The Berkeley Atlas

A database of neutron-induced gamma-ray production cross sections at 14 MeV

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The Berkeley Atlas Team

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Early Career

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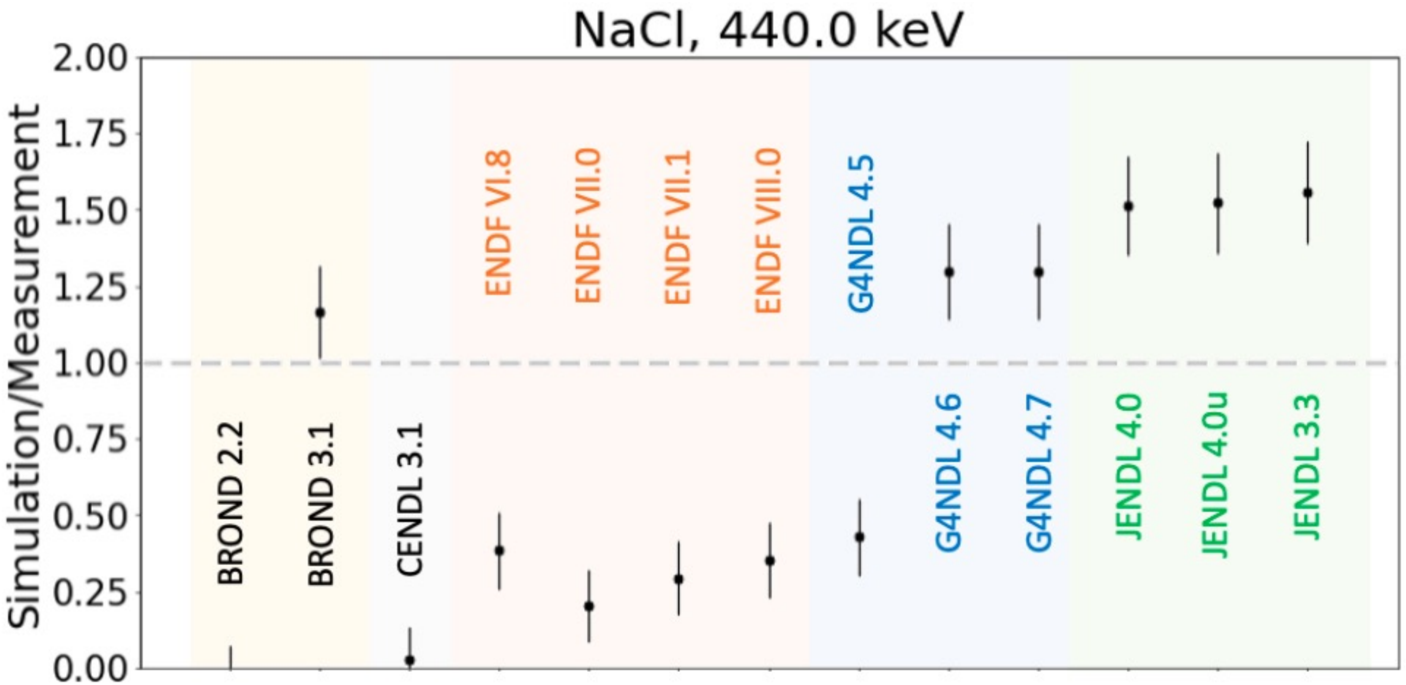
Motivation – Nuclear Data Deficiencies

- Experimental work has revealed that nuclear data is not sufficient for many elements of interest. Improved nuclear data is required.
- Prior efforts in this area have identified:
  - Spurious (not-real) gamma-ray peaks
    - *Lim et al.,* (2017)
    - *Mauborgne et al.* (2020)
  - Unphysical gamma-ray emission energy distributions (peak shapes):
    - *Prettyman et al.* (2006)
    - *Peplowski* (2020)
  - Inaccurate gamma-ray production rates
    - *Yamashita et al.* (2003)
    - *Bruckner et al.* (2011)
    - *Mauborgne et al.* (2020)
    - *Peplowski* (2020).



GEANT4 fails to reproduced 440-keV gamma-ray production from Na, as measured during a benchmarking experiment detailed by Peplowski (2020).

Applications: Explosive detection, Buried land mines, **Planetary Science,** Chemical weapons, UXO analysis, Drug detection, In-Vivo body composition, Minerals mining and exploration, Bulk materials (coal, cement)

Berkeley Atlas Project

- Leverage an existing DT + API system & extensive experience to produce an atlas of cross sections, measured at 14 MeV neutron energy
  - Upgrade the system to include an array of HPGe detectors
  - Here, "atlas" means identical measurements on a range of target materials of interest for applied nuclear sciences.
- Provide cross-section measurements to the NNDC for evaluation and incorporation into future neutron cross section libraries releases.

Table 2. Preliminary list of target isotopes and gamma-rays for this study

Isotope	Gamma-Ray Lines (keV)	Isotope	Gamma-Ray Lines (keV)	Isotope	Gamma-Ray Lines (keV)
^{12}C	**4438**	^{35}Cl	1763	^{59}Co	1099, 1190, 1292, 1459, 1481
^{14}N	**2313**	^{39}K	1454	**^{58}Ni**	**1454**
^{16}O	**6129**	^{40}Ca	3736	**^{60}Ni**	**1332**
^{23}Na	**440, 1634**	^{48}Ti	983	^{63}Cu	670, 962
^{24}Mg	**1369**	^{52}Cr	1434	^{65}Cu	771
^{26}Mg	**1809**	^{54}Cr	834	^{64}Zn	992
^{27}Al	**843, 1014, 2211**	^{55}Mn	858	^{66}Zn	1039, 1873
^{28}Si	**1779**	**^{54}Fe**	**1408**	^{90}Zr	1761
^{32}S	2232	**^{56}Fe**	**846, 1238, 1811**	^{208}Pb	2616

The Atlas will include gamma-ray production cross sections for 27 different isotopes (38 different gamma-ray emissions) for materials of interest to the wide variety of applied nuclear fields listed previously.

Associated Particle Imaging (API)

DT-API tags emitted 14 MeV neutrons with corresponding alpha particle, addressing the challenges presented:

1) Counting alphas → direct measure of neutrons on target
2) Position + time resolution allows background suppression.
3) Alpha-gamma coincidence ensures prompt reactions only.

