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A Measurement of the $^{18}O(\alpha,n)^{21}Ne$ Reaction for R Matrix Applications

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Collaborators!

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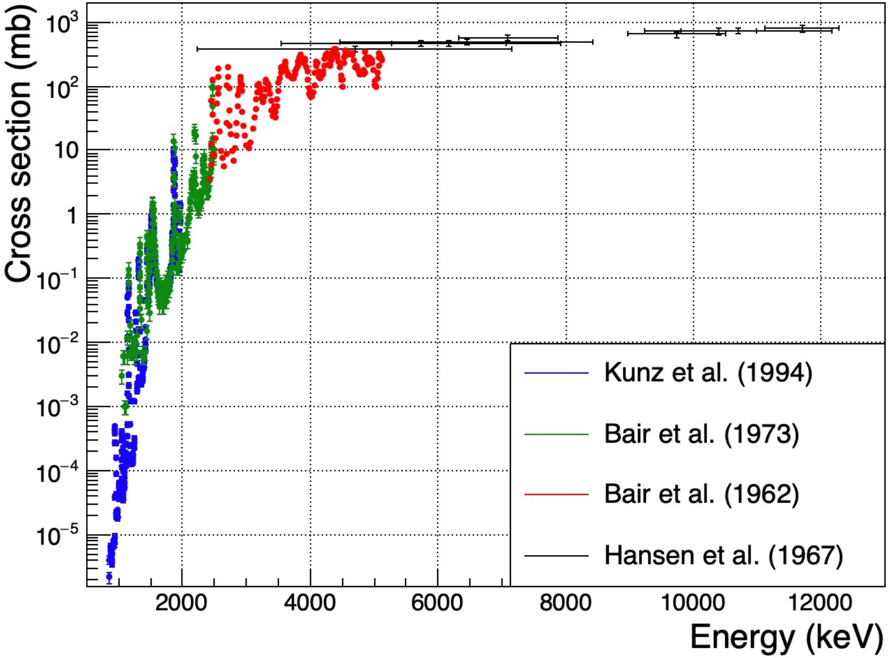
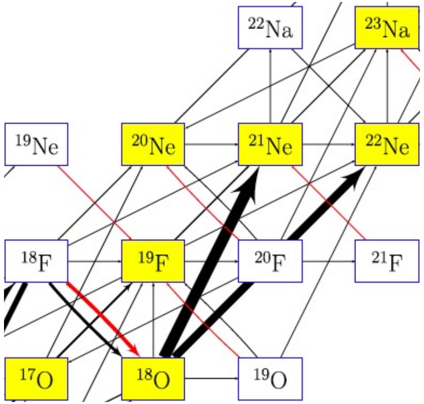
Why $^{18}O(\alpha,n)^{21}Ne$?

- Historically there has been significant interest in this reaction
  - Measurements spanning over 60 years!
  - Varying levels of uncertainty – not well characterized over the full range
  - Angle-integrated total cross sections – no branching ratios
- Implications far reaching
  - Nuclear astrophysics
  - Nuclear security
  - Rare-event physics
  - Geophysics

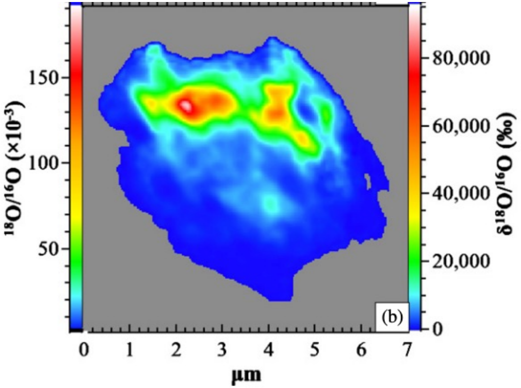


$^{18}O(\alpha,n)^{21}Ne$ in Nuclear Astrophysics

- s-process in massive stars
  - $^{18}O(\alpha,n)^{21}Ne$ produces the bulk of neutrons during explosive He-shell burning
  - $^{18}O(\alpha,n)^{21}Ne$ reaction important in innermost He shell
  - Reaction rate affects production of ^{15}N
- Massive star ejecta
  - Inner He-rich zones play a role in formation of supernova carbonaceous dust
  - Spatially correlated "hot spots" of ^{18}O in low-density graphite grains
  - Variation from terrestrial abundance up to 98,000%!



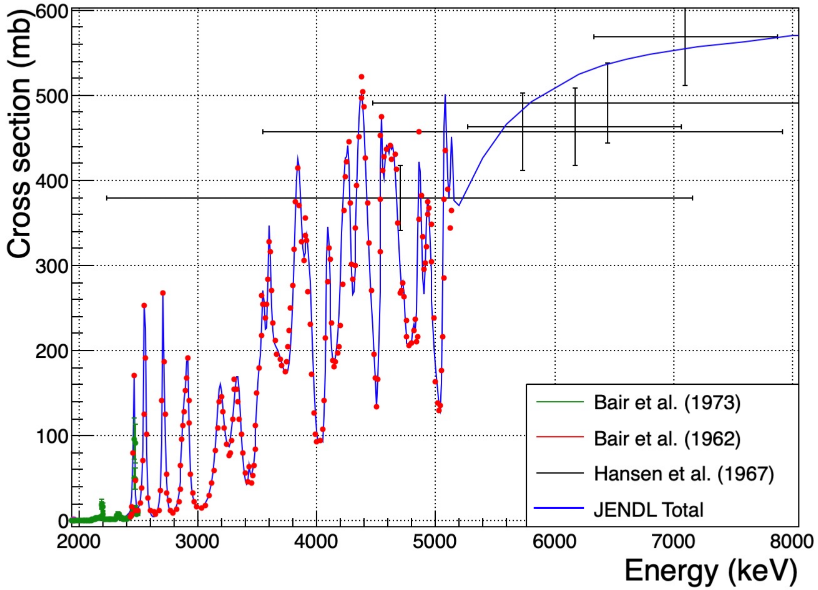
Modified from Bojazi and Meyer (2014)



