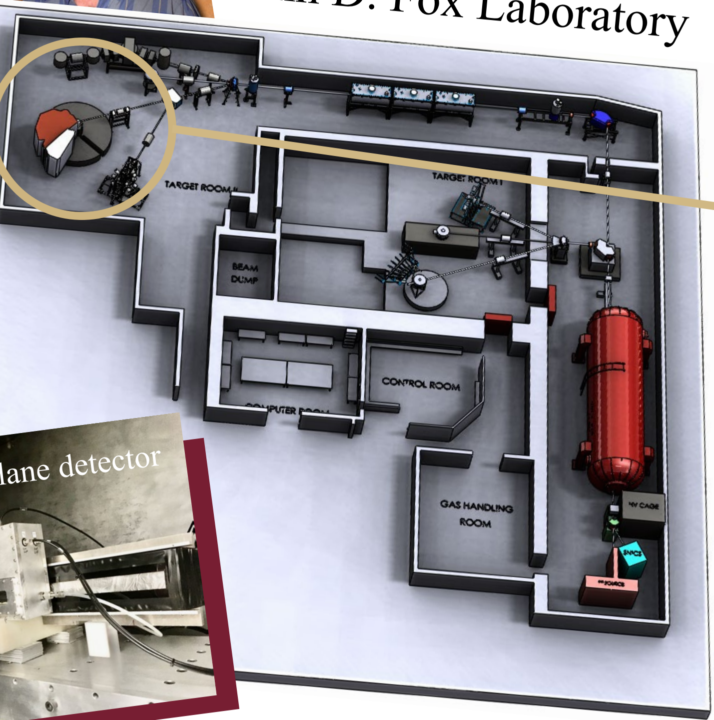
Nuclear Structure of Actinides with (t,p), the FSU Super-Enge Split-Pole Spectrograph and its ancillary detectors

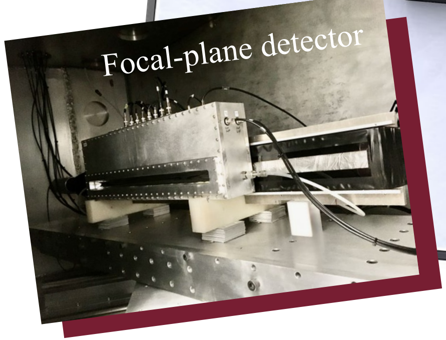
Dr. Mark-Christoph Spieker (FSU)

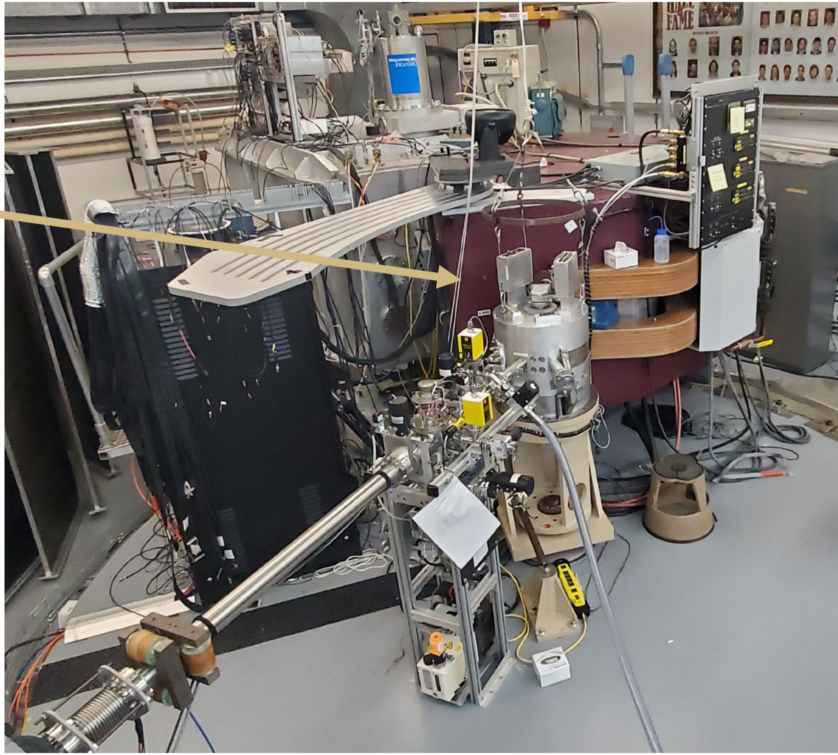
TRITON 2024, Department of Physics, Florida State University

