



# Recent Results from CoGNAC Neutron Scattering Measurements at LANL

K. J. Kelly, M. Devlin, J.M. O'Donnell, M. Paris, P. Copp, G. Hale,  
E.A. Bennett

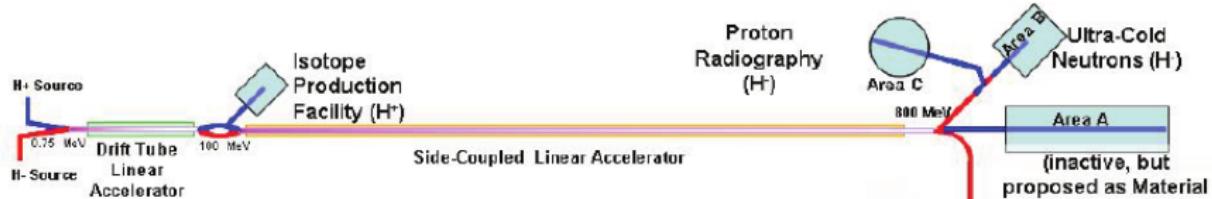
WINS 2023

## Outline

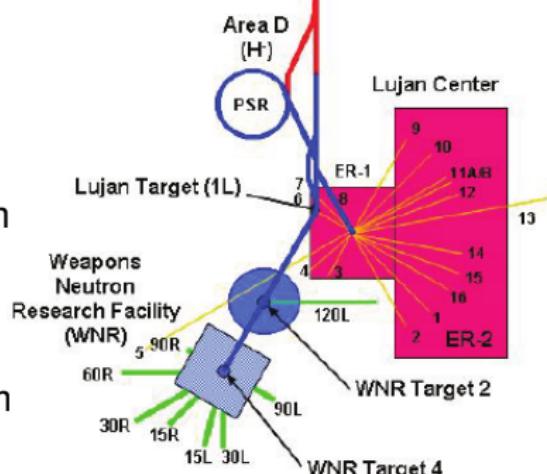
- Assuming No Motivation Need for Scattering Measurements
- The Los Alamos Neutron Science Center
- Liquid Scintillators and CoGNAC  $n\gamma$  Analysis
  - $n\gamma$  Data Analysis Approach, Demonstrated with  $^{12}\text{C}(n,n'\gamma)$
  - $n\gamma$  Analysis of  $^{56}\text{Fe}(n,n'\gamma)$
- Liquid Scintillator  $\gamma$ -only Analysis Method
  - $\gamma$ -only Demonstration with  $^{12}\text{C}(n,n'\gamma)$
  - $\gamma$ -only Analysis of  $^{16}\text{O}(n,n\gamma)$
- Future Experiment Plans ( $^{28}\text{Si}$ ) and Outlook
  - See P. Copp Talk on Thursday for CLYC/TLYC Development Update



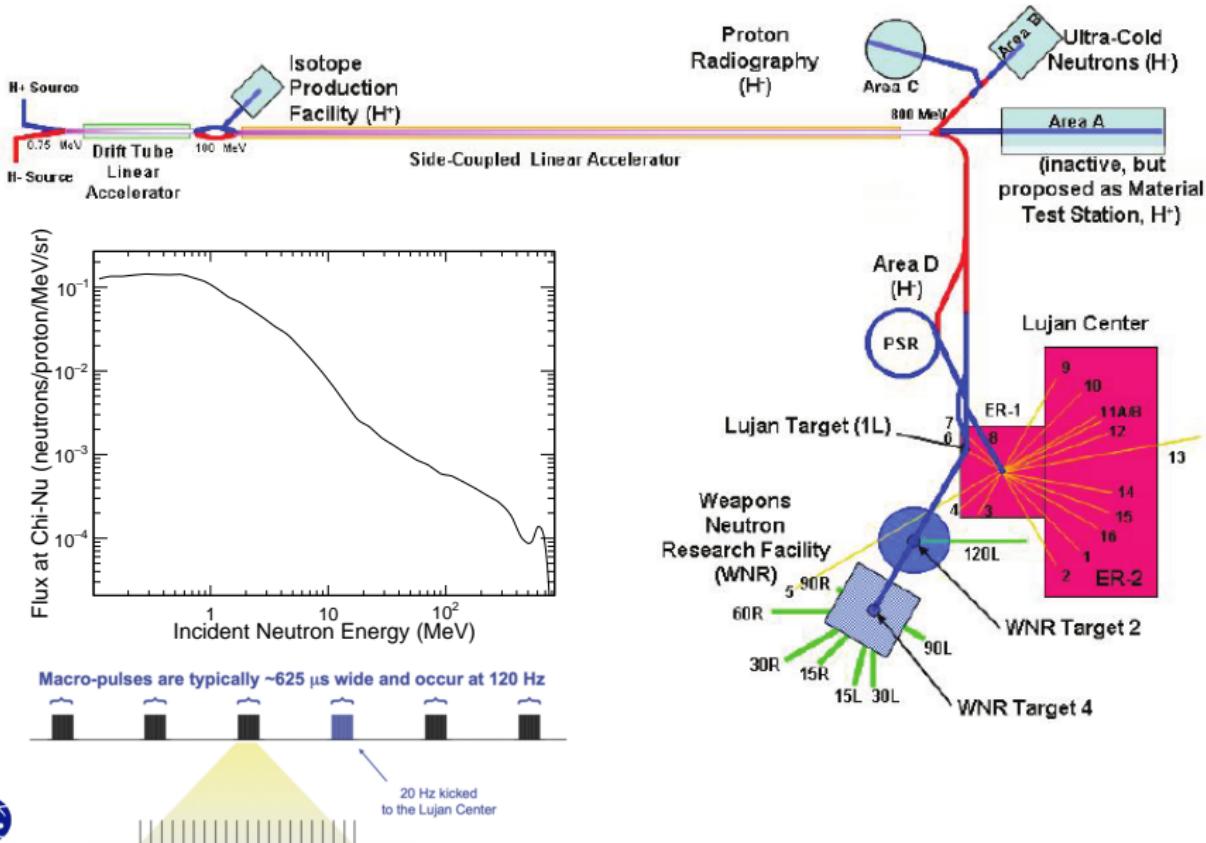
# The LANSCE Facility: Pulsed White $n$ Source



- **Lujan Target**
  - Moderated neutron target
  - Thermal –  $\approx$ MeV neutrons
  - Proton beam travels down
  - Flight paths perpendicular to  $p$  beam
- **WNR Facility**
  - Unmoderated tungsten target
  - Different flight path angles to  $p$  beam
  - Can obtain different flux shapes
  - 1.8  $\mu$ s between  $p$  pulses

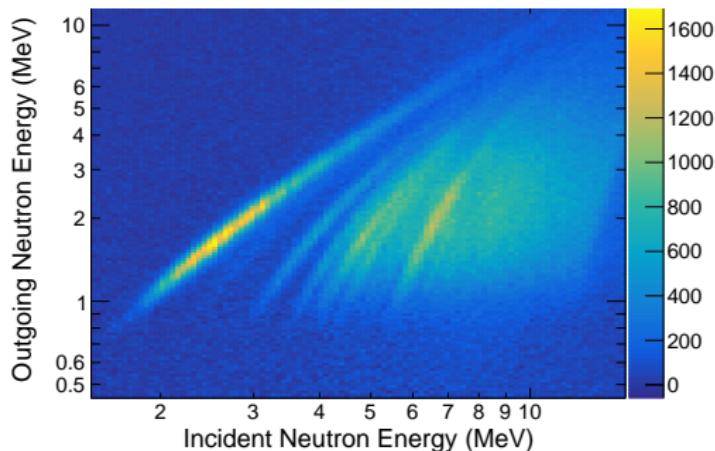
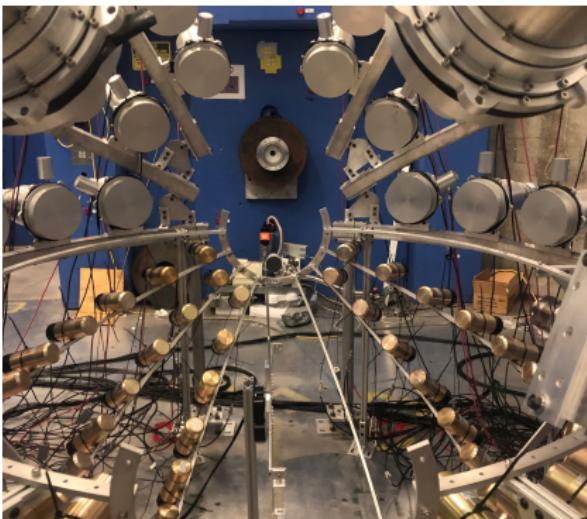