Groopman et al., Astrophys. J Lett. (2012)

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

- Verification of nuclear material relies on accurate modelling of neutron emission processes
  - (α,n) reactions contribute a significant neutron source
  - Neutron source calculations for low-burnup fuels, such as uranium oxide, rely on nuclear data
  - JENDL only comprehensive evaluation of (α,n)
- For neutron source calculations, ^{210}Po alpha decay at 5.3 MeV
  - Between 3.5 – 5.13 MeV JENDL on average overestimates cross section by 1.7%
  - As the energy increases, the discrepancy between evaluation and data gets bigger



Previous R Matrix work on ^{18}O

- R matrix:
  - Phenomenological method of accurately describing low energy cross sections in nuclear reactions
- Previous ^{18}O R matrix work by Pigni (Pigni et al. (2020))
  - Neutron energy spectrum of an enriched ^{18}O plutonium oxide matrix (Anderson (1967)) compared to R matrix evaluations
- What data is needed to improve R matrix calculations?
  - Partial cross sections
  - Detailed angular distributions
  - If possible, additional reaction channels

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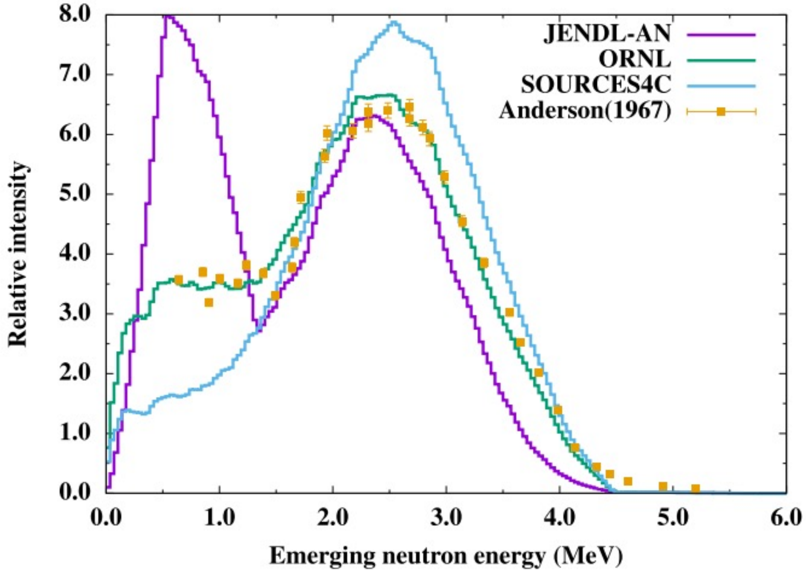
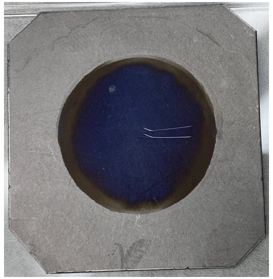


M.T. Pigni et al., Prog. Nucl. Energy 118 (2020)

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

- Experimental campaign in Nov 2019 at Notre Dame Nuclear Science Laboratory
  - 5 MV single-ended Sta. Ana accelerator
  - 2-8 MeV He beam
- 97% enriched ^{18}O water anodized onto a tantalum backing
  - ~10 μg/cm^2 ^{18}O target
- 10 ODeSA detectors every 7.5° on a swing arm
  - 10-point angular distribution at every point
  - 20-point angular distribution on resonances
- 2 HPGe detectors at 55° and 125° to measure secondary γ-rays



