Improving the $^{238}\text{U}(n,n')$ cross section using neutron-gamma coincidences

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BLUF (Bottom Line Up Front)

LBNL
- Built and benchmarked the *Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering* (GENESIS).
- Performed $^{56}\text{Fe}(n,xn\gamma)$ and $^{238}\text{U}(n,x\gamma)$ production runs in 2021.
- Analysis underway

LANL
- Took first Chi-Nu + HPGe data 9/19
- $^{56}\text{Fe}+n$ data (performed under separate funding) provides a path forward for $^{238}\text{U}$

BNL/NNDC
- Preparing for evaluation using other data set ($^{86}\text{Kr}$)
- Working with LBNL to develop an event generator that will allow for a forward fit comparison to the evaluation.
GENESIS at the 88-Inch cyclotron

Cave 5 GENESIS Measurement Setup
Berkeley Lab

DTOF
Kinematic Flux Monitor

Scintillators
HPGe

Neutron Source
VAULT

Bending Magnet
Switching Magnet

D-beam

\[
\phi_n \text{ in } 10^8 / \text{MeV/ster/µC}
\]

Neutron Energy (MeV)

DTOF 14 MeV D on C

Neutron Monitor
Photomultiplier Tube
Foil Packs
Concrete
Sand Bags
VAULT

Sand
Concrete

Indium Foils
CAVE 01
CAVE 02

#1
#2

GENESIS at the 88-Inch cyclotron

WANDA 2023 – L.A. Bernstein

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GENESIS has been fully modeled in GEANT and benchmarked using $^{252}\text{Cf}$ and multiple $\gamma$-ray sources. This benchmarking together with the finite energy range of our beam allows for multiple simultaneous measurements.
Our goal of propagating modeled observables through a detector response function requires **accurate** simulation of GENESIS.

Percent level agreement in measured and simulated gamma response with isotropic and extended sources.

Cf-252 source used to benchmark integral and differential neutron detection efficiency.
$^{56}$Fe neutron-gated $\gamma$ spectrum

- 846.7 keV $2^+_1 \rightarrow 0^+_1$
- 1037.8 keV $2^+_2 \rightarrow 0^+_1$
- 1238.2 keV $4^+_1 \rightarrow 2^+_1$
- 2113.1 keV $2^+_3 \rightarrow 2^+_2$

J.M. Gordon
Yrast $4^+ \rightarrow 2^+$ (1238 keV) to $2^+ \rightarrow 0^+$ (847 keV) ratio

\[
\begin{align*}
4_1^+ & \rightarrow 2_1^+ (E_x = 2085 \text{ keV}) \\
2_1^+ & \rightarrow 0_1^+ (E_x = 847 \text{ keV})
\end{align*}
\]

Significant differences seen 140-160 ns after RF, e.g.:
- 1.2-1.3 MeV
- 2.9-3.2 MeV
- 11.7-15.3 MeV

\[
\Phi_n (10^8 \text{MeV/MeV/sr/uc})
\]

Majority of yield coming in below 4 MeV is consistent with significant compound emission

What about (n,elastic)?

*A. Negret et al., PRC 90, 034602 (2014)
Yrast $4^+ \rightarrow 2^+ (1238 \text{ keV})$ to $2^+ \rightarrow 0^+ (847 \text{ keV})$ ratio

$4_1^+ \rightarrow 2_1^+ (E_x = 2085 \text{ keV})$

$2_1^+ \rightarrow 0_1^+ (E_x = 847 \text{ keV})$

Significant differences seen 140-160 ns after RF, e.g.:

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- 11.7-15.3 MeV

A blank-subtracted neutron spectrum shows elastically-scattered neutrons at forward angles

Analysis to be completed in CY23

*A. Negret et al., PRC 90, 034602 (2014)*
We are developing a forward fit process to determine optimal neutron reaction modeling parameters using Talys Reaction Models ($E_n$, $q_n$) based on multiple measurements and optimizations.

