# Experimental Capabilities at the LBNL 88-Inch Cyclotron

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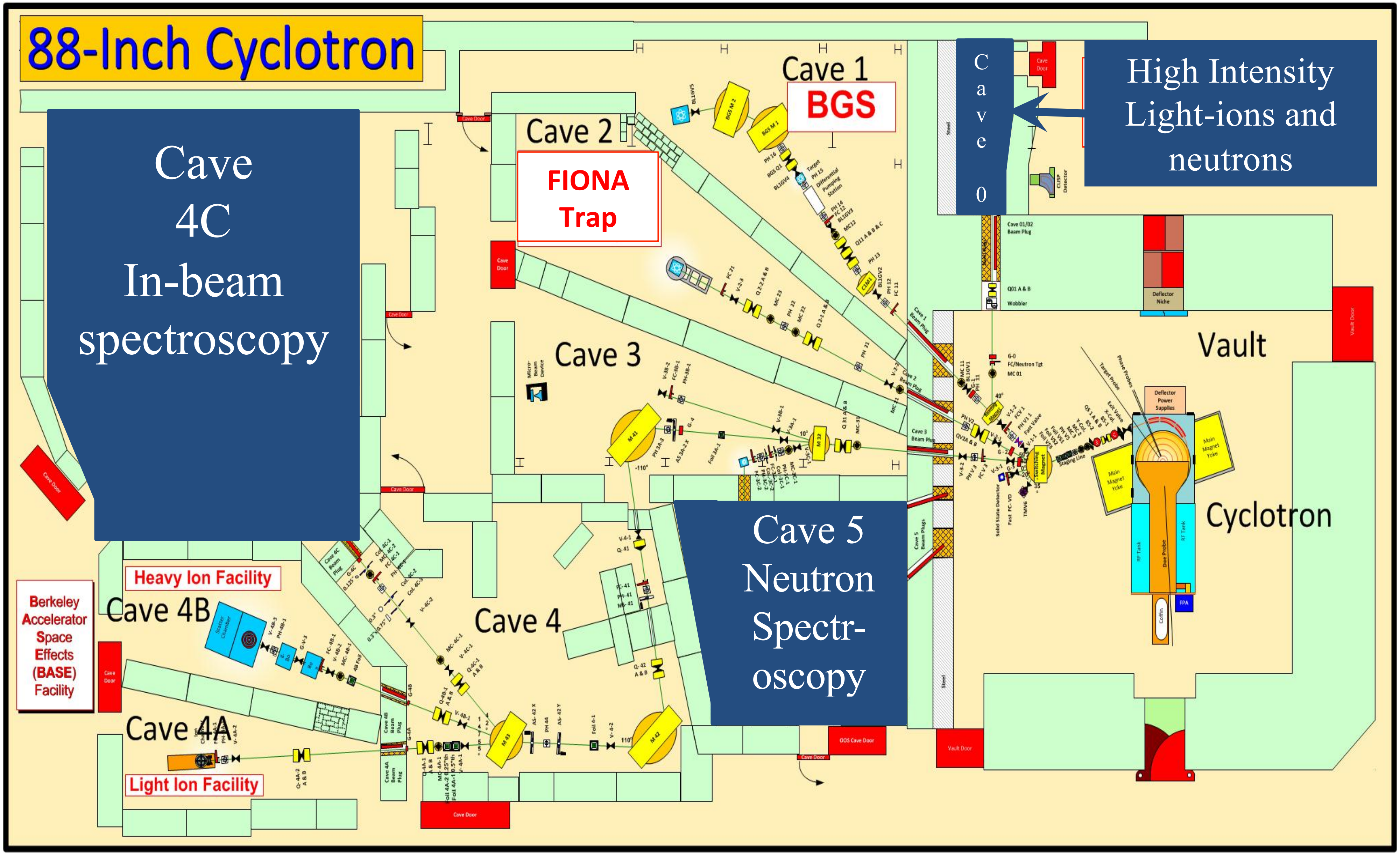
http://nucleardata.berkeley.edu

# The LBNL 88-Inch Cyclotron capabilities for Isotope Production R&D



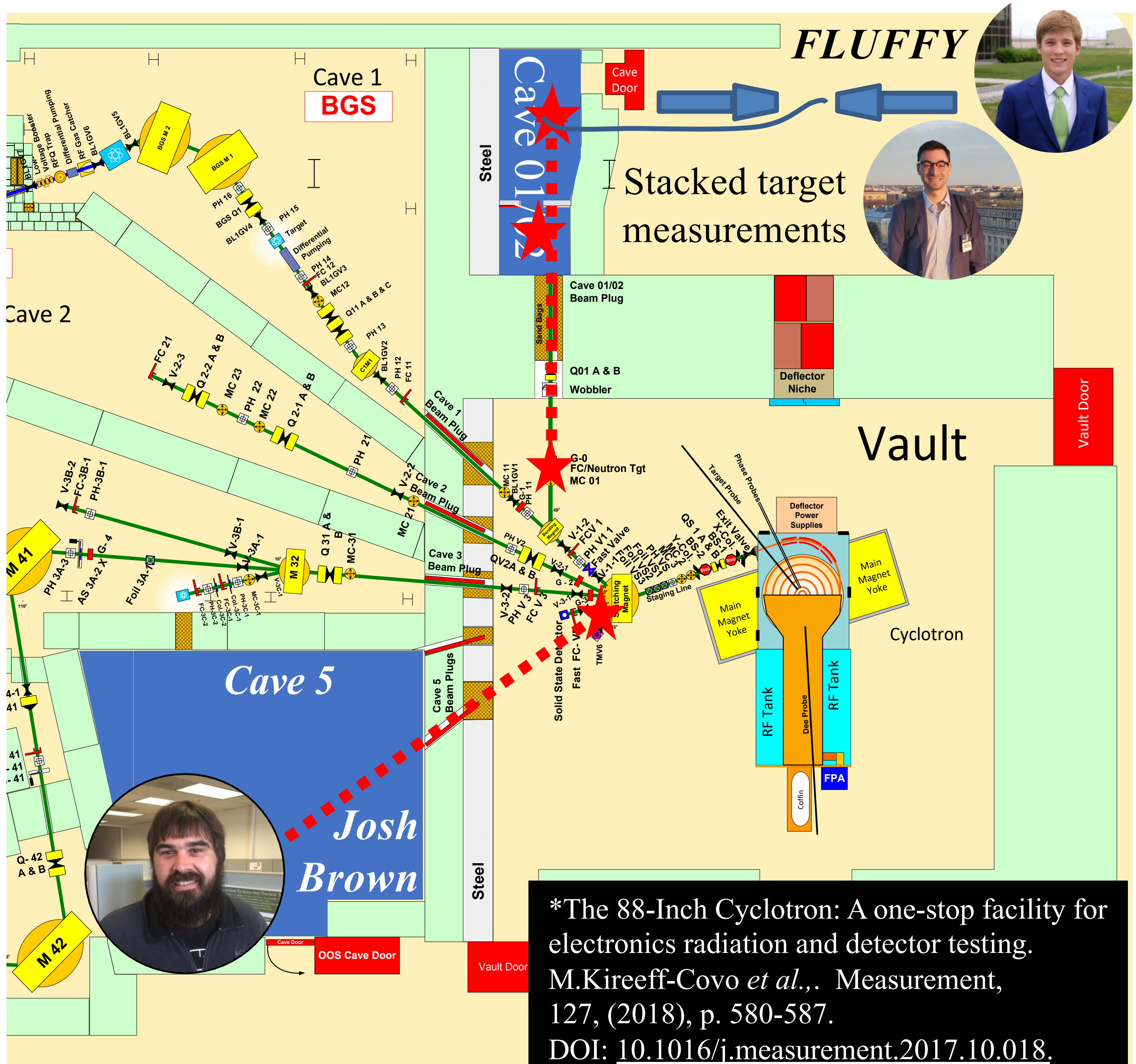
# We can produce high-intensity, variable energy neutron beams at two locations for spectroscopy and cross section measurements