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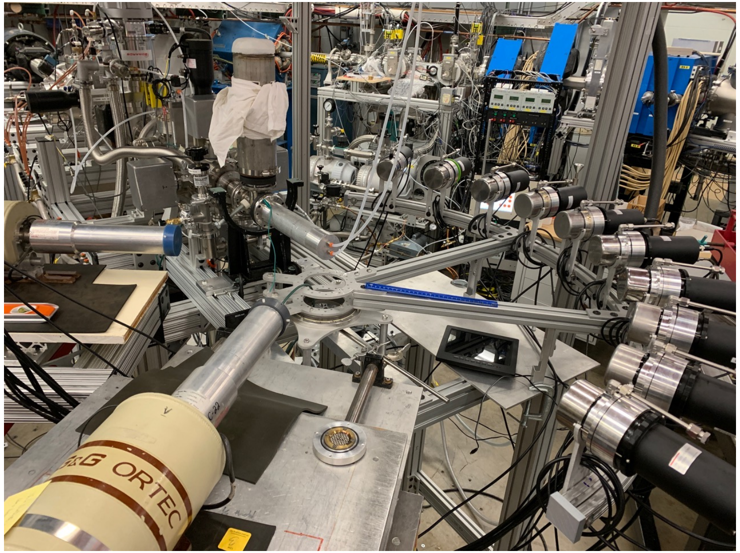
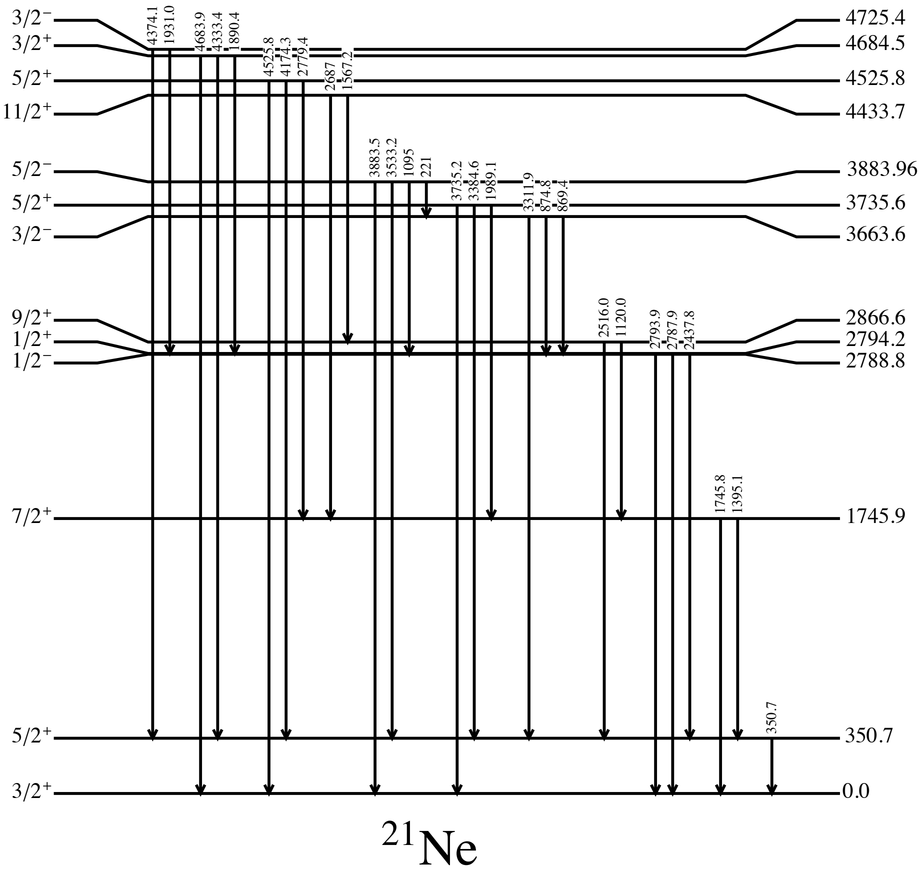


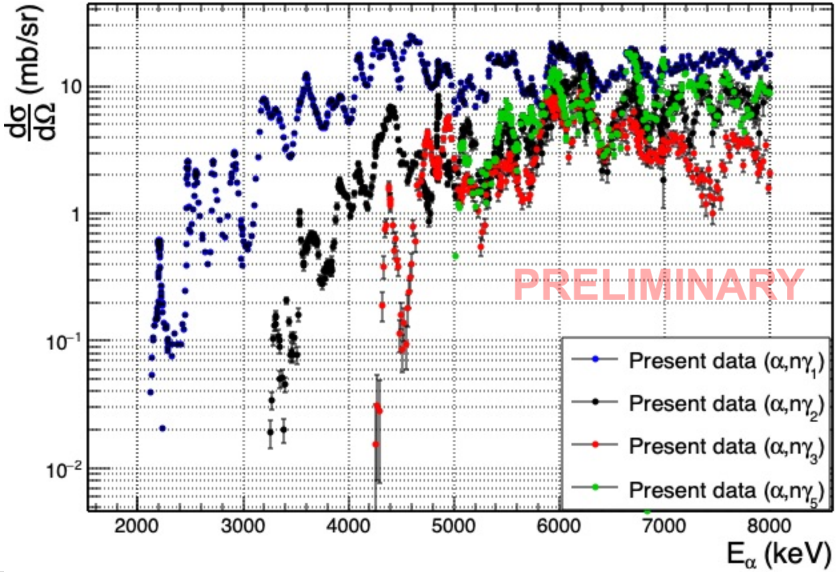
What do we expect to see?

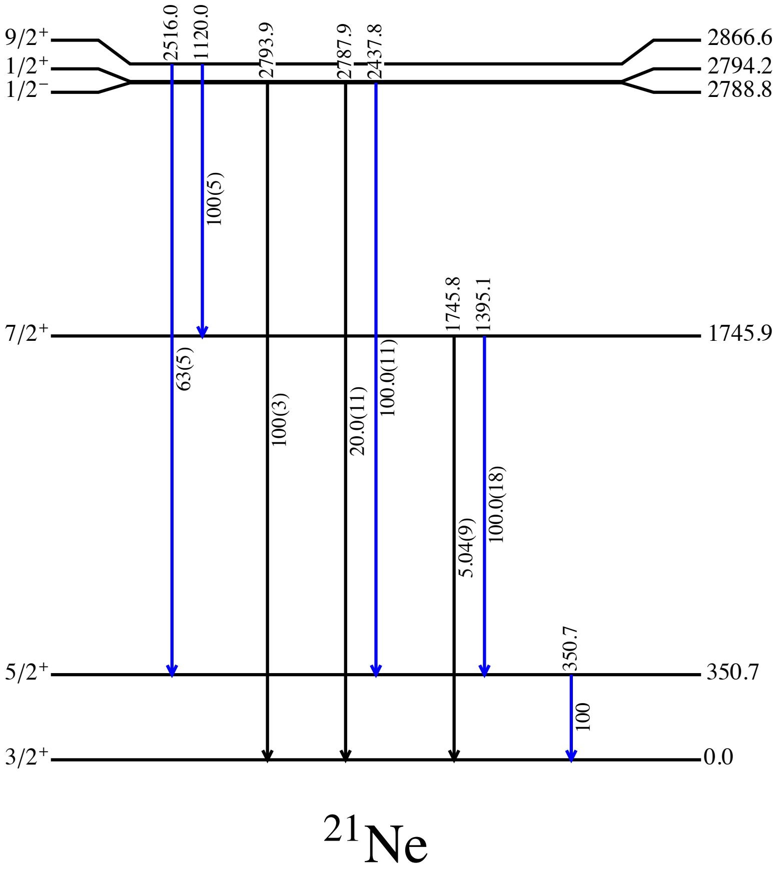
- ^{21}Ne has reasonably high level density above 2 MeV in excitation energy
- Over the energy range we measured, 2 – 8 MeV:
  - Energetically possible to populate many states
  - Neutron detection threshold ~500 keV
  - At highest incident alpha energy, can see up to 12th excited state
  - Due to detection resolution, closely spaced states (< 350 keV) will not be individually resolved