20 input parameters, including:
- Level density parameters
- Gamma-ray strength function
- Optical model parameters
- Branching ratios

Wait for it Jo…

**Yrast** $\frac{4_1^+ \rightarrow 2_1^+}{2_1^+ \rightarrow 0_1^+}$ ratio

$\chi^2$/dof = 1.647
We are developing a forward fit process to determine optimal neutron reaction modeling parameters using YAHFC Reaction Models $\sigma(E_n, \theta_n)$.

20 input parameters, including:
- Level density parameters
- Gamma-ray strength function
- Optical model parameters
- Branching ratios

Monte Carlo codes provide a simpler approach to error propagation.
Neutron-gated $^{238}$U Yrast Cascade

$103.5 \text{ keV} \quad 4_1^+ \rightarrow 2_1^+$

$158.5 \text{ keV} \quad 6_1^+ \rightarrow 4_1^+$

$211.2 \text{ keV} \quad 8_1^+ \rightarrow 6_1^+$
Neutron-gated $^{238}$U Off-yrast Transitions

Analysis to be completed in CY23

- $886.2 \text{ keV} \quad 1^- \rightarrow 2^+_1$
- $925.7 \text{ keV} \quad 3^- \rightarrow 2^+_1$
- $952.7 \text{ keV} \quad 6^+_2 \rightarrow 6^+_1$
- $1014.6 \text{ keV} \quad (3^+_1) \rightarrow 2^+_1$
- $1060.3 \text{ keV} \quad 2^+_3 \rightarrow 0^+_1$
- $1112.3 \text{ keV} \quad 1^- \rightarrow 0^+_1$
We just completed a run using beam sweeping with 10 s on and 1 s off run to measure \(\beta\)-delayed and prompt \(\gamma\)-rays with a new compact geometry to increase neutron-gamma coincidences.

The in-beam and beam-off \((n,f\gamma)\) data is being analyzed by NSSC graduate student Preston Awedisean.
We also ran $^{35}\text{Cl}(n,x)^\ast$ 8/21 and 10/22

Differential Experiment #3
$^{35}\text{Cl}(n,p)$ and $^{35}\text{Cl}(n,\alpha)$ from a CLYC (Ce:Cs$_2^6$LiYCl$_6$) Active Target

Differential Experiment #2
$^{35}\text{Cl}(n,n')$ & $^{35}\text{Cl}(n,\gamma)$ using NaCl tablet

Simultaneous measurements of multiple exit channels should help address compensating uncertainties in reaction modeling

Integral Experiment #1
Production of $^{35}\text{S}$ and $^{32}\text{P}$ via $^{35}\text{Cl}(n,p)$ and $^{35}\text{Cl}(n,\alpha)$ on a NaCl tablet (Ni monitor foil)

*Funded under an NEUP Grant
This part of the experiment is allowing us to determine $\Phi(E_n < 1 \text{ MeV})$

**Differential Experiment #3**

$^{35}\text{Cl}(n,p)$ and $^{35}\text{Cl}(n,\alpha)$ from a CLYC ($\text{Ce:Cs}_2\text{LiYCl}_6$) Active Target

$^{35}\text{Cl}(n,p)$ and $^{35}\text{Cl}(n,\alpha)$ from a CLYC ($\text{Ce:Cs}_2\text{LiYCl}_6$) Active Target

*Funded under an NEUP Grant*
Improving low-energy neutron spectroscopy using CLYC

- Traditional PSD methods for CLYC provide poor separation between alphas and protons (making fast neutron spectroscopy difficult)
- Our new technique provides clean separation, allowing extension of neutron spectrum measurements down to 10s of keV

**Alpha gated**

\[ ^{6}\text{Li}(n,t)\alpha \]

\[ ^{6}\text{Li}(n_{\text{low}},t)\alpha \]

**Proton gated**

Fast neutrons via \[ ^{35}\text{Cl}(n,p) \]
CLYC-6 (Ce:Cs$_2^6$LiYCl$_6$) allows for determination of the neutron flux using the well-known $^6$Li(n,t)α reaction.
Collaborators on the work you’ve seen today

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