Improving the $^{238}$U(n,n’) cross section using neutron-gamma coincidence

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BLUF (Bottom Line Up Front)

**LBNL**
- Built and benchmarked the *Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering* (GENESIS).
- Performed $^{56}\text{Fe}(n,x\gamma)$ 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

**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

DTOF 14 MeV D on C

Neutron Source

Neutron Energy (MeV)

\[ \Phi_n \text{ in } 10^8/\text{MeV}\text{sr} \text{/}\text{uC} \]

Neutron Energy (MeV)

\[ \Phi_n \text{ in } 10^8/\text{MeV}\text{sr} \text{/}\text{uC} \]
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.
Case Study – $^{35}\text{Cl}(n,x)^* \text{ not just } ^{35}\text{Cl}(n,p) – 8/21$

**Differential Experiment #3**
$^{35}\text{Cl}(n,p)$ and $^{35}\text{Cl}(n,\alpha)$ from a CLYC (Ce:Cs2LiYCl6) Active Target

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

**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)

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

*Funded under an NEUP Grant*
$^{56}$Fe neutron-gated $\gamma$ spectrum

846.7 keV $2^+_1 \rightarrow 0^+_1$

1037.8 keV $2^+_2 \rightarrow 0^+_1$

1238.2 keV $4^+_1 \rightarrow 2^+_1$

1810.7 keV $2^+_2 \rightarrow 2^+_1$

2113.1 keV $2^+_3 \rightarrow 2^+_2$
Yrast $4^+ \rightarrow 2^+$ (1238 keV) to $2^+ \rightarrow 0^+$ (847 keV) ratio

\[
\frac{4_1^+ \rightarrow 2_1^+ (E_x = 2085 \text{ keV})}{2_1^+ \rightarrow 0_1^+ (E_x = 847 \text{ keV})}
\]

\[
N_n(E_n, \theta_n) \text{ gated on the } 2_1^+ \rightarrow 0_1^+
\]

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

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

Analysis and interpretation to be completed in FY22

* A. Negret et al., PRC 90, 034602 (2014)

J.M. Gordon
Neutron-gated $^{238}$U Yrast Cascade

103.5 keV
$2^+_1 \rightarrow 0^+_1$

158.5 keV
$4^+_1 \rightarrow 2^+_1$

211.2 keV
$6^+_1 \rightarrow 4^+_1$
Neutron-gated $^{238}\text{U}$ Off-yrast Transitions

Analysis and interpretation to be completed in FY23
BONUS! Neutron-gated $^{238}$U(n,f) Transitions

Numerous other (n,f) transitions identified as well along with attendant neutron spectral information: $E_n, \theta_n, \nu(E)$
Complementary scattered neutron measurements are being performed using Chi-Nu at Los Alamos (K.J. Kelly)

- Precision timing allows for quantification of the energy difference between the incident and scattered neutrons (e.g., the “missing mass” approach) allows for clear identification of specific state population for nuclei with low level density

**GENESIS + Chi-Nu provides a complete picture of (n,n’ reactions**

*Funded under LANL LDRD*
Analysis technique (M. Vorabbi – BNL/NNDC)

1. **Forward process**: close loop, vary the model to match the measurement (common technique in high-energy physics)

2. **Backward process**: use bank of events to fine tune the analysis procedure
Preparation for $^{238}$U analysis (M. Vorabbi, BNL)

In preparation for the analysis on $^{56}$Fe(n,n'$\gamma$) and/or $^{238}$U(n,n'$\gamma$) BNL evaluated $^{86}$Kr(n,n'$\gamma$)

Why $^{86}$Kr?

• it was measured using GEANIE, so has many of the same features we expect in proposed experiments
• it is near a closed shell, so has high-lying resonances much like $^{56}$Fe
• it is relevant for astrophysics and as a NIF gas diagnostic

It is the perfect case study!!!

• The optical potential was fitted to simultaneously reproduce the total cross section and the first inelastic gamma
• The evaluated file has been submitted to the ENDF library for review
• The associate paper has been submitted to Nuclear Data Sheets https://arxiv.org/abs/2109.08178
Collaborators and Acknowledgments

L.A. Bernstein\textsuperscript{1,2}, J.C. Batchelder\textsuperscript{1}, D.L. Bleuel\textsuperscript{3}, D. Brown\textsuperscript{4}, \textit{J.A. Brown}\textsuperscript{1}, M. Devlin\textsuperscript{5}, B.L. Goldblum\textsuperscript{2,1}, \textit{J.M. Gordon}\textsuperscript{1,3}, \textit{K.J. Kelly}\textsuperscript{5}, T. Laplace\textsuperscript{1}, G. Nobre\textsuperscript{4}, \textit{M. Vorabbi}\textsuperscript{4}

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This work has been performed under the auspices of the U.S. Department of Energy by Lawrence Berkeley National Laboratory under contract No. DE-AC02-05CH1123, Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344, Brookhaven National Laboratory under Contract No. DEAC02-98CH10886 and Los Alamos National Laboratory operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001).