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

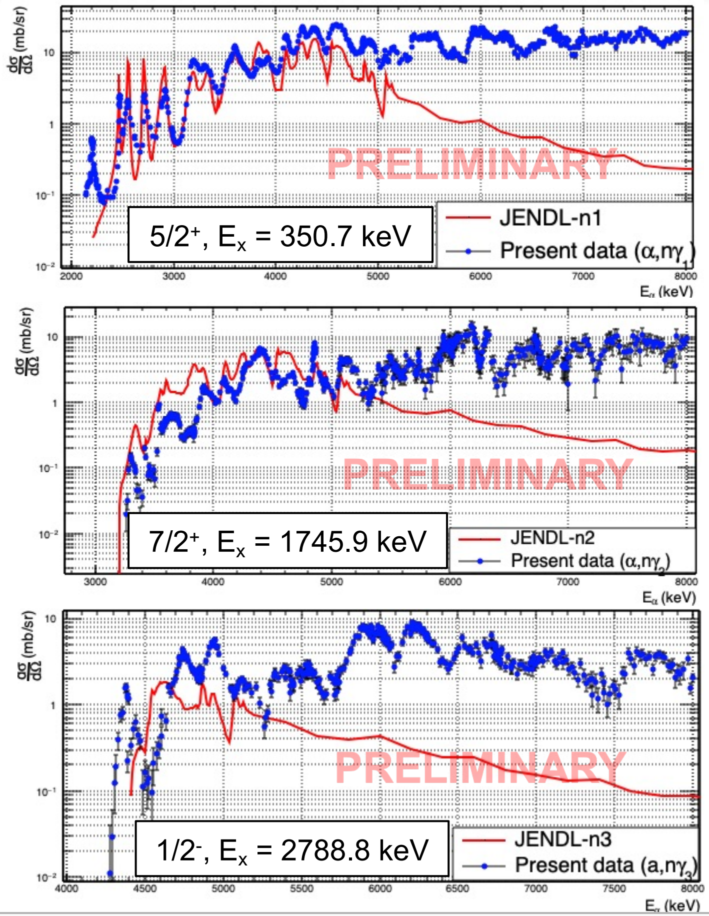
- Gamma ray partial cross sections extracted for $^{18}O(\alpha,n\gamma)^{21}Ne$ (blue)
  - Partial cross sections for 1st, 2nd, 3rd and 5th





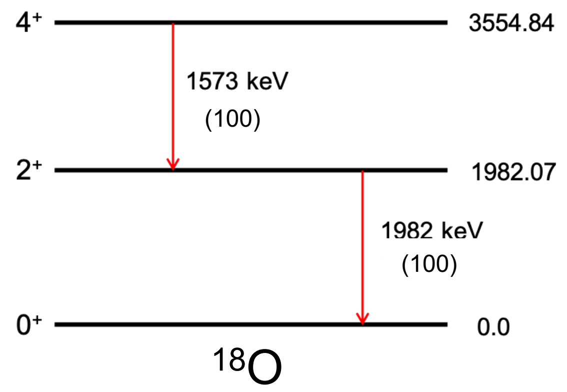
$^{18}O(\alpha,n\gamma)^{21}Ne$ Cross Sections

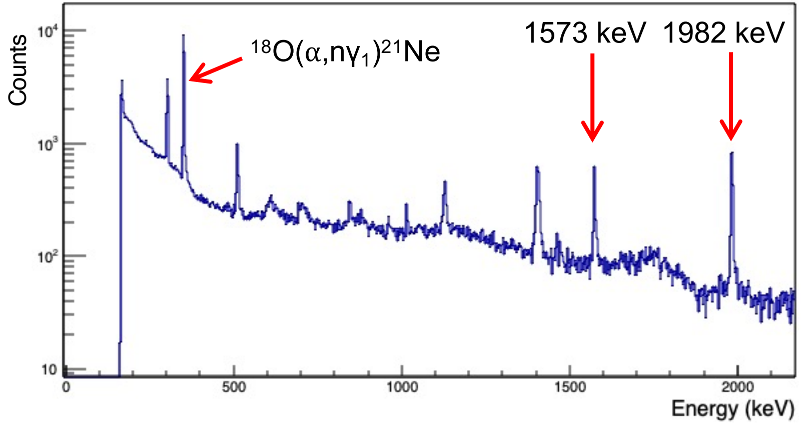
- Comparing to JENDL partial cross sections
  - JENDL is the most commonly used evaluation of (α,n) reactions
- JENDL makes assumptions when calculating partial cross sections
  - JENDL uses Hauser-Feshbach statistical model to predict cross sections – not valid for light nuclei
  - $9/2^+$ state considered to be in Hauser-Feshbach continuum, no comparison available



