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

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

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

- **s-process in massive stars**
  - $^{18}\text{O}(\alpha,n)^{21}\text{Ne}$ produces the bulk of neutrons during explosive He-shell burning
  - $^{18}\text{O}(\alpha,n)^{21}\text{Ne}$ reaction important in innermost He shell
  - Reaction rate affects production of $^{15}\text{N}$

- **Massive star ejecta**
  - Inner He-rich zones play a role in formation of supernova carbonaceous dust
  - Spatially correlated “hot spots” of $^{18}\text{O}$ in low-density graphite grains
  - Variation from terrestrial abundance up to 98,000%!

Modified from Bojazi and Meyer (2014)

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

- Verification of nuclear material relies on accurate modelling of neutron emission processes
  - \((\alpha,n)\) 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 \((\alpha,n)\)

- For neutron source calculations, \(^{210}\text{Po}\) 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
Measurement of $^{18}\text{O}(\alpha,\text{n})^{21}\text{Ne}$

- 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 $^{18}\text{O}$ water anodized onto a tantalum backing
  - $\sim$10 $\mu$g/cm$^2$ $^{18}\text{O}$ 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 $\gamma$-rays
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 12\textsuperscript{th} excited state
  - Due to detection resolution, closely spaced states (< 350 keV) will not be individually resolved
\(^{18}\text{O}(\alpha,\gamma)^{21}\text{Ne}\) Cross Sections

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

- Comparing to JENDL partial cross sections
  - JENDL is the most commonly used evaluation of $(\alpha,n)$ 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
$^{18}\text{O}(\alpha,\alpha')^{18}\text{O}$ 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
$^{18}\text{O}(\alpha,\alpha'\gamma)^{18}\text{O}$ Cross Sections

- Able to extract inelastic cross section for 1\textsuperscript{st} and 2\textsuperscript{nd} excited state in $^{18}\text{O}$
- 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, $\bar{R}$, a neutron energy spectra can be extracted
  - Able to extract spectroscopic information independent of ToF

\[
\bar{S} = \bar{R} \bar{x}
\]

- $\bar{S}$ = Measured light spectrum
- $\bar{R}$ = Response matrix
- $\bar{x}$ = Neutron energy spectrum
$^{18}\text{O}(\alpha,n)^{21}\text{Ne}$ 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

\[
\begin{align*}
\text{E}_\alpha &= 2619 \text{ keV} \\
3/2^+ \text{ gnd} \quad \text{1/2}^+ \text{ 1st ex.} \\
\end{align*}
\]

\[
\begin{align*}
\text{E}_\alpha &= 7583 \text{ keV} \\
1/2^+ \text{ 1st ex.} \quad \text{3/2}^+ \text{ gnd} \\
\end{align*}
\]
$^{18}\text{O}(\alpha, n)^{21}\text{Ne}$ 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 $\sim 8$ MeV
  - Further angular distribution analysis to follow
\( ^{18}\text{O}(\alpha, n)^{21}\text{Ne} \) 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
$^{18}\text{O}(\alpha,n)^{21}\text{Ne}$ 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 $^{18}\text{O}(\alpha,n)^{21}\text{Ne}$ reaction for over 60 years
  – Impacts many sub-fields of nuclear physics

• Neutron source calculations for nonproliferation rely on nuclear data

• Measured $^{18}\text{O}(\alpha,n)^{21}\text{Ne}$ reaction at Notre Dame in November 2019
  – Extracted $^{18}\text{O}(\alpha,n\gamma)^{21}\text{Ne}$ partial differential cross sections
  – Extracted $^{18}\text{O}(\alpha,\alpha'\gamma)^{18}\text{O}$ partial differential cross sections
  – Preliminary neutron partial cross sections

• Next steps
  – Extract full neutron partial cross sections via spectrum unfolding
  – Extract full angular distributions