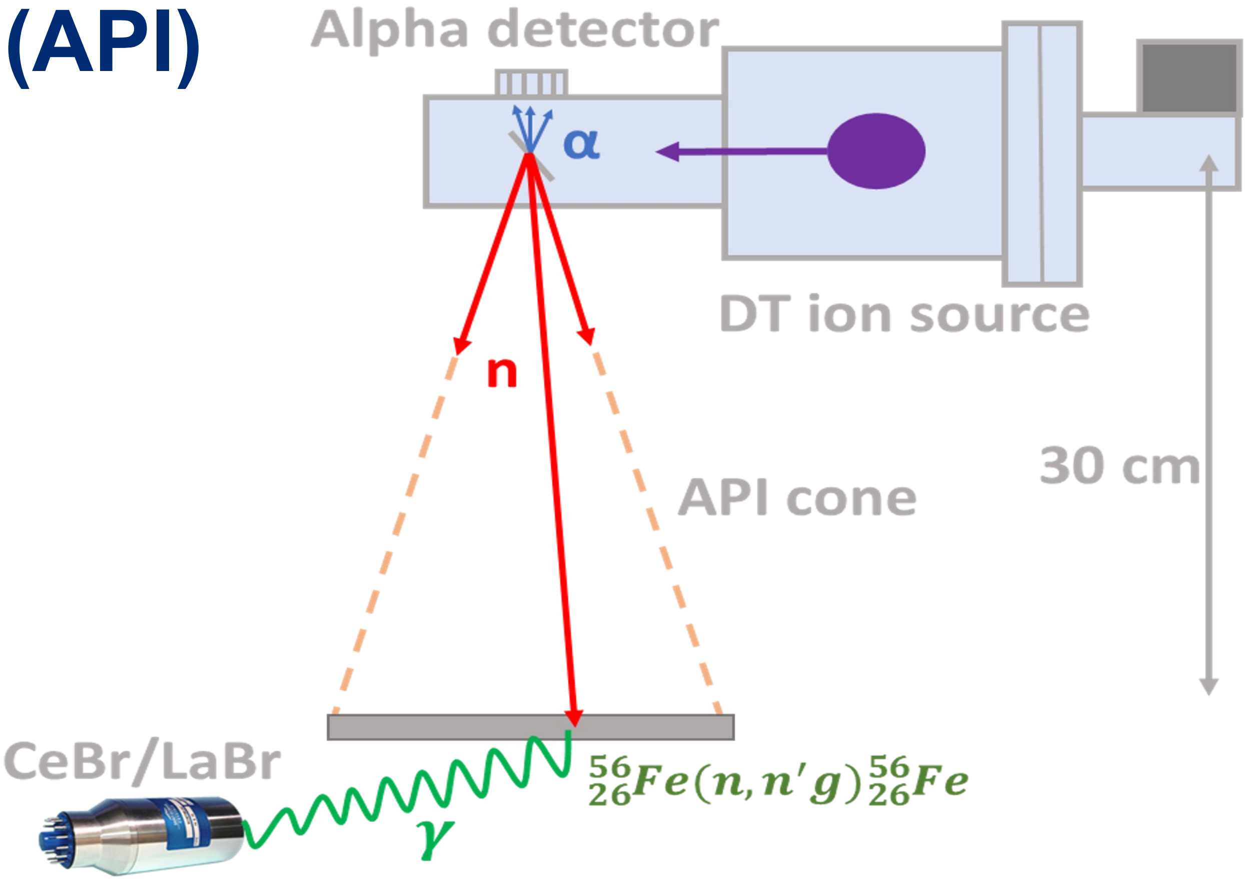
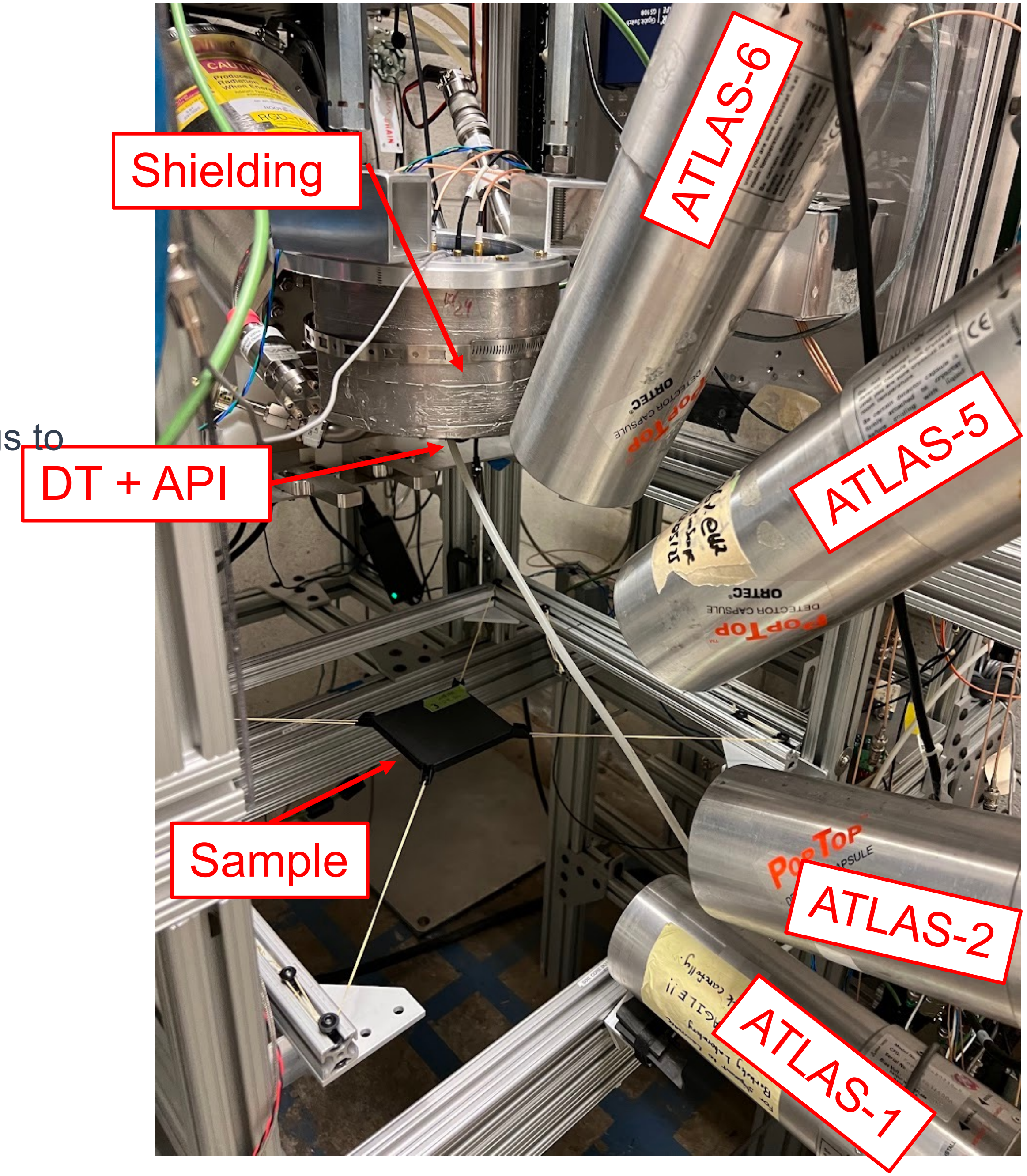


Table 1: Results of this work as compared to some accepted literature values.

Organization	Year	Energy (Mev)	σ - 847 keV (mb)	σ - 1238 keV (mb)
LBL [Ayllon-Unzueta et al, 2022]	2022	14.1 ± ?	695 ± 5.1%	339 ± 5.1%
GELINA [Negret et al., 2014]	2014	14.14 ± 0.14	699 ± 4.1%	356 ± 5.0%
LANL [Nelson et al., 2005]	2004	14.50 ± 0.10	705 ± 3%	N/A
ORNL [Dickens et al., 1990]]	1990	14.53 ± 0.56	621 ± 4.7%	290 ± 5.5%
Talys [TALYS, 2023]	-	14.1	741	386

Year 2 Accomplishments: Incorporating an array of HPGe

- DT neutron generator w/ API
  - API: YAP scintillator + pixelated PMT readout
  - Thin (XX) Cu target w/ angled orientation to limit alpha particle and neutron scattering
  - Low-mass sample holder, suspended on Kevlar strings to minimize material in the neutron cone
- 4-module array of HPGe detectors



