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

Lee Bernstein

Department of Nuclear Engineering
University of California, Berkeley

Nuclear Science Division
Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

BLUF (Bottom Line Up Front)

LBNL

- Built and benchmarked the *Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering* (GENESIS).
- Performed ^{56}Fe(n,xnγ) and ^{238}U(n,xγ) production runs in 2021.
- Analysis underway

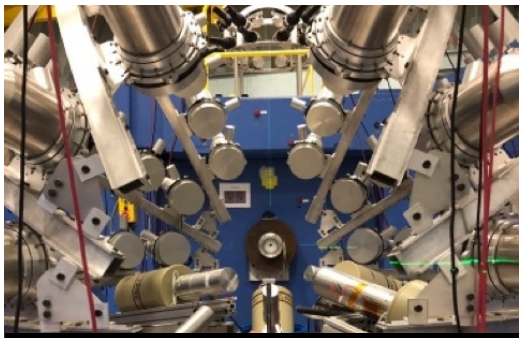
Josh Brown

Joey Gordon

Cyclotron running smoothly and CoVID restrictions easing

LANL

- Took first Chi-Nu + HPGe data 9/19
- ^{56}Fe+n data (performed under separate funding) provides a path forward

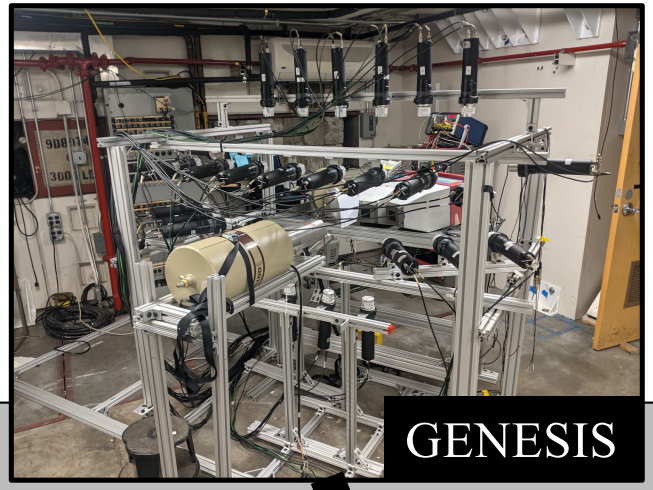


Chi-Nu + HPGe

BNL/NNDC

- Preparing for evaluation using other data set (^{86}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