The Super-Enge Split-Pole Spectrograph @ FSU

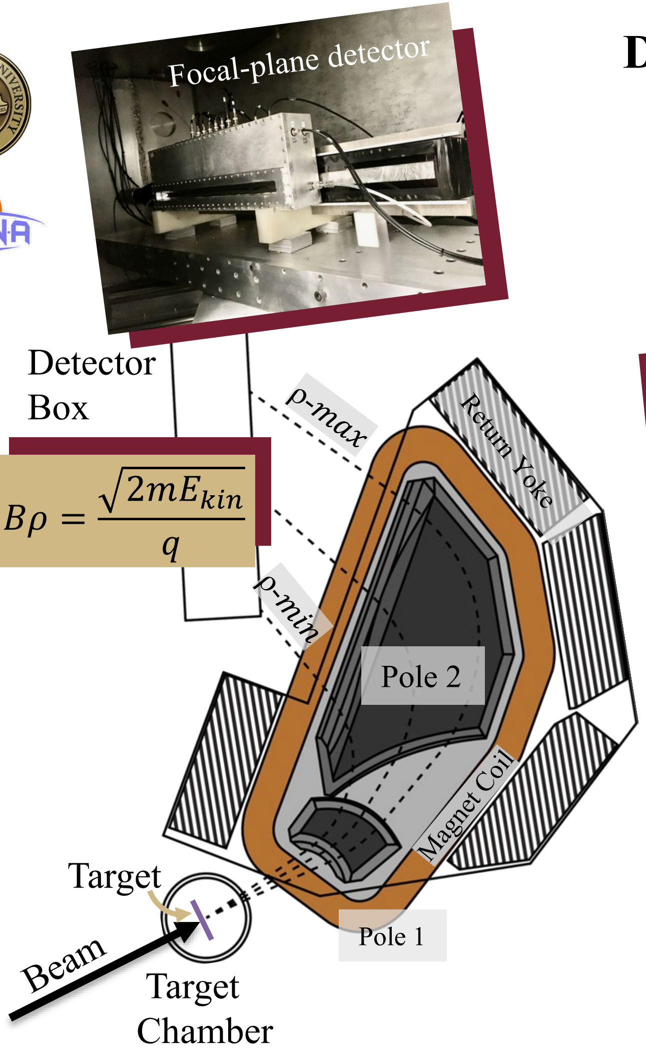
John D. Fox Laboratory







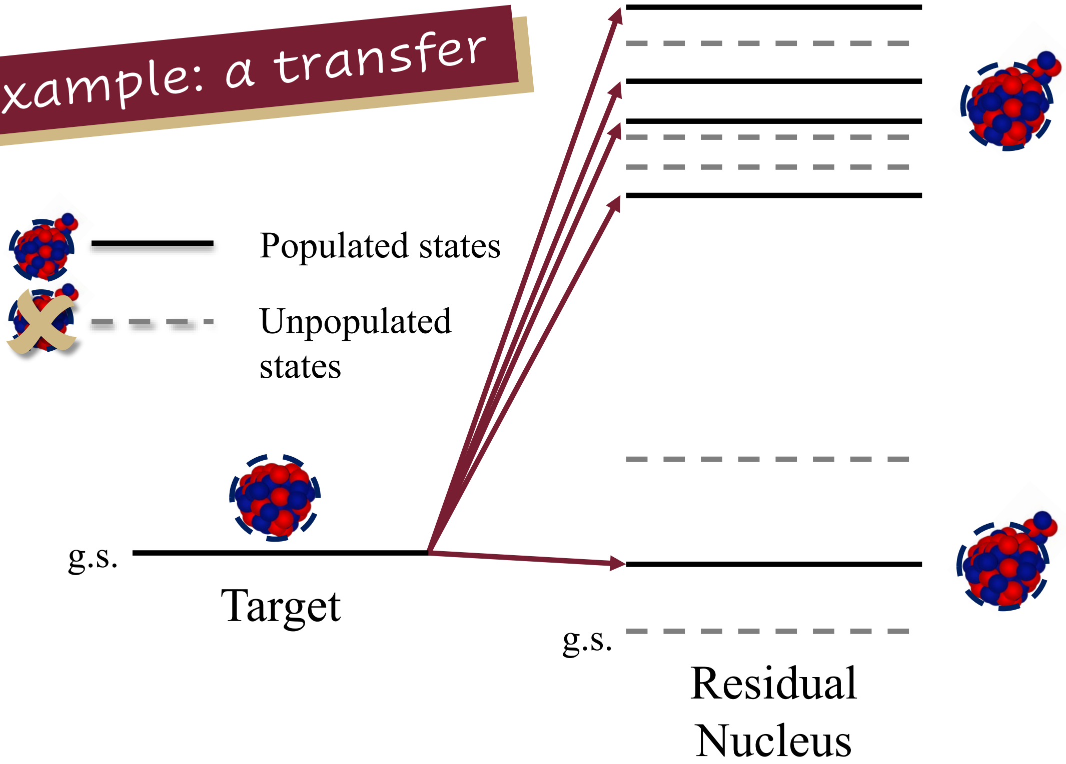
Direct reactions at the FSU SE-SPS [Selective population]