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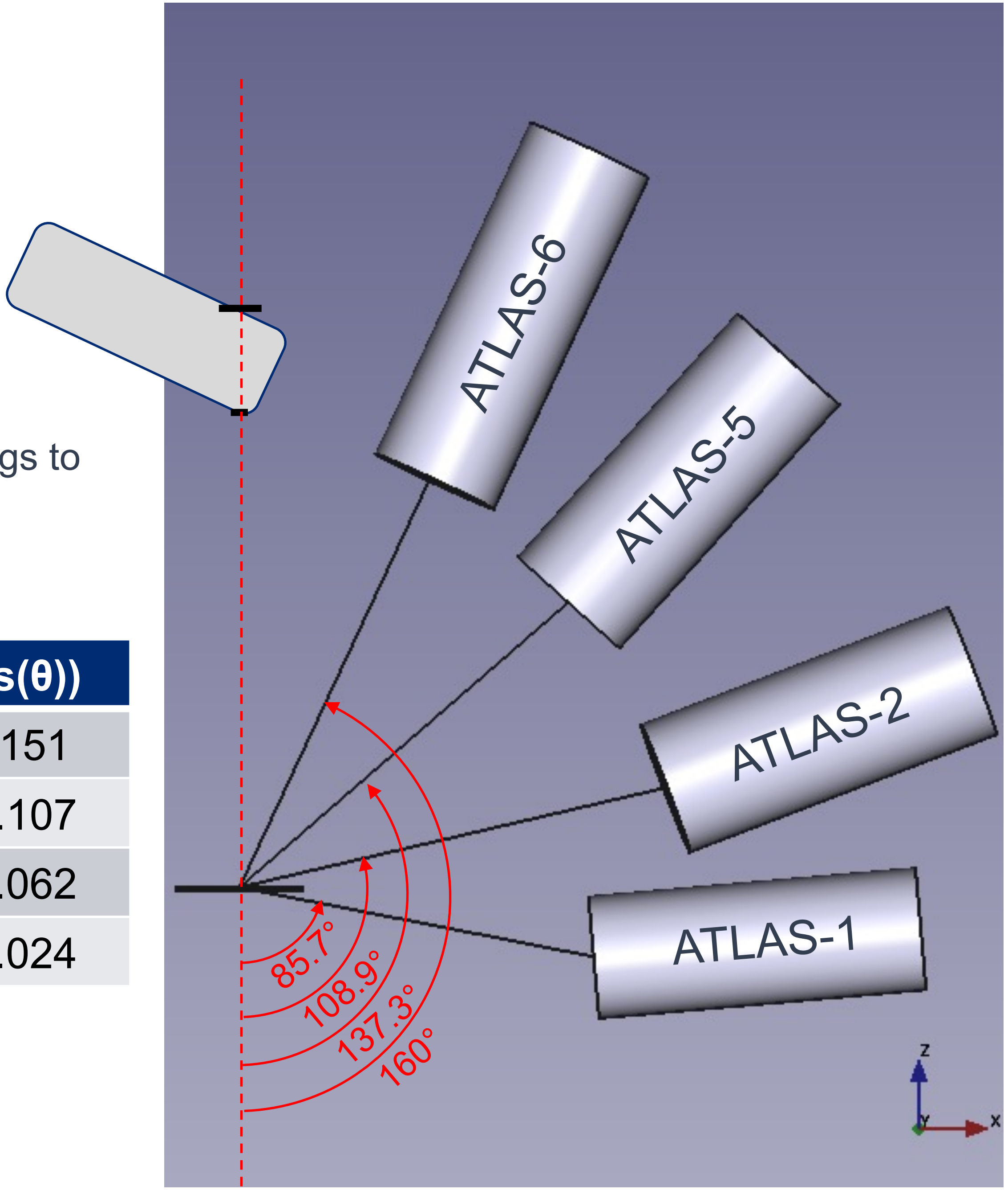
Detector	Efficiency	Angle (deg)	Angle (cos(θ))
ATLAS-1	74%	85.7 ± 8.7	0.075 ± 0.151
ATLAS-2	118%	108.9 ± 6.5	-0.324 ± 0.107
ATLAS-5	88%	137.3 ± 5.2	-0.735 ± 0.062
ATLAS-6	81%	160 ± 4	-0.940 ± 0.024



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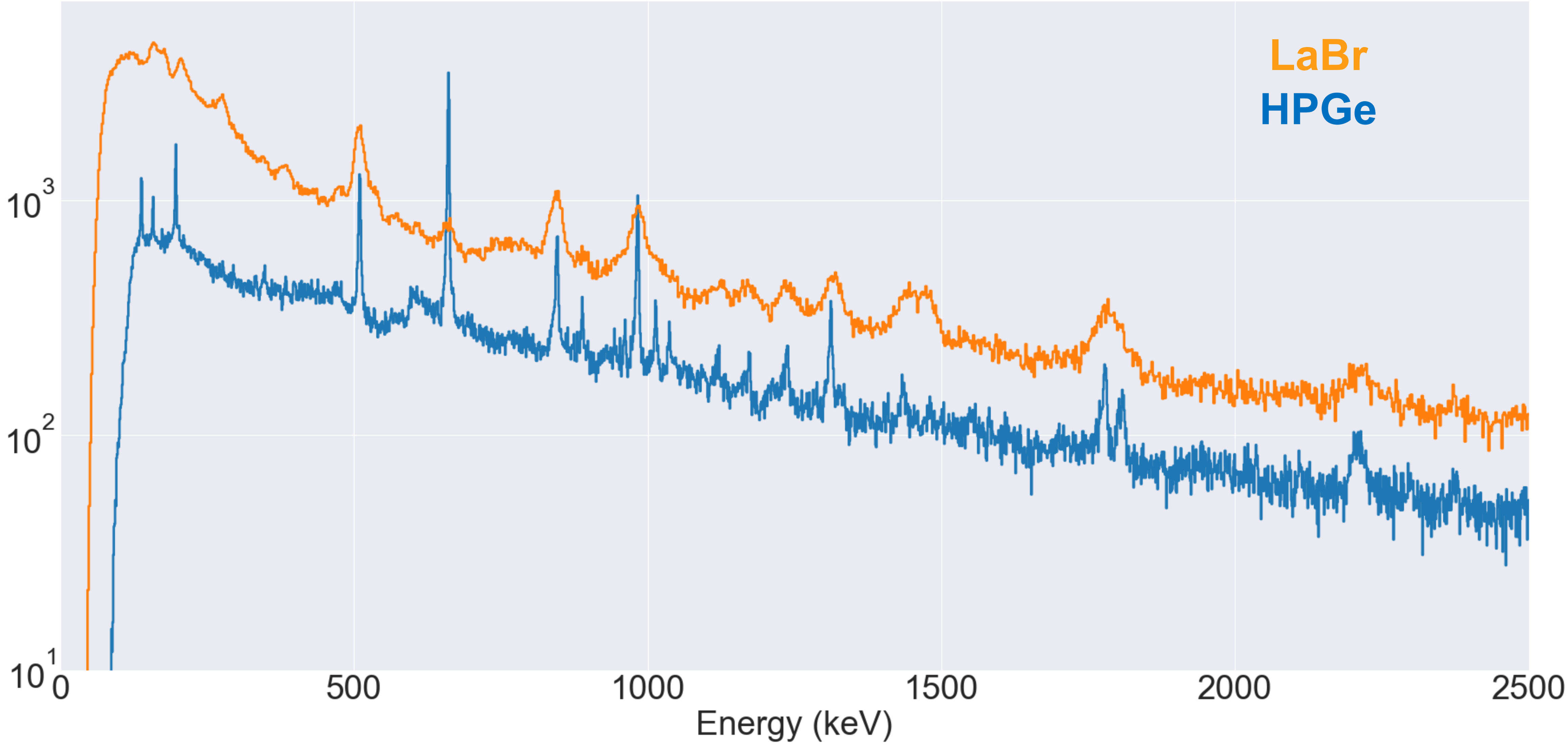
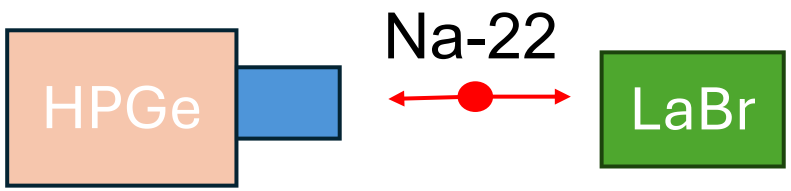
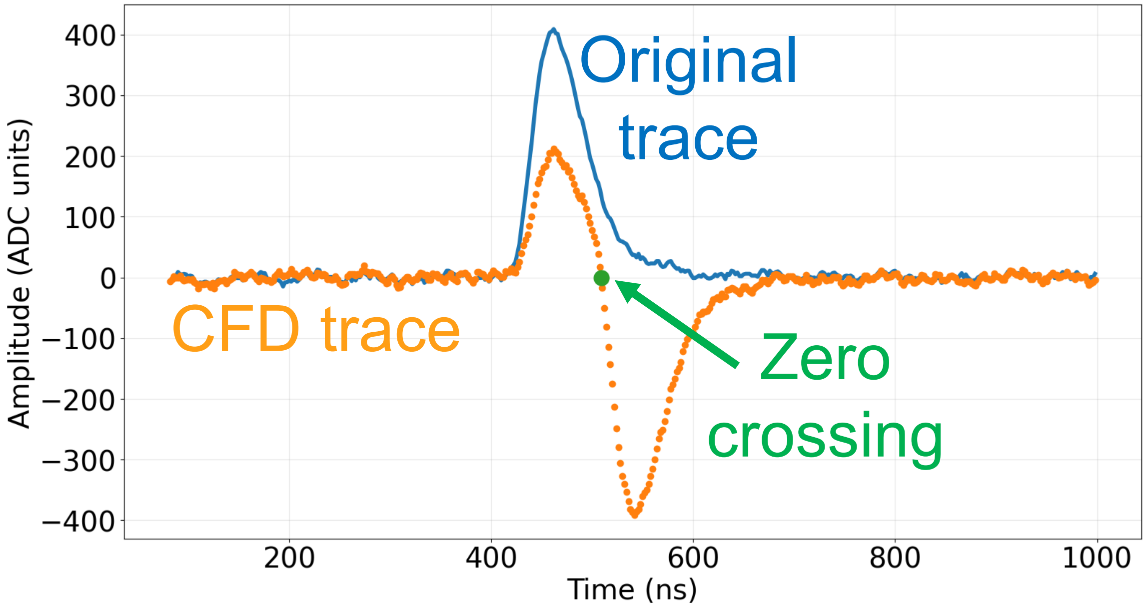