## Cave 0

- Stacked target cross section measurements for Isotope production.
- Fast Loading Unloading Facility for Fission Yields (FLUFFY) system for cyclical activation fission yield measurements.
- Max flux using breakup in the cave: $10^{12}$ n/s/cm$^2$

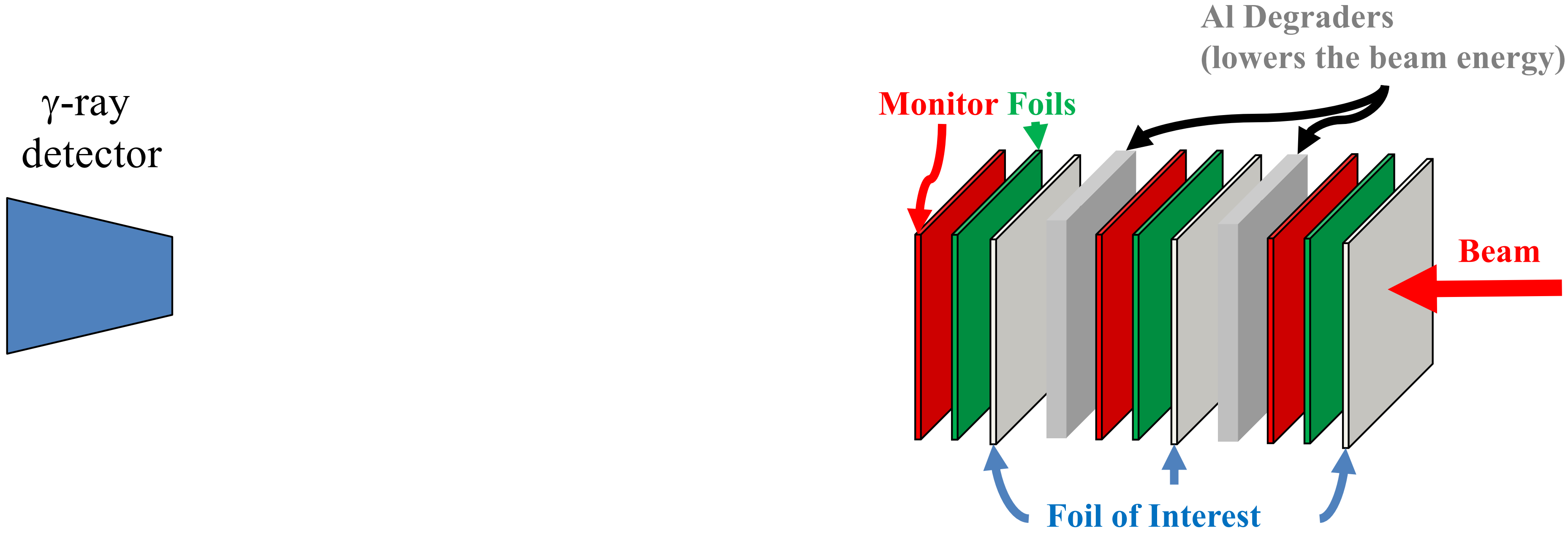
## Cave 5

- Prompt (n,xγ) data using the Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering (GENESIS).
- Neutron Scintillator characterization studies




*The 88-Inch Cyclotron: A one-stop facility for electronics radiation and detector testing. M.Kireeff-Covo *et al.*,. Measurement, 127, (2018), p. 580-587.
DOI: 10.1016/j.measurement.2017.10.018.

# The stacked target method allows for charged particle cross section measurements over a range of beam energies via activation




1. Irradiate a stack of foil that includes **monitor targets** that where the reaction rates are known and **targets** we want to determine the production rate on and "**beam degraders**" which lower the beam energy.
2. Put the targets in front of the γ-ray detector after the experiment to measure the decay of the radioactive products formed during irradiation.
3. This allows the production rate of the **unknown** target to be determined relative to the **known targets**.


* Patent submitted (LBNL/UC)

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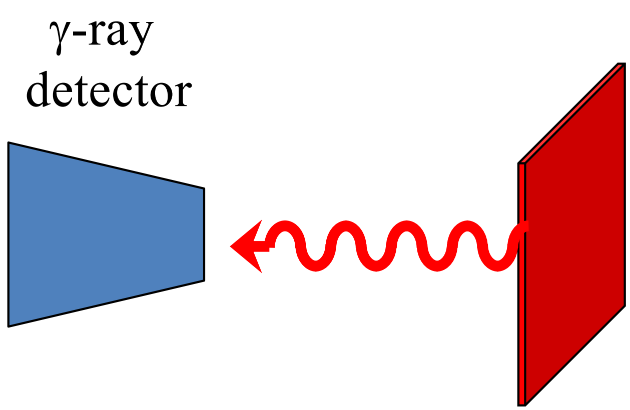