Neutron Source

VAULT

Bending Magnet

Switching Magnet

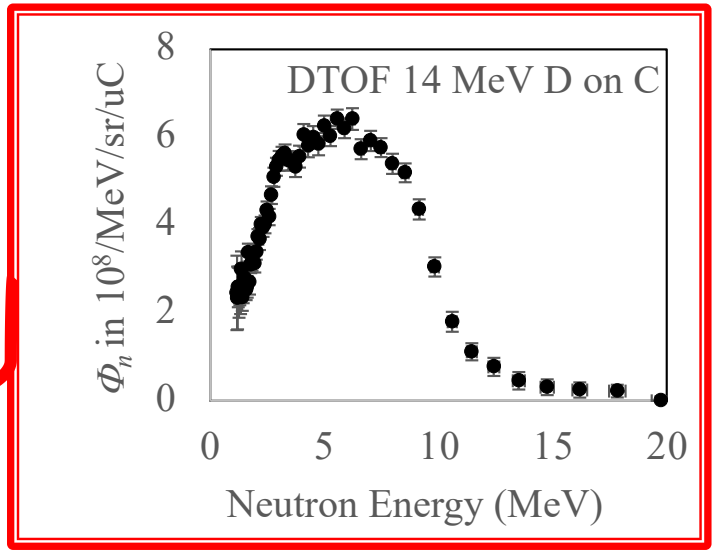
D-beam

Cave 5 GENESIS
Measurement Setup
Berkeley Lab

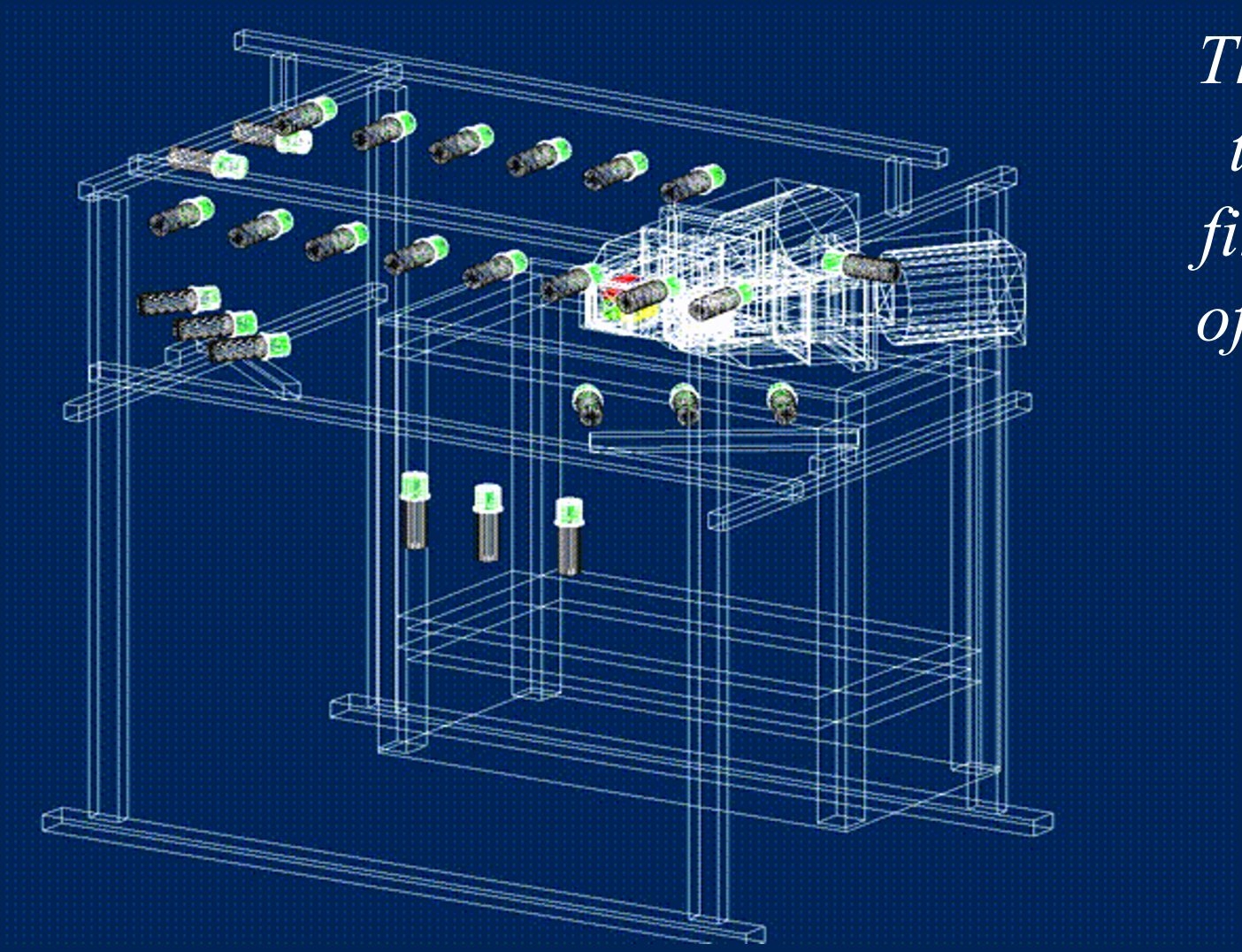
Scintillators

DTOF
Kinematic
Flux Monitor

HPGe



GENESIS has been *fully modeled* in GEANT and benchmarked using ^{252}Cf and multiple γ-ray sources



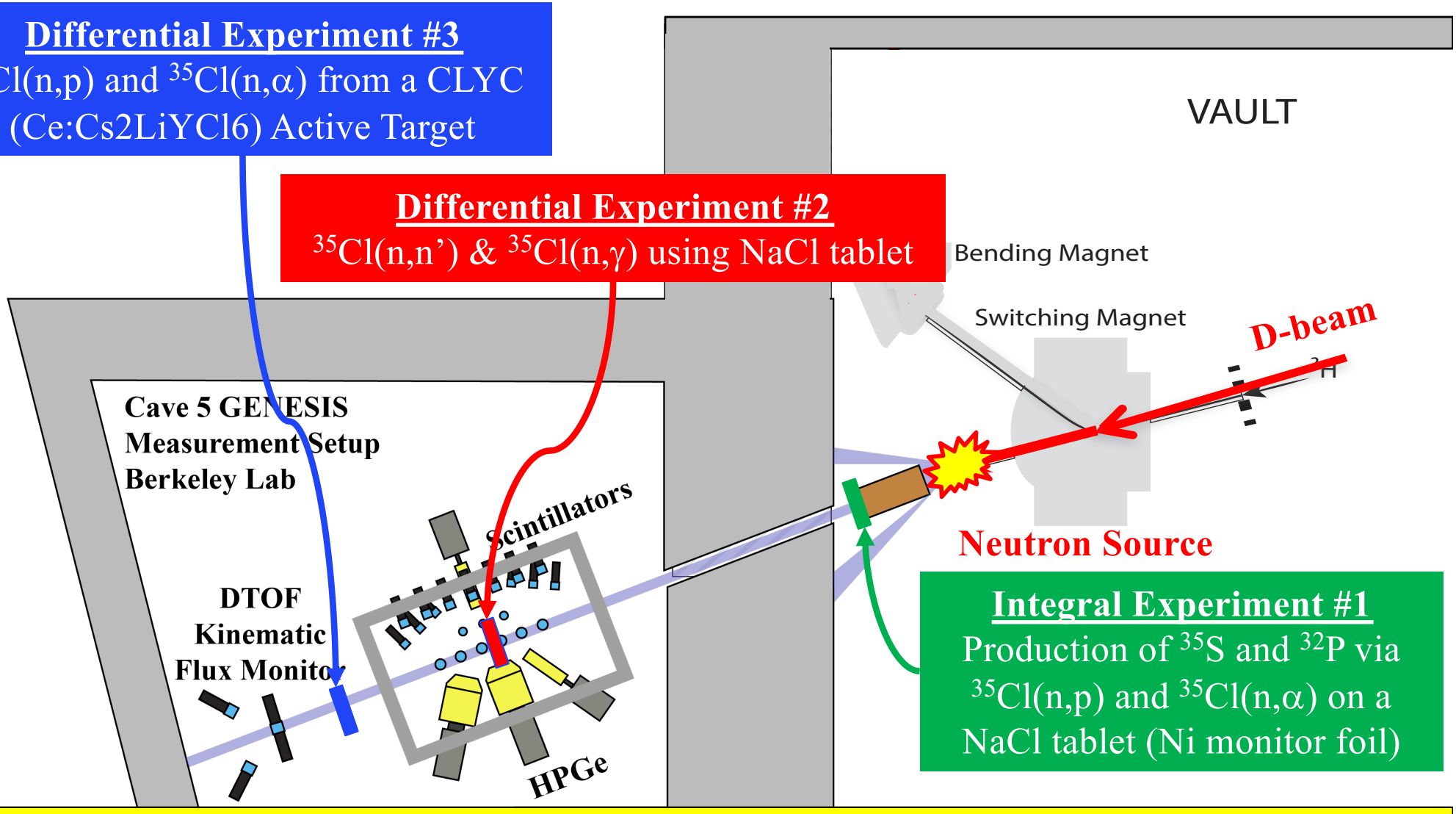
This benchmarking together with the finite energy range of our beam allows for multiple simultaneous measurements