Year 2 Accomplishments:
Improving the time-resolution of the HPGe detectors

- Optimizing Constant Fraction Discrimination (CFD) parameters:
  - γ- γ coincidence from Na-22 source (511-keV) was used to develop the timing approach for the new HPGe detectors.



LaBr (Heritage Approach)



$$CFD_i = \sum \omega f_i(t) - f_i(t - D)$$

Constant fraction

Delay

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The slow charge collection of HPGe initially lead to very poor timing performance:
- 30 ns (HPGe) vs. 2 ns ($LaBr_3$)

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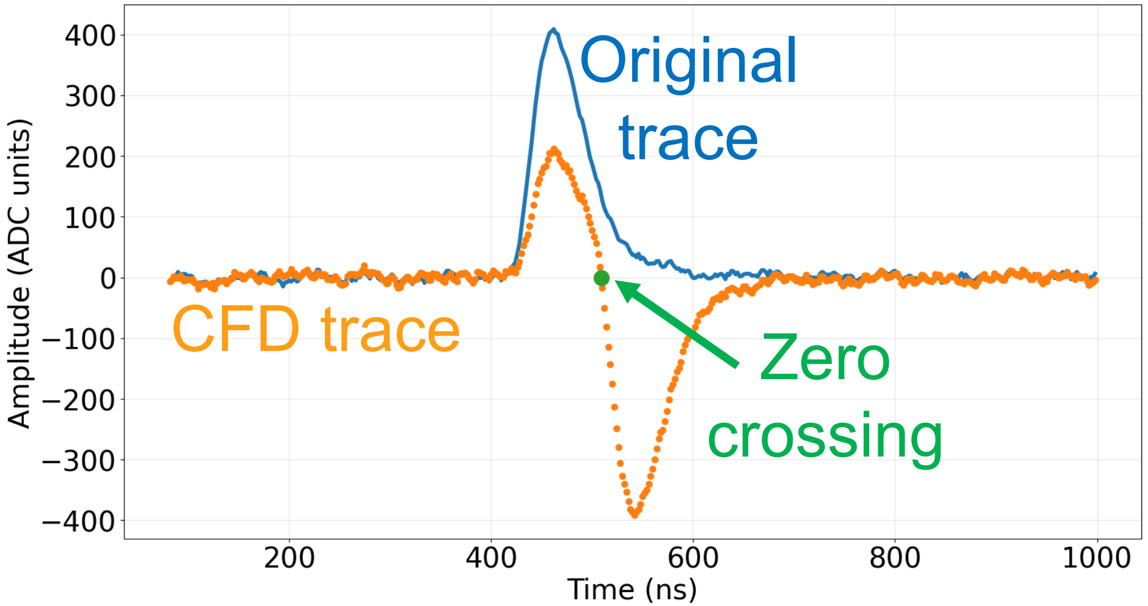
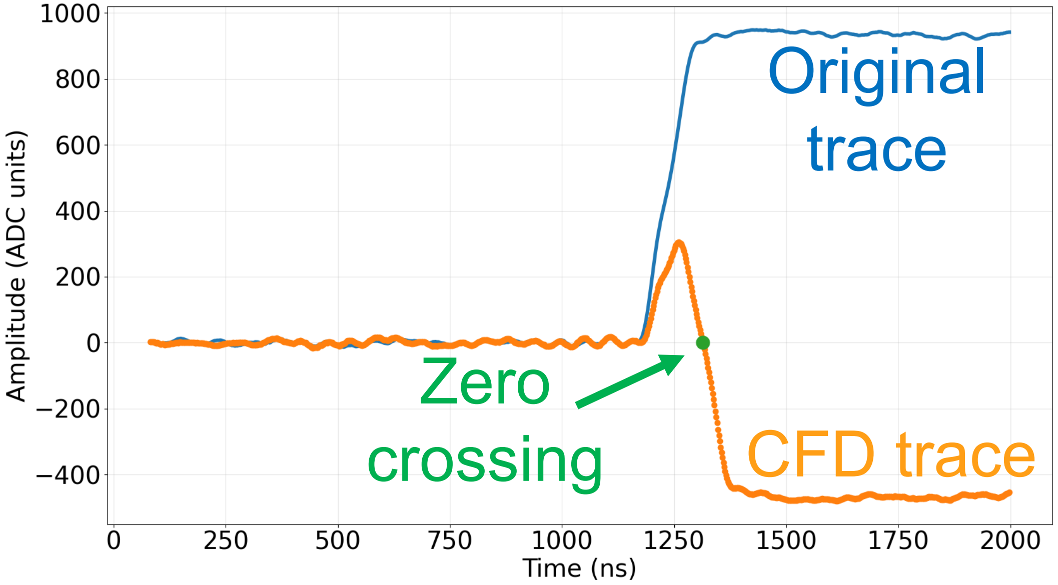
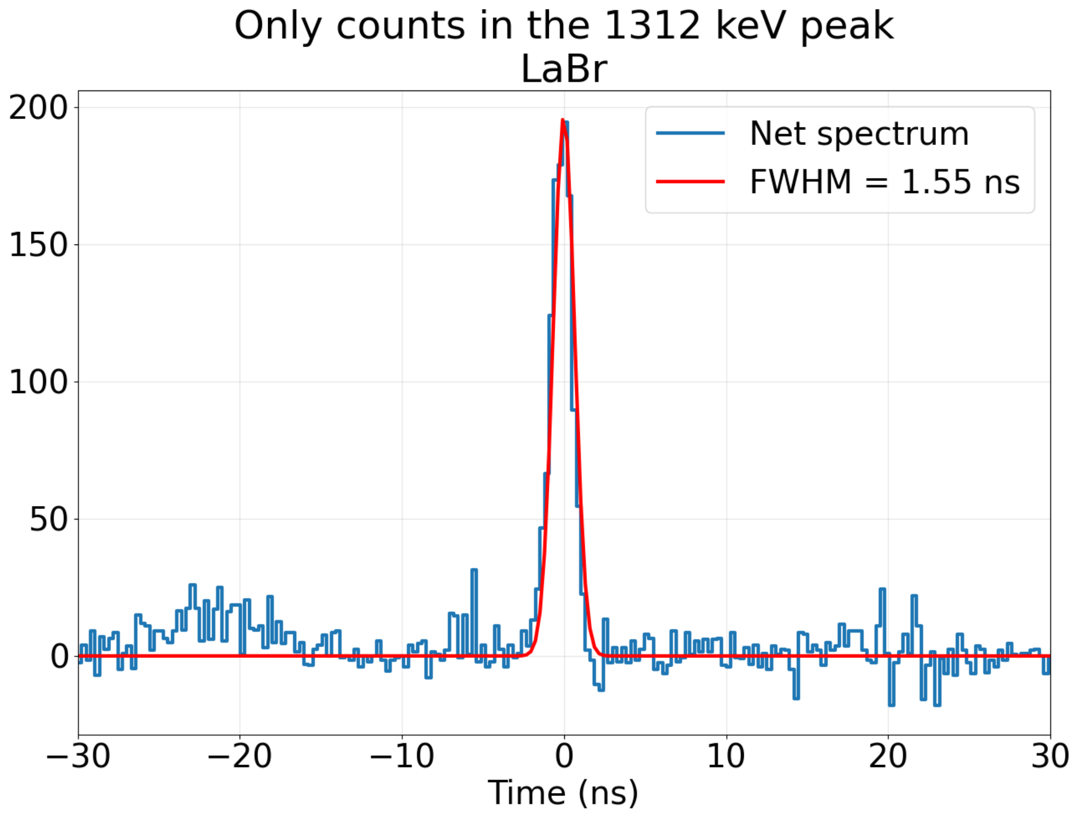


