Los Alamos
NATIONAL LABORATORY

Emerging Detection Capabilities for Nuclear Deterrence

Keegan J. Kelly

2025 Workshop for Applied Nuclear Data Activities

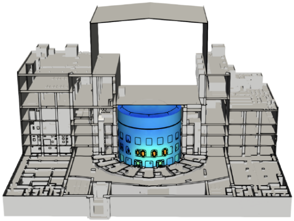
NNSA National Nuclear Security Administration

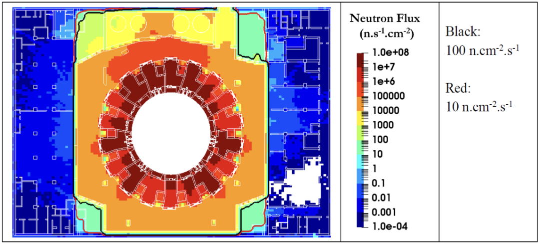
LA-UR-25-21178

Outline

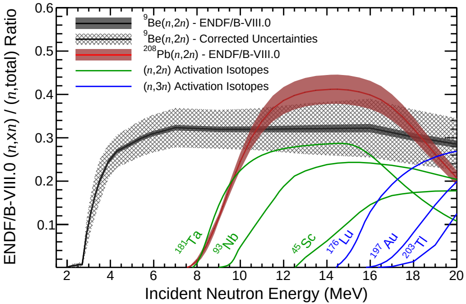
- White-Source $(n,2n)$ and $(n,3n)$ Measurements Capabilities with CLYC-7 n-n Coincidences
- The DAPPER array
- GENESIS Forward Analysis at the LBNL 88-inch Spectrometer
- Exotic fission measurements with the FRIB High-Rigidity Spectrometer
- Microcalorimeters for Nuclear Data Measurements

Fusion Reactors Rely on $(n,2n)$ and $(n,3n)$ Rxns





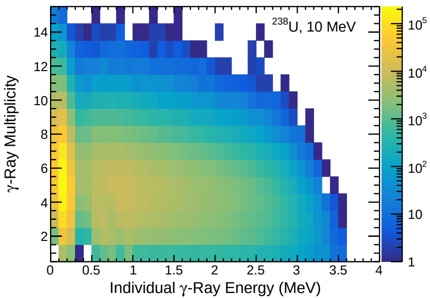
ITER_D_3FM52L - Radiation environment for equipment during operations by R Juarez

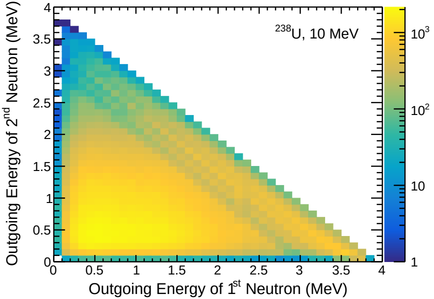


- n breeding essential for t production via ^{6}Li(n,t), to drive d-t
  - ^{9}Be$(n,2n)$ and ^{208}Pb$(n,2n)$
- Activation-based flux measurements motivate a suite of $(n,2n)$ measurements

Traditionally: γ-rays, Activation, or n Counting

Calculated with CoH_3 - T. Kawano, Springer Proceedings in Physics 254 (2021) 27





→ Traditional methods do not measure emitted n information

→ Detection of both $(n,2n)$ neutrons captures 100% of strength.

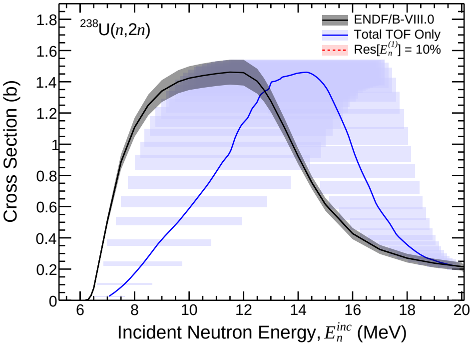
Continuous white-source neutron measurements are ideal, but neutron TOF degeneracies are problematic

