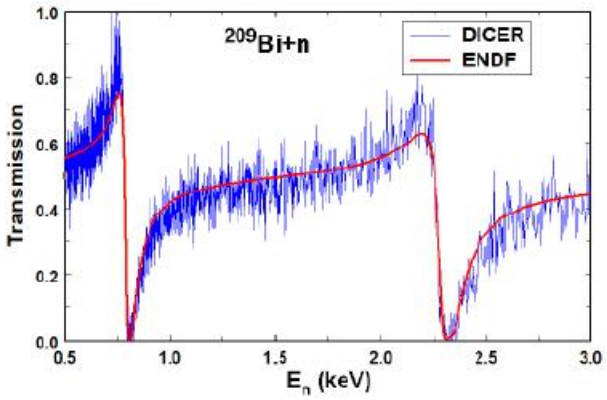


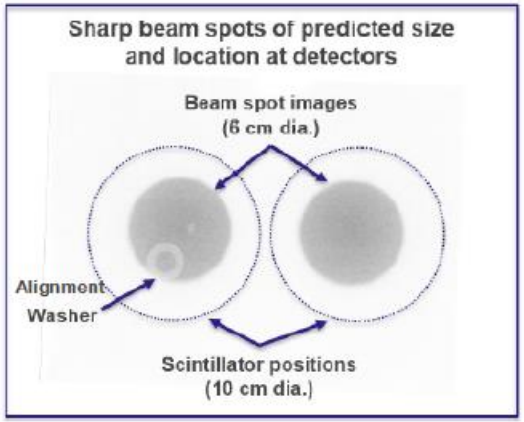
PI: Paul Koehler

DICER Update

- 1-mm-diameter binocular collimator system installed and successfully tested
  Measurements on ^{95}Mo and ^{209}Bi in agreement with previous results
  Cuts experiment time in half and minimizes required sample
- Three acceptable chemistries for ^{88}Zr sample identified
  DICER experiment scheduled for summer 2021
- Completed DICER measurement with liquid argon sample
  Motivated by DUNE neutrino experiment, led by UC Davis



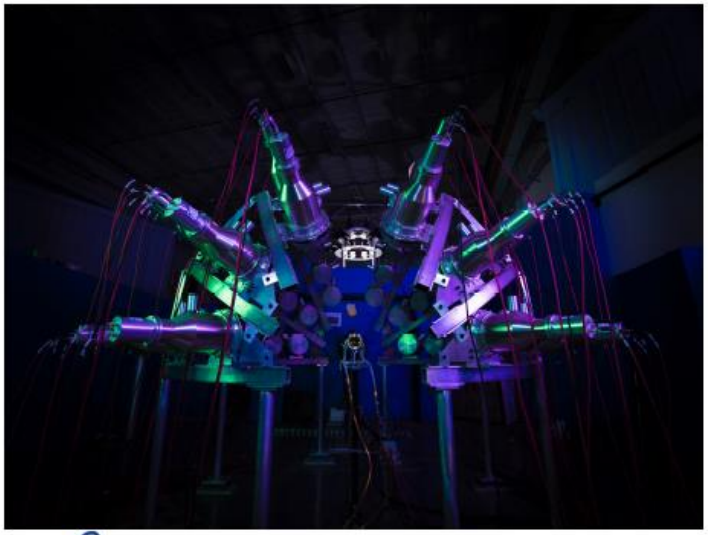


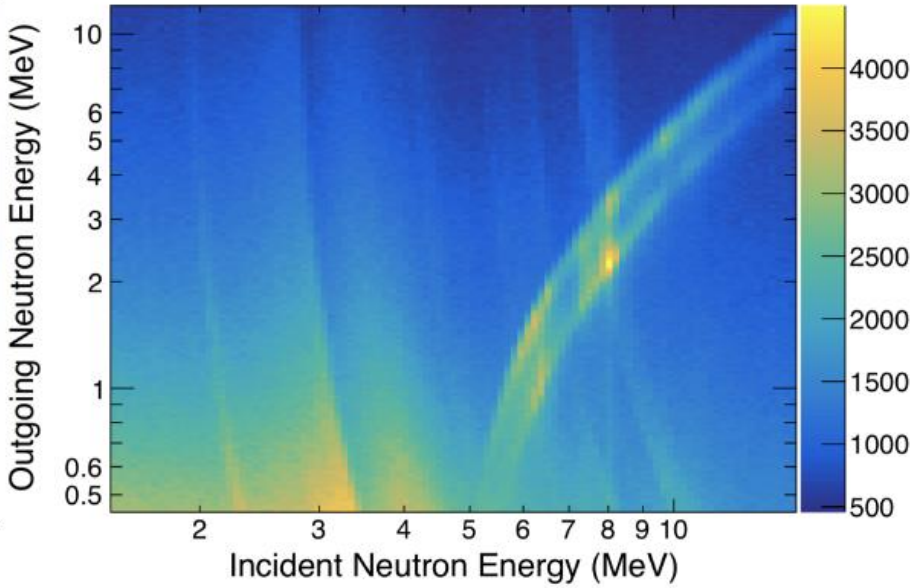


Scattering Analysis with the Chi-Nu Liquid Scintillators

- Liquid scintillators have poor decent PSD and timing, but γ energy resolution
- Can still learn about a more ideal n-γ using this array
- Start with easy case: natural carbon
  - Note: utilized the RPI sample changer for these measurements

Begin by simply looking for n-γ coincidence in post-processing analysis





Los Alamos NATIONAL LABORATORY EST. 1943

Operated by Triad National Security, LLC for the U.S. Department of Energy's NNSA

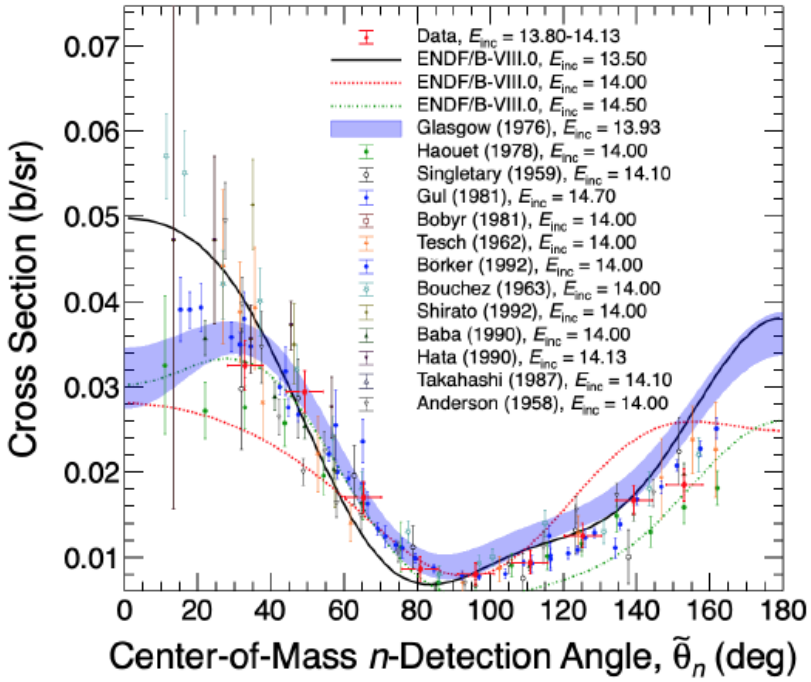
Slide 2 of 12

NNSA

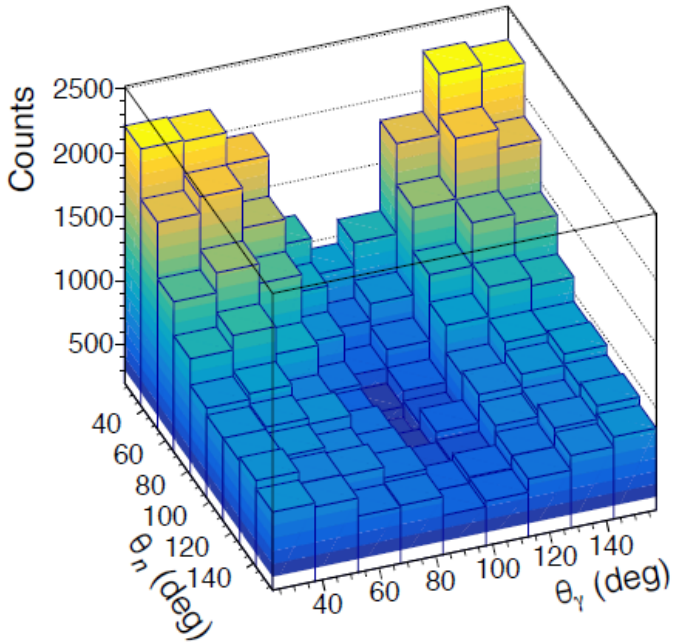
Correlated n-γ Distributions Collected as Well

Extract n angular distributions from elastic scattering and correlated n-γ distributions from inelastic scattering

Inelastic n Distributions (13.80–14.13 MeV)



Correlated n-γ Distributions (6.17–6.31 MeV)