# The LANSCE Facility: Pulsed White $n$ Source

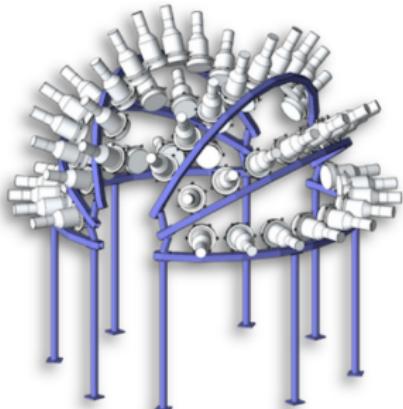
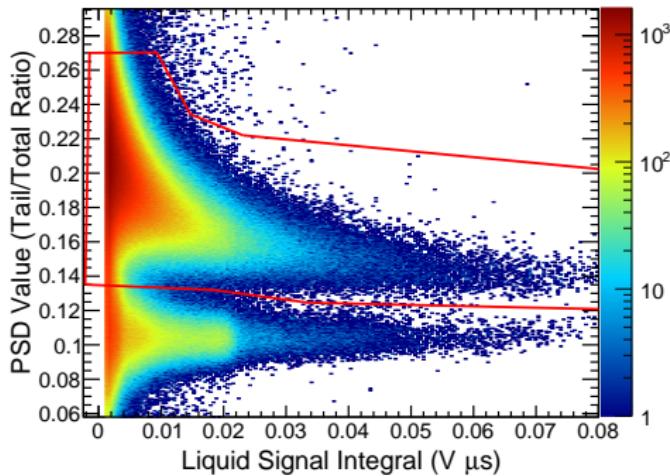


# CoGNAC Coincident $n$ - $\gamma$ Measurements

- PSD  $n$ - $\gamma$  separation  $\Rightarrow$  treat each detector as both  $n$  and  $\gamma$  detector
  - Incident Neutron Energy,  $E_n^{inc}$ , from  $t_0 - t_\gamma$  time difference
  - Outgoing Neutron Energy,  $E_n^{out}$ , from  $t_\gamma - t_n$  time difference
- Map the  $n$ - $\gamma$  coincidence space across all liquid scintillator angles

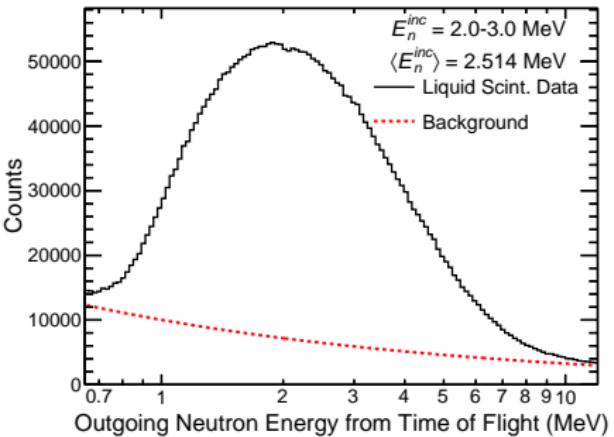
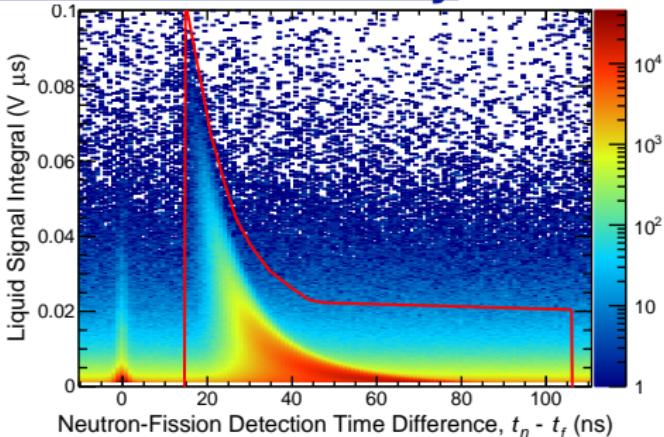
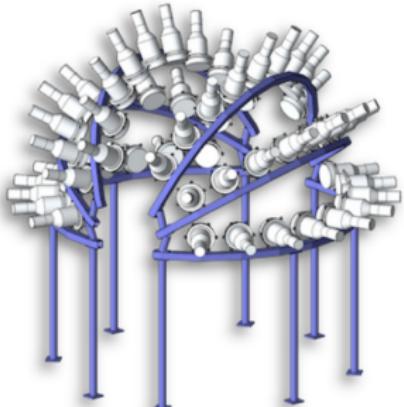


# Properties of the Liquid Scintillator Array



- Span  $\theta = 30\text{--}150^\circ$  at  $15^\circ$  increments
- Six angles in  $\phi$ ,  $\approx 10\%$  of  $4\pi$
- PSD for  $n\text{-}\gamma$  separation
- $\approx 1$  ns time resolution
- Allows for mapping of  $n\text{-}\gamma$  dist.

# Properties of the Liquid Scintillator Array



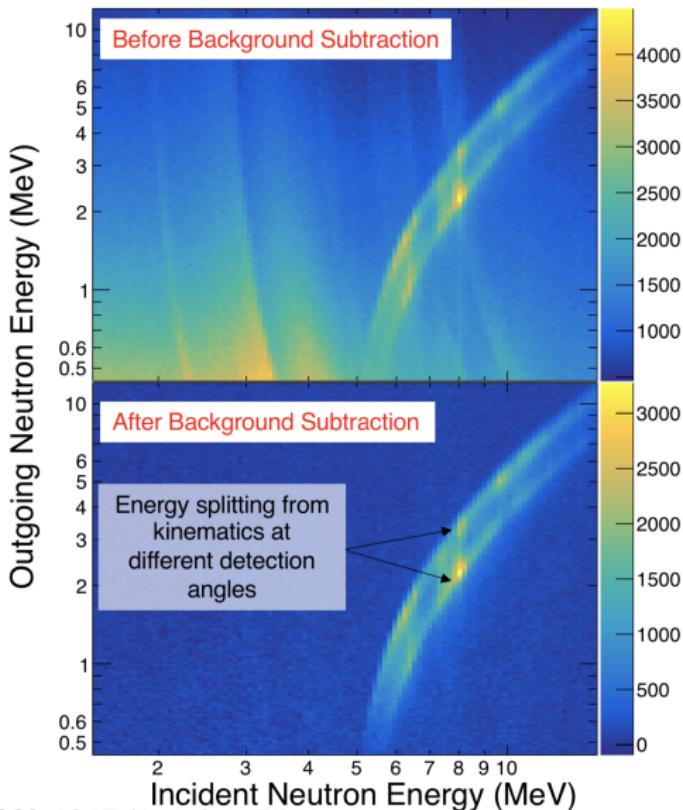
# Random Coincidence Backgrounds Eliminated

- Random coincidence rates derived from Poisson probabilities for *uncorrelated* detection rates <sup>†</sup>
  - true coincidence rate must be low
- Calculate the total probability for:
  1. Detecting a  $\gamma$  at time  $t_\gamma$
  2. Not detecting  $n$  over coinc. time  $t_n - t_\gamma$
  3. Detecting  $n$  at time  $t_n$

$$\begin{aligned}\text{Coinc. Rate} &= r_b = r_\gamma r_n \Delta t \\ &\Rightarrow b = \frac{\gamma n}{N_{t_0}}\end{aligned}$$

with  $\gamma, n = \text{counts}$

- Works remarkably well here, but what are the backgrounds?

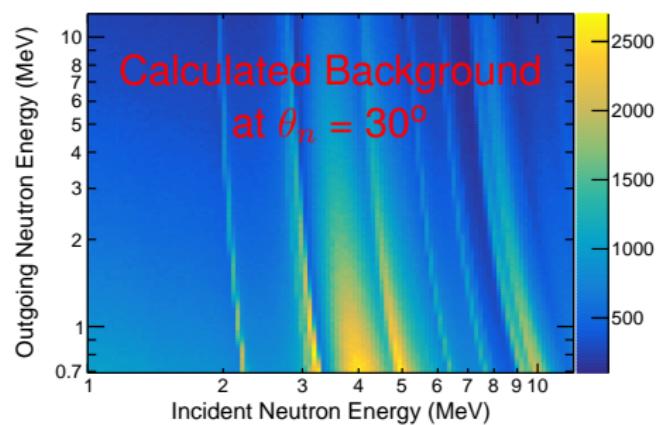
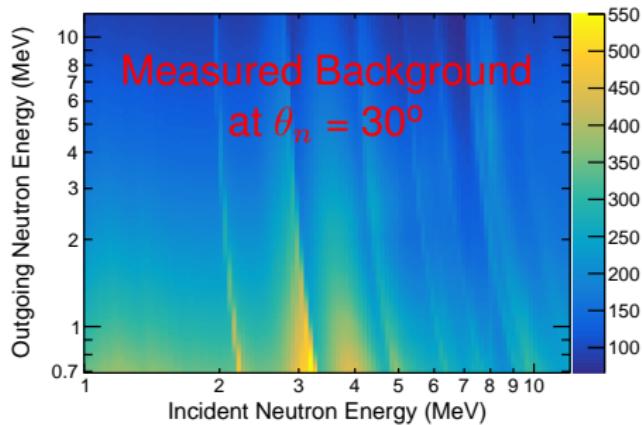


<sup>†</sup>O'Donnell, NIMA 805 (2016) 87, Kelly et al. NIMA 1045 (2023) 167531

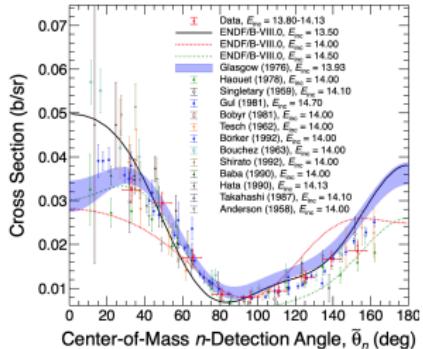


# Backgrounds from $\gamma$ -Anticoincident Neutrons

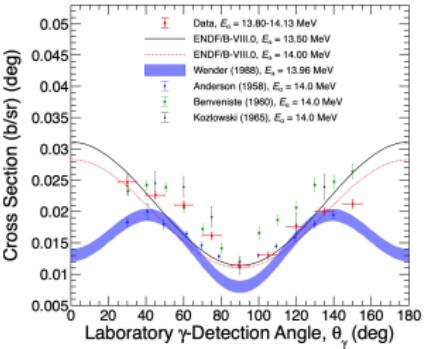
- The elastic scattering  $^{12}\text{C}(n,n)$  reaction is a likely source
- Do a simple Monte Carlo calculation for this background:
  - Sample incident neutrons from WNR FP15L flux shape
  - Calculate  $E_n^{out}$  from sample  $E_n^{inc}$ , convert to TOFs
  - Vary TOFs according to random  $\gamma$  timing, recover new  $E_n^{inc'}$  and  $E_n^{out'}$
  - Fill histogram with counts =  $\sigma(E_n^{inc})$
- Possible to extract cross sections from this background?...maybe...