Josh Brown

Case Study – ^{35}Cl(n,x)* *not just ^{35}Cl(n,p) – 8/21*

Differential Experiment #3
^{35}Cl(n,p) and ^{35}Cl(n,α) from a CLYC (Ce:Cs2LiYCl6) Active Target

Differential Experiment #2
^{35}Cl(n,n') & ^{35}Cl(n,γ) using NaCl tablet

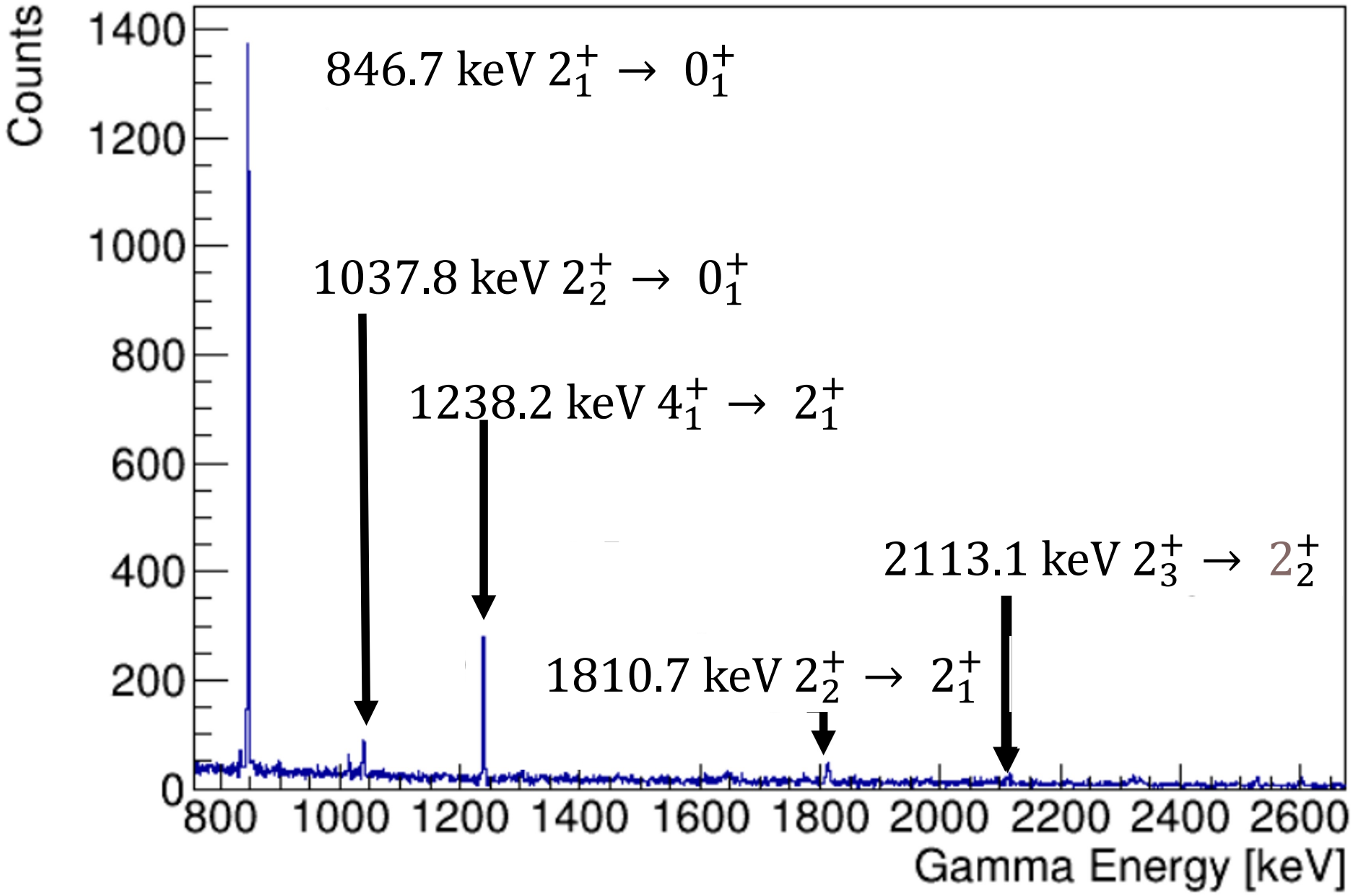


Integral Experiment #1
Production of ^{35}S and ^{32}P via ^{35}Cl(n,p) and ^{35}Cl(n,α) on a NaCl tablet (Ni monitor foil)