Very few experiments have measured n-γ distributions

→ Measured at limited energies and angles

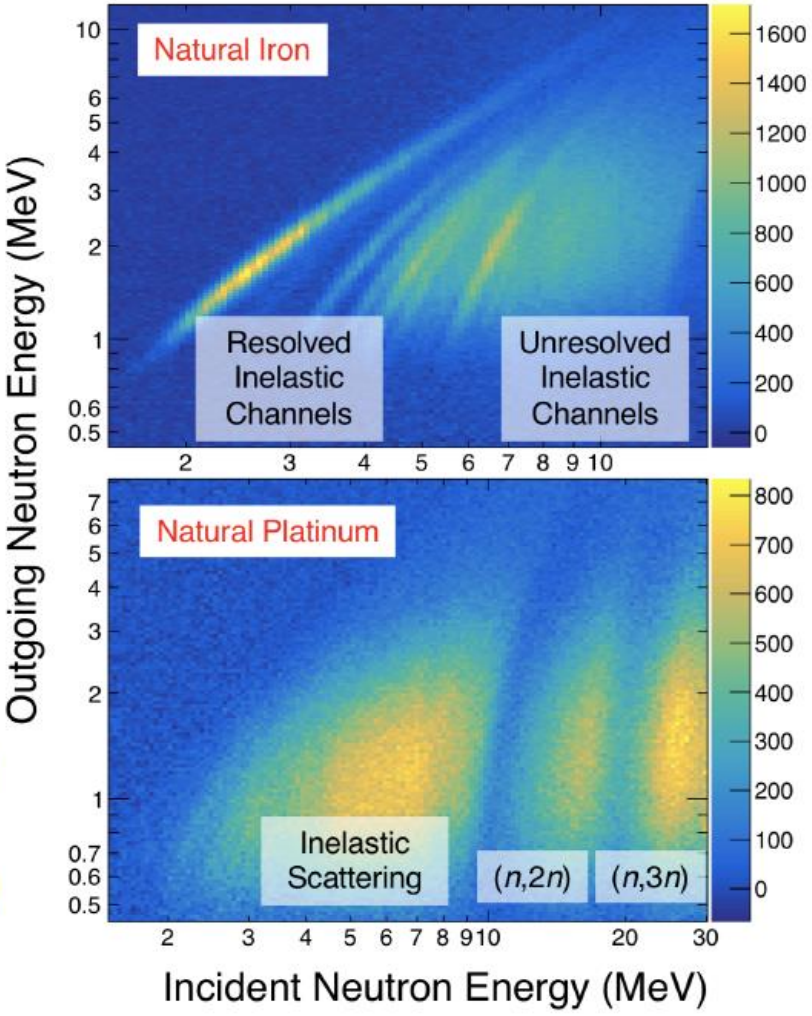
Measurements of Fe and Pt Show Capabilities

Natural Fe

- Separation of low-lying states is possible
- Extensions to lower energies could separate more states
- Shows separation limitations based on level density

Natural Pt

- Six naturally-occurring Pt isotopes
- Continuously high net level density
- Clearly observe onset of $(n,2n)$ and $(n,3n)$ channels
  - Separable from inelastic scattering



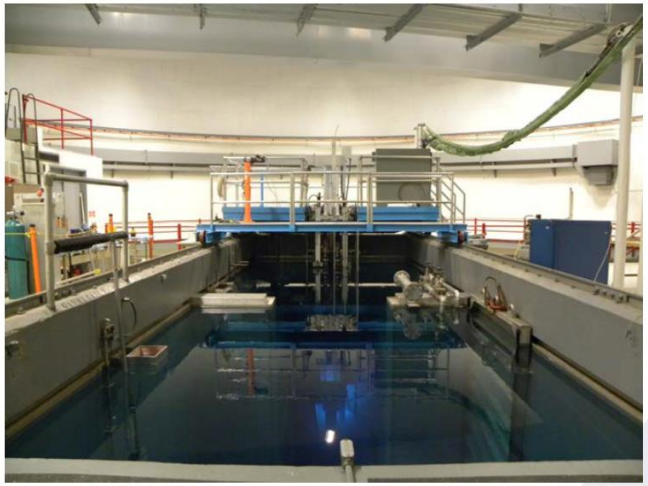
University of Massachusetts Lowell

- New UML capability for measurements of nuclear data: capture gammas from Mn-56

M. Jandel, CSWEG 2020, 11/30/2020

UMASS LOWELL RESEARCH REACTOR (UMLRR)

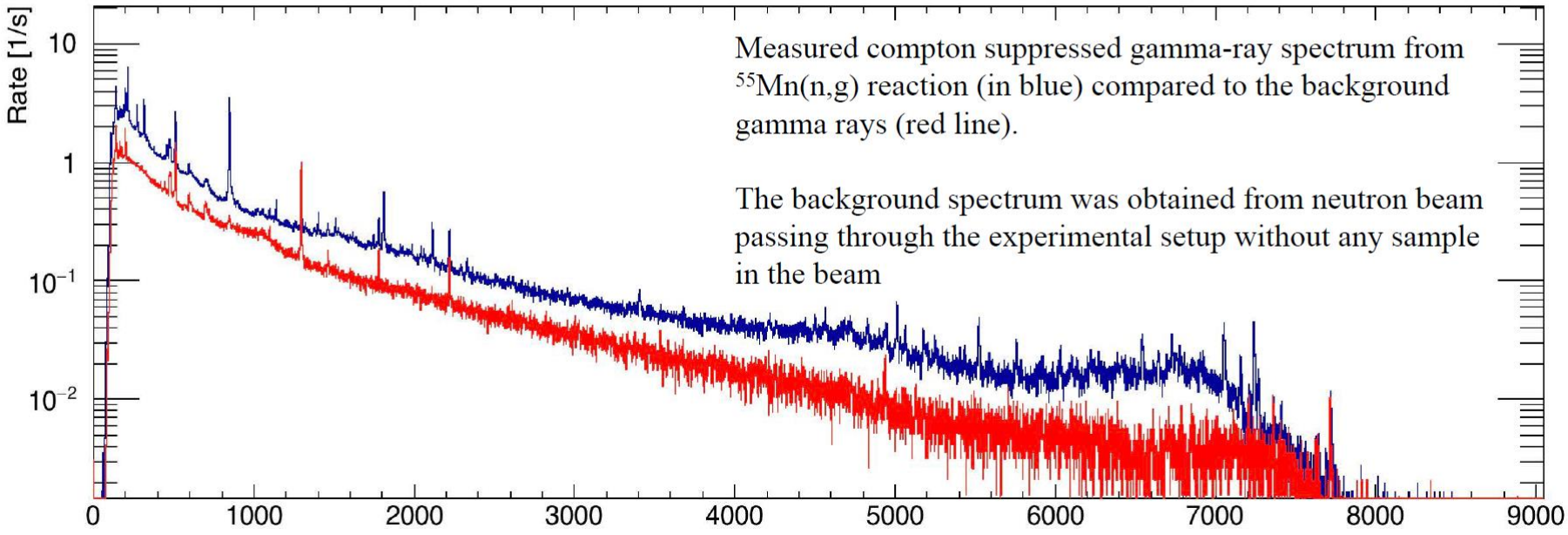
- Open pool with 75,000 gallons of demineralized water
- High-density, steel reinforced concrete (Approx. 1000 tons) surrounds the pool
- 1 MW power
- 2.5 x 10^{13} neutrons/cm^2/s in core
- Many facilities available for research including thermal column, beam ports, fast neutron irradiator, pneumatic sample irradiation system.



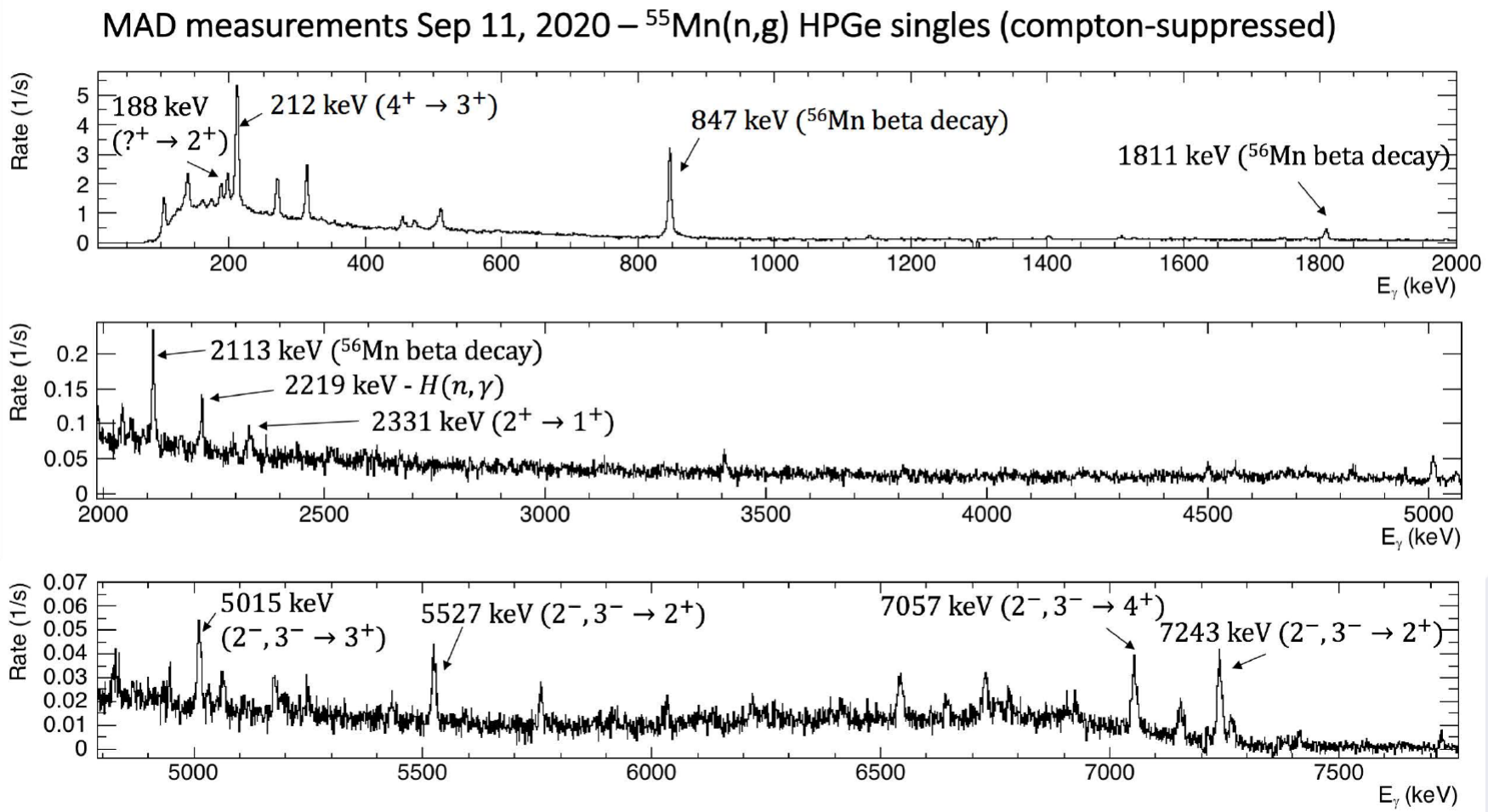
Learning with Purpose

UML – DATA ON ^{55}MN(N,G)