$^{18}O(\alpha,\alpha')^{18}O$ Cross Sections

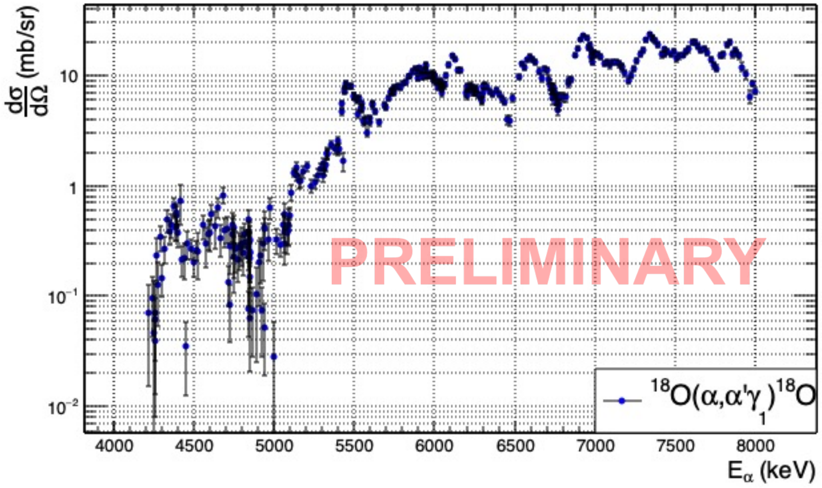
- Improved R matrix constraint from inclusion of additional reaction channels
- Significant inelastic yield seen in experiment
- For previous R matrix analyses inelastic cross section not included

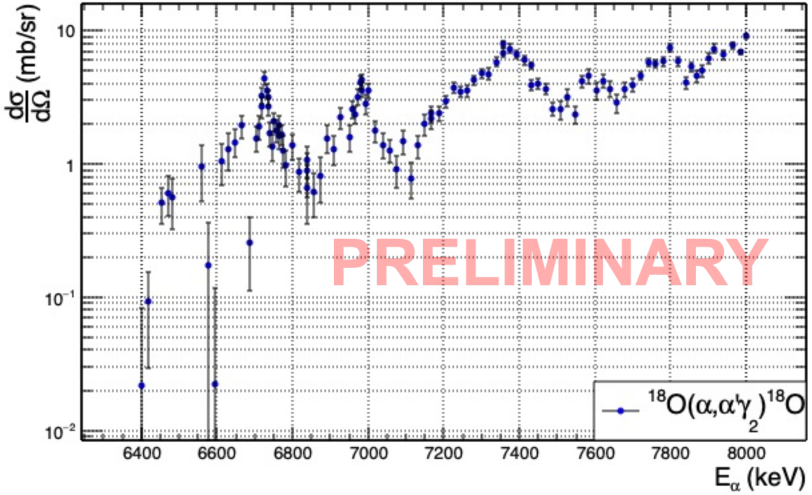




$^{18}O(\alpha,\alpha'\gamma)^{18}O$ Cross Sections

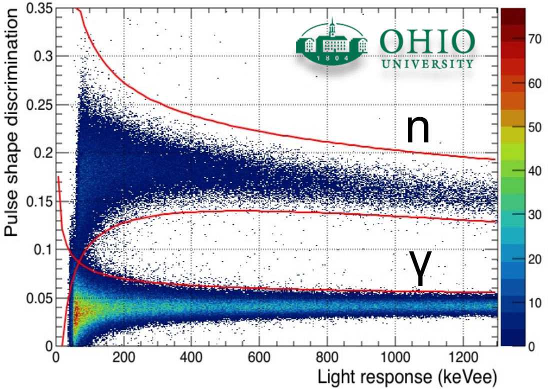
- Able to extract inelastic cross section for 1st and 2nd excited state in ^{18}O
- No experimental data to compare to directly
- Provides additional channels to constrain R matrix fit

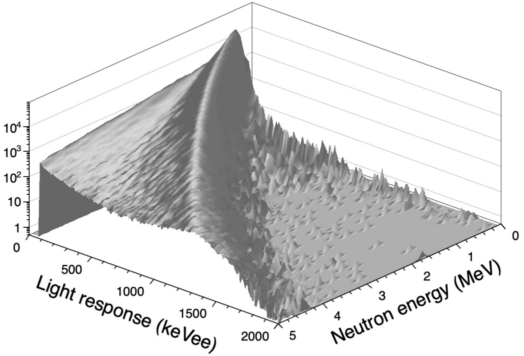


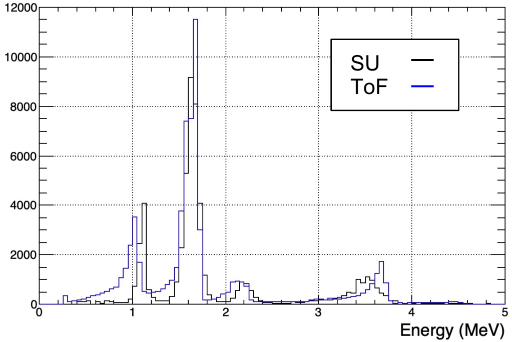


Neutron Spectroscopy

- ORNL Deuterated Spectroscopic Array - ODeSA
- 10 deuterium-enriched liquid scintillator detectors
  - Utilize spectrum unfolding method of neutron spectroscopy
- Designed and built in-house at ORNL
- Array fully characterized at Ohio University
  - Light response and response matrix
  - Absolute efficiency
  - Systematically defined PSD