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

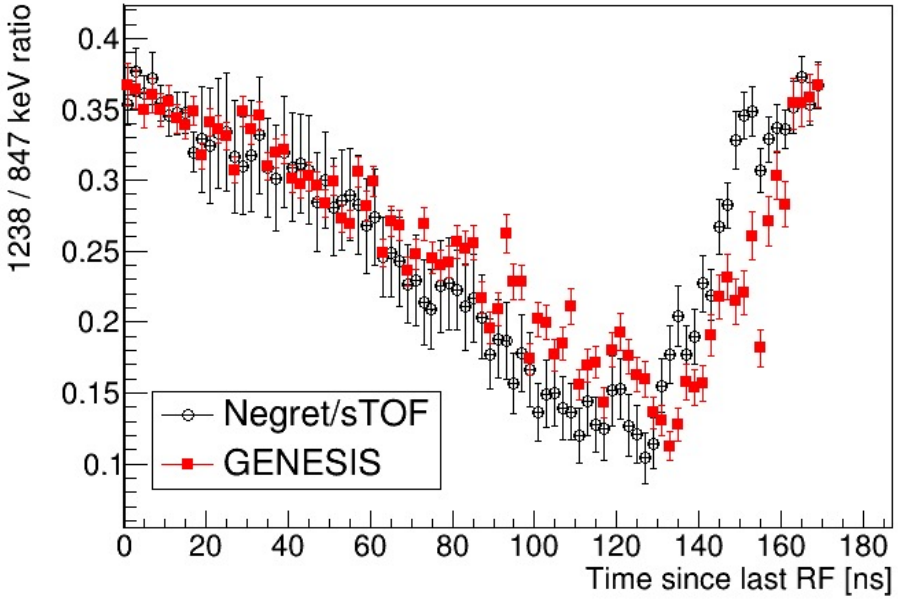
*Funded under an NEUP Grant

^{56}Fe neutron-gated γ spectrum

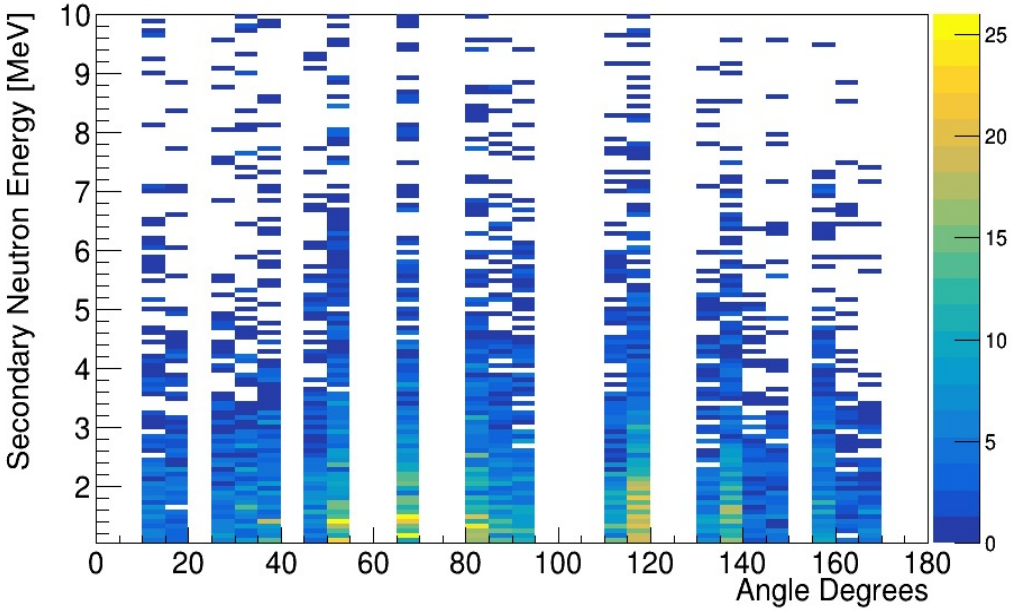


Yrast $4^+ \rightarrow 2^+$ (1238 keV) to $2^+ \rightarrow 0^+$ (847 keV) ratio

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

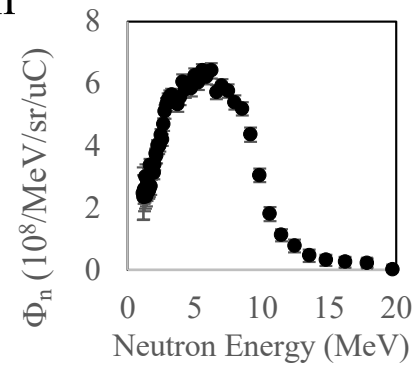