- Data obtained at full reactor power of 1 MW
- DAQ handles high rates well



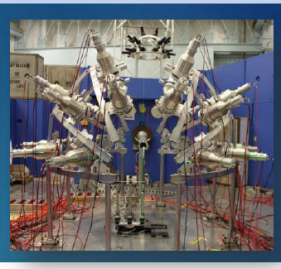
UML – DATA ON ^{55}MN(N,G)



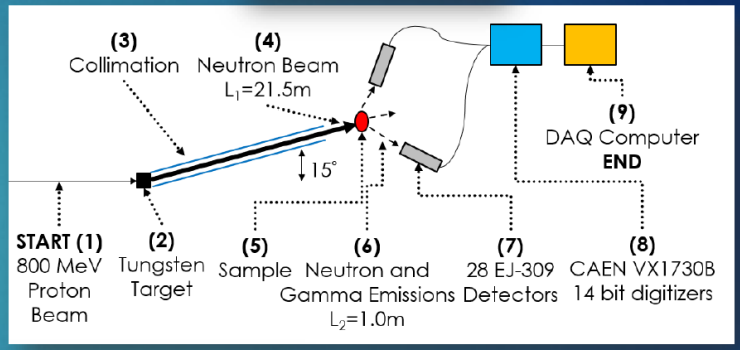
Nuclear data measurement and analysis at RPI

- Neutron Induced Neutron Emission in U-235 and Pu-239

Experimental Setup – Overview



- High energy protons induce spallation on a Tungsten target
- Neutrons up to 800 MeV are emitted isotropically and collimated into a beam
- A sample is placed in the neutron beam and the emissions are recorded by EJ-309 liquid scintillation detectors
- The detection signal is routed through a digitizer and the timestamp, head, tail, and total integral information, and detector number are written to disk.
- Four CAEN VX1730B 14-bit digitizers
  - 500 MHz sampling rate



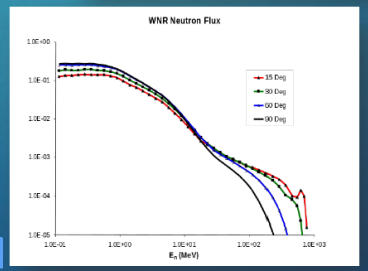
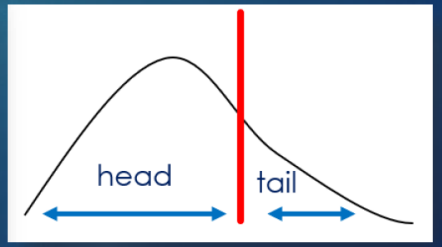
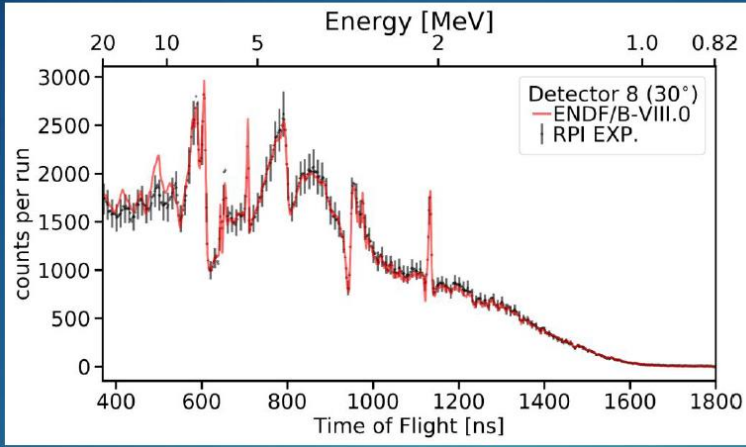
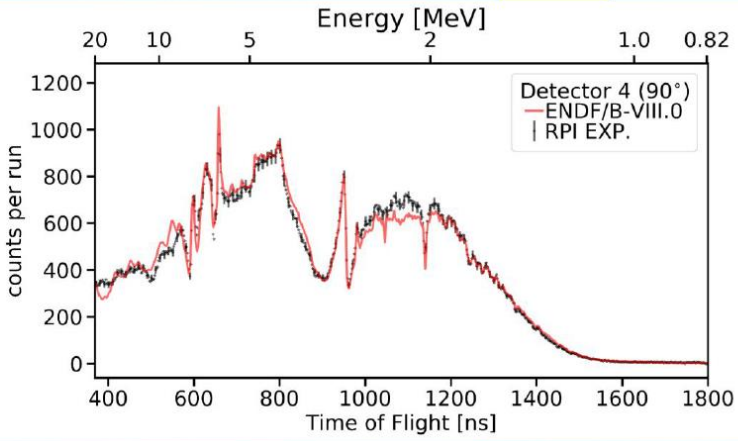


Image source: https://lansce.lanl.gov/facilities/wnr/_assets/images/wnr-neutron-flux.png

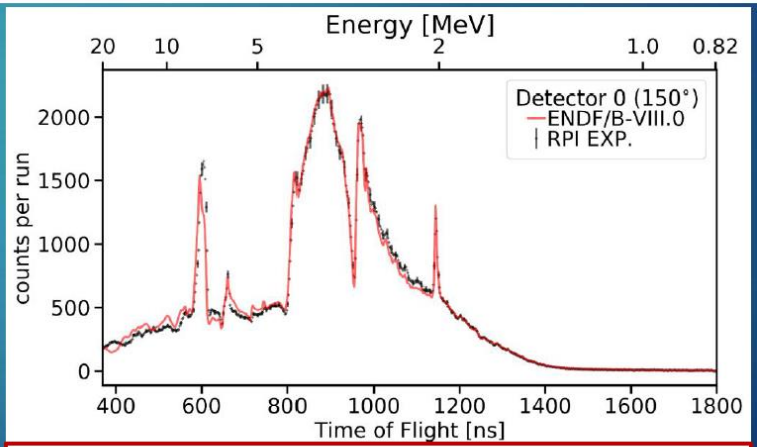


Carbon



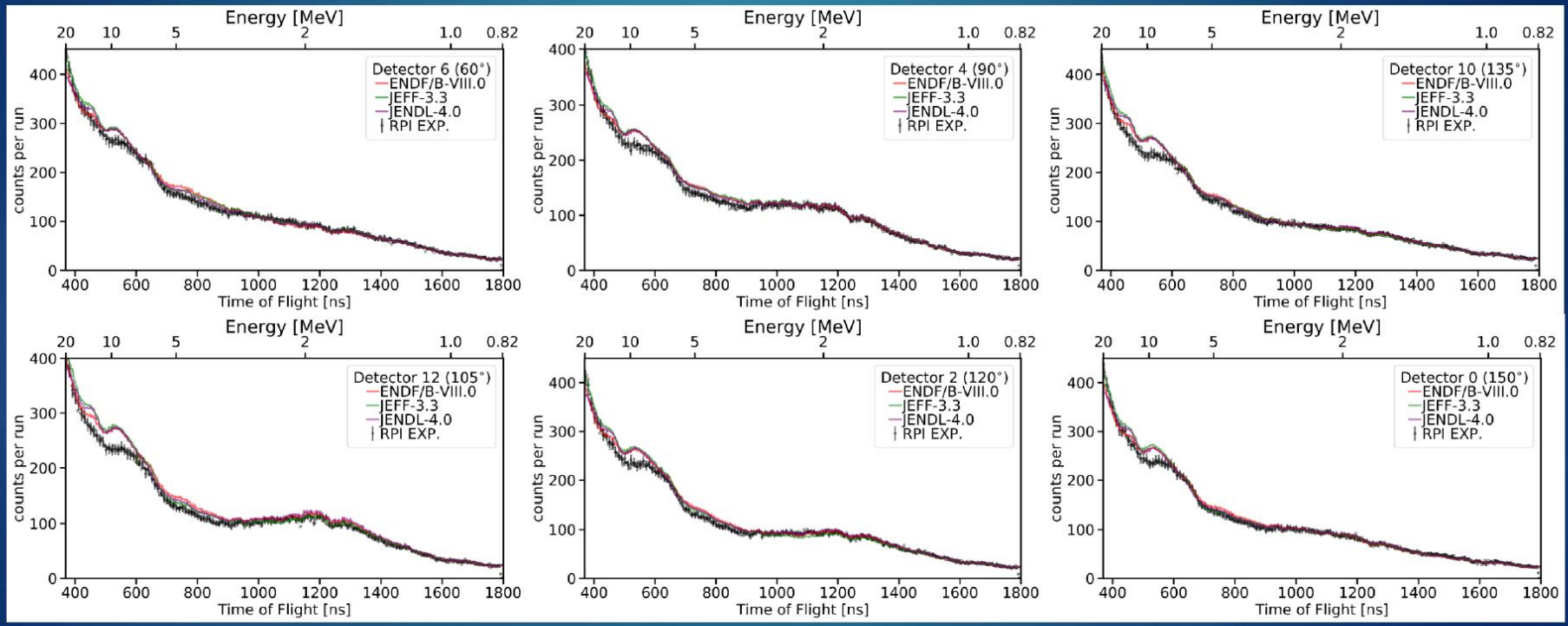


- Overall Carbon measurements and simulation are in good agreement at all angles
- For some angles and incident neutron energies differences are observed
- Further investigation of carbon double differential cross section might be needed

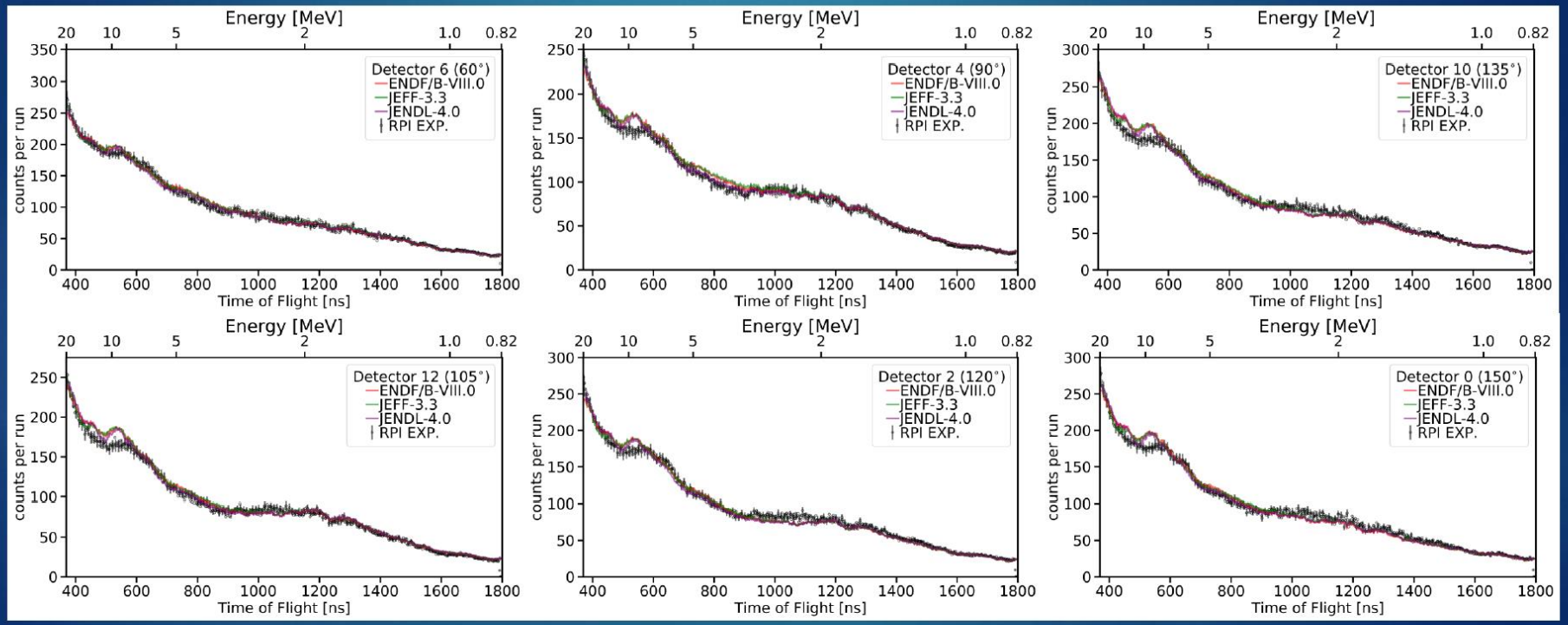


Discrepancies found are not correlated with shapes of the flux or efficiency, or discrepancies found in ^{235}U and ^{239}Pu.

^{235}U – Angles ≥ 60°



^{239}Pu – Angles ≥ 60°

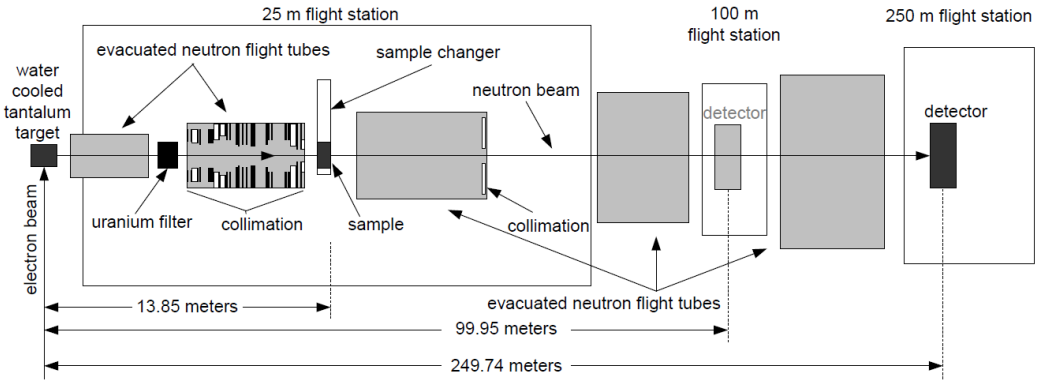


Nuclear data measurement and analysis at RPI (NNL talk)

- Hf(n,tot) Measurement in the High Energy Region at the RPI LINAC

High Energy Transmission System at RPI

- Located at the Gaerttner Linear Accelerator (LINAC) Center at Rensselaer Polytechnic Institute (RPI)
- Large area, modular, liquid scintillation detector
  - Located at 250 meter time-of-flight station
  - Long flight path, narrow neutron burst width, fast detector and electronics
  - High-accuracy transmission measurements (~1% - 3%)
  - Excellent counting rate, good signal-to-noise
  - Measurement range of ~0.5 to ~20 MeV
- Fission chambers on independent flight path monitor neutron beam stability



2/7

Hf Samples

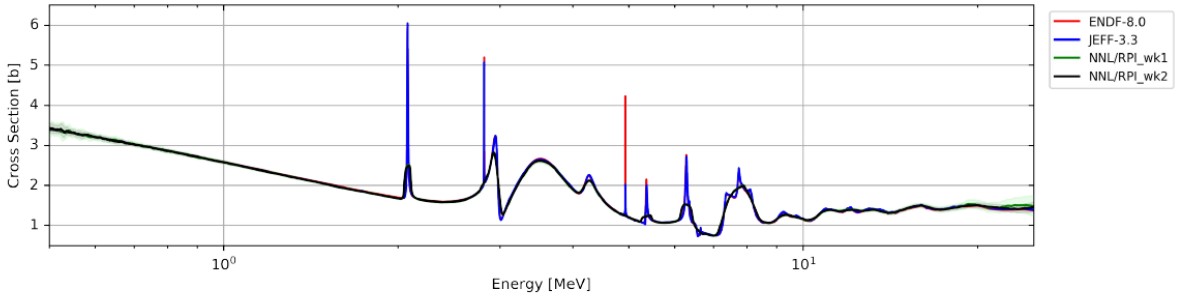
- 99.9% pure Hf
- Samples
  - 7 cm (2 – 3.5 cm thick cylinders stacked)
  - 9 cm (2 – 4.5 cm thick cylinders stacked)
  - 13 cm thick carbon reference

Impurity	PPM	Impurity	PPM	Impurity	PPM	Impurity	PPM
Ag	0.44	Al	0.4	As	<0.005	Au	<0.5
B	<0.005	Ba	<0.005	Be	<0.005	Bi	<0.05
Br	<0.005	Ca	0.008	Cd	<0.5	Ce	<0.005
Cl	0.097	Co	0.16	Cr	1.51	Cs	<0.005
Cu	0.038	Dy	<0.005	Er	<0.005	Eu	<0.005
F	<0.5	Fe	54.2	Ga	<0.005	Ge	<0.005
Hg	<5	Ho	<0.005	I	<0.05	In	<0.005
Ir	0.89	K	0.031	La	<0.005	Li	<0.005
Lu	<0.005	Mg	<0.005	Mn	0.043	Mo	<0.005
Na	0.013	Nb	<0.005	Nd	<0.005	Ni	0.99
Os	<0.5	P	0.009	Pb	<0.05	Pd	<0.05
Pr	<0.005	Pt	<0.5	Rb	<0.005	Re	<0.005
Rh	<0.005	Ru	<0.005	S	0.77	Sb	<0.05
Sc	0.007	Se	<0.05	Si	1.66	Sm	<0.005
Sn	<0.05	Sr	<0.005	Ta	0.22	Tb	<0.005
Te	<0.05	Th	<0.005	Ti	0.31	Tm	<0.005
U	<0.005	V	<0.005	W	0.015	Y	<0.005
Yb	<0.005	Zn	0.029	Zr	0.576		

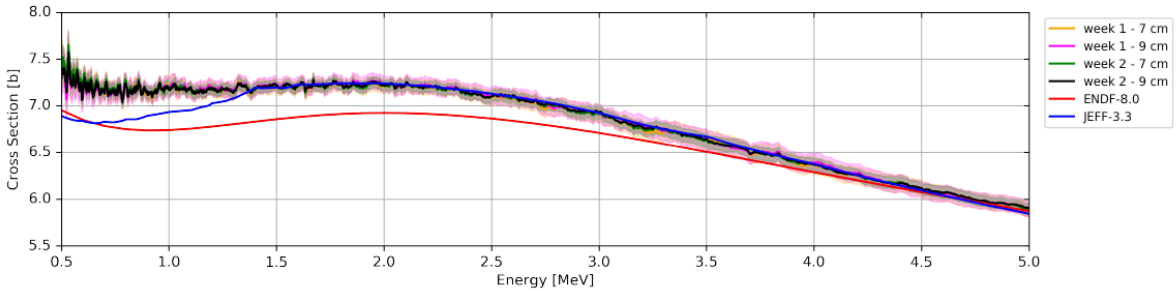
Sample	thickness (cm)	diameter (cm)	mass (g)	areal number density (atoms/b)
Hf-35mm-01	3.505±0.004	5.081±0.003	938.4±0.1	0.1562±0.0002
Hf-35mm-02	3.508±0.002	5.088±0.002	941.6±0.1	0.1563±0.0001
Hf-45mm-01	4.507±0.002	5.089±0.002	1209.9±0.1	0.2007±0.0001
Hf-45mm-02	4.505±0.002	5.082±0.002	1206.5±0.1	0.2007±0.0001
7cm Hf sample	7.012±0.004	5.084±0.002	1880.0±0.1	0.3124±0.0001
9cm Hf sample	9.012±0.002	5.086±0.001	2416.4±0.1	0.4013±0.0001

Results

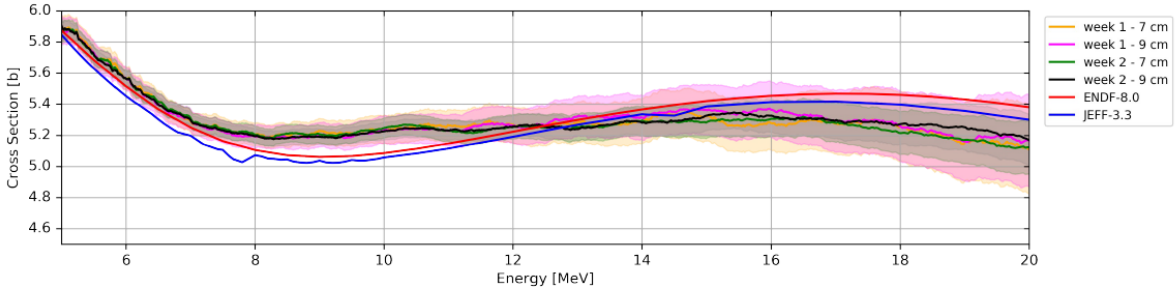
Carbon
0.5 – 20 MeV



Hafnium
0.5 – 5 MeV



Hafnium
5 – 20 MeV

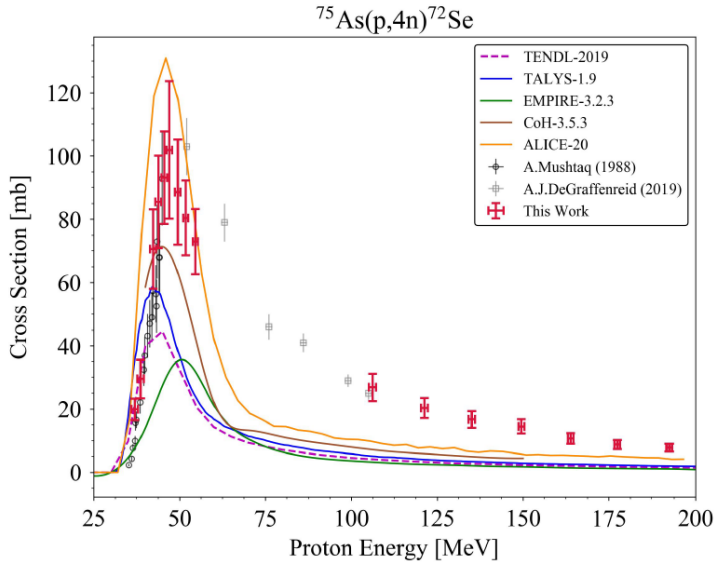


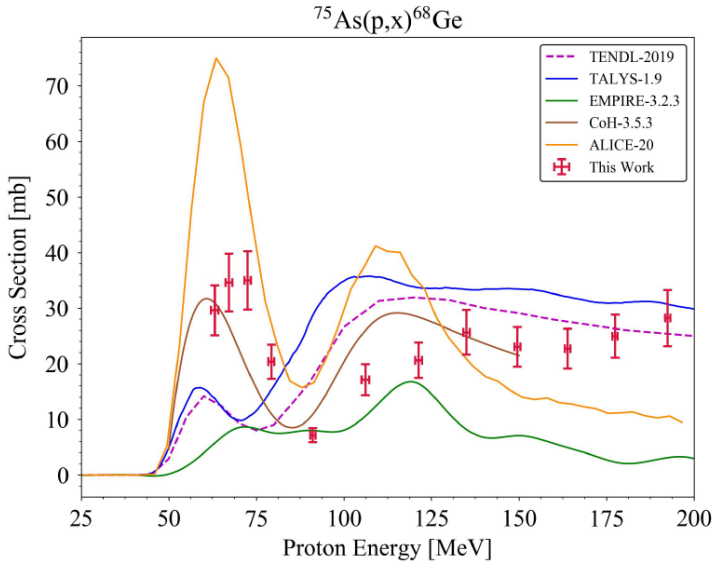
6/7

Cross Section measurements at LBNL and UC-Berkeley

- **Fission**
- FLUFFY - Independent fission product yields for short-lived isotopes
- **Neutron Scattering**
  - GENESIS - *Inelastic scattering on* ^{56}Fe, ^{238}U *for fast-reactor applications*
- **Isotope Production**
  - ^{75}As(p,x)^{72}Se & ^{75}As(p,x)^{68}Se - *PET Imaging*
  - ^{nat}Sb(p,x)^{117m}Sn - *Therapeutic/Diagnostic*
  - ^{226}Ra(n,2n)^{225}Ra -> ^{225}Ac - *Targeted Alpha Therapy*
  - Secondary Neutrons from Deuteron Breakup
  - ^{232}Th(p,4n)^{229}Pa -> ^{229}Th - *Long lived* ^{225}Ac *generator*

^{75}As(p,x) Reactions from 35-200 MeV

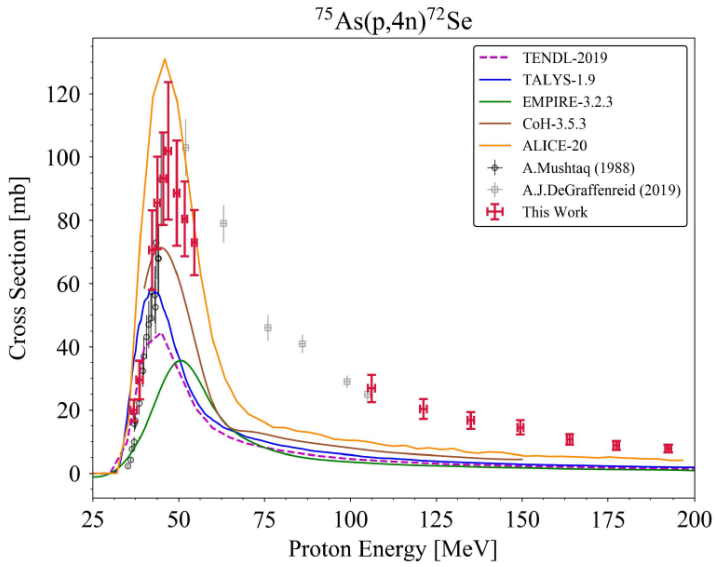


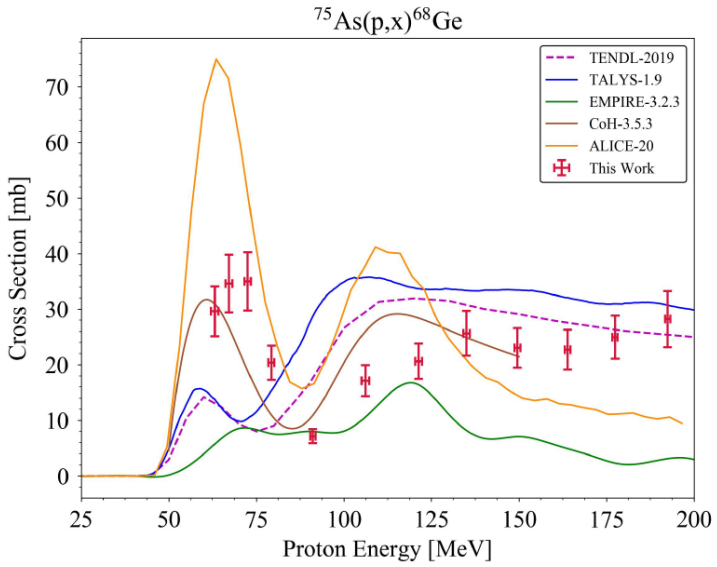


Large body of high-energy reaction data (many channels, up to 200 MeV)

Modeling is particularly sensitive to pre-equilibrium

^{75}As(p,x) Reactions from 35-200 MeV





Large body of high-energy reaction data (many channels, up to 200 MeV)

Modeling is particularly sensitive to pre-equilibrium

University of Kentucky Accelerator Laboratory Activities

University of Kentucky Accelerator Laboratory (UKAL)

- 7-MV single-ended Van de Graaff accelerator
- p, d, ^{3}He and α beams
- pulsed and bunched beam:
  - f = 1.875 MHz and Δt ~1 ns
- primarily conducts neutron-induced reactions and scattering experiments