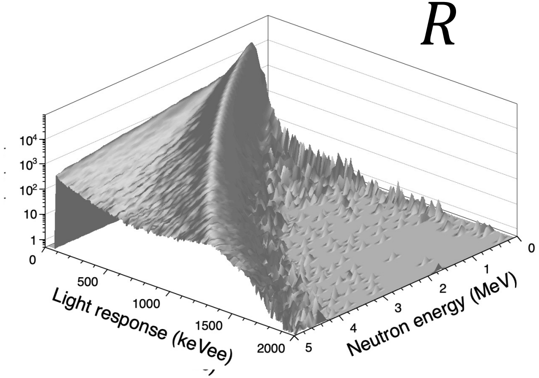


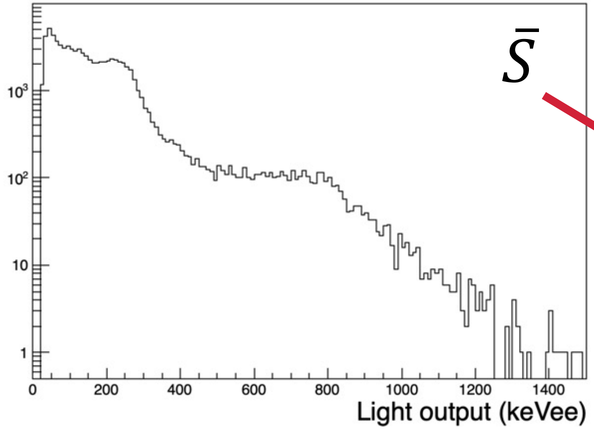


Spectrum unfolding – how does it work?

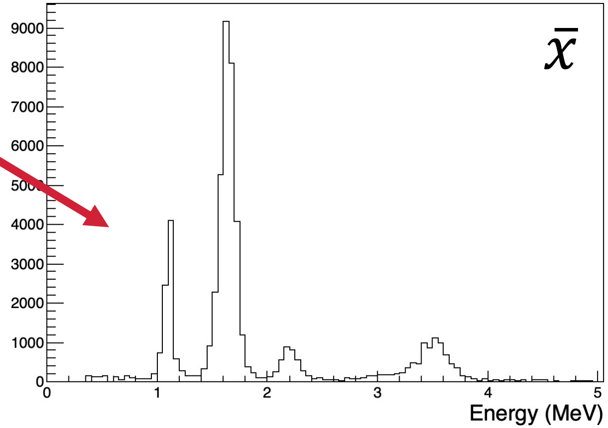
- Using MLEM and the detector response matrix, $\bar{\bar{R}}$, a neutron energy spectra can be extracted
  - Able to extract spectroscopic information independent of ToF

$\bar{\bar{R}}$





$\bar{\bar{R}}^{-1}$

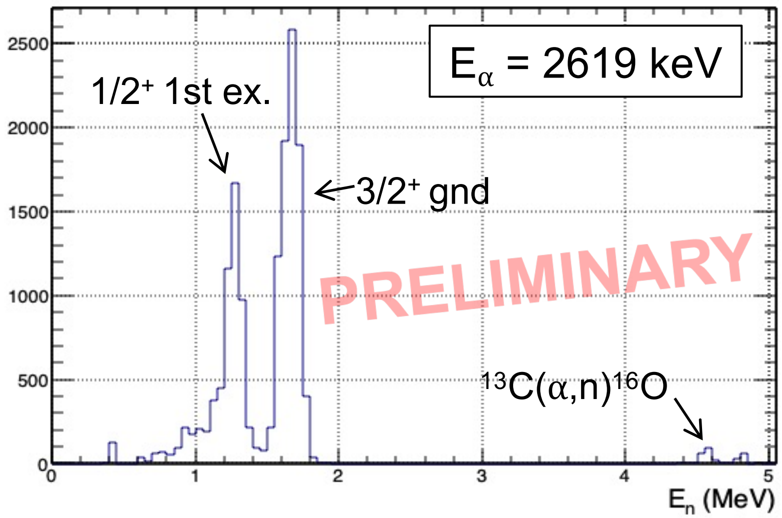


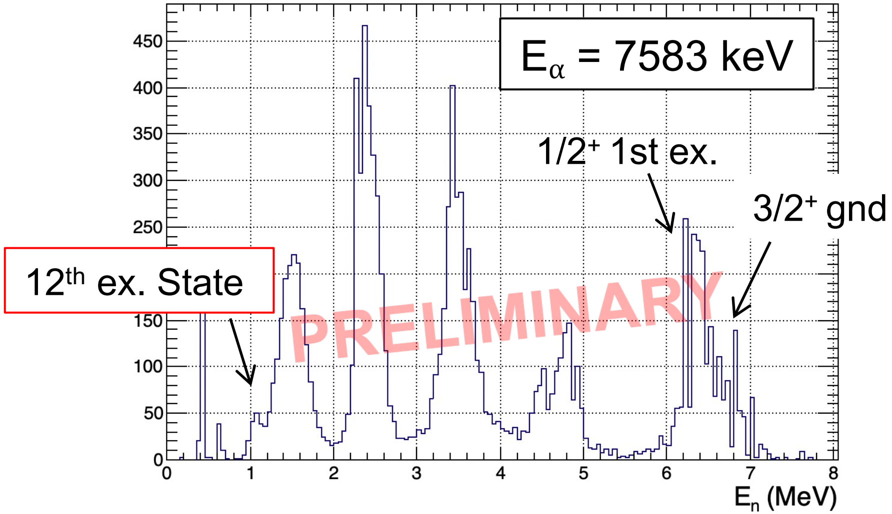
$$\bar{S} = \bar{\bar{R}}\bar{x}$$

$\bar{S}$ = Measured light spectrum
$\bar{\bar{R}}$ = Response matrix
$\bar{x}$ = Neutron energy spectrum