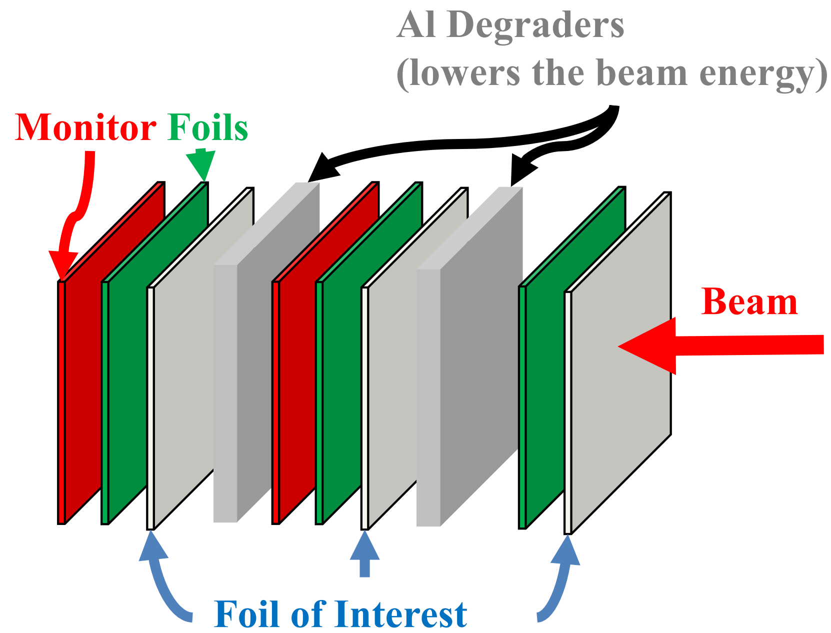


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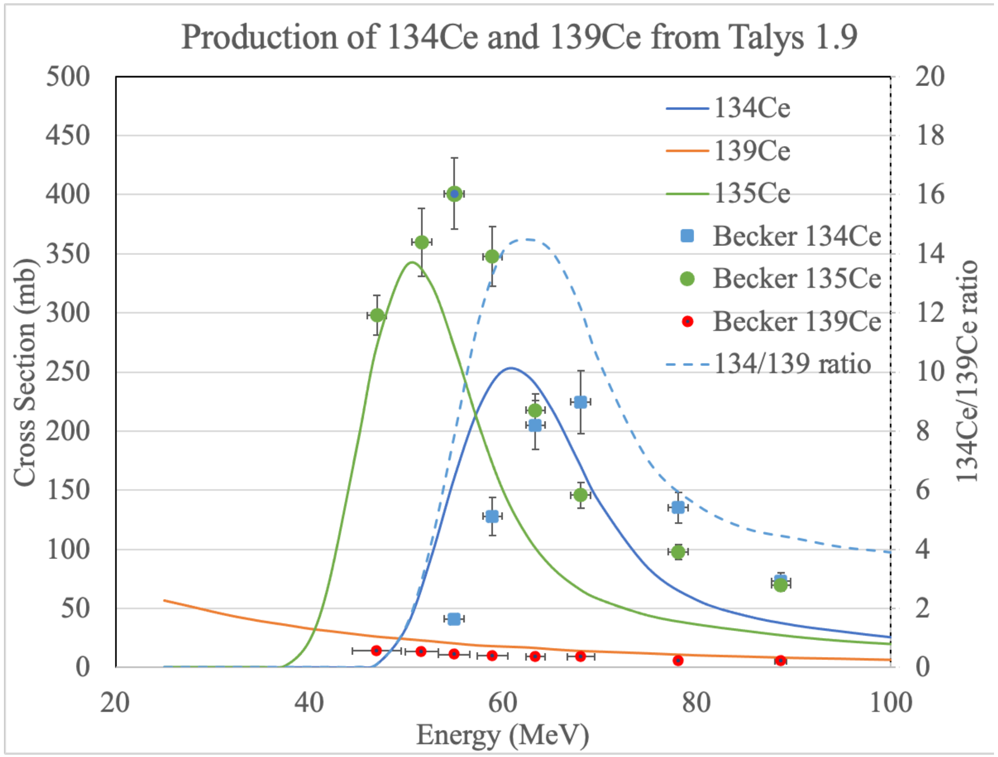
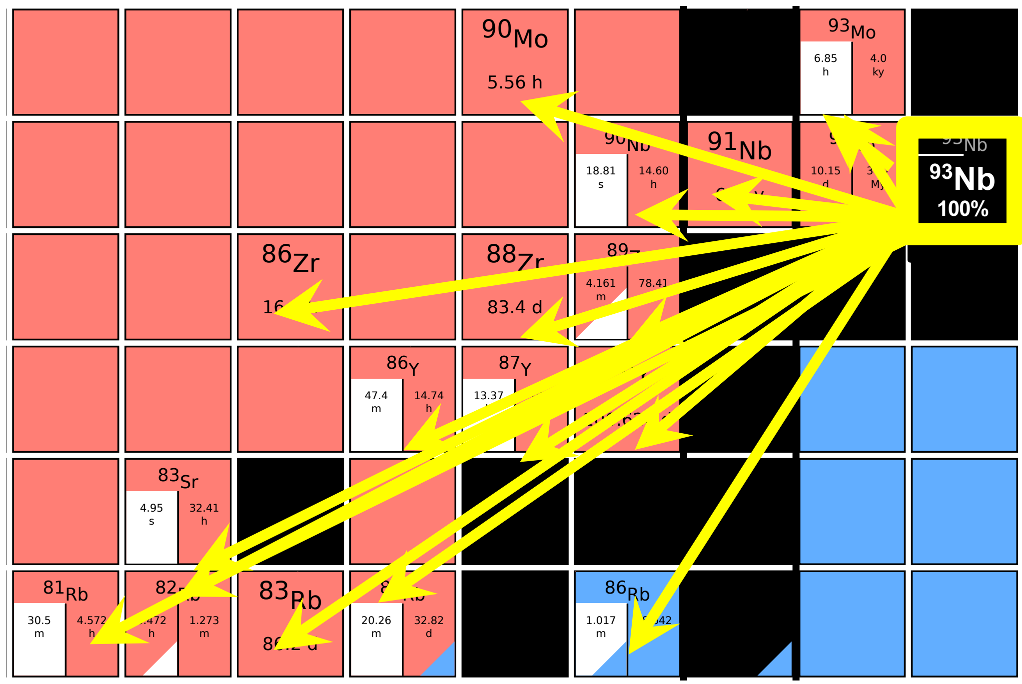
# Our work as a part of the TREND collaboration suggests that significant changes are needed to accurately model high-energy (p,x) isotope production




**23 excitation functions for $^{93}$Nb(p,x)**




**34 excitation functions for $^{nat}$Cu,$^{nat}$Ti(p,x)**

**21 excitation functions for $^{75}$As(p,x)**

Morgan Fox

*Experiments have been performed on Nb, As, Sb and Tl using proton beams up to 55 MeV at LBNL*

*M. B. Fox *et al., PRC, 103(3):034601, 2021 and PRC 104, 064615 (2021)*

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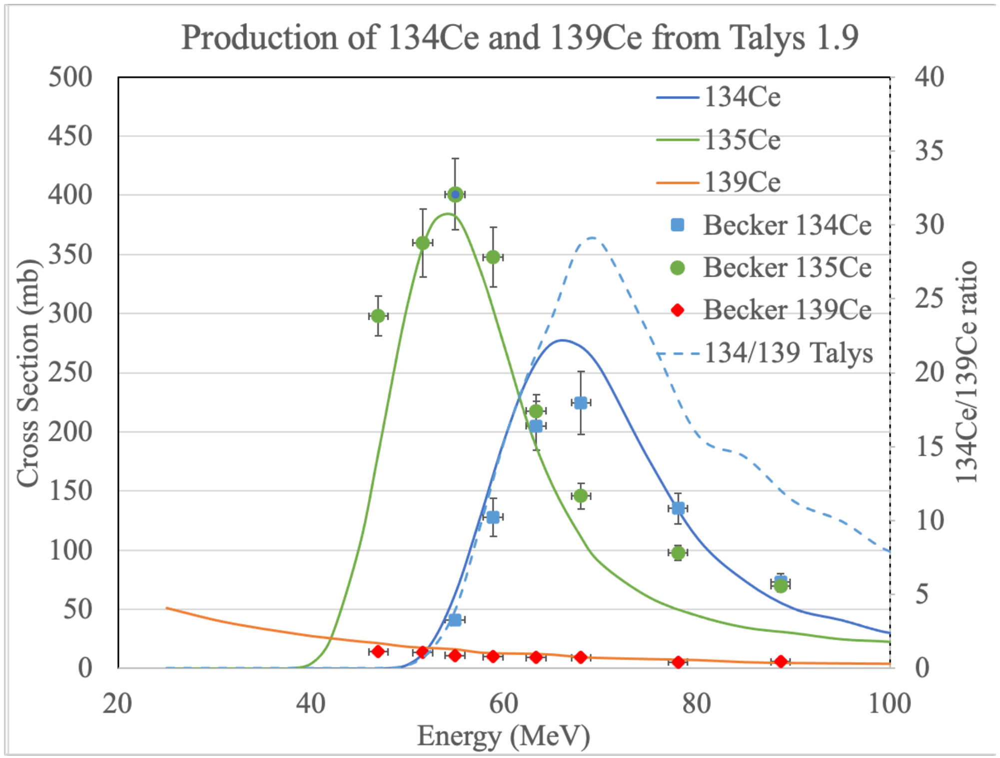


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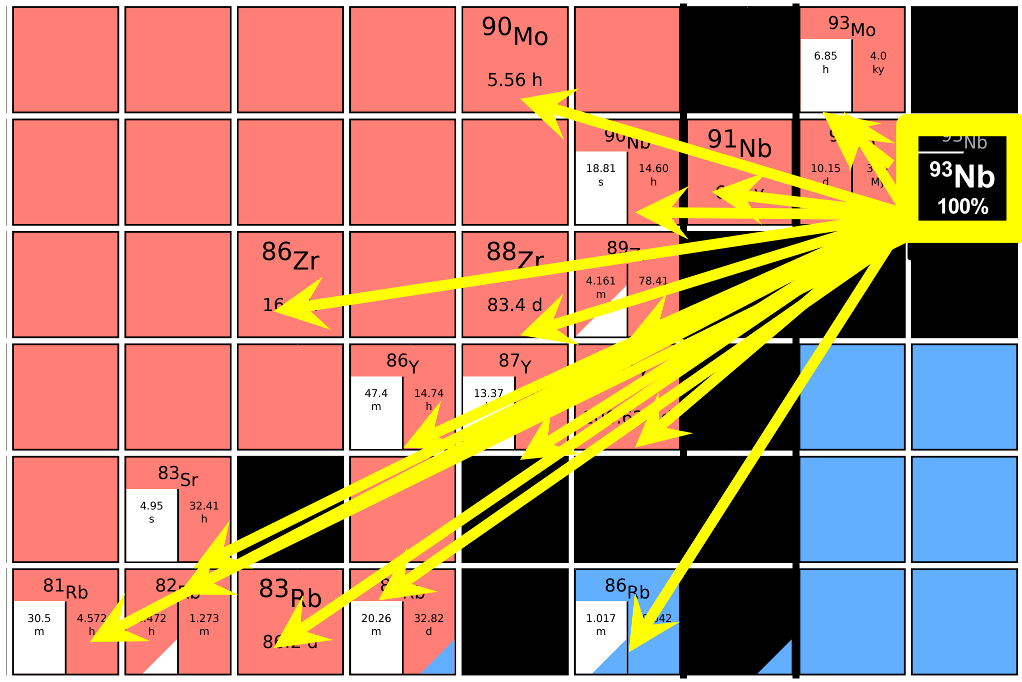