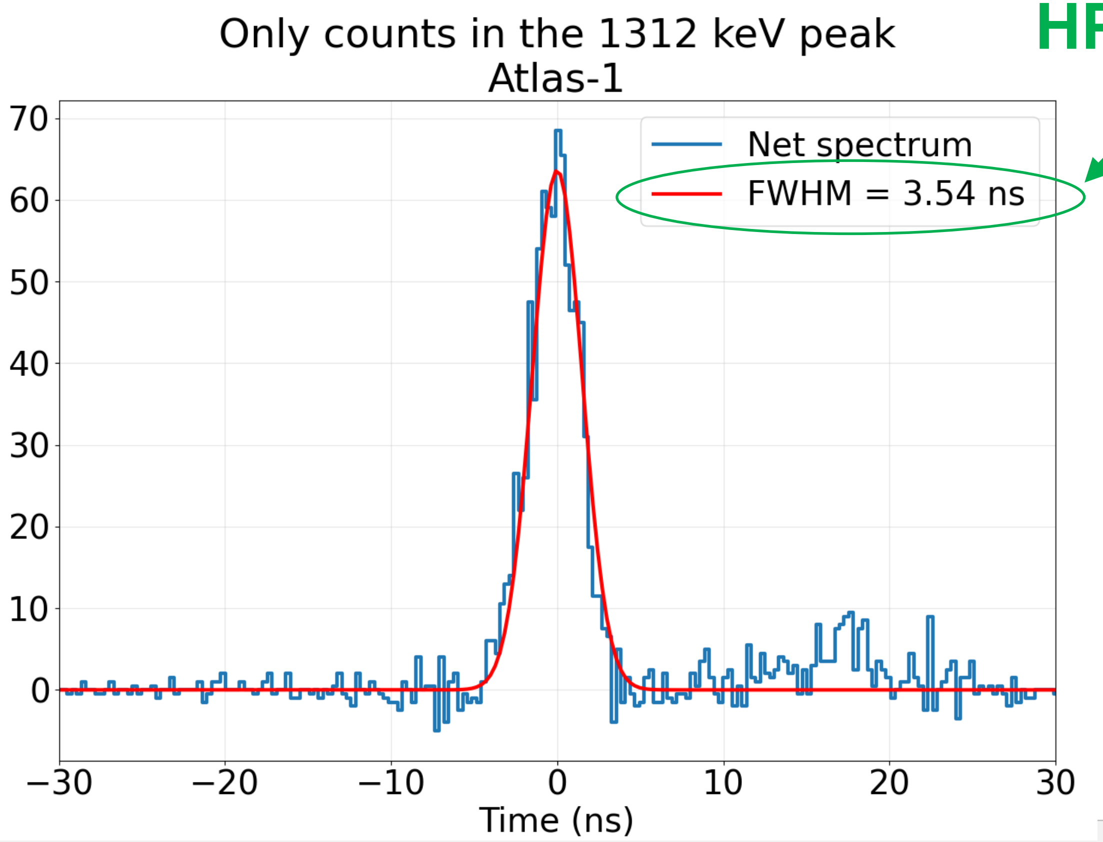
New HPGe Detectors



Year 2 Accomplishments:
Improving the time-resolution of the HPGe detectors

- We designed a new process wherein we log the charge collection trace for each event, then perform the CFD analysis to improve the timing.
  - We achieved a system 3.5 ns resolution with HPGe detectors – factor of 10 improvement!





Extremely good for HPGe!!