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

- Due to light response resolution, as neutron energy increases separation of peaks becomes more difficult
  - Response matrix can be constrained to extract closely spaced peaks
  - Experiment scheduled at LANL to improve response matrix >5 MeV





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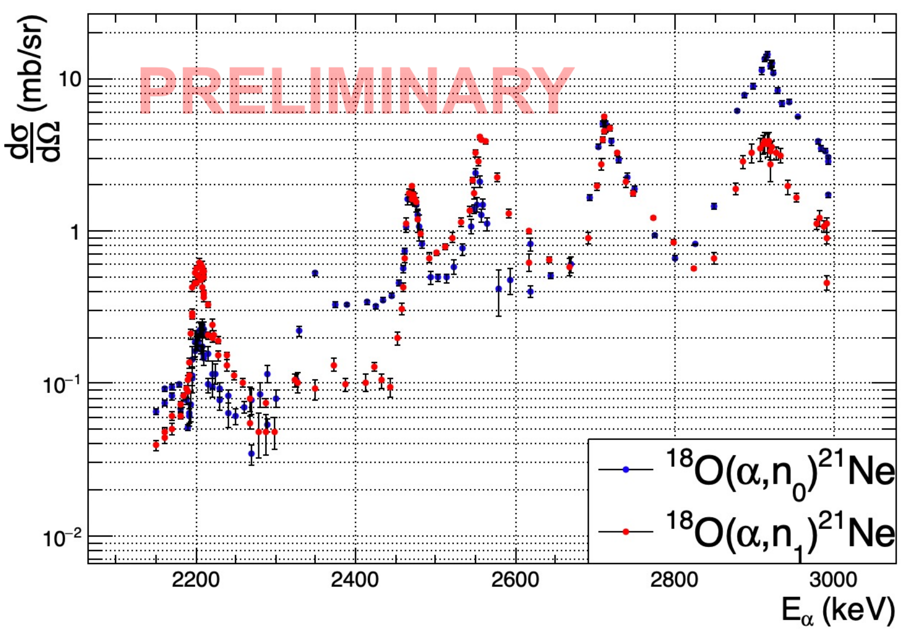
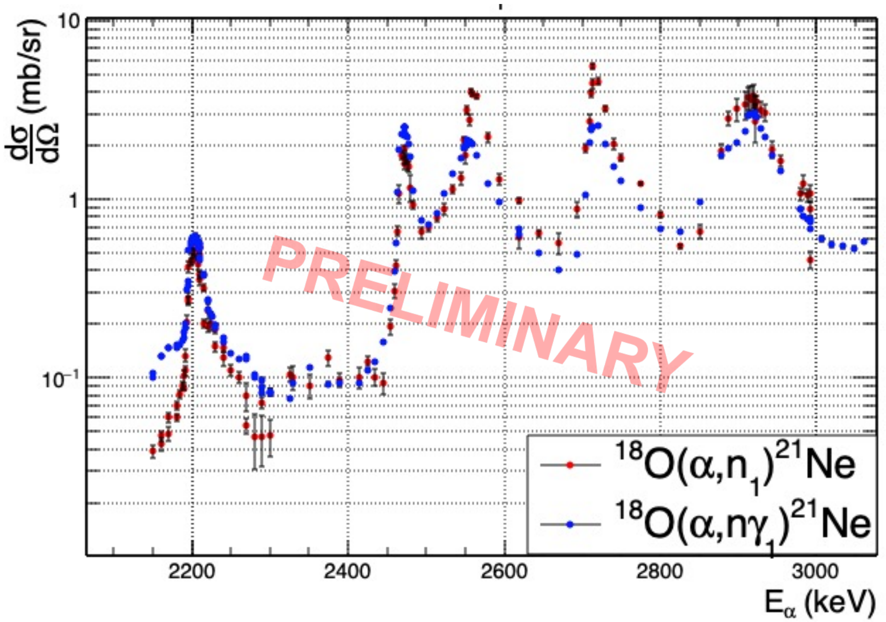
$^{18}O(\alpha,n)^{21}Ne$ Neutron Partial Differential Cross Sections

- Extraction of neutron yield curves and partial cross sections underway
  - Ground state (n_0) and first excited state (n_1)
- Differing shapes for n_0 and n_1 suggests changing contributions from excited states
  - Analysis ongoing for energies up to ~8 MeV
  - Further angular distribution analysis to follow



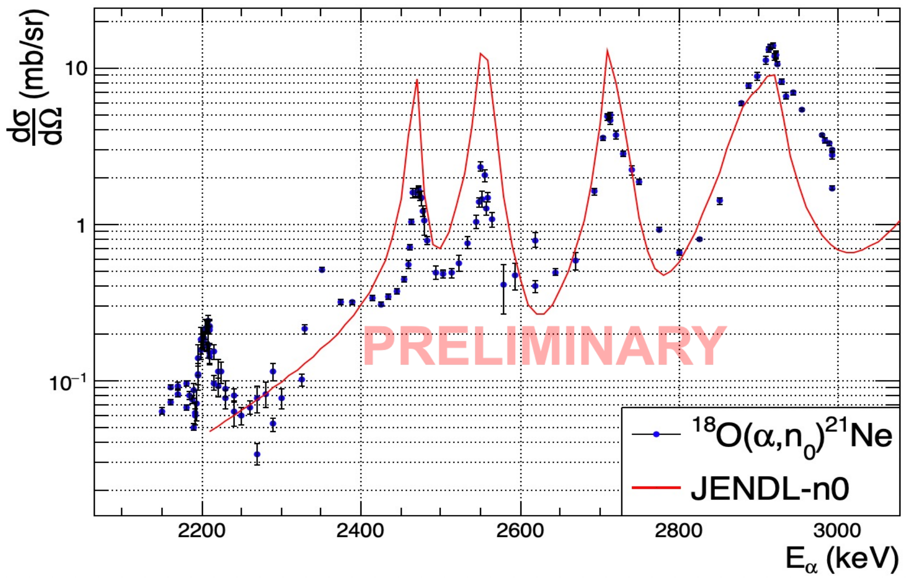
$^{18}O(\alpha,n)^{21}Ne$ Neutron Partial Differential Cross Sections