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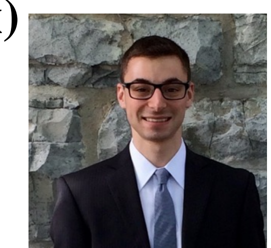

Morgan Fox

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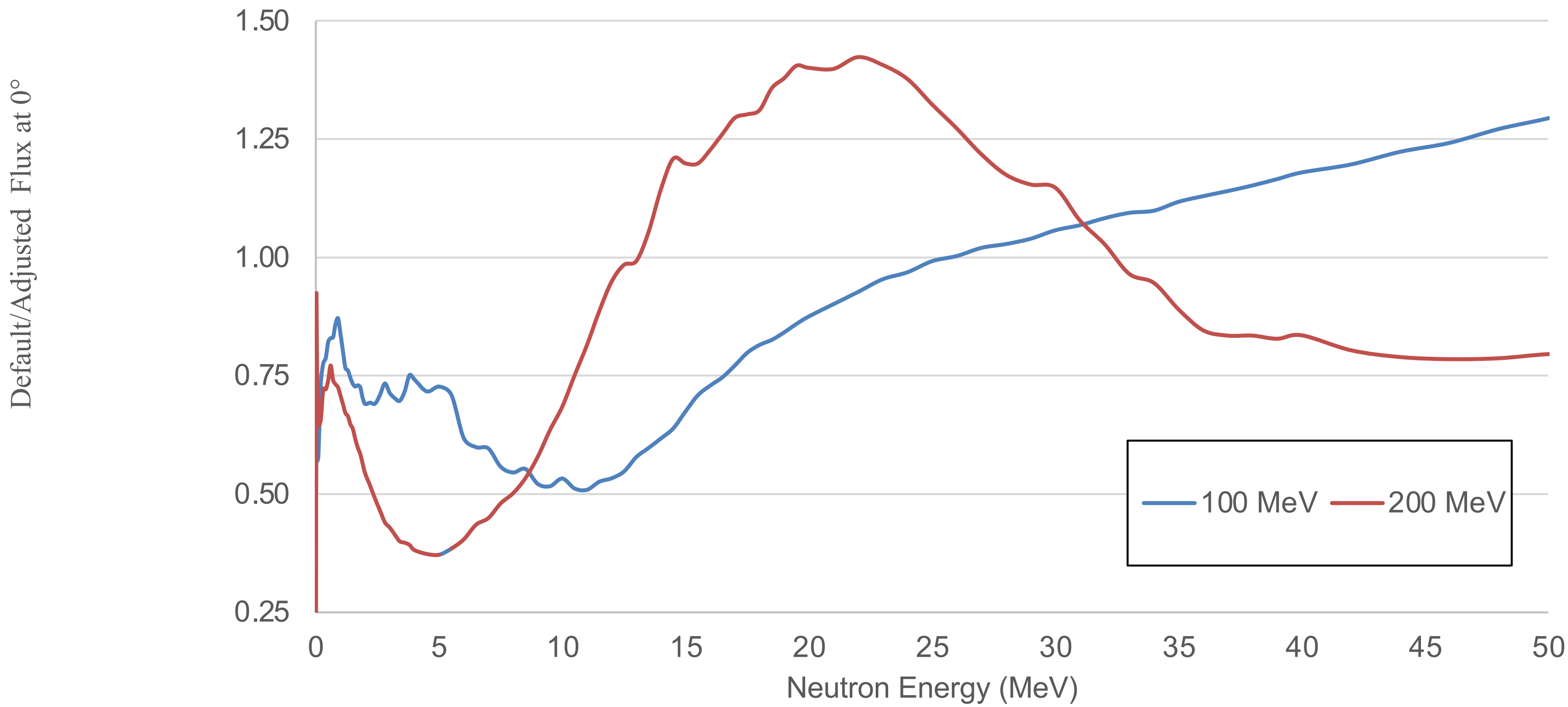
# What are the effects of these changes on the neutron flux look like behind a thick target at BNL-BLIP or LANL-IPF?




There is a sizable neutron flux behind all thick target stacks at these Isotope Production facilities

# We've also quantified neutron production from thick target deuteron breakup using both Time-of-Flight* and foil activation

**Double Time-of-Flight***

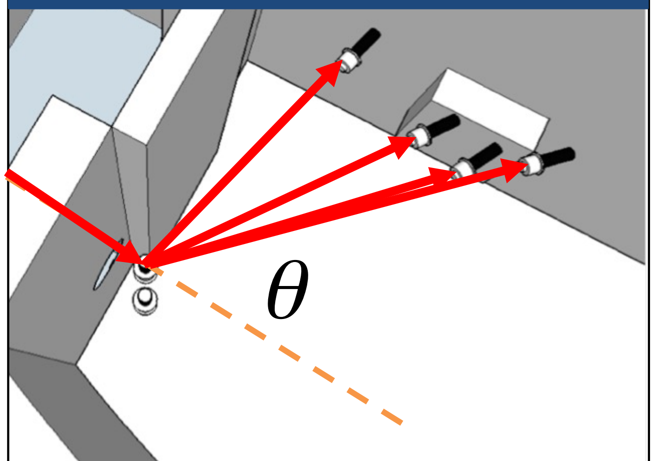
- Neutrons scatter off a target cell neutron scintillator and into an array of scatter cells allowing for energy determination down to ≈0.5 MeV without contributions from temporally adjacent beam pulses.

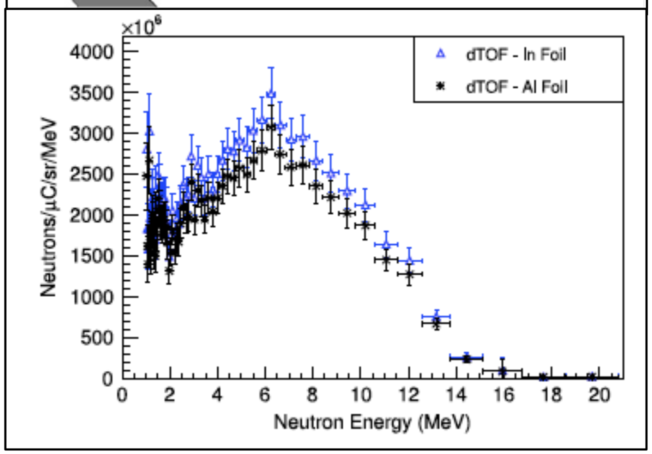
*K.P. Harrig *et al.*, Nuclear Inst. and Methods in Physics Research, A 877 (2018) 359–366