Year 2 Accomplishments:
First round of measurements

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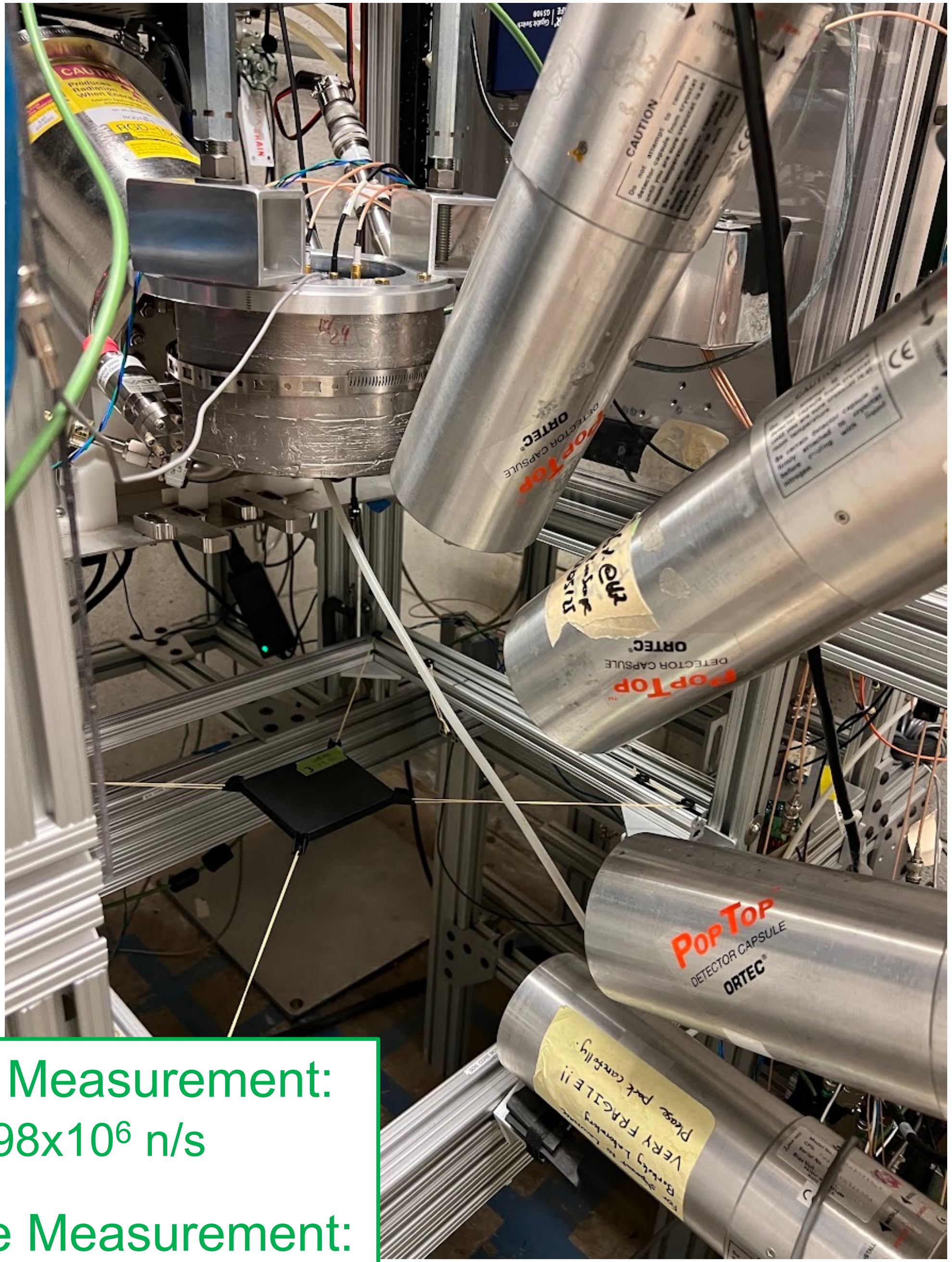
Additionally, we have observed $^{27}Al(n,n'p)^{26}Mg$

Year 2 Accomplishments: Data Analysis

- **Data selection**
  - **Paired sample and no-sample (background) measurements**
- XY cut
  - Use position information to remove γ-ray signals from neutrons not illuminating the sample
- dt calibration & cut
  - Calibrate time values (dt) and use dt information to remove γ-ray signals not originating from the target
- Energy calibration
  - Calibrate & sum γ-ray spectra
- γ-ray peak event summing
  - Sample and no-sample measurements
- Neutron fluence calculation & normalization
- Calculate cross section



Al Sample Measurement:
30.0 hrs, 1.98×10^{6} n/s

No Sample Measurement:
11.0 hrs, 1.88×10^{6} n/s

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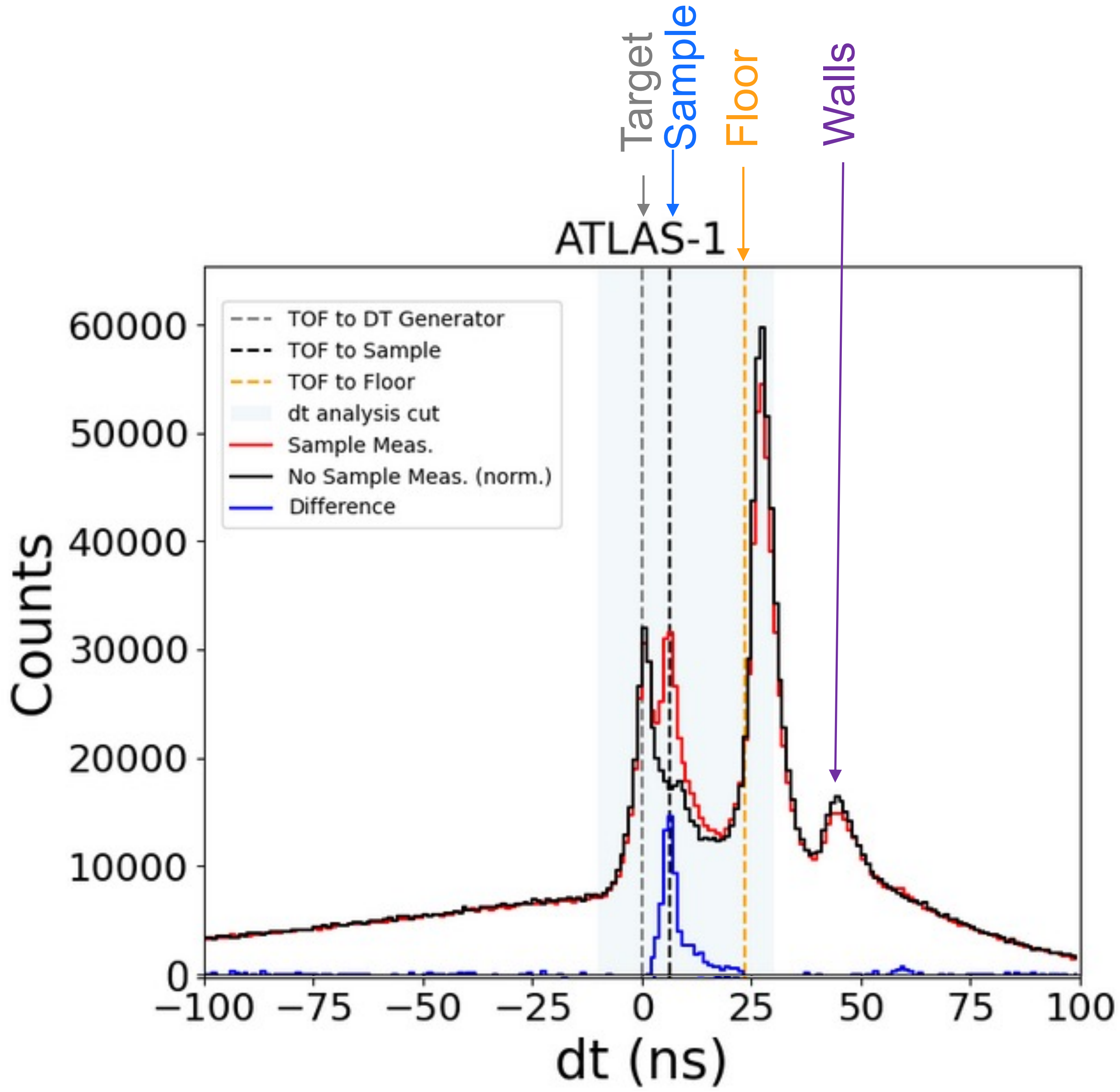