$N_n(E_n, \theta_n)$ gated on the $2_1^+ \rightarrow 0_1^+$



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

- ~~1.2-1.3 MeV~~
- 2.9-3.2 MeV
- ~~11.7-12.3 MeV~~

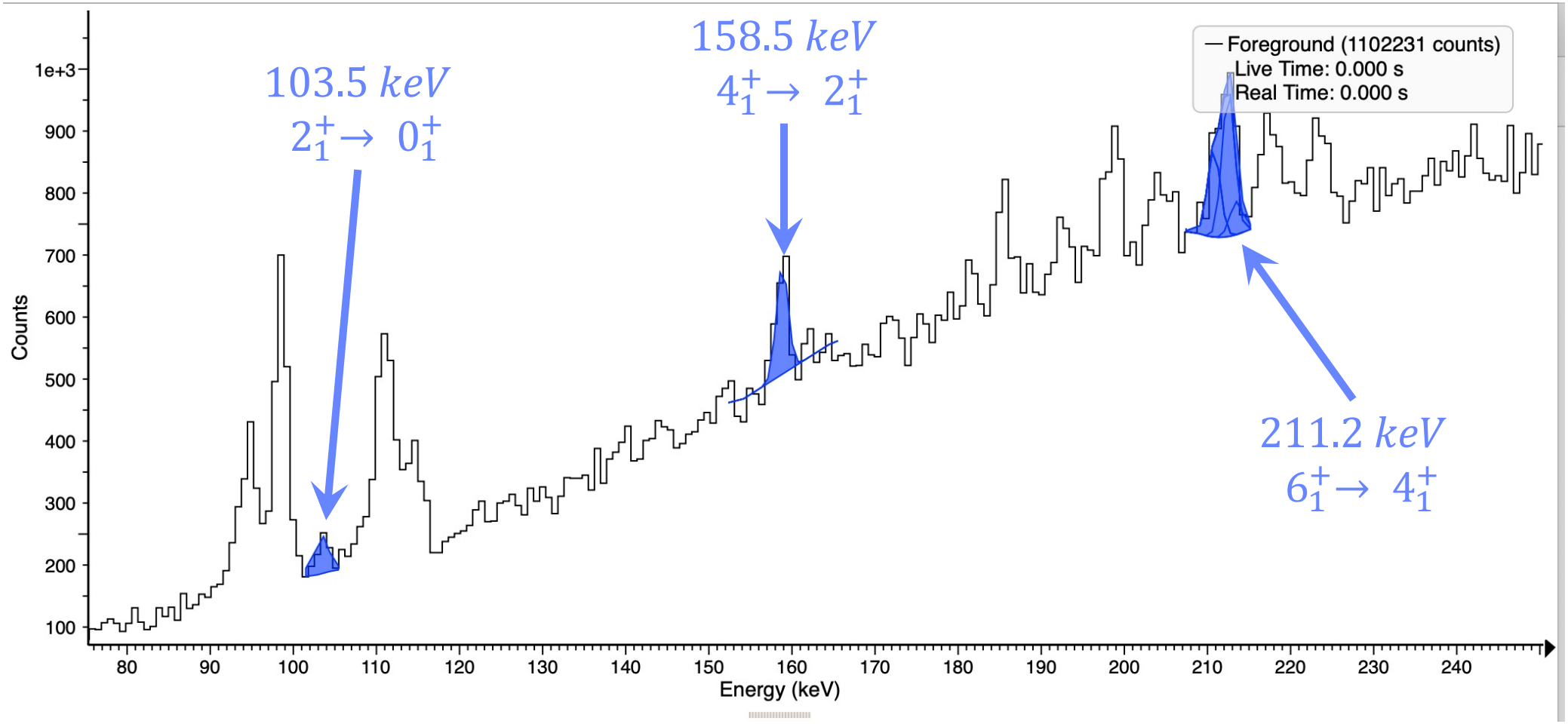


Majority of yield coming in below 4 MeV is consistent with significant compound emission

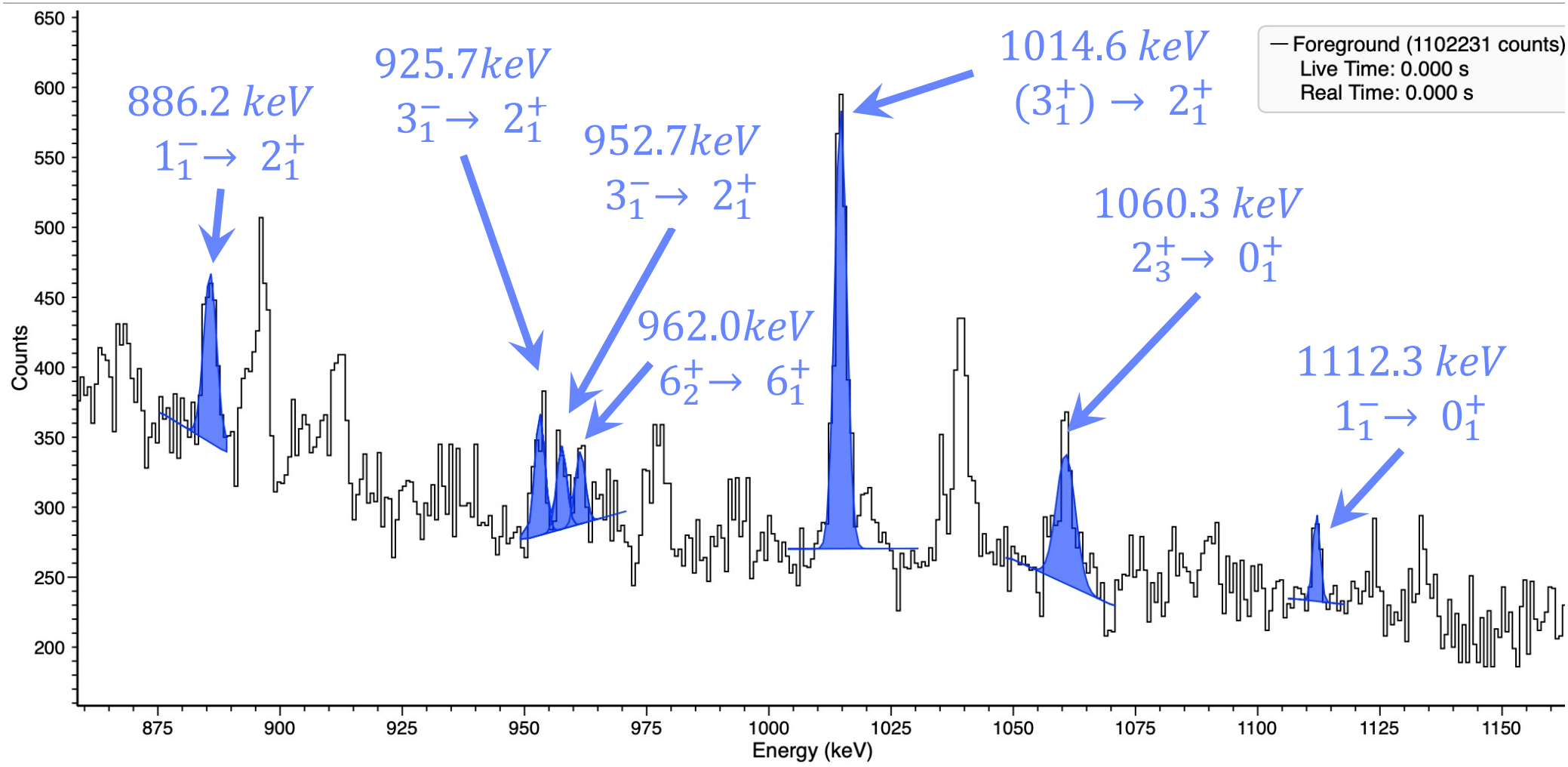
Analysis and interpretation to be completed in FY22