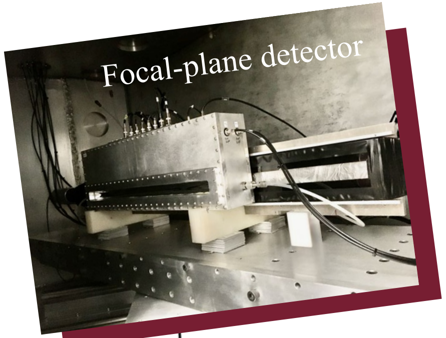
$$B\rho = \frac{\sqrt{2mE_{kin}}}{q}$$

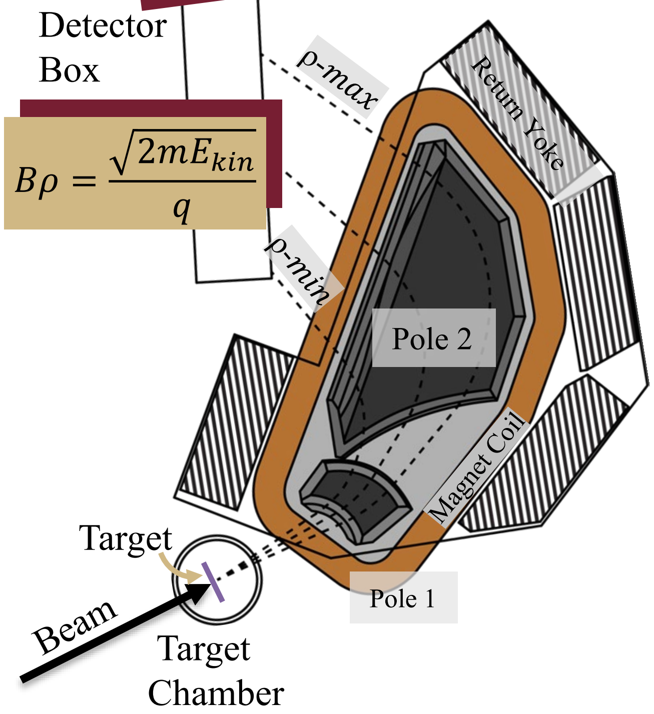
Use direct reactions to selectively populate excited states.