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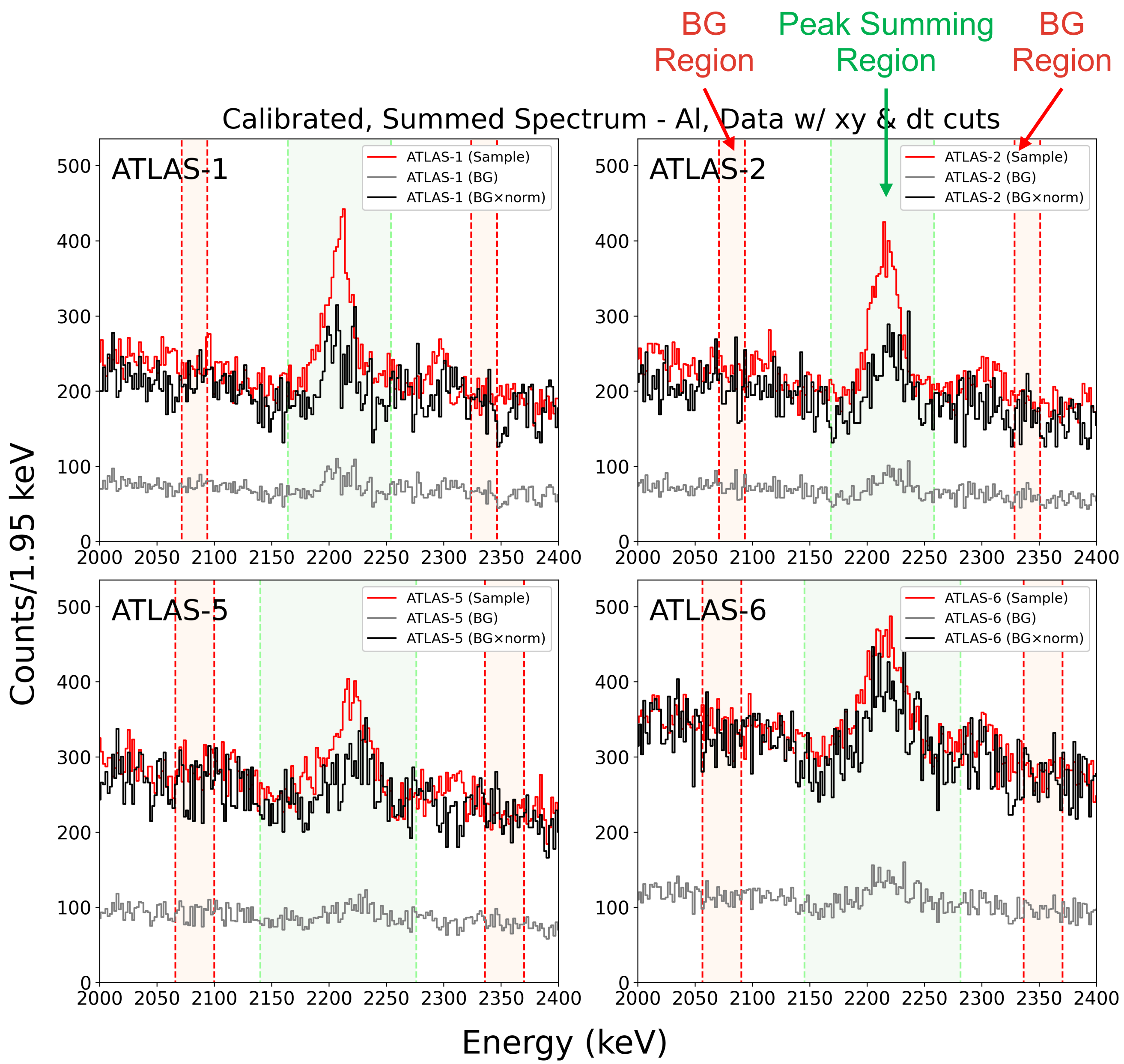

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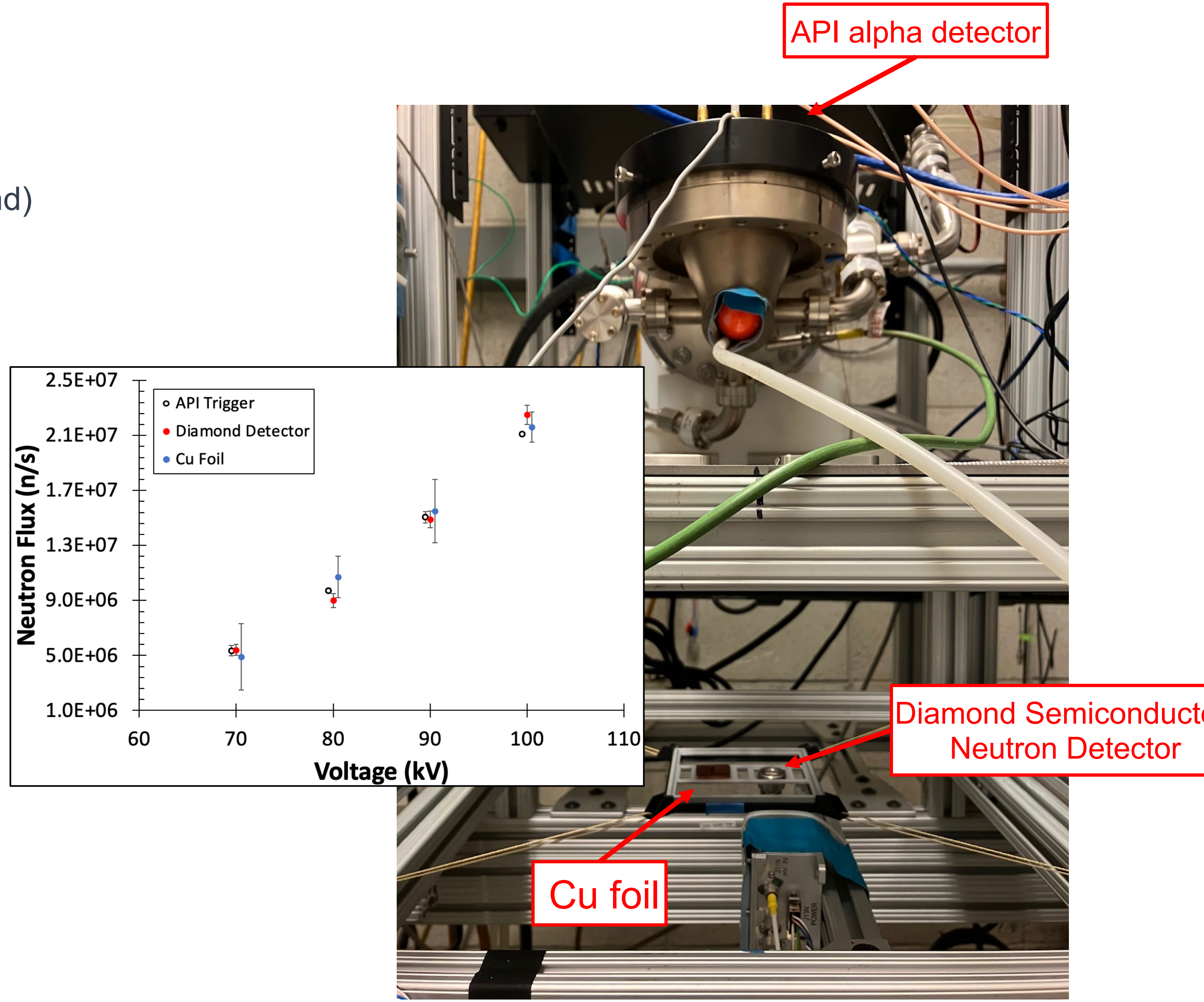