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

Neutron-gated ^{238}U Yrast Cascade

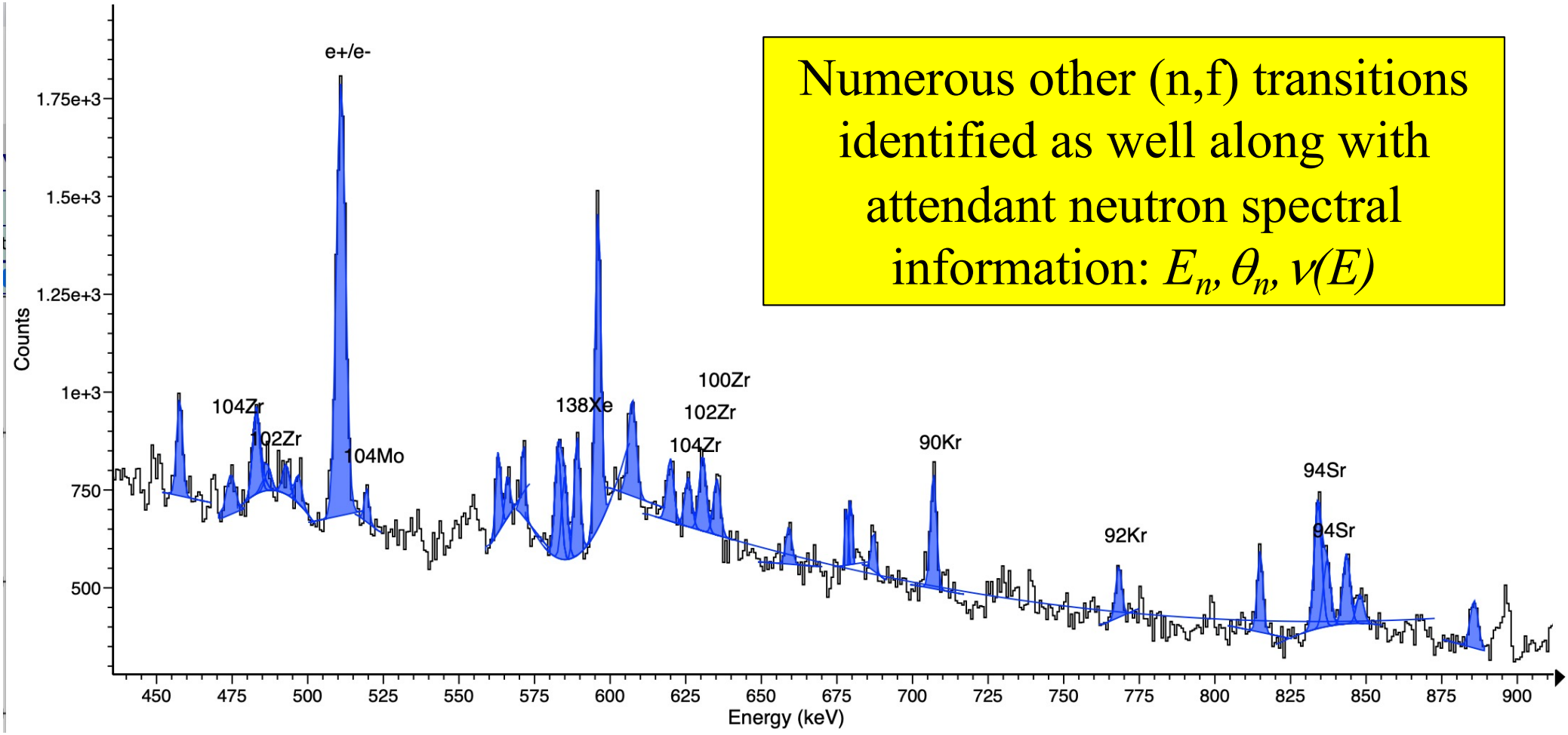


Neutron-gated ^{238}U Off-yrast Transitions



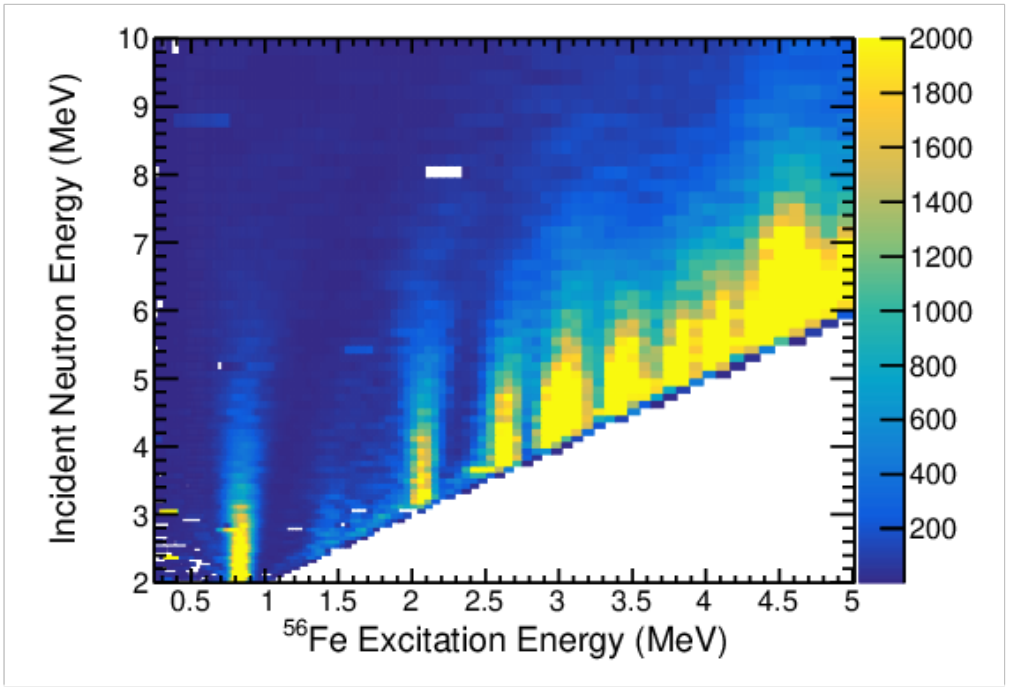
Analysis and interpretation to be completed in FY23