Degeneracies of White Sources can be Solved

Neutron energies for $(n,2n)$ for $(n,3n)$ reactions at white sources are degenerate

$$T_n^{(1)} = t_n^{inc} + t_n^{(1)} = \text{First TOF}$$
$$T_n^{(2)} = t_n^{inc} + t_n^{(2)} = \text{Second TOF}$$

BUT, measuring one neutron energy breaks the degeneracy!



$$t_n^{(1)} = \left(\frac{l_{out}}{c}\right)\left[1 - \left(1 + \frac{E_n^{(1)}}{m_n c^2}\right)^{-2}\right]^{-1/2} \Rightarrow t_n^{inc} = T_n^{(1)} - t_n^{(1)} \Rightarrow E_n^{inc}, E_n^{(2)}$$

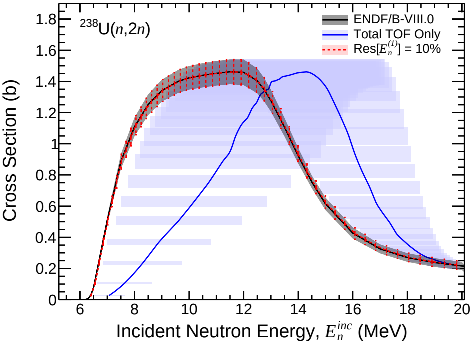
LANSCE can provide continuous $(n,2n)$ and $(n,3n)$ measurements with emitted neutron energy and angular information

Degeneracies of White Sources can be Solved

Neutron energies for $(n,2n)$ for $(n,3n)$ reactions at white sources are degenerate

$$T_n^{(1)} = t_n^{inc} + t_n^{(1)} = \text{First TOF}$$
$$T_n^{(2)} = t_n^{inc} + t_n^{(2)} = \text{Second TOF}$$

BUT, measuring one neutron energy breaks the degeneracy!



$$t_n^{(1)} = \left(\frac{l_{out}}{c}\right)\left[1-\left(1+\frac{E_n^{(1)}}{m_n c^2}\right)^{-2}\right]^{-1/2} \Rightarrow t_n^{inc} = T_n^{(1)} - t_n^{(1)} \Rightarrow E_n^{inc}, E_n^{(2)}$$

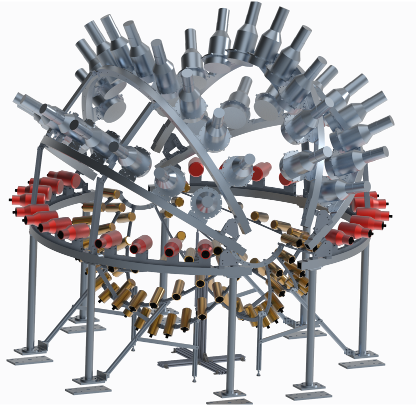
LANSCE can provide continuous $(n,2n)$ and $(n,3n)$ measurements with emitted neutron energy and angular information

Accomplished with CLYC-7 E_n Data and CoGNAC

- Upgrade CoGNAC to include a series of high-volume CLYC-7 scintillators

- ^{35}Cl(n,p) measures $E_n^{(1)}$ directly

- EJ-309 and CLYC-6 detectors provide $T_n^{(2)}$ measurement to low energy

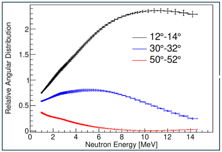


Applicable to 20+ (n,$2n$) and (n,$3n$) measurements for DOE SC NP FES, and could lead to a decade+ campaign for OES / SAT and PAT

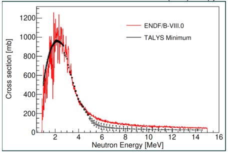
Funded by the DOE Early Career Research Program

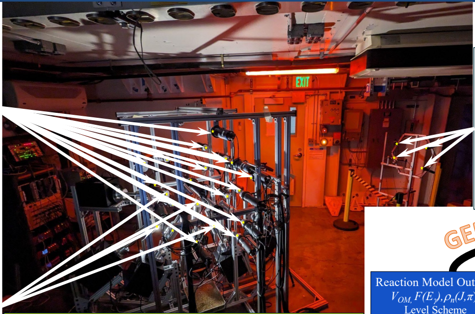
GENESIS is performing simultaneous energy differential and integral measurements of the (n,xnγ) reactions to help better inform evaluation