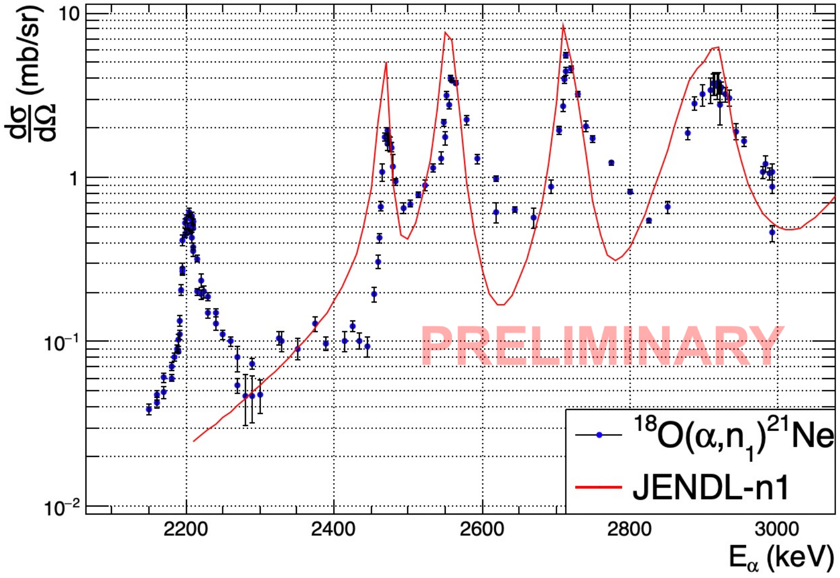
- First excited state cross section measured using two detector technologies
  - HPGe detectors measure gamma rays with gamma spectroscopy
  - Deuterated scintillator detectors measure neutrons with spectrum unfolding
- Remarkably good agreement between neutrons and gamma rays
  - Differences explained by angular distributions
  - Measured at different angles



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

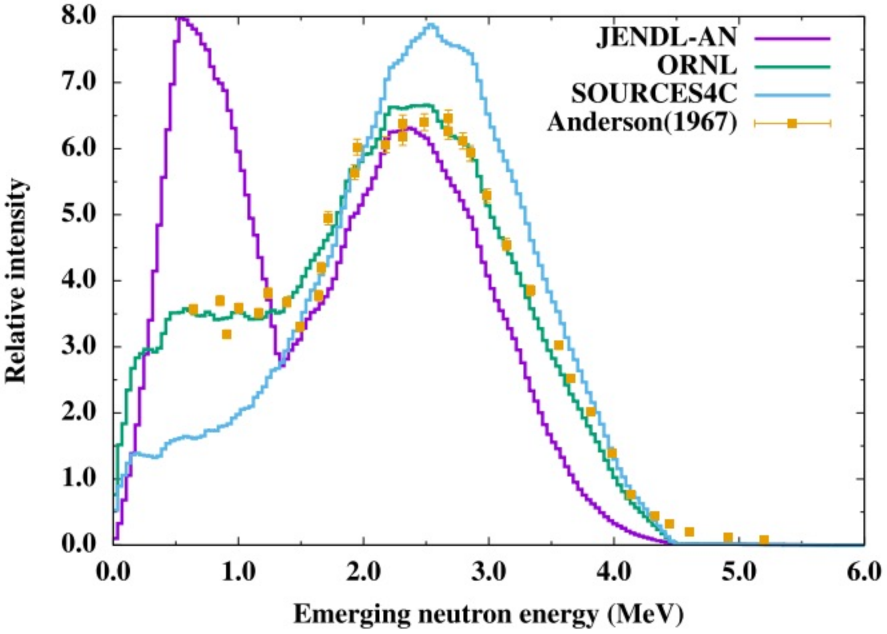
- JENDL resonance structure reasonable
  - Still resonances below JENDL
  - n_1 seems reasonable, but n_0 contribution appears underestimated at lower energies





Impacts on future R matrix analyses

- What data is needed to improve R matrix calculations?
  - Partial cross sections
  - Detailed angular distributions
  - Additional reaction channels
- Partial cross sections measured
  - using both neutrons and secondary gamma rays
- Detailed neutron angular distributions allow for further constraint
- Inelastic cross section for alpha scattering on ^{18}O measured



M.T. Pigni et al., Prog. Nucl. Energy 118 (2020)

Summary and Outlook

- Active interest in $^{18}O(\alpha,n)^{21}Ne$ reaction for over 60 years
  - Impacts many sub-fields of nuclear physics
- Neutron source calculations for nonproliferation rely on nuclear data
- Measured $^{18}O(\alpha,n)^{21}Ne$ reaction at Notre Dame in November 2019
  - Extracted $^{18}O(\alpha,n\gamma)^{21}Ne$ partial differential cross sections
  - Extracted $^{18}O(\alpha,\alpha'\gamma)^{18}O$ partial differential cross sections
  - Preliminary neutron partial cross sections
- Next steps
  - Extract full neutron partial cross sections via spectrum unfolding
  - Extract full angular distributions