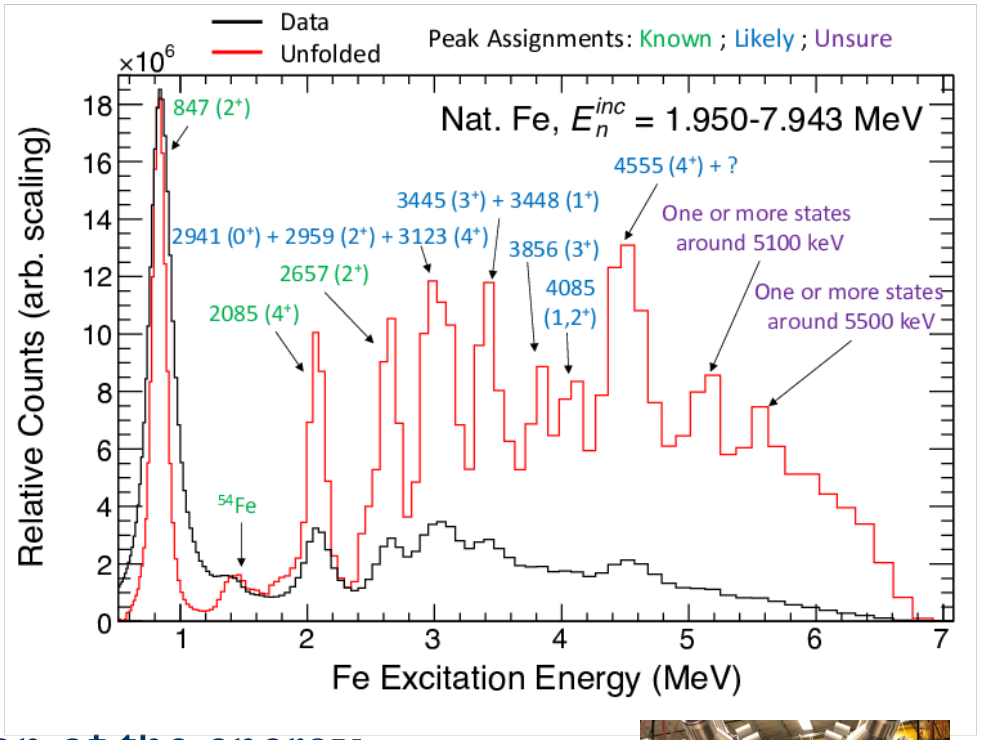
BONUS! Neutron-gated ^{238}U(n,f) Transitions



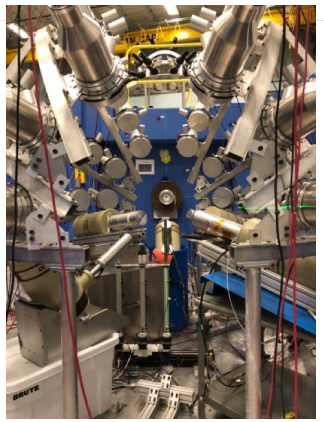
Numerous other (n,f) transitions identified as well along with attendant neutron spectral information: $E_n, \theta_n, \nu(E)$

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

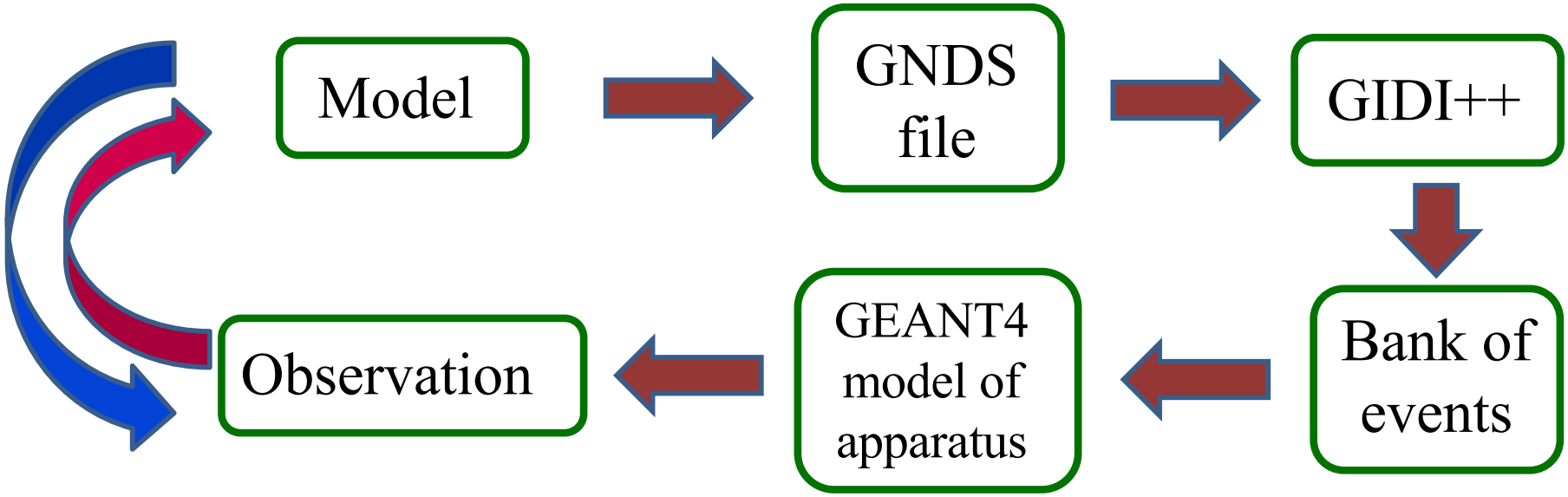


GENESIS + Chi-Nu provides a complete picture of (n,n') reactions

*Funded under LANL LDRD

K.J. Kelly, Devlin, O'Donnell, Neudecker, and Bennett, NIMA, 1010 (2021) 16555
Gold, An Iterative Unfolding Method for Response Matrices, ANL-6984, 1964, http://dx.doi.org/10.2172/46349252