26 neutron detectors $N(E_n, \theta_n)$

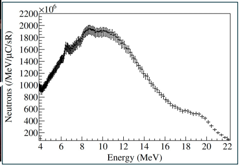


7 HPGe Detector $N(E_\gamma, \theta_\gamma)$

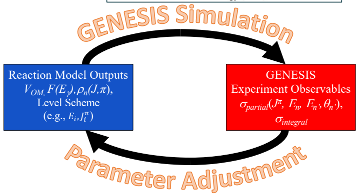




Neutron flux measurement with $E_{max} < 22$ MeV



Reaction model parameters are iteratively adjusted to best reproduce GENESIS observables



DAPPER

Detector Array for Photons, Protons, and Exotic Residues

Contact: Alan McIntosh; alanmcintosh |at| tamu.edu

Neutron capture x-sect needed on unstable isotopes for

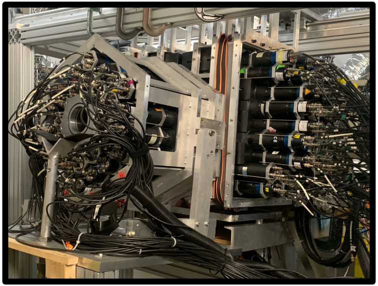
- stockpile science
- nuclear forensics
- advanced reactor design
- nuclear astrophysics

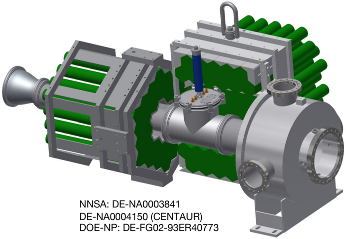
Can't measure everything. Can't measure certain things at all.

Need for nuclear data to constrain models, improve predictions.

$^{A}X + {}^{2}H \rightarrow {}^{A+1}X + {}^{1}H + g$

- photons: 800 lbs BaF2 → individual gamma energy, total gamma energy, gamma multiplicity; segmented for Doppler correction
- protons: S3 annular silicon → excitation energy
- exotic residues: zero degree ionization chamber →discriminate beam & reaction of interest @ >600k pps





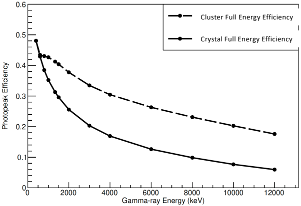
- Multiple analysis methods: Forward (multi-step cascade), Oslo, Shape
- Systematic measurements along isotopic chains
- Multiple detector arrays: DAPPER, Hyperion, etc.
- Multiple surrogate reactions: (d,p), (p,p'), (3He,4He), (t,p), (p,d)…

NNSA: DE-NA0003841
DE-NA0004150 (CENTAUR)
DOE-NP: DE-FG02-93ER40773

<u>**Detector Array for Photons, Protons, and Exotic Residues**</u>

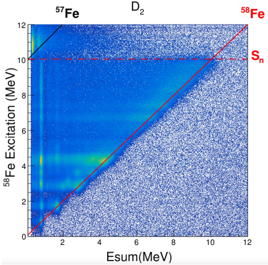
Contact: Alan McIntosh; alanmcintosh |at| tamu.edu

DAPPER



High efficiency: 24% @ 8 MeV

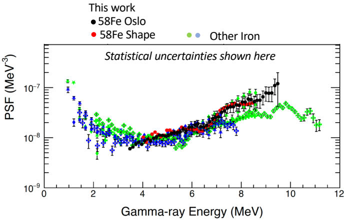
clustering (addback) boosts efficiency



Excitation vs gamma energy:
Large yield in total detection

E* and Eg contain information on

- Nuclear Level Density
- Photon Strength Function



Extracted 58Fe PSF and NLD
Parallel analyses agree

55Fe PSF and NLD in progress
See Arthur Alvarez's Poster!

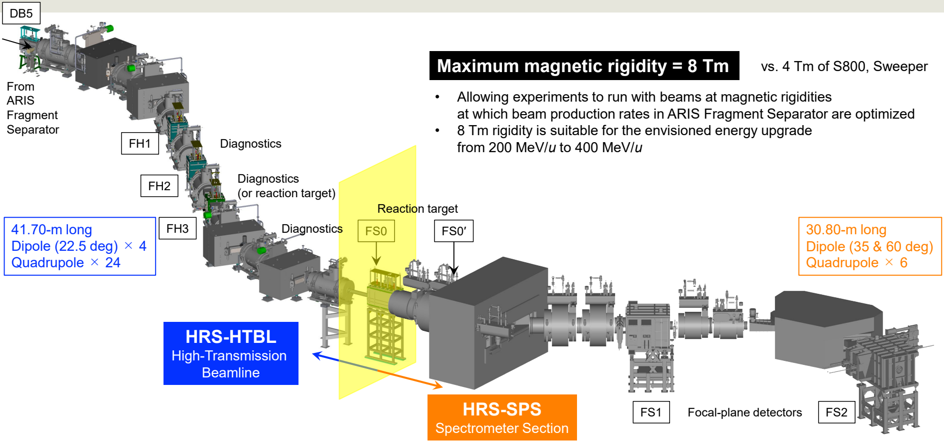
TEXAS A&M UNIVERSITY Cyclotron Institute

NNSA: DE-NA0003841
DE-NA0004150 (CENTAUR)
DOE-NP: DE-FG02-93ER40773

Overview of HRS Consisting of HRS-HTBL & HRS-SPS

Maximum magnetic rigidity = 8 Tm vs. 4 Tm of S800, Sweeper

- Allowing experiments to run with beams at magnetic rigidities at which beam production rates in ARIS Fragment Separator are optimized
- 8 Tm rigidity is suitable for the envisioned energy upgrade from 200 MeV/*u* to 400 MeV/*u*

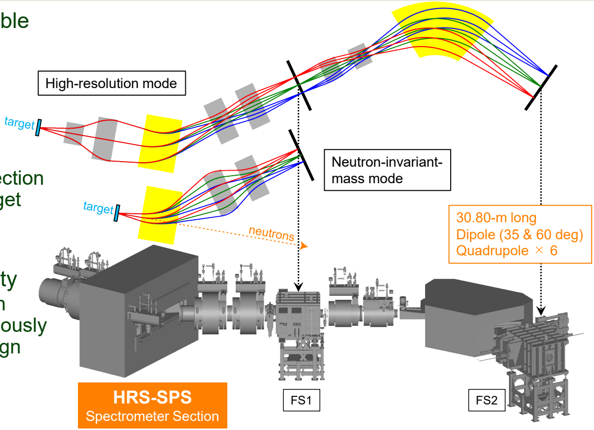


R. Zegers - HRS for Fission Measurements - FIESTA 2024

- Pure FRIB beam is incident on a production target
  - Select isotope of interest, and transport to HRS
- Interaction with Reaction Target produces nucleus that will fission “in flight”

Multiple Operational Modes of HRS-SPS Facilitates Various Science Programs under Optimal Conditions

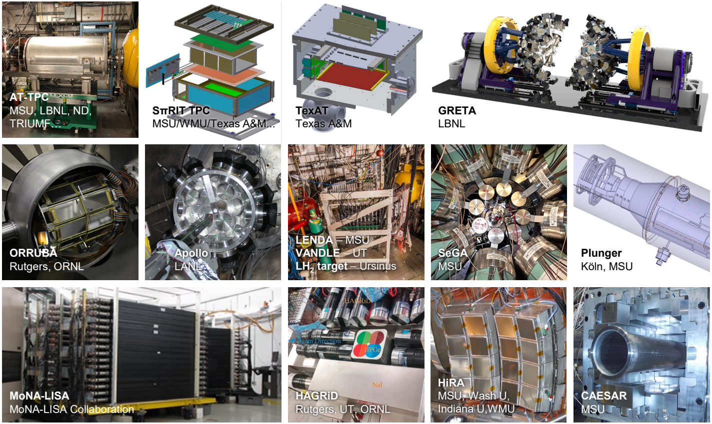
- Multiple operational modes available in a single hardware setup
  - Lattice layout is optimized for **high-resolution mode** in which the majority of experiments will run
  - **Neutron-invariant-mass mode** is specialized for invariant-mass spectroscopy with fast neutron detection at forward angles, with reaction target placed in front of the first dipole
- Interface with auxiliary detectors is coordinated with user community
  - Input from users (organized through the HRS Working Group) is continuously sought to ensure that the HRS design accommodates user program and facilitates detector installation



R. Zegers - HRS for Fission Measurements - FIESTA 2024

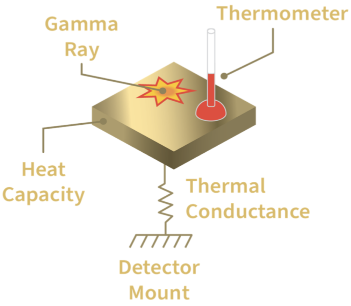
- Excitation energy of fissioning nucleus can be measured event-by-event
- High rigidities and excitations from surrogate reactions emulate neutron capture preceding fission

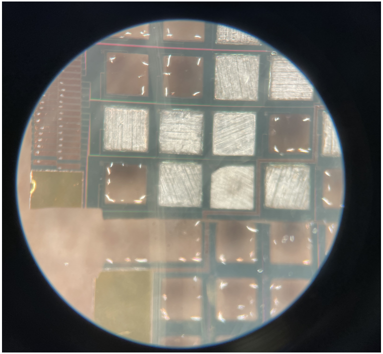
Adaptability to Measure Variety of Rxn Outputs



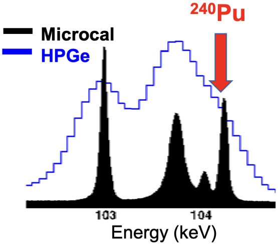
- Able to fission fragment and prompt observable data directly with CGMF, FREYA, etc.
  - Models limited by structure of neutron-rich fragments from fission

Microcalorimeters as Specialized Tools for ND



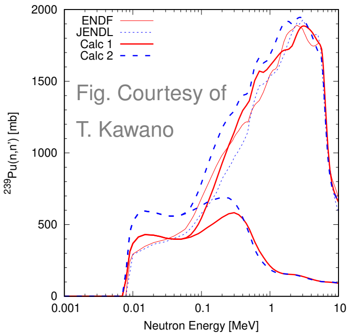


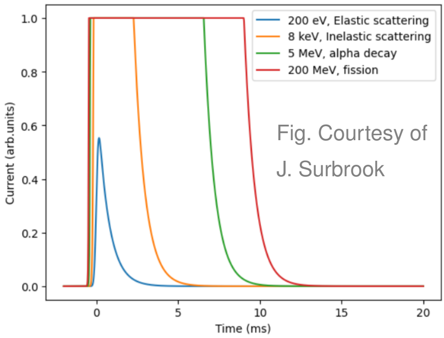
- For narrow-focus, specialized cases, microcalorimeters are unrivaled
- Commonly used for decay or x-ray spectroscopy



Images from J. Ward, LA-UR-23-32260

μCals May Yield Elusive Actinide Scattering Data





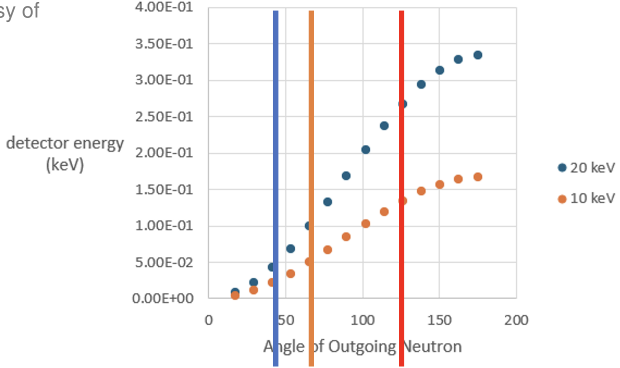
The onset of the ^{239}Pu(n,n') reaction to the 7.9 keV first excited state is a fundamental missing component for nuclear model development

- The trajectory of $\sigma(n,n')$ can vary wildly based on details of first inelastic channel

μCals can observe both (n,n) and (n,n') using only the recoiling nucleus

μCals May Yield Angular Distributions Too!

Fig. Courtesy of
J. Surbrook

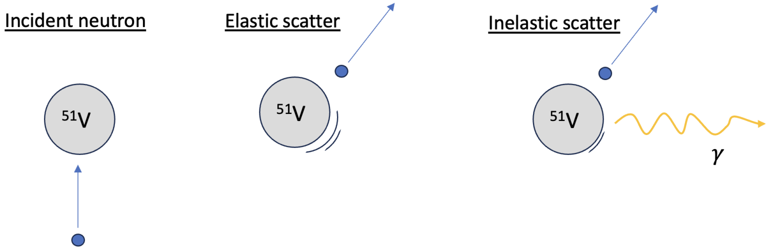


The energy deposited into the μCal is correlated to the energy and angle of the emitted neutron

→ Neutron angular distributions can be calculated from measurements of the parent nucleus

14 MeV Measurements with DT Generators

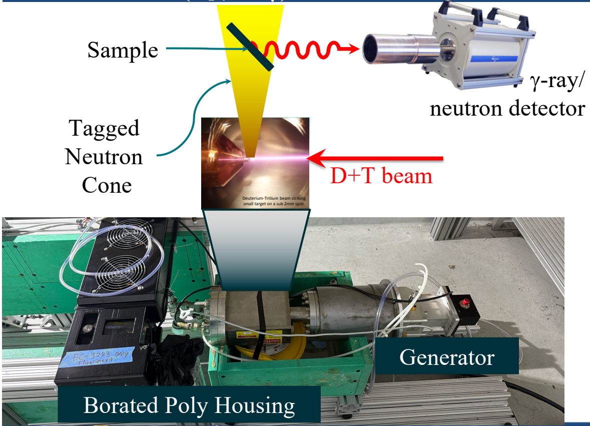
Fig. Courtesy of J. Surbrook



High-precision 14 MeV Measurements for fusion and more applications are possible

See poster by Jason Surbrook

The Berkeley team is also developing a DT-API system on campus to measure (n_{14},xnγ) cross sections with little-to-no flux uncertainty



Simple Count Rate Estimate

$$R_{\alpha-\gamma/n} = \sigma(N)_{sample}\Phi_n$$

For a 10 g sample 1 m away from a 1 cm scintillator @ 5 cm:

$$N_{sample} \approx 10^{23} atoms$$

$$\Phi_n \approx 10^8 \frac{n}{s} \times \left(\frac{1}{100}\right)^2 \rightarrow \approx 10^9 \frac{n}{day}$$

$$\rightarrow R_{\alpha-\gamma/n} = \frac{10^8}{\sigma\,(barn) \bullet day}$$

***10^5* peak counts/day for a 0.1% detection efficiency**

See L. Bernstein talk tomorrow in Fusion Nuclear Data session

THANK YOU!

$\rightarrow$CoGNAC (n,xn) detector development funded by DOE Office of Science via Early Career Research Program.

$\rightarrow\mu$Cal initial investigations for nuclear data funded by NA-113, as part of the CoGNAC neutron scattering program at LANL.

$\rightarrow$GENESIS and DT-API work at LBNL were performed under the auspices of the Office of Nonproliferation Research and Development (NNSA/NA-22) and the US Nuclear Data Program at Lawrence Berkeley National Laboratory (Contract No. DEAC02-05CH11231) and the Stewardship Science Academic Alliance Program under Grant DE-NA0004064 at the University of California, Berkeley.

Direct questions to kkelly@lanl.gov