**Foil Activation**

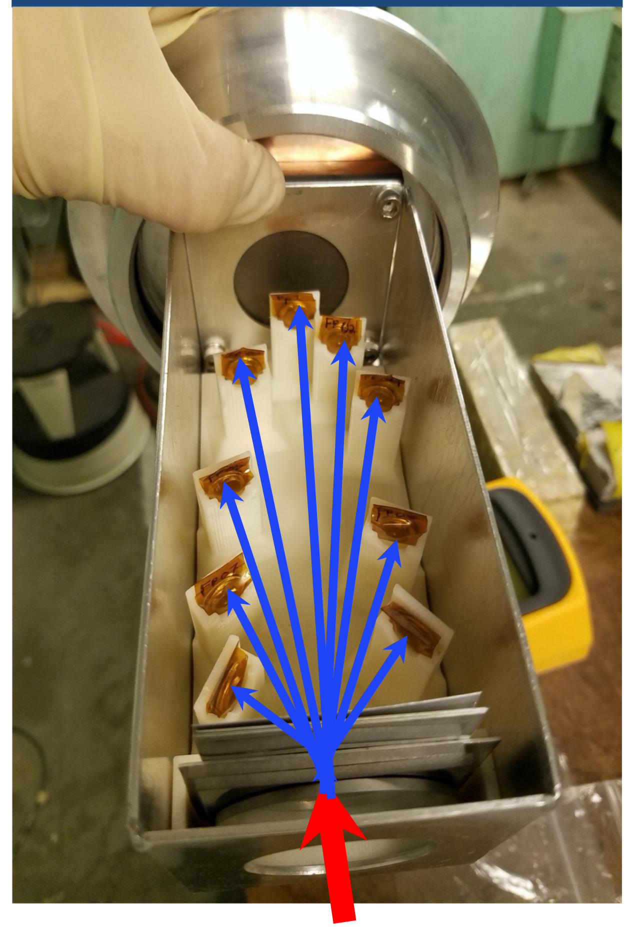
- Arrays of activation foils are located at defined angles with respect to the breakup target and the spectrum is determined via spectral decomposition.

Time-of-Flight (TOF)



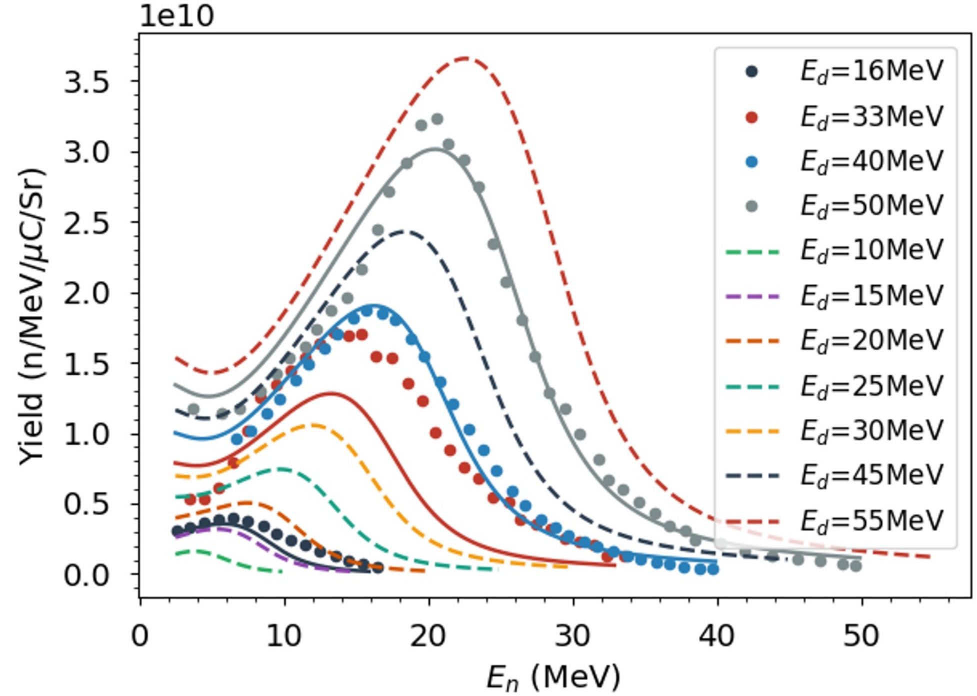

Mounted Foil Holder



Our goal was the development of a physics-based model of deuteron breakup

# Jon Morrell developed a combined 5 parameter model* that describes the double-differential neutron production cross section

- Breakup cross section from Kalbach[1] parameterization
- $P(E_n)$, $P(\theta)$ from R. Serber[2] (Phys. Rev. 72, 11 (1947)
- Evaporation component from Talys (Maxwell-Boltzmann)
- One flat background parameter
- Fit yields to literature data[3,4]




[3]Meulders (1975) - 16, 33, 50 MeV
[4]Saltmarsh (1977) - 40 MeV

$$\frac{d^2\sigma(\epsilon_d)}{d\Omega dE_n} = \sigma_{BU}(\epsilon_d)P(E_n)P(\theta)$$

1 width parameter each

Shape & Magnitude

$$Y(E_n, E_d, \hat{\Omega}) = n\int_{\hat{\Omega}}\int_0^{E_d}\frac{d^2\sigma(\epsilon_d)}{d\Omega dE_n}\left(\frac{d\epsilon_d}{dx}\right)^{-1}d\epsilon_d d\Omega$$