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)

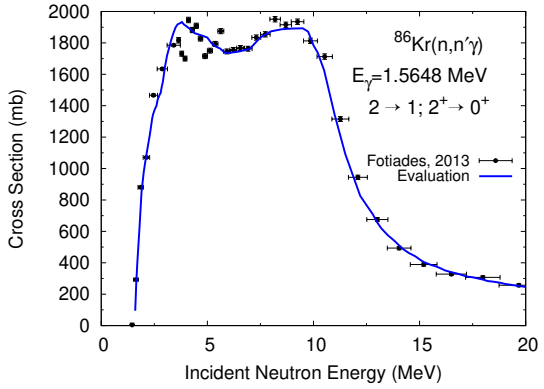
In preparation for the analysis on ^{56}Fe(n,n'γ) and/or ^{238}U(n,n'γ) BNL evaluated ^{86}Kr(n,n'γ)

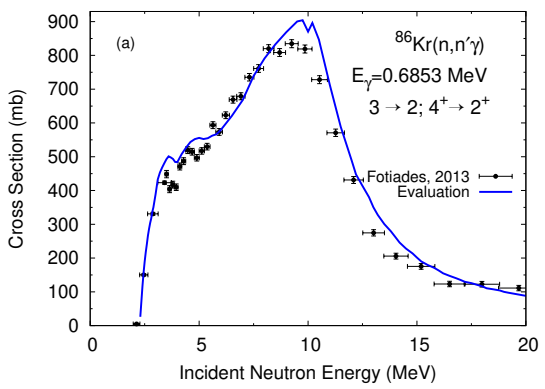
Why ^{86}Kr?

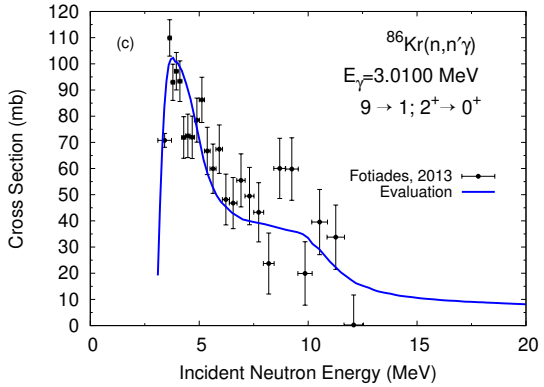
- it was measured using GEANIE, so has many of the same features we expect in proposed experiments
- it is near a closed shell, so has high-lying resonances much like ^{56}Fe
- it is relevant for astrophysics and as a NIF gas diagnostic

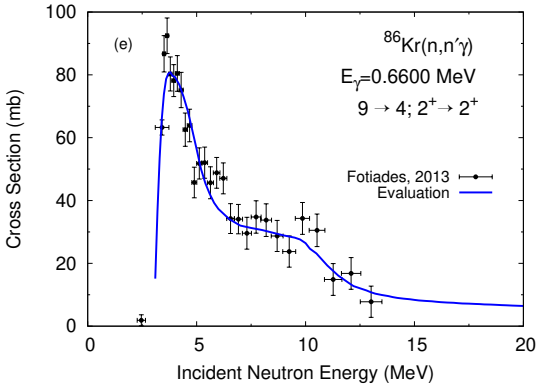
  It is the perfect case study!!!

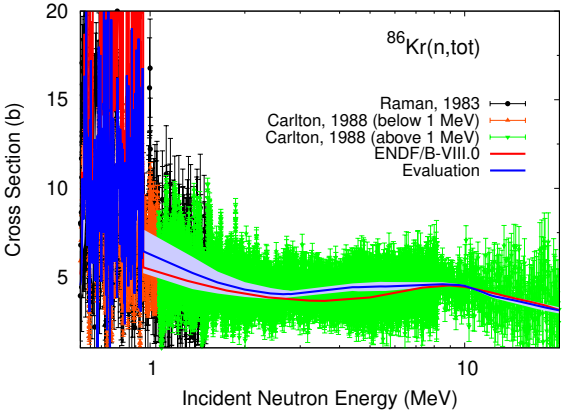
- The optical potential was fitted to simultaneously reproduce the total cross section and the first inelastic gamma
- The evaluated file has been submitted to the ENDF library for review
- The associate paper has been submitted to Nuclear Data Sheets https://arxiv.org/abs/2109.08178

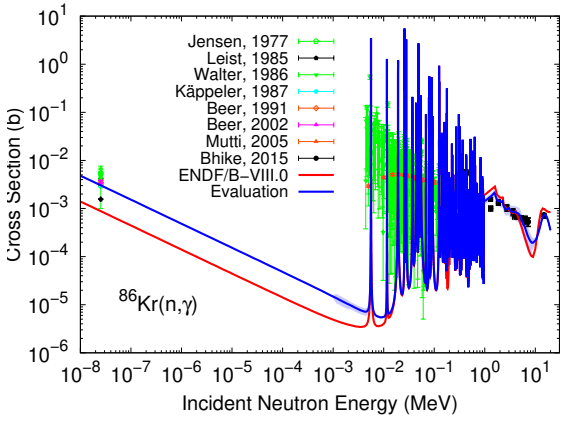












Brookhaven National Laboratory

Collaborators and Acknowledgments

L.A. Bernstein[1,2], J.C. Batchelder[1], D.L. Bleuel[3], D. Brown[4], ***J.A. Brown[1]***, M. Devlin[5], B.L. Goldblum[2,1], ***J.M. Gordon[1,3]***, ***K.J. Kelly[5]***, T. Laplace[1], G. Nobre[4], ***M. Vorabbi[4]***

[1]University of California – Berkeley Department of Nuclear Engineering
[2]Lawrence Berkeley National Laboratory – Nuclear Science Division
[3]Lawrence Livermore National Laboratory
[4]Brookhaven National Laboratory
[5]Los Alamos National Laboratory

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).