Example: a transfer



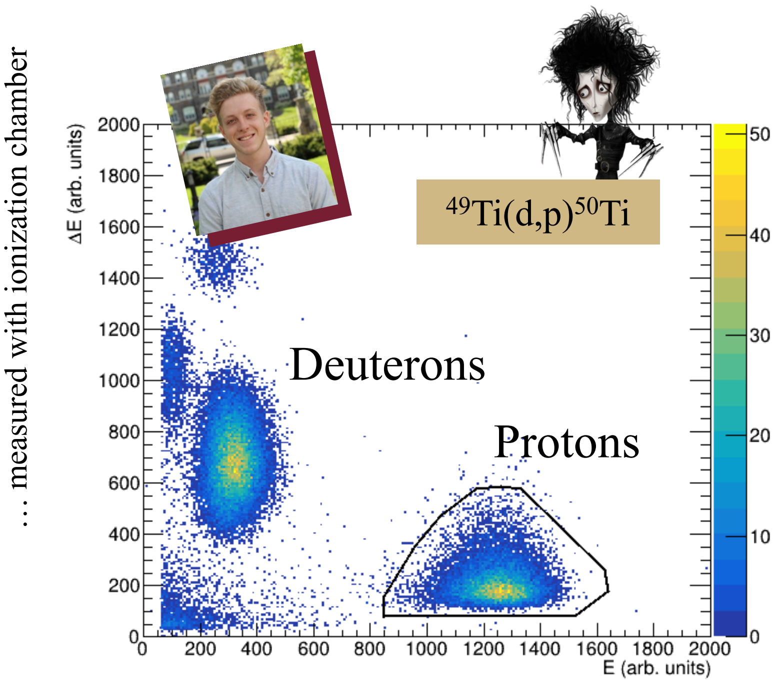
The Super-Enge Split-Pole Spectrograph @ FSU





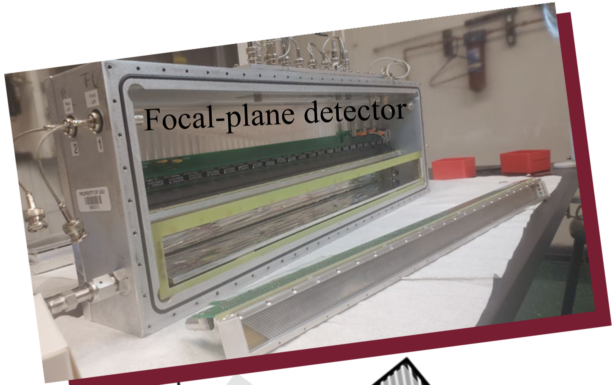
$$B\rho = \frac{\sqrt{2mE_{kin}}}{q}$$

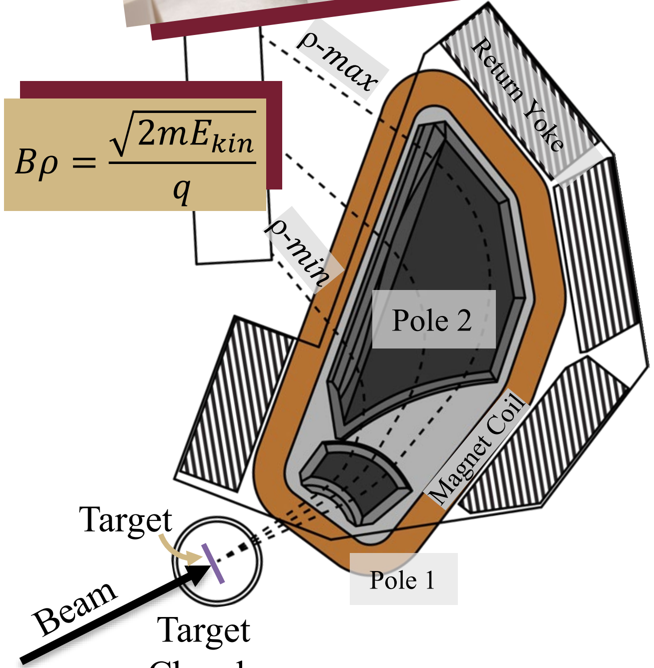
Particle identification to choose reaction of interest.



… measured with plastic scintillator

The Super-Enge Split-Pole Spectrograph @ FSU