Jon Morrell

[1]C. Kalbach Phys. Rev. C 95, 014606 (2017). [2]R. Serber, Phys. Rev 72, 11 (1947)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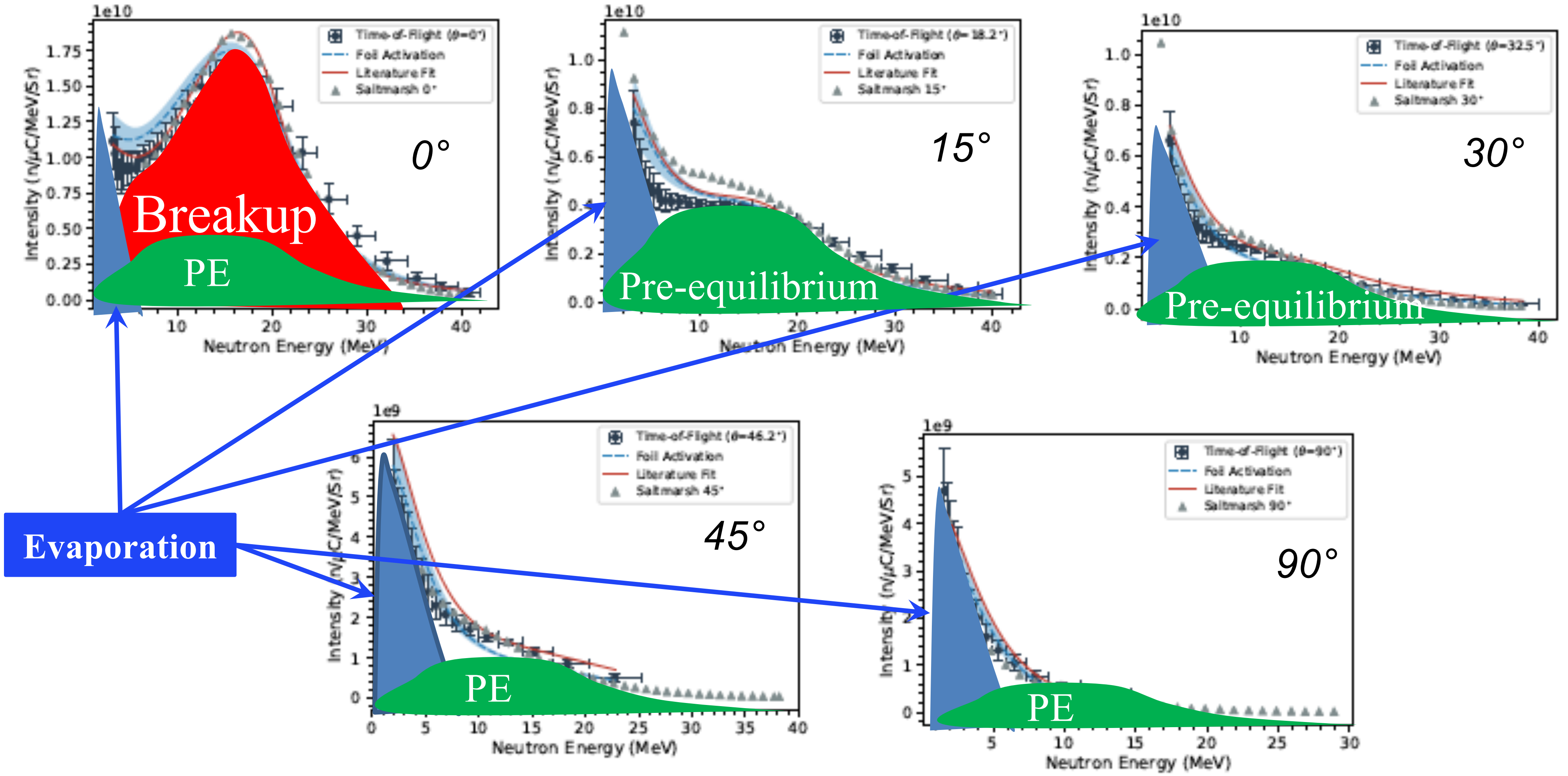
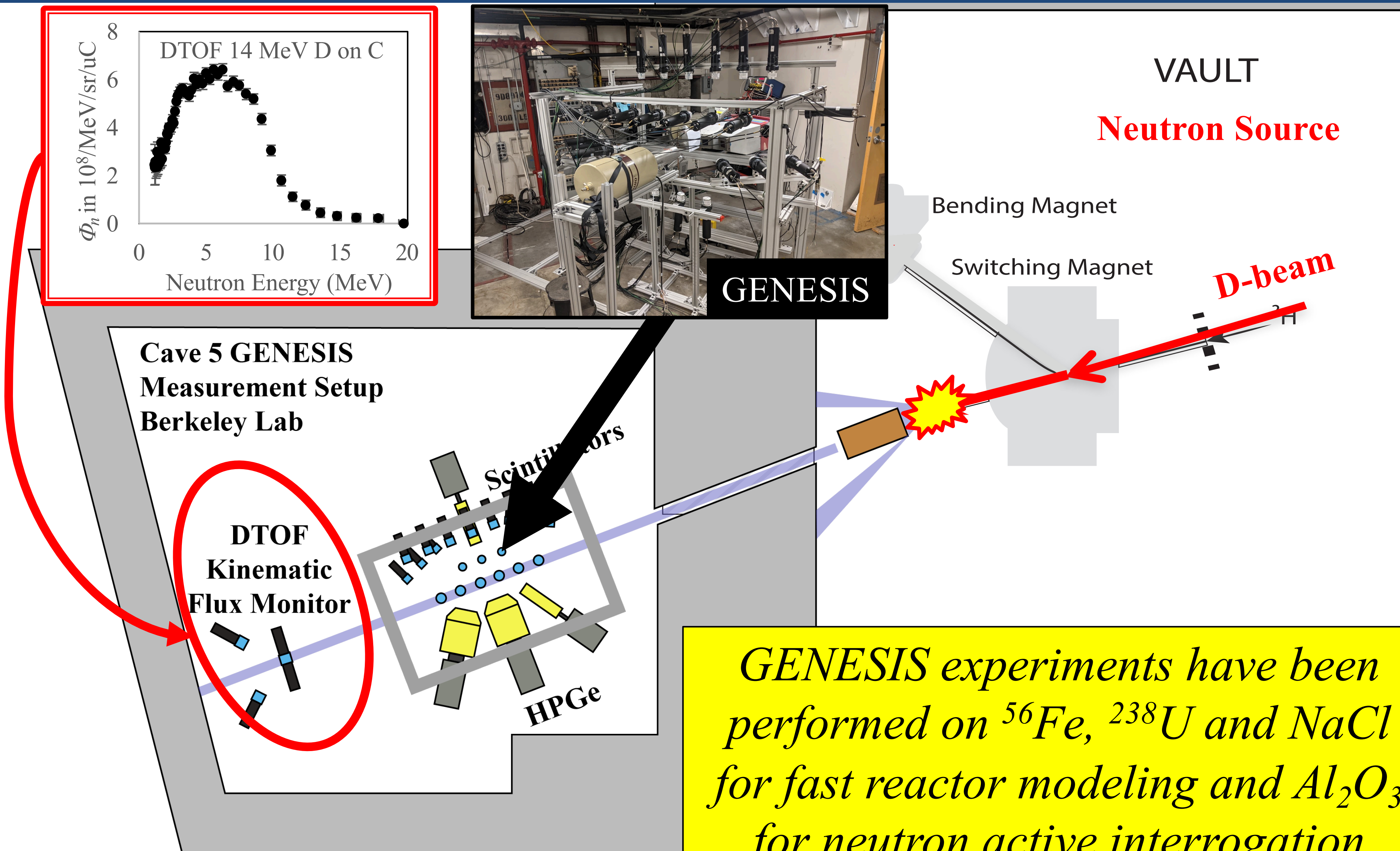
# We benchmarked the model for 40 MeV deuterons on a thick Be breakup target using activation and time-of-flight




$$\iint_{\theta,E_n}^{all} {}^{d^2\sigma}\!/_{dE_n d\theta_n}\, d(\cos\theta)\, d\phi \approx \mathbf{1-10\%}\ depending\ on\ E_D$$

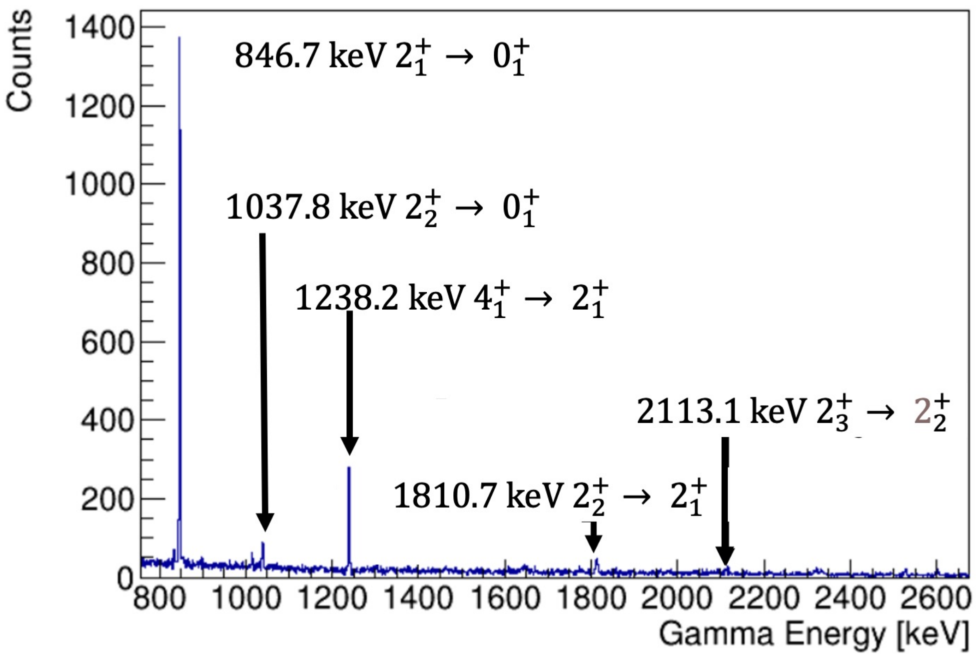
# We use these neutrons to measure *(n,xnγ)* using the Gamma Energy Neutron Energy Spectrometer for Inelastic Scattering (GENESIS)




*GENESIS experiments have been performed on $^{56}$Fe, $^{238}$U and NaCl for fast reactor modeling and $Al_2O_3$ for neutron active interrogation*