Year 2 Accomplishments:
Modeling ^{27}Al(n,n'γ) partial cross sections

Calculations include:

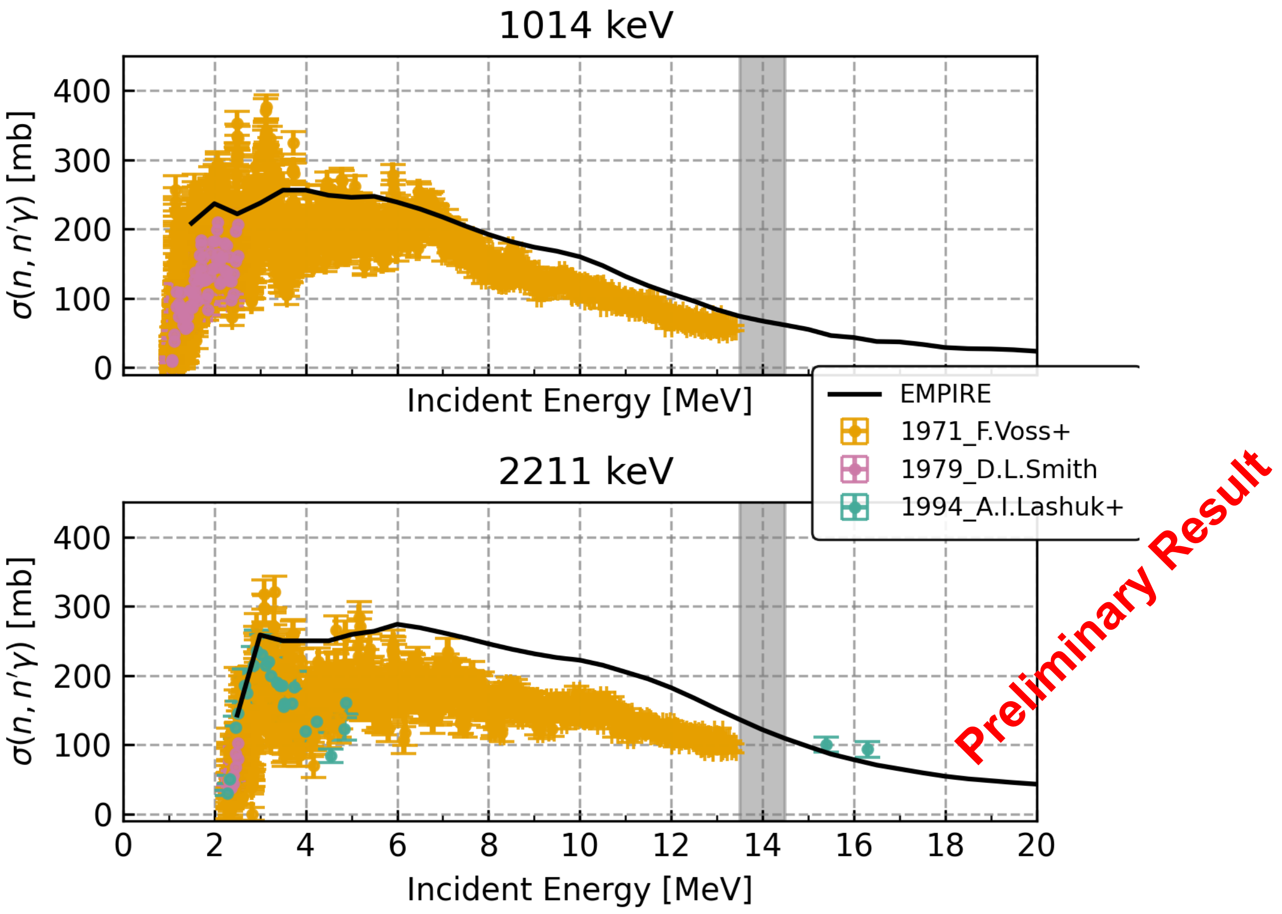
- *"fast" region;*
- Direct level population + feeding from higher levels + Continuum population and decay.

$$\sigma(n, n'\gamma) = \sigma_{\text{dir}} + \sigma_{\text{feed}} + \sigma_{\text{cont}}$$

Ongoing:

- Tune continuum γ-decay / feeding (level density + γ-strength / branching) to reduce the 2211-keV (keep 1014 keV);
- Add (n,npγ_{1809}) as a constraint on decay competition.

Reaction	σ_{EMPIRE} [mb]
^{27}Al(n,n'γ_{1014})^{27}Al	67.28
^{27}Al(n,n'γ_{2211})^{27}Al	121.47



Summary and Project Status

- The Berkeley Atlas Project is:
  - Creating a new database of nuclear reaction data that is directly responsive to needs outlined in the WANDA 2021 report (*Kolos et al.*, 2022).
  - Working at all points of the nuclear data pipeline – including measurement, evaluation, modeling, library production, and application.
  - Educating the next generation of nuclear data scientists.
- We are in the final year of our three-year long project.
  - In 2025, we completed the first measurement campaign, which included C, O, Mg, Al, Si, Ti, and Fe.
  - We plan to resume the experiment soon and complete the measurements.
- We will produce a series of papers detailing the technique, our measurements, and supporting nuclear reaction modeling.
  - In addition to the proposed reactions, we expect to also report some (n,np) and (n,2n) reaction cross sections.
- Data will be used to update ENDF libraries in support of a broad range of applied nuclear sciences.

U.S. DEPARTMENT OF ENERGY | Office of Science

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Statistical and Systematic Uncertainties

Cross Section:

$$\sigma = \frac{(c_S - n_B c_B)}{T_L \epsilon \Omega a} \frac{1}{N_t N_n A}$$

Target:

$$N_t = \frac{\rho d N_A}{A_w}$$

Neutrons on Target:

$$N_n = t_{CH9} \frac{\Omega_{Sample}}{\Omega_{API}}$$

Term		Units	Type	Uncertainty	Notes
Counts in γ-ray peak (sample meas.)	c_s	n/a	Statistical	1 - 3%	varies by sample
Counts in γ-ray peak (background meas.)	c_b	n/a	Statistical	1 - 3%	varies by sample
Background normalization	n_b	n/a	Statistical	0.001%	API trigger rate
Live Time	T_L	s	Systematic	TBD	High rate, coincidence experiment
Photopeak detection efficiency - GEANT4 Benchmark - GEANT4 Statistics	ϵ	n/a	Systematic Statistical	3 – 10% ~0.1%	varies w/ energy, detector $\propto$ # of GEANT4 histories
Solid Angle	Ω	n/a	Systematic	2.5%	HPGe detector position accuracy
γ-ray attenuation (sample and detector housing)	a	n/a	Systematic	--	Assume GEANT4 is correct
Atom density of sample	N_t	cm^{-2}	Systematic	1%	Measured vs. ref. density & size of target
Neutron fluence on sample	N_n	cm^{-2}	Statistical Systematic	0.001% <5.5%	API trigger rate Geometry of API
Area of sample	A	cm^2	Systematic	0.04%	Geometry of sample