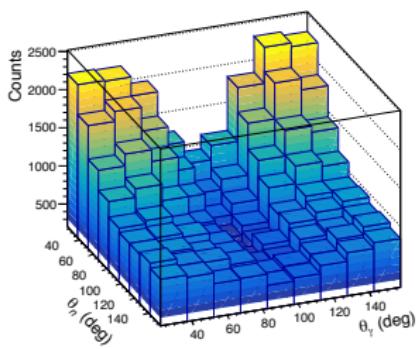
# Extract $n$ , $\gamma$ , and Correlated $n$ - $\gamma$ Distributions



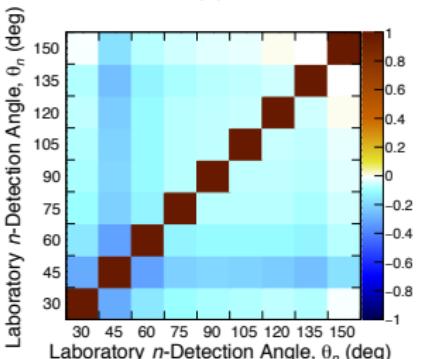
(a)



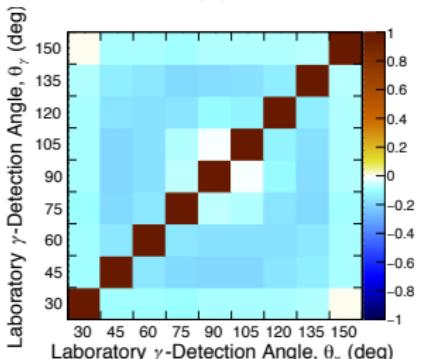
(b)



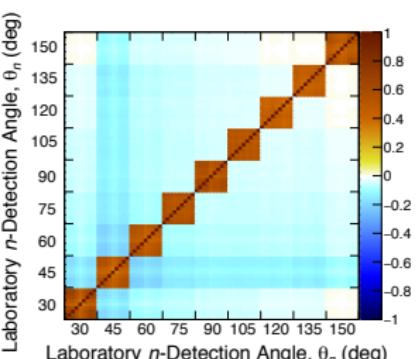
(c)



(d)



(e)

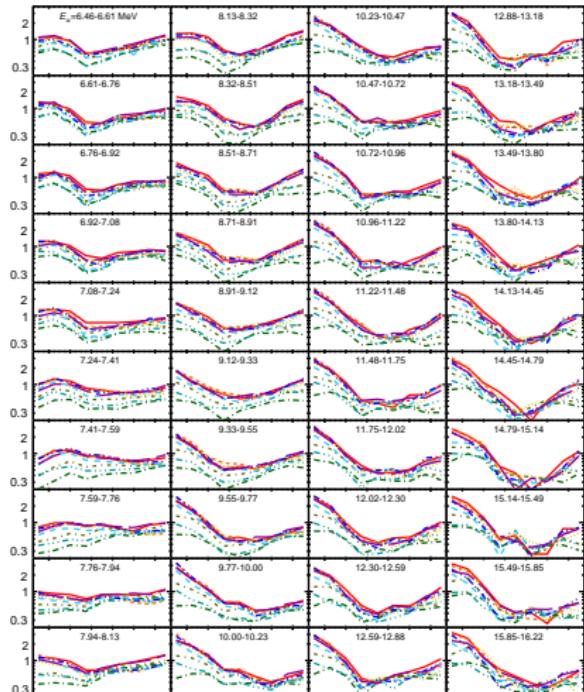


(f)

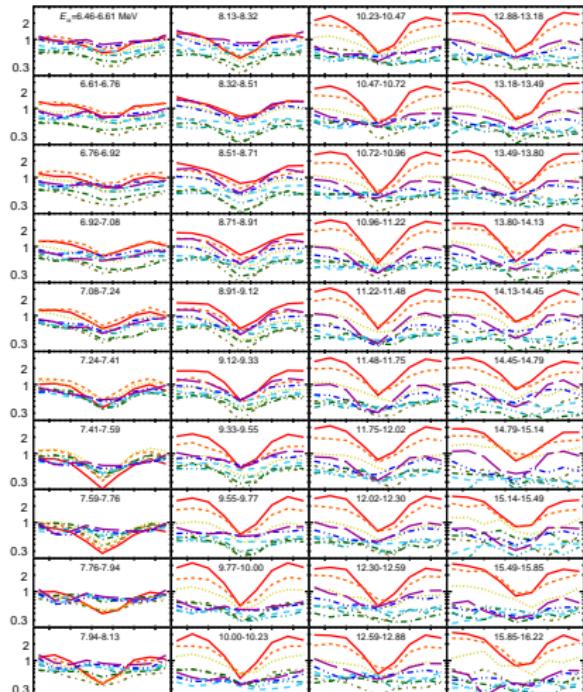


# Corr. $n$ - $\gamma$ Distributions for Wide Range of $E_n^{inc}$

Normalized  $W(\theta)$  ( $\times 10^4$ )



Normalized  $W(\theta)$  ( $\times 10^4$ )



# Iterative Unfolding of Neutron Spectra

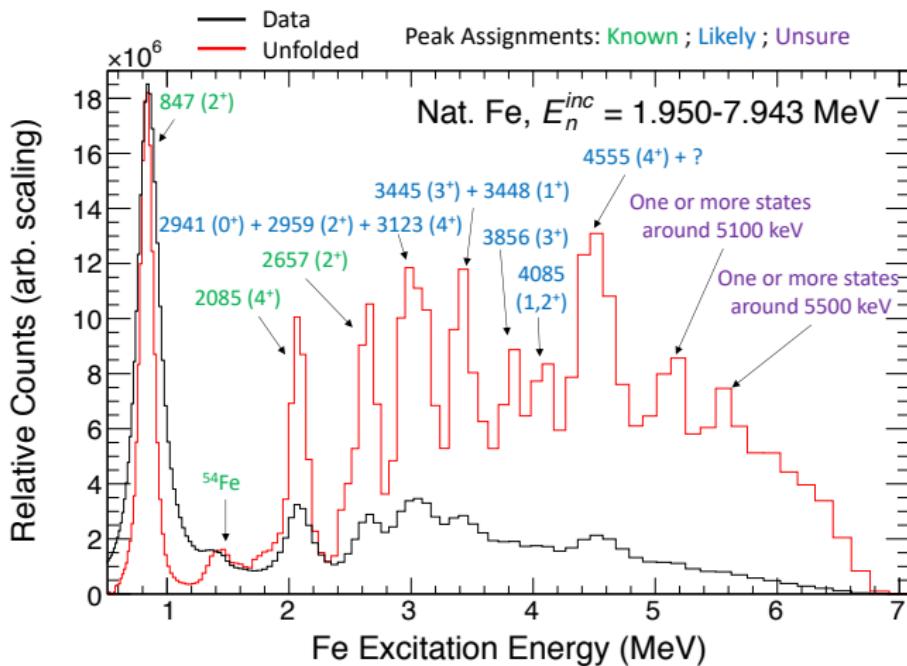
$$m_{\alpha|\beta}^{(n+1)}(E) = \frac{m_{\alpha|\beta}^{(n)}(E)c_{\alpha}(E)}{\sum_{i=1}^N \mathcal{R}(E, E_i)m_{\alpha|\beta}^{(n)}(E_i)}$$