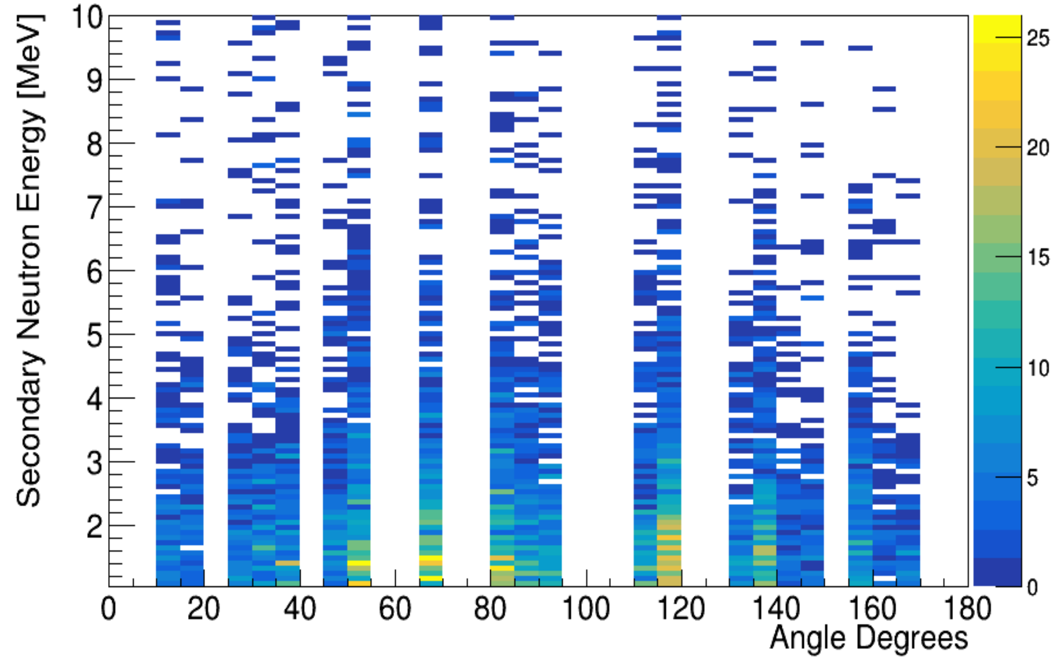
# $^{56}$Fe GENESIS data ( $2^+ \longrightarrow 0^+$ (847 keV) ratio

$N_\gamma(E_\gamma)$
gated on prompt neutrons




Gamma-rays up to 10 MeV measured for incident $E_n$ from 10 keV to 20 MeV

$N_n(E_n, \theta_n)$ gated on the 847 keV $2_1^+ \rightarrow 0_1^+$



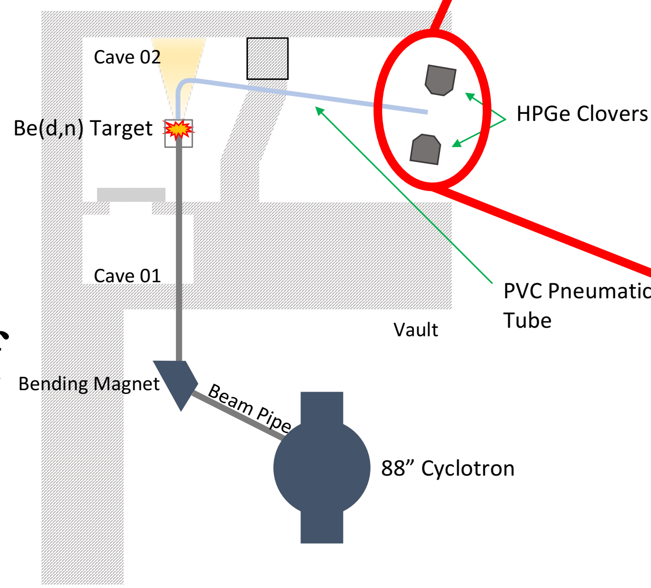

Majority of neutrons have $E_n \leq 4$ MeV, which is consistent with significant compound emission

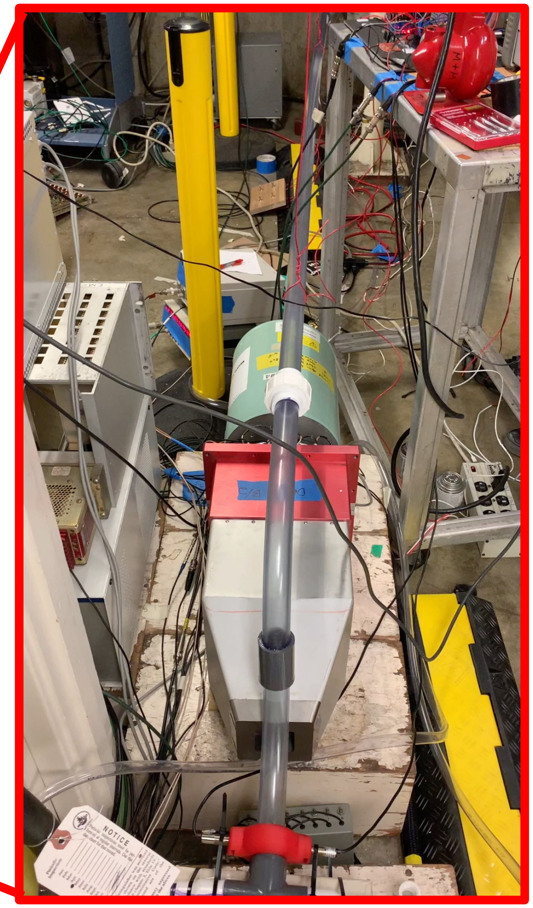
**GENESIS will not only produce data needed for active interrogation but will also lead to improved shielding**

J.M. Gordon

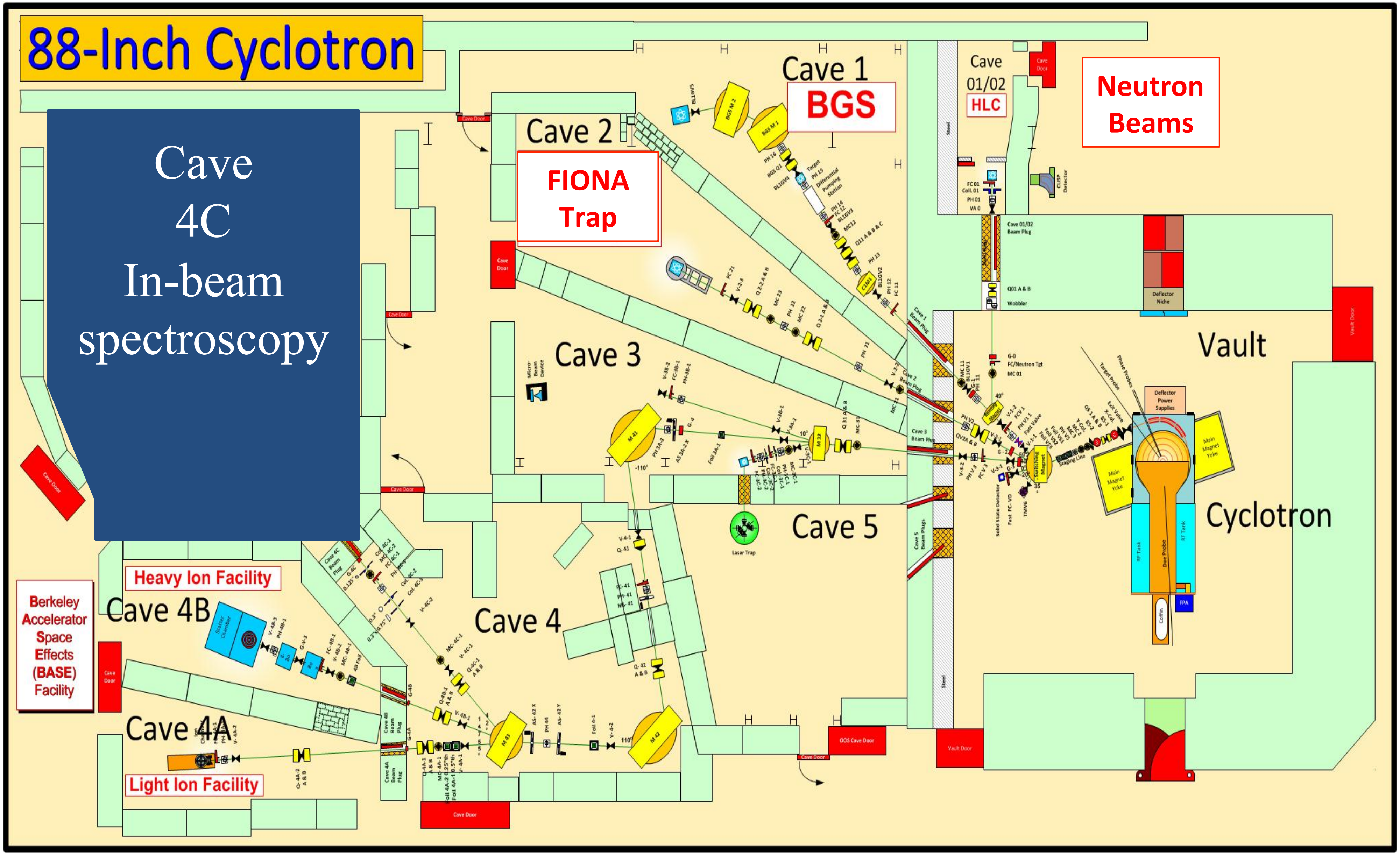
# In Cave 0 we can also perform cyclical neutron irradiations and measure activities with $t_{1/2} > 0.5\ s$