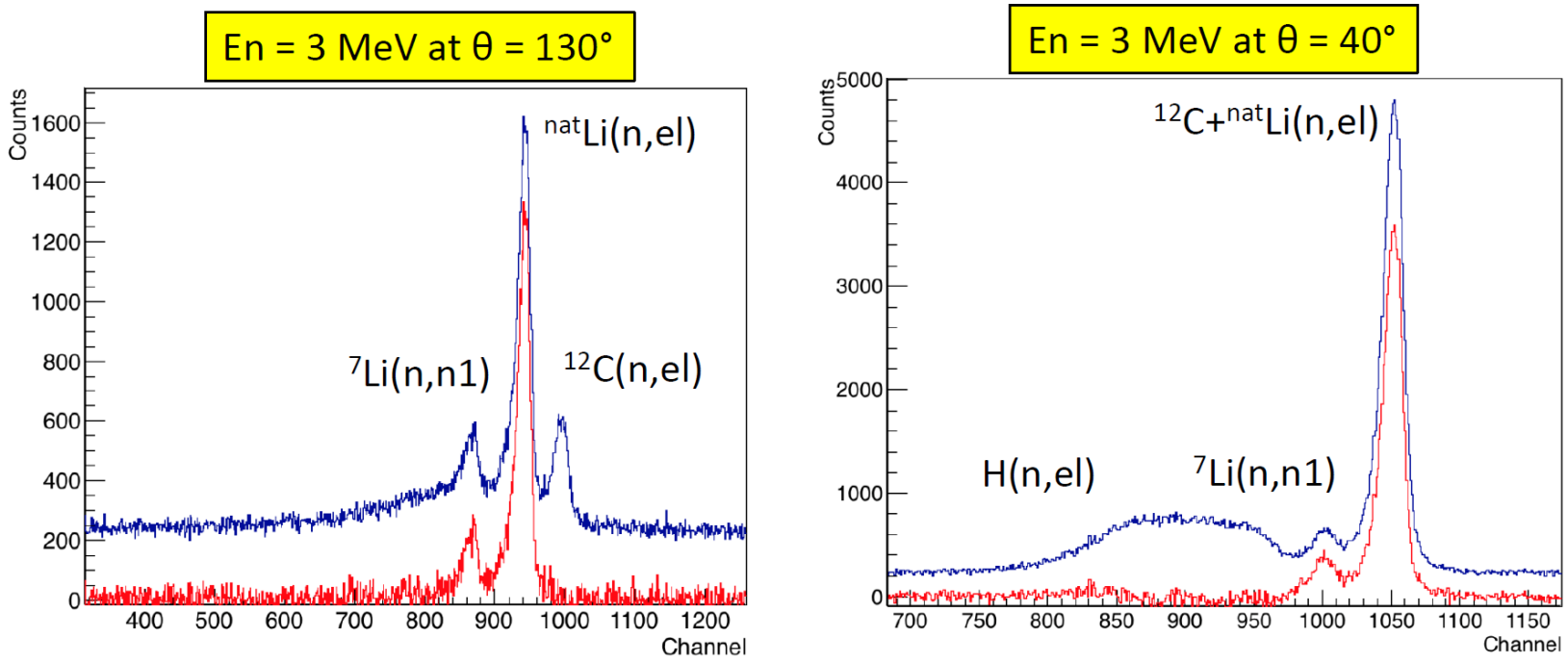
Basic Nuclear Science

- Nuclear structure via (n,n'γ)
  - Level Schemes and Transitions
  - Spectroscopic Information
  - DSAM Lifetimes

Applied Nuclear Science

- Cross section measurements
  - (n,n') - Elastic and inelastic cross sections
    ^{23}Na, ^{56}Fe, ^{54}Fe, ^{12}C, ^{nat}Si, ^{nat}Li
  - (n,n'γ) - γ-ray production cross sections
    Level cross sections
- Detector development

^{nat}Li Li(n,n)



- ^{nat}Li scattering sample was placed inside a polyethylene container. Hence, the additional C and H elastic peaks in the raw spectra (blue).
- Spectra subtracted with contribution by the container (red) display over subtraction due to the H(n,el) bump as shown in the histogram at the right.

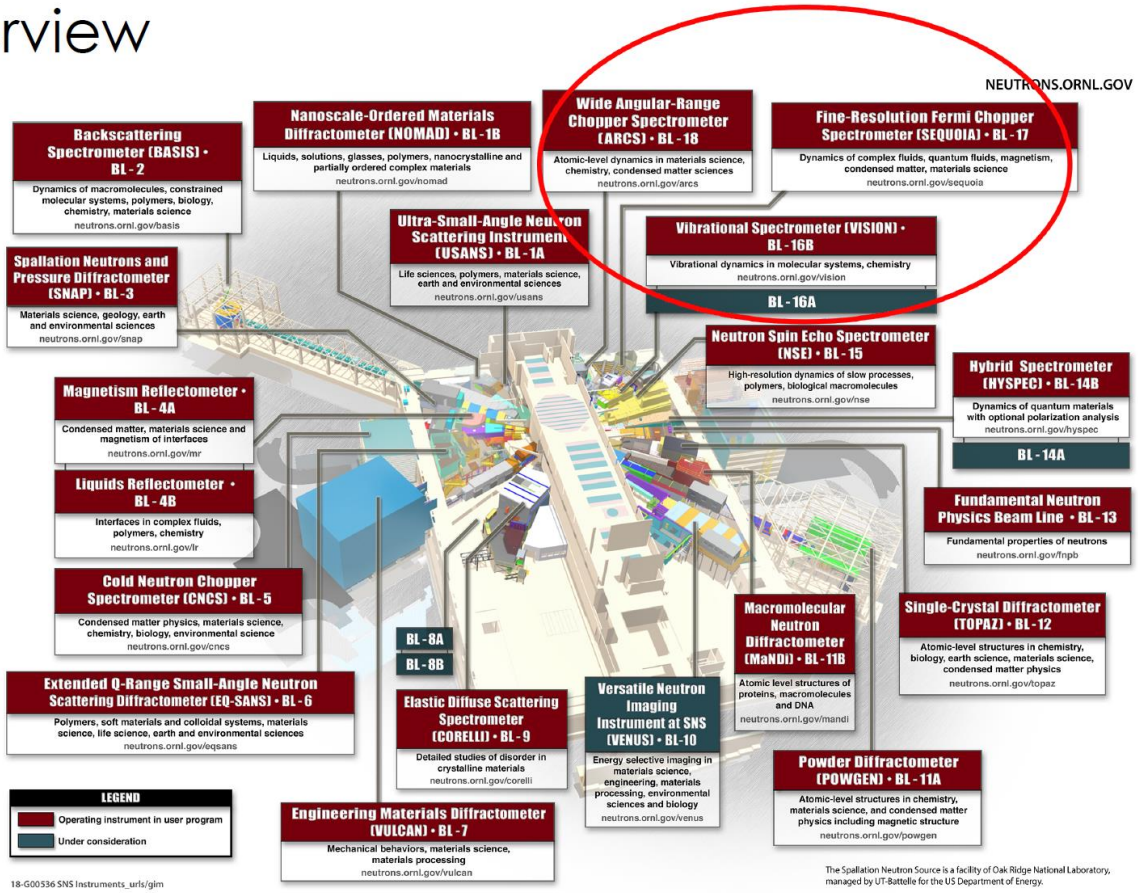
Measurement Status

Measurements	Status
^{nat}Li(n,n) & (n,n'γ)	1. Measured γ-ray excitation function 0.8-4.5 MeV with accompanying angular distributions in 0.1 MeV steps on LiF target. 2. Measured 2.0 & 3.0 MeV (n,n') data angular distributions on Li metal target
^{19}F(n,n) & (n,n'γ)	1. Measured γ-ray excitation function 0.8-4.5 MeV with accompanying angular distributions in 0.1 MeV steps on LiF target. 2. Measured a trial LiF(n,n) angular distribution 3. May go to a CaF_2 or TaF target. Traditional target is CF. 4. The 89 ns lifetime of the 197 keV level causes huge problems in our n & γ TOF spectra. 5. Current DAQ software not equipped to take time-tagged event mode data. → Ben Crider
^{24}Mg(n,n'γ)	0. 24Mg is very deformed like 23Na 1. Measured γ-ray excitation function 0.9-4.5 MeV with accompanying angular distributions . 2. a4 coefficients remain complicated
^{nat}Si(n,n) & (n,n'γ)	1. Isotopically enriched samples not available. 2. Don't appear to be learning anything from the data we took.

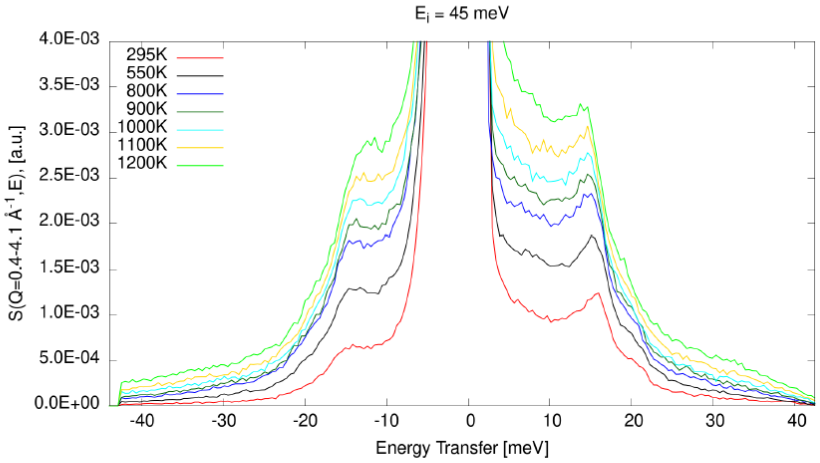
Oak Ridge National Laboratory

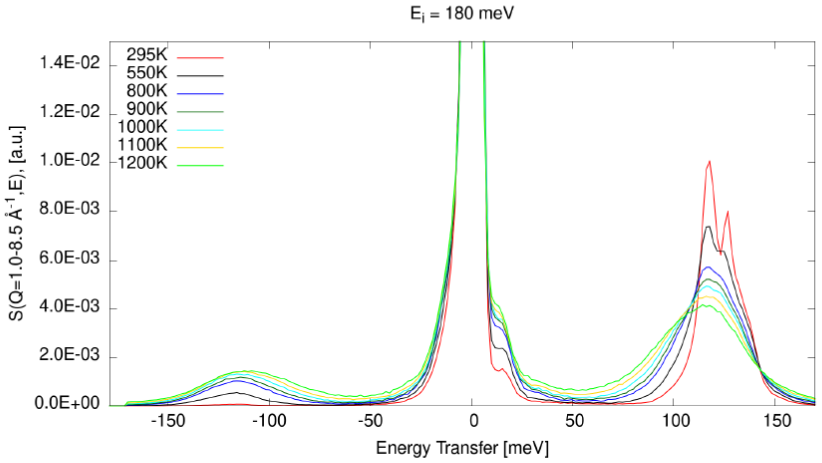
- Thermal Neutron Scattering Measurements at the ORNL Spallation Neutron Source

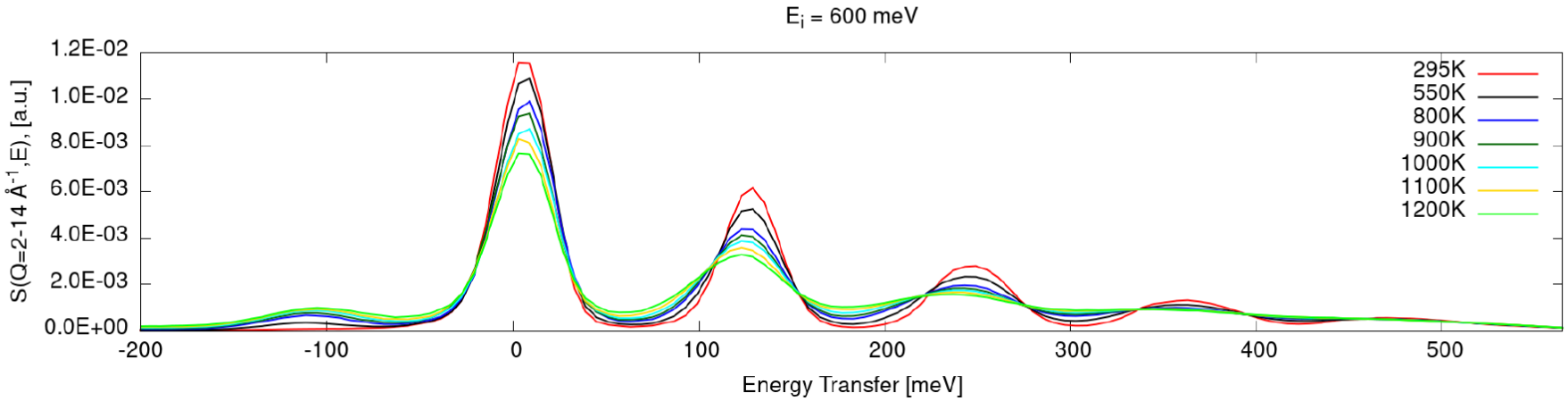
SNS Overview



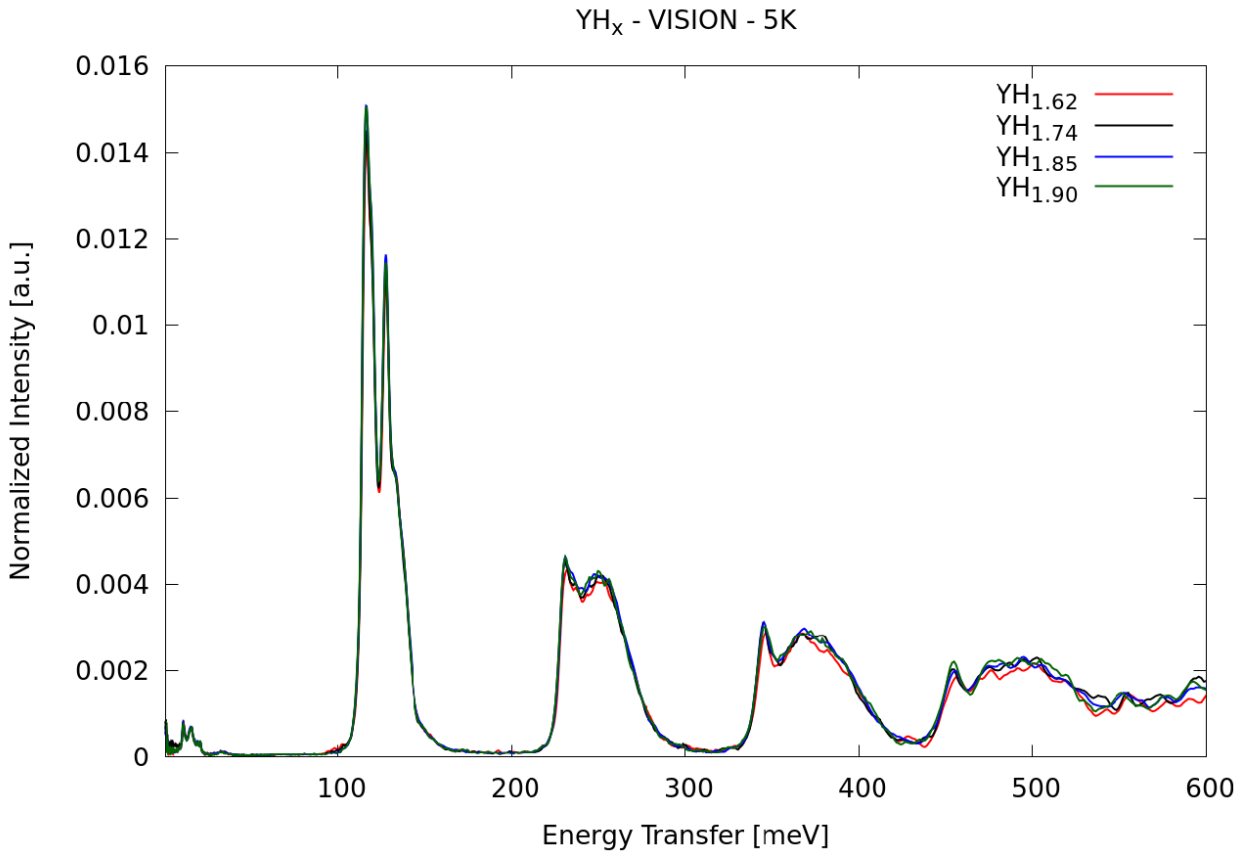
YH_x: ARCS Measurements—Temperature Comparison



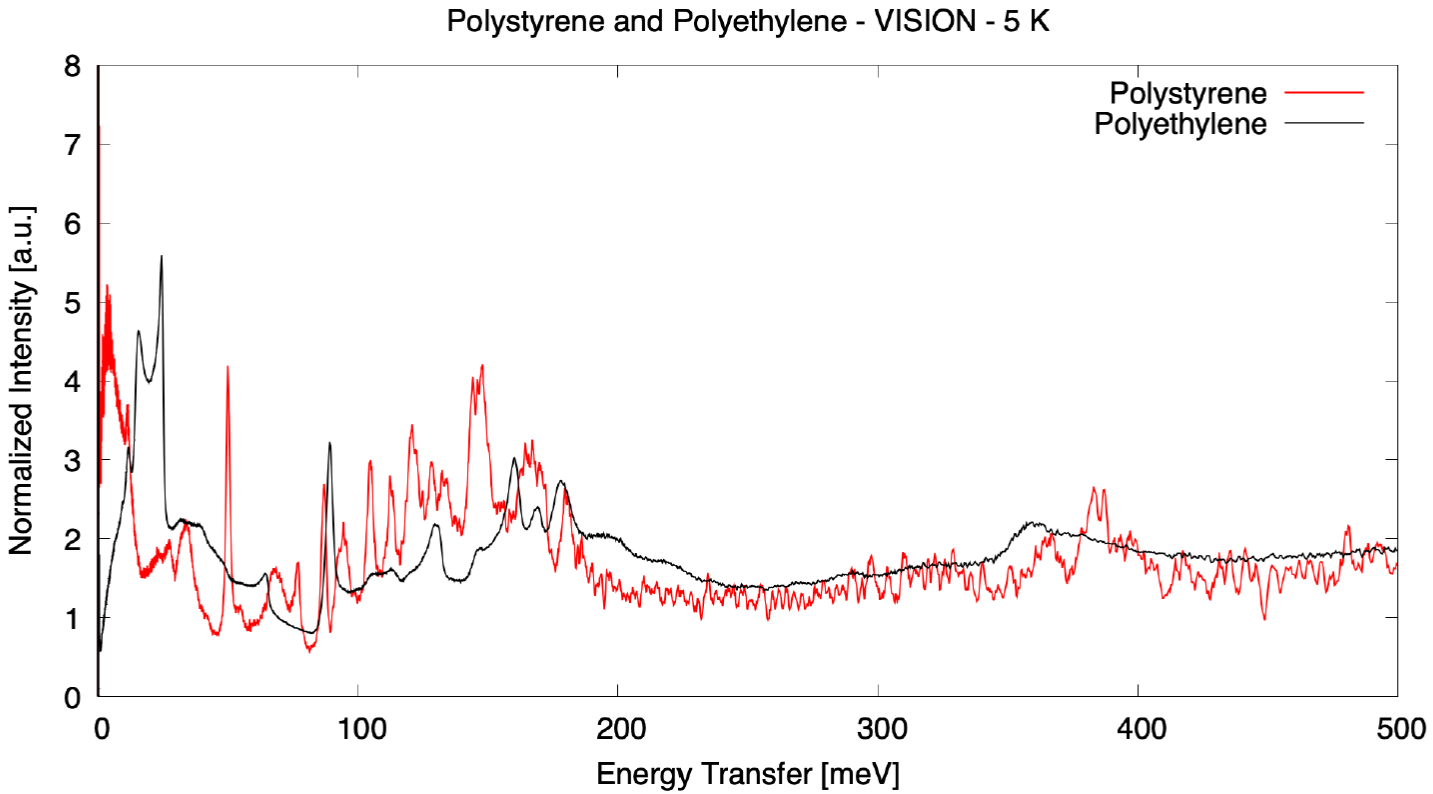




YH_X: VISION Measurements



Polystyrene: Comparison with Polyethylene



University of Notre Dam

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

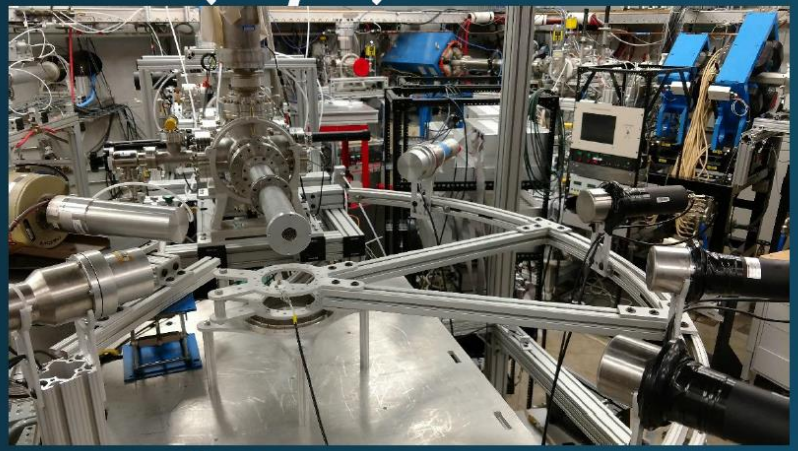
How can we get this data in an efficient and cost effective way?

- 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)

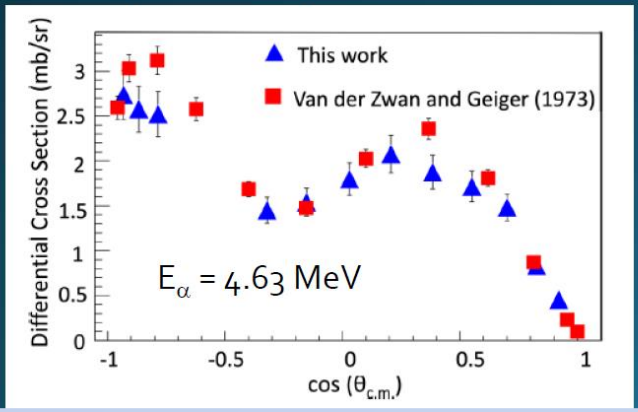
Michael Febbraro

Febbraro et al. (2019)

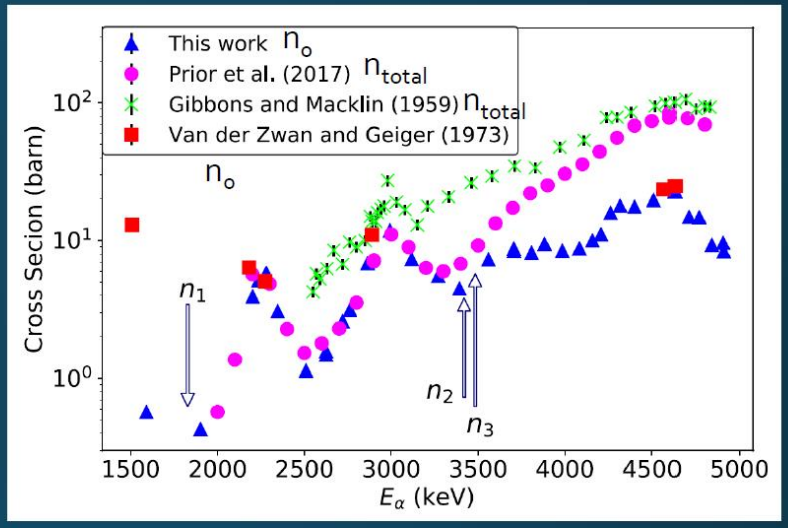
$^{10}B(\alpha,n)^{13}N$

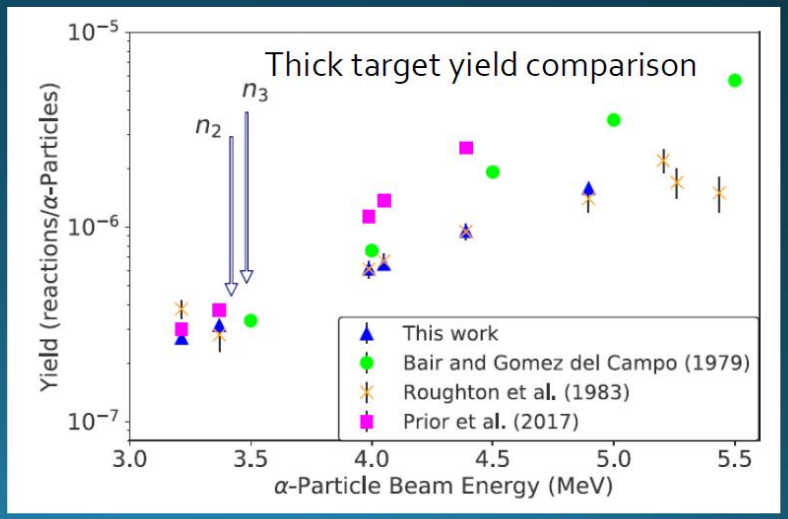


2017 Setup

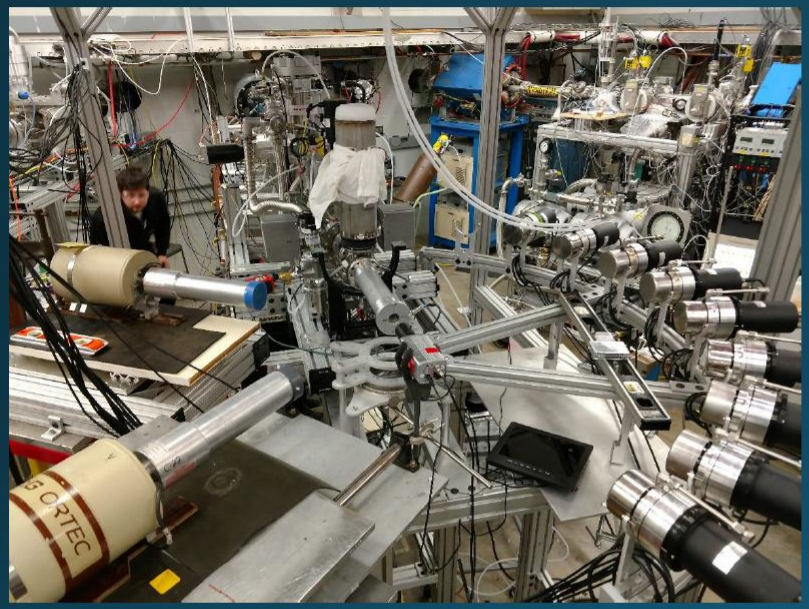


Liu et al. (2019)



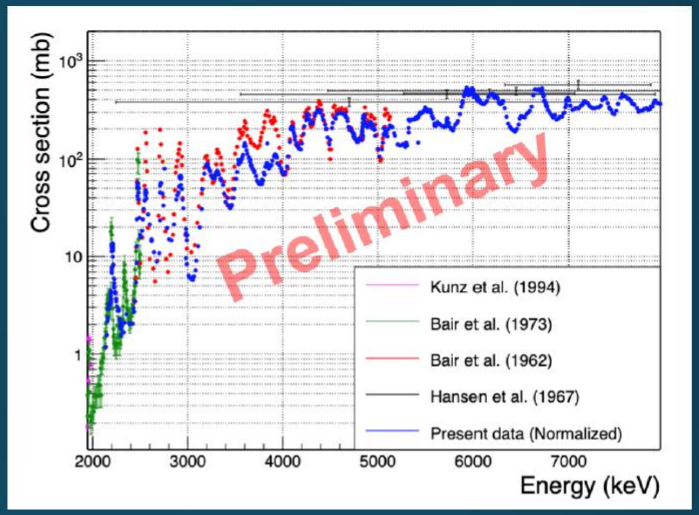


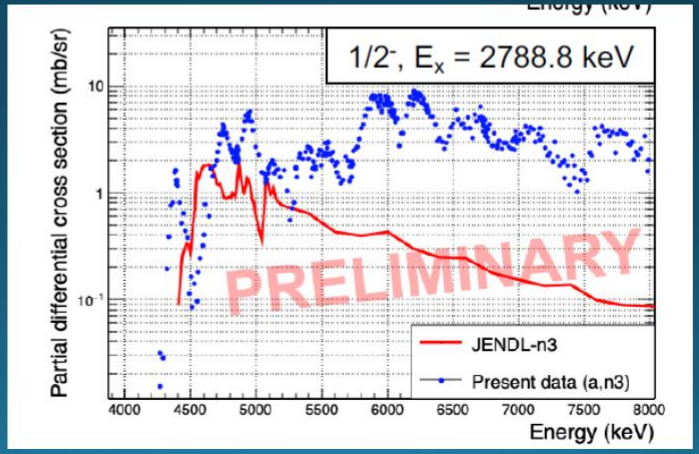
$^{18}O(\alpha,n)^{21}Ne$



2019 Setup

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





Becca Toomey (Rutgers)

GEANIE data

For more - check the CSEWG web site

https://indico.bnl.gov/event/7233/timetable/#20201130.detailed

- **Full presentations**
- **Additional talks:**
  - Standards update
  - EXFOR status
  - Decay Data Measurements for Applications
- **Evaluation and validation sessions**