Kelly et al., NIMA 1010 (2021) 165552

Kelly et al., NIMA 866 (2017) 182

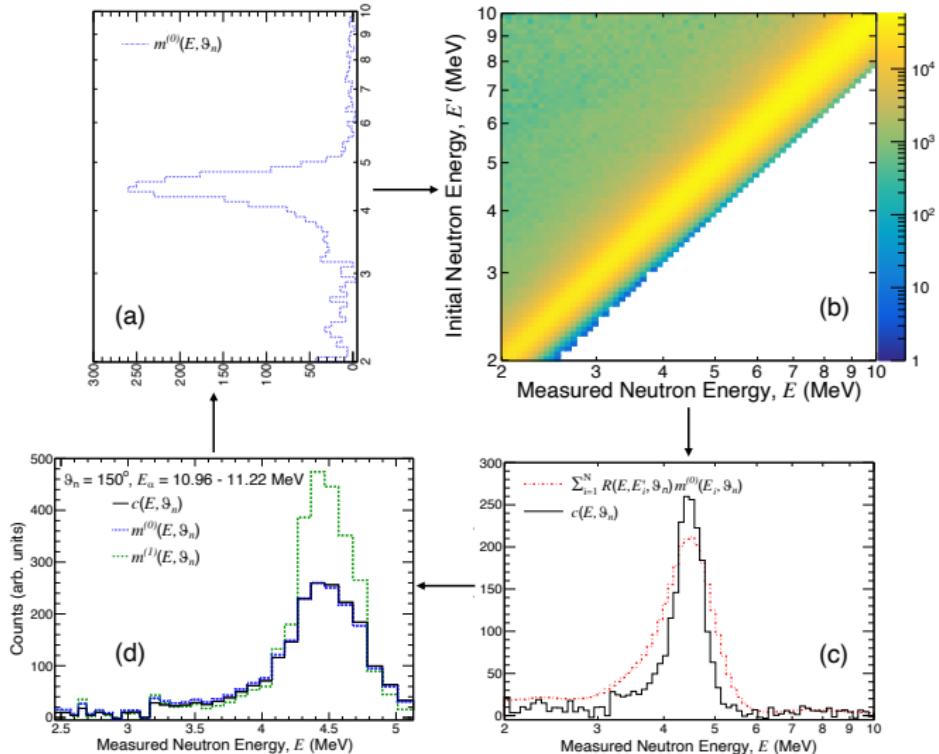
Gold, Report ANL-6984 (1964)

- Improves resolution of state excitations
- Corrects for environmental  $n$  scattering effects
- Extract full strength of each excited state
  - Demonstrated with continuous PFNS in MCNP



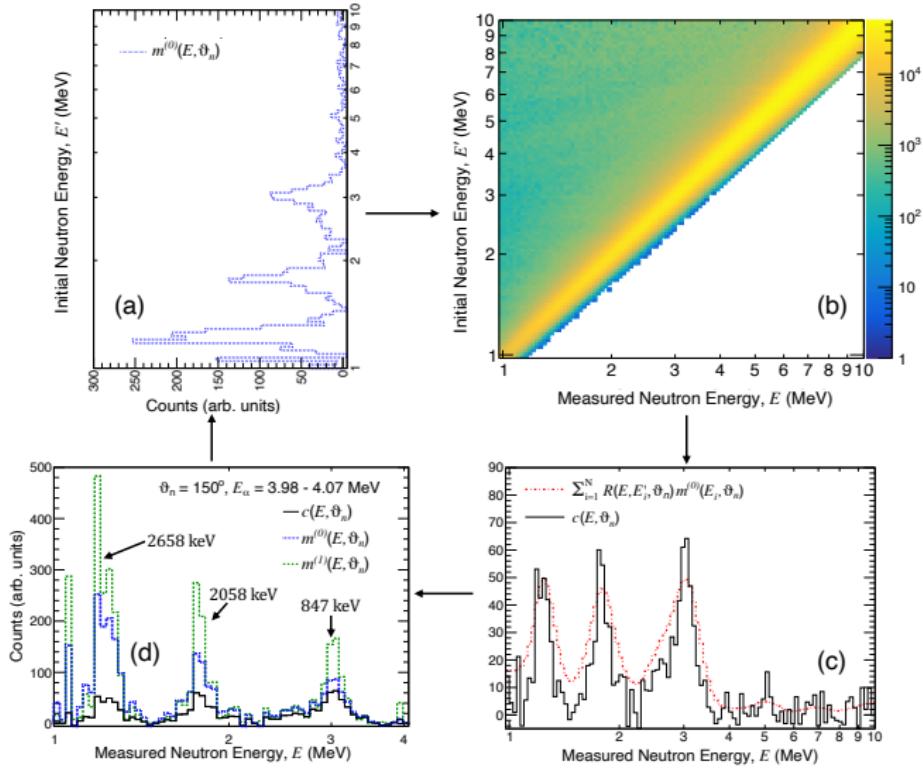
# Schematic of Unfolding Procedure - $^{12}\text{C}$

$$m_{\alpha|\beta}^{(n+1)}(E) = m_{\alpha|\beta}^{(n)}(E) \frac{c_\alpha(E)}{\sum_{i=1}^N \mathcal{R}(E, E_i) m_{\alpha|\beta}^{(n)}(E_i)}$$



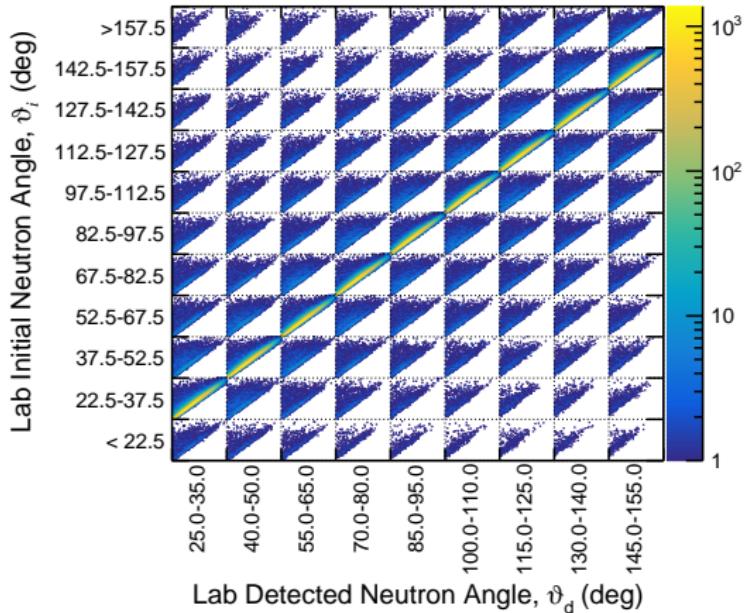
# Schematic of Unfolding Procedure - $^{56}\text{Fe}$

$$m_{\alpha|\beta}^{(n+1)}(E) = m_{\alpha|\beta}^{(n)}(E) \frac{c_\alpha(E)}{\sum_{i=1}^N \mathcal{R}(E, E_i) m_{\alpha|\beta}^{(n)}(E_i)}$$



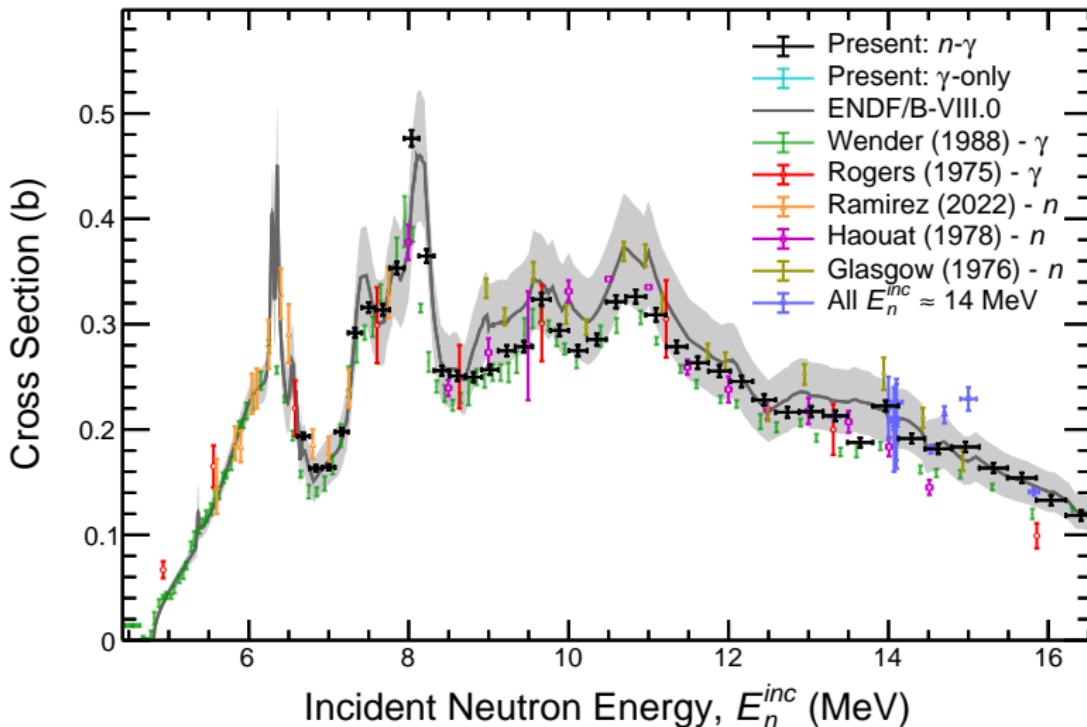
LA-UR-23

# Ang. Dist. Integration and Response Distortions

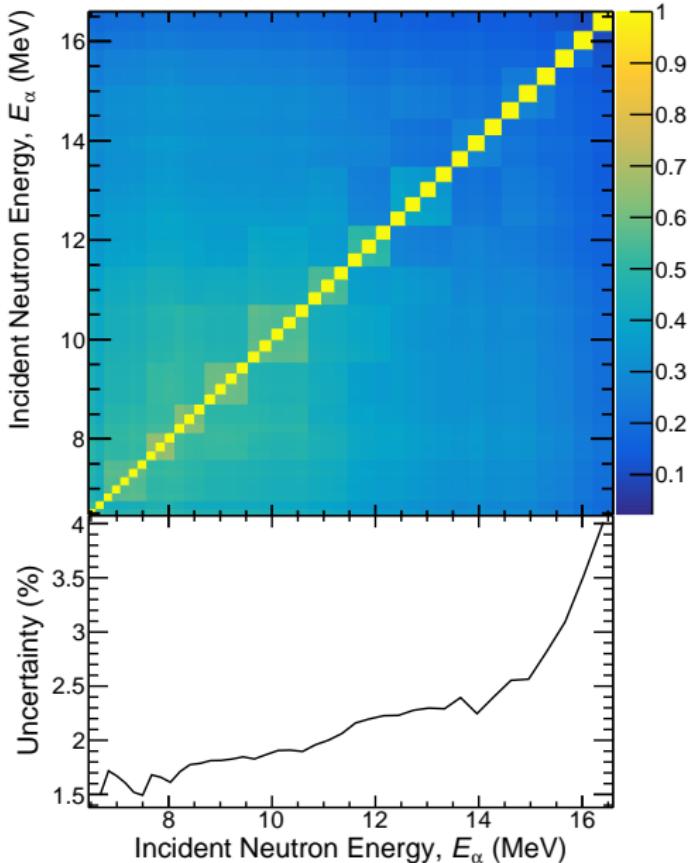


- Integrate over  $\theta_\gamma$  and Leg. polynomial fit  $n$  angular distributions
  - Use F-statistical test for  $L_{max} = 2, 4$ , and  $6$  to determine optimal fit
- Integrate optimal fit to obtain relative XS values for each channel

## $n\text{-}\gamma$ $^{12}\text{C}(n,n'\gamma)$ Results



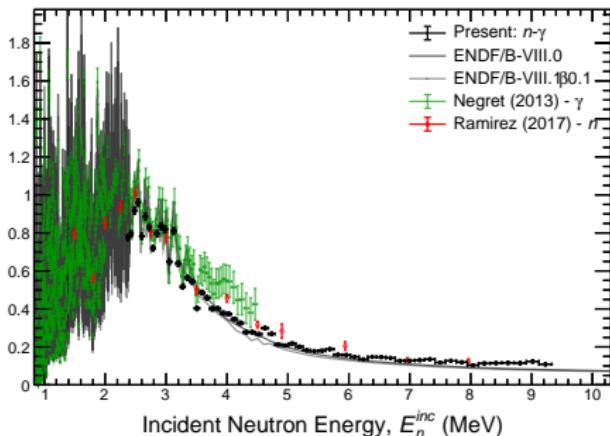
## $n$ - $\gamma$ $^{12}\text{C}(n,n'\gamma)$ Results



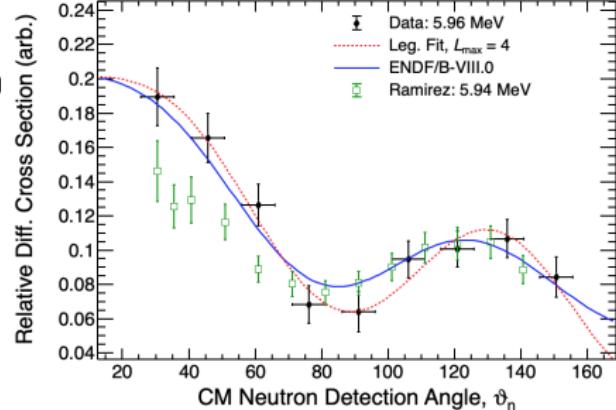
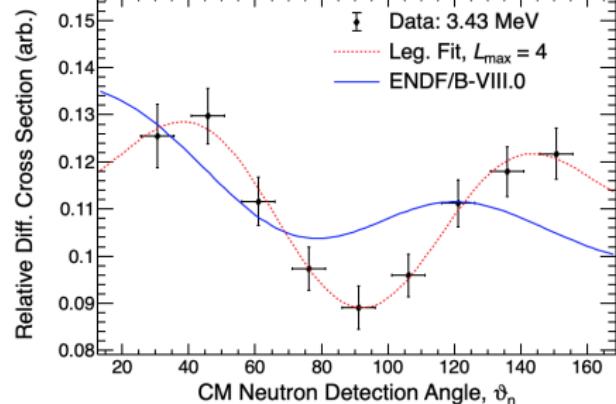
- Covariance derivations and results described in recent PRC
  - Kelly, et al. PRC **108** (2023) 014603
- Essential component of all nuclear data results

# $^{56}\text{Fe}(n,n'\gamma) - 0.847 \text{ MeV}$

Cross Section (b)

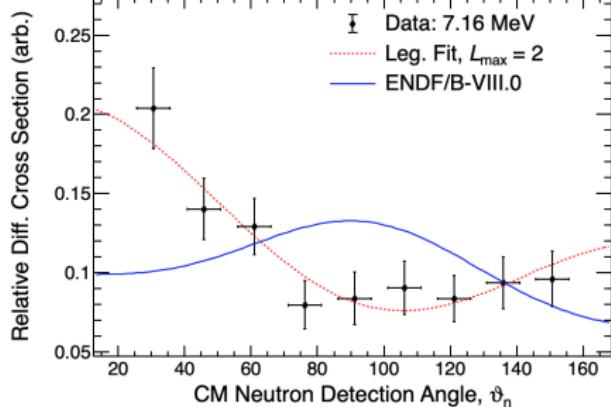
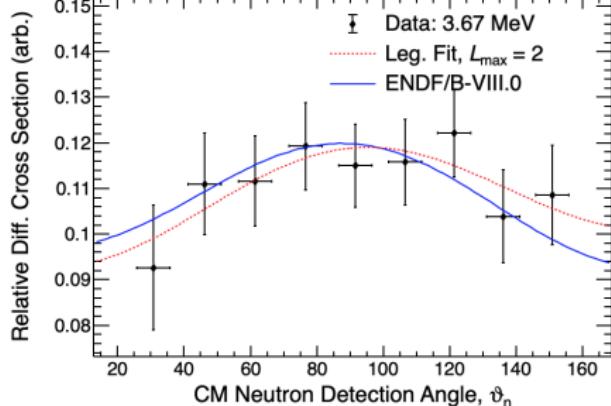
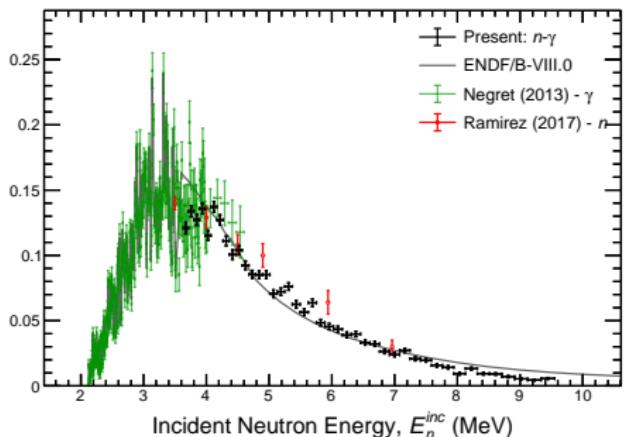


- $^{56}\text{Fe}$  data also include correction for natural target isotopic composition
  - Sys. unc. from this correction not yet included
- Resonances impact measured angular distributions
- Evaluations use average params



# $^{56}\text{Fe}(n,n'\gamma) - 2.058 \text{ MeV}$

Cross Section (b)

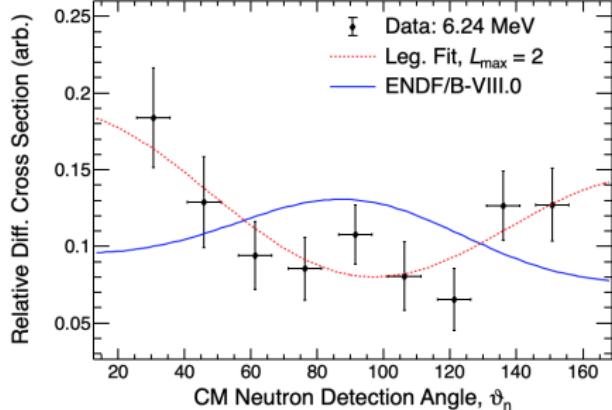
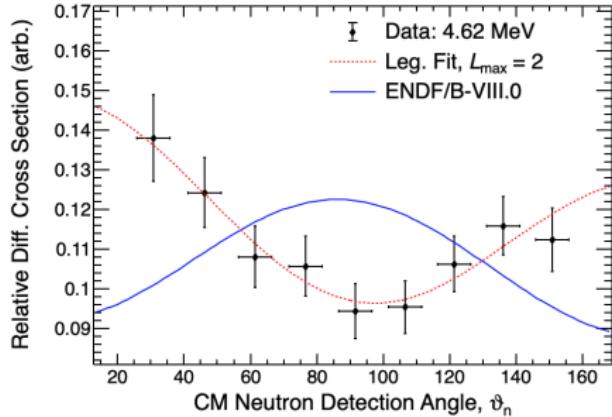
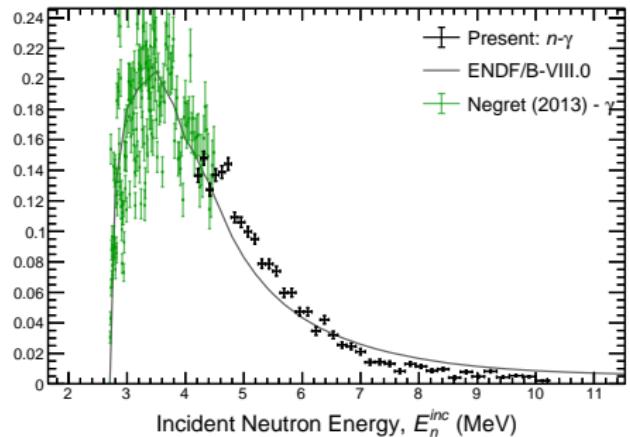


- $^{56}\text{Fe}$  data also include correction for natural target isotopic composition
  - Sys. unc. from this correction not yet included
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- Evaluations use average params



# $^{56}\text{Fe}(n,n'\gamma) - 2.658 \text{ MeV}$

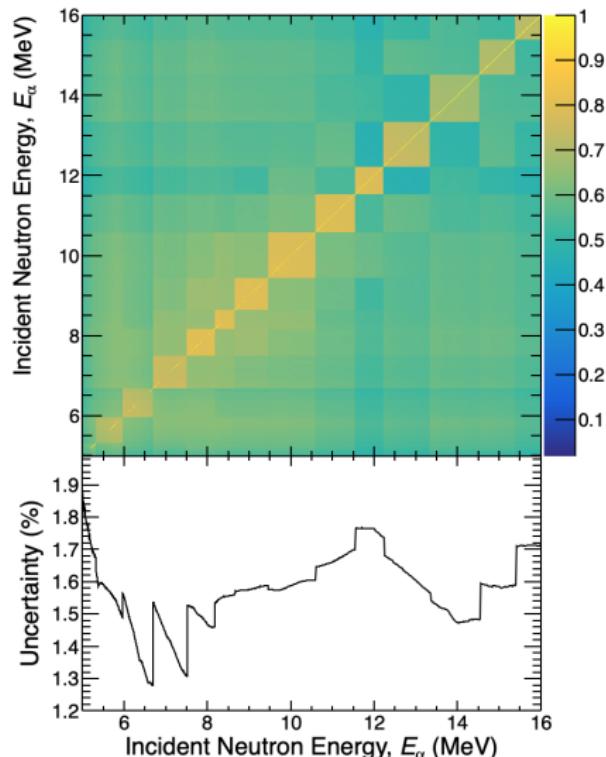
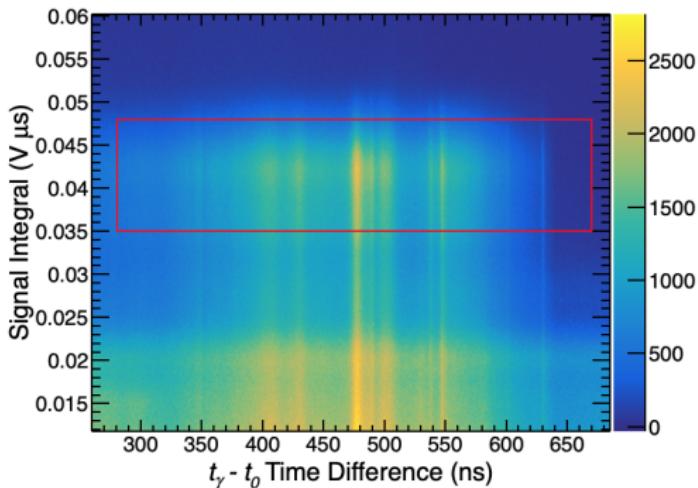
Cross Section (b)



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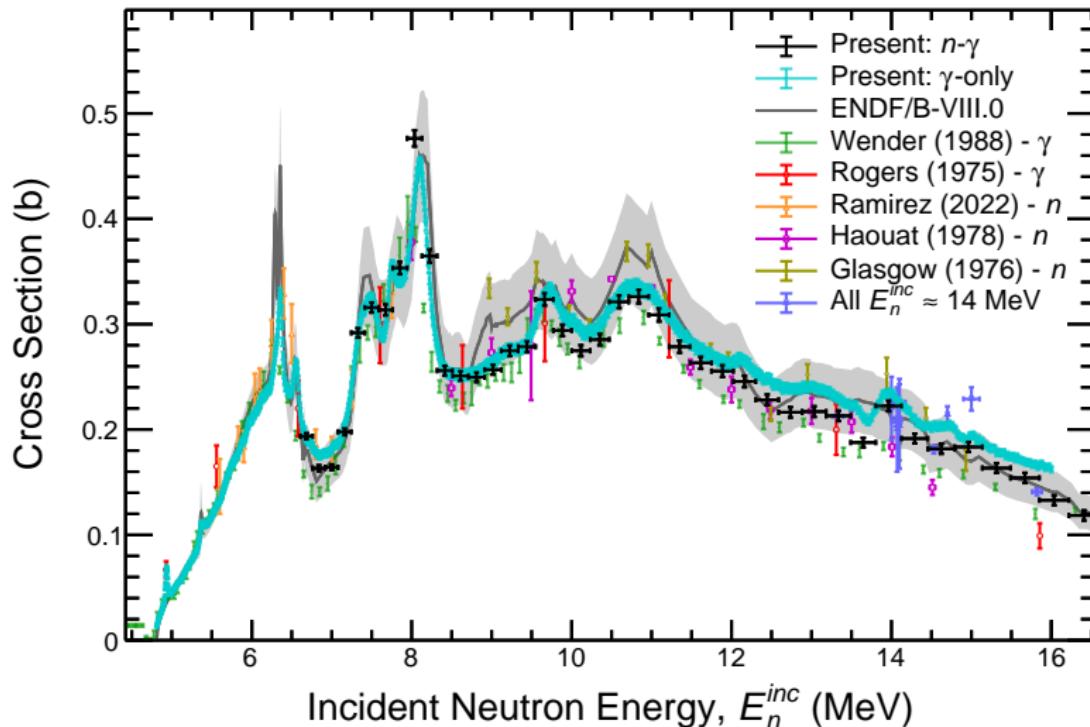
# $\gamma$ -only Liq. Scint. Analysis Possible with $^{12}\text{C}$



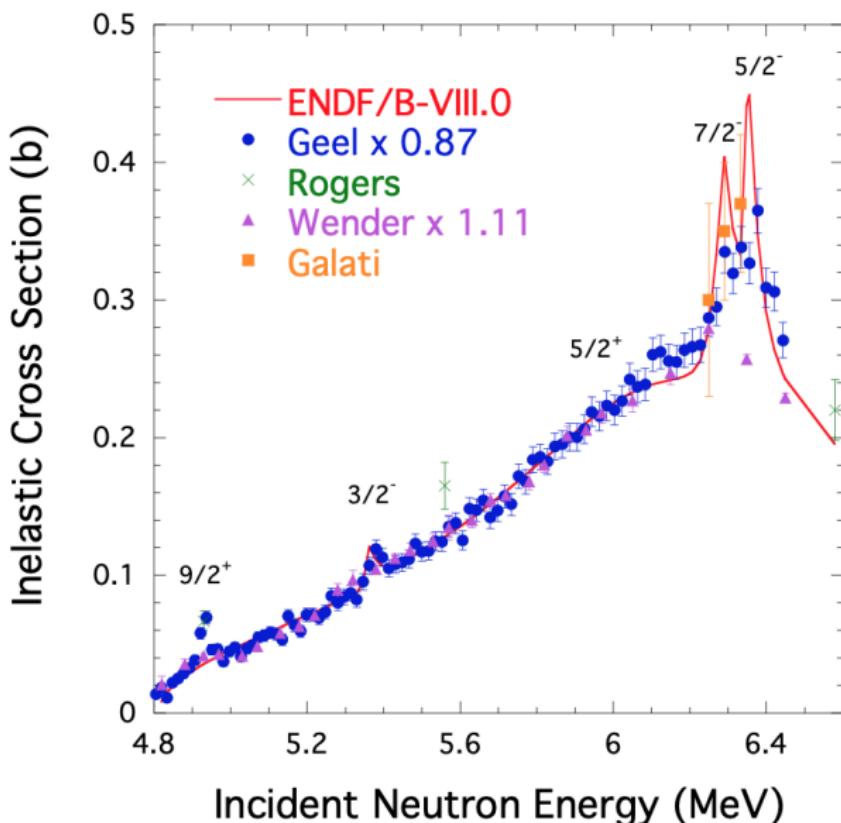
- No  $\gamma$  competition
  - Broad gate on high-E  $\gamma$  rays extracts high-precision result
  - Insensitive to  $>10\%$  fluctuations of gate position



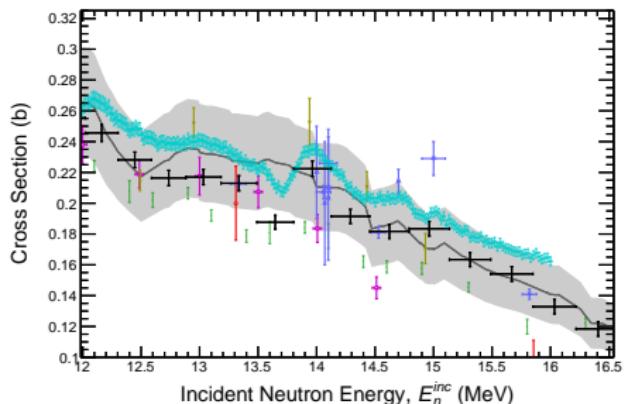
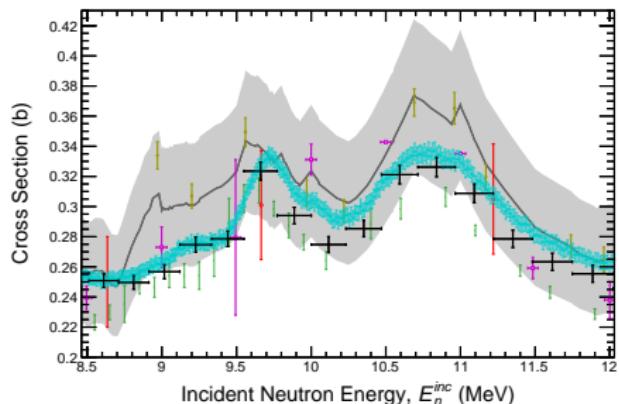
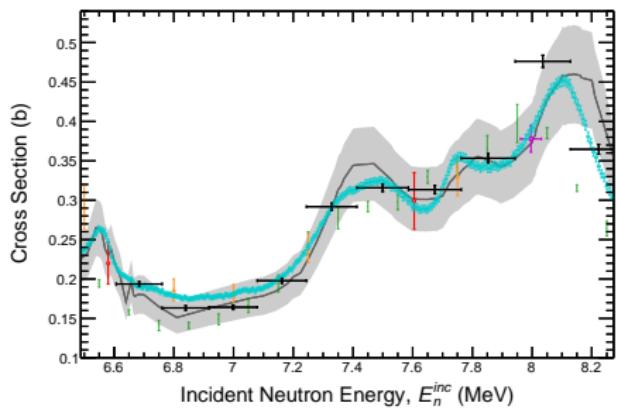
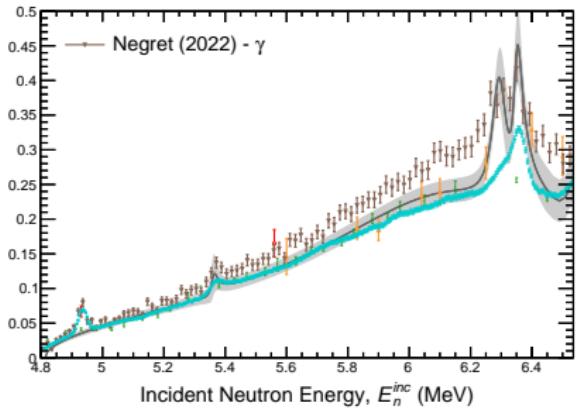
# $\gamma$ -only $^{12}\text{C}(n,n'\gamma)$ Results



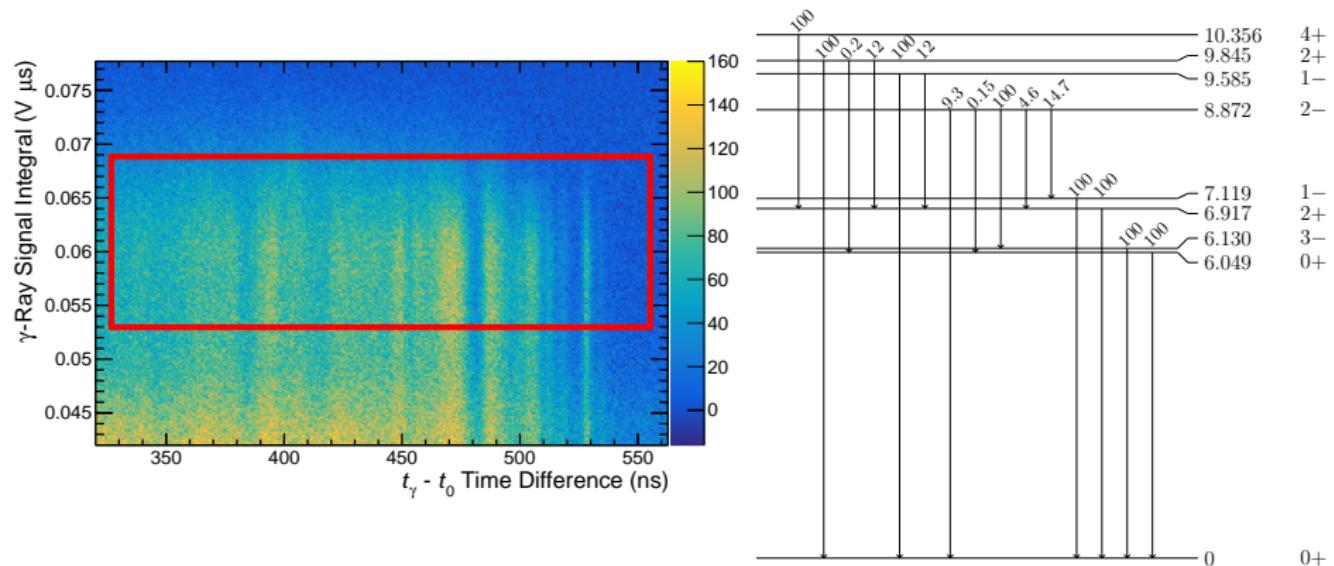
# ENDF/B-VIII.0 $^{12}\text{C}(n,n'\gamma)$



# Zoom-In for $\gamma$ -only Analysis Precision and Detail



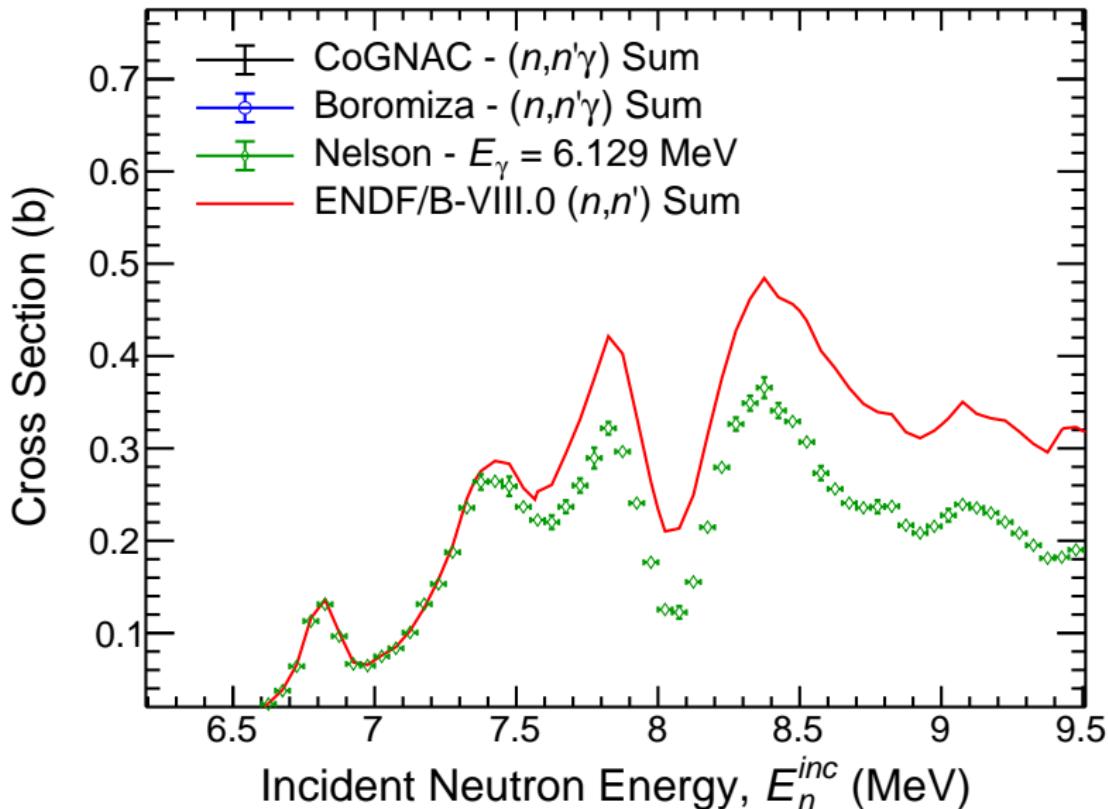
# $\gamma$ -only Analysis of $^{16}\text{O}(n,n'\gamma)$



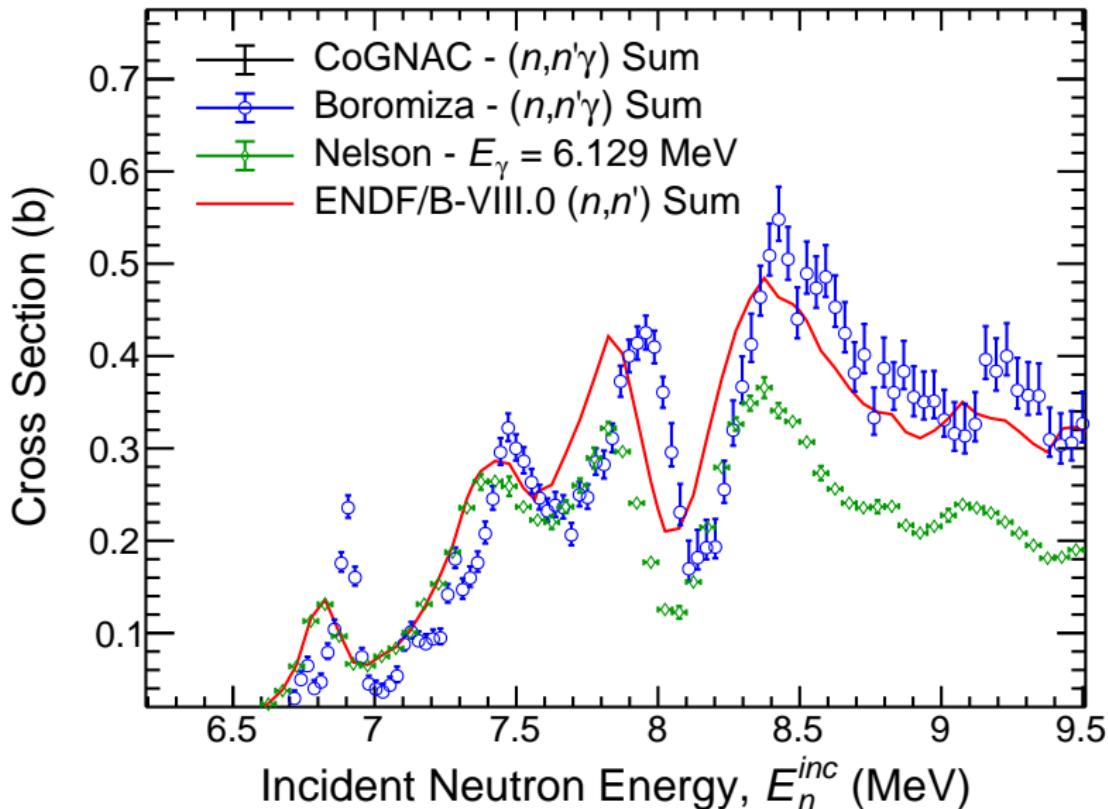
- Lowest 4 states in  $^{16}\text{O}$  decay entirely to the ground state
  - only  $\approx 3\%$  difference in  $\gamma$  efficiency from  $E_\gamma = 6.1\text{--}7.1 \text{ MeV}$
- 8.872 keV 5<sup>th</sup> state decays 99.3% through first 4 states
- 6<sup>th</sup>, 7<sup>th</sup> decay to ground, higher decay through first 4 states
  - Charged particle emission takes over above  $E_n^{inc} = 10\text{--}12 \text{ MeV}$



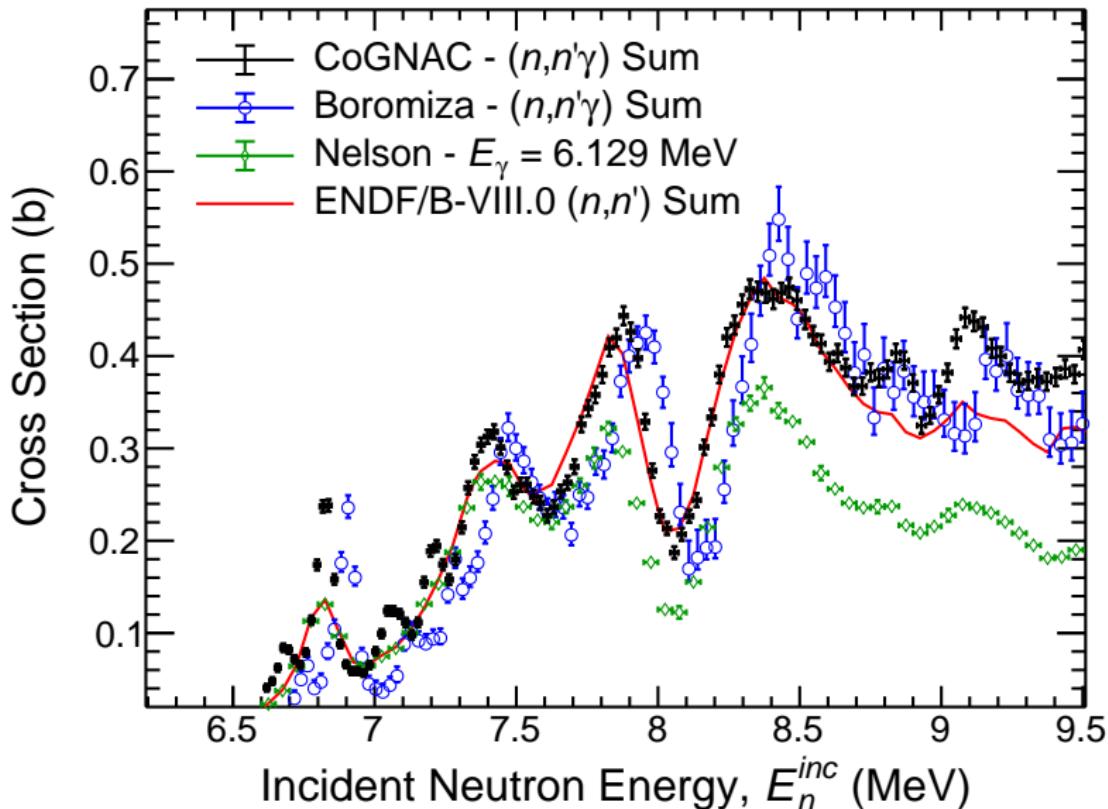
## Preliminary Results for $^{16}\text{O}(n,n'\gamma)$



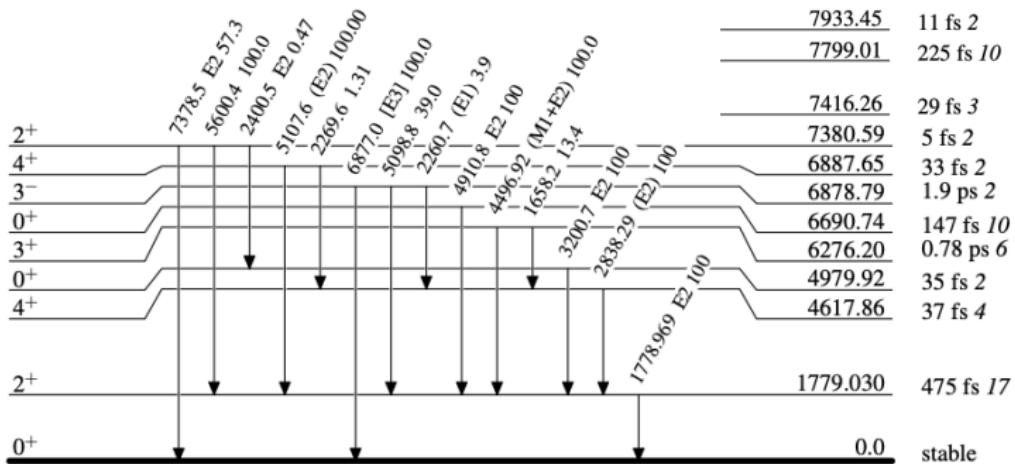
# Preliminary Results for $^{16}\text{O}(n,n'\gamma)$



## Preliminary Results for $^{16}\text{O}(n,n'\gamma)$



# Prospects for Si Data Analysis Paths - $\gamma$ and $n\text{-}\gamma$



- 1<sup>st</sup> state easily accessible in  $n\text{-}\gamma$ , and  $\gamma$ -only for  $\approx 3$  MeV
- 2<sup>nd</sup> & 3<sup>rd</sup> states likely separable after unfolding
  - Both decay entirely to the 1<sup>st</sup> state with 4<sup>th</sup>, thus  $\gamma$ -only should capture full  $(n, n'\gamma)$
- 4<sup>th</sup> separable after unfolding; 5<sup>th</sup> state may overlap with 6<sup>th</sup> & 7<sup>th</sup>
- Combined results for 8<sup>th</sup> & 9<sup>th</sup>, and 10<sup>th</sup> & 11<sup>th</sup> could be possible

# Measurement Summary and Outlook

## Summary

- $^{28}\text{Si}(n,n'\gamma)$  with high-purity target
  - $n\gamma$  and  $\gamma$ -only analysis to be applied with liquid scintillators
  - Re-measurement of  $^{16}\text{O}$  was desired, but not likely this year
- Implement CLYC detectors with improved parameters - See P. Copp Talk
  - CLYC  $n\gamma$  and  $\gamma$ -only capabilities to be demonstrated with  $^{12}\text{C}$
  - Readily expandable to  $^{28}\text{Si}$  analysis
- Anticipating publication submission for  $^{56}\text{Fe}$ ,  $^{16}\text{O}$  next year
  - Possibly  $^{27}\text{Al}$  as well

## Future Plan

- High-purity  $^{56}\text{Fe}$ ,  $^{9}\text{Be}(n,n)$  and  $(n,2n)$
- Expand CoGNAC capabilities to broadly include  $(n,2n)$  and  $(n,3n)$
- Extract  $(n,n)$  cross sections and angular distributions from  $^{12}\text{C}$ ,  $^{27}\text{Al}$ ,  $^{28}\text{Si}$ , and more



# THANK YOU!

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