- The Fast Loading User Facility for Fission Yields (FLUFFY) has been developed at LBNL to rapidly shuttle actinide samples between a neutron source and counting array.
- Transport times: **<1 s**
- Flux: $\mathbf{8.3 \times 10^8\ n/cm^2/s}$
- This high flux along with the rapid transport time allows for the observation of 80+% of the yield in peak mass chains.

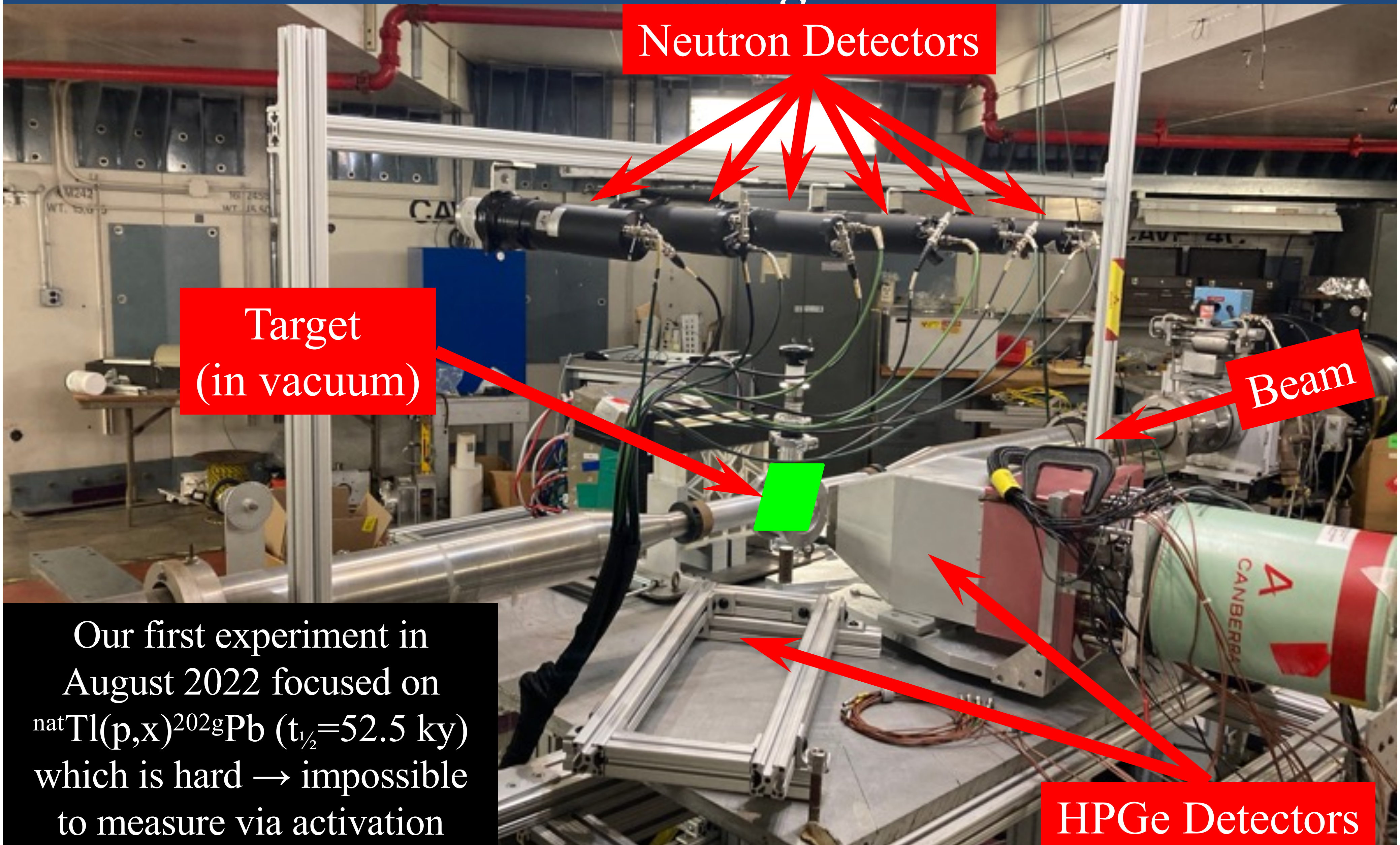


# In Cave 4C we can perform in-beam (p,xn+γ) measurements for Isotope Production



# In Cave 4C we can mount in-beam neutron-gamma coincident measurements using elements of GENESIS




Our first experiment in August 2022 focused on $^{nat}$Tl(p,x)$^{202g}$Pb ($t_{1/2}$=52.5 ky) which is hard → impossible to measure via activation

# Summary

- The 88-Inch cyclotron provides a broad range of light-ion and neutron beams that can be used to address outstanding nuclear data needs for isotope production, nonproliferation, stopping power measurements and space effects testing including:
  - Stacked target charged particle activation technique;
  - $(n,xn\gamma)$ cross section measurements using GENESIS;
  - Cyclical neutron irradiation for fission yield using FLUFFY;
  - In-beam $(p,xn\gamma)$ coincident measurements (Cave 4C), and
  - Charged-particle stopping power measurements (not shown)
- Our research shows that significant changes are needed to reaction modeling to ensure that accelerator-driven isotope production is optimized for both yield and purity.

# Thank You!

*Catherine Apgar[1], Jon Batchelder[1], Lee Bernstein[1,2], Eva Birnbaum[3], Cathy Cutler[4], Morgan Fox[1*], Arjan Koning[5], Amanda Lewis[1**], Dmitri Medvedev[4], Jonathan Morrell[3***], Meiring Nortier[3], Ellen O'Brien[3], Etienne Vermeulen[3], Andrew Voyles[1]*

[1] *University of California-Berkeley Dept. of Nuclear Engineering*
[2] *Lawrence Berkeley National Laboratory*
[3] *Los Alamos National Laboratory*
[6] *ABrookhaven National Laboratory*
[**] *Now at Terrestrial Energy (Canada)*
[**] *Now at Naval Nuclear Laboratory*
[***] *Now at Los Alamos National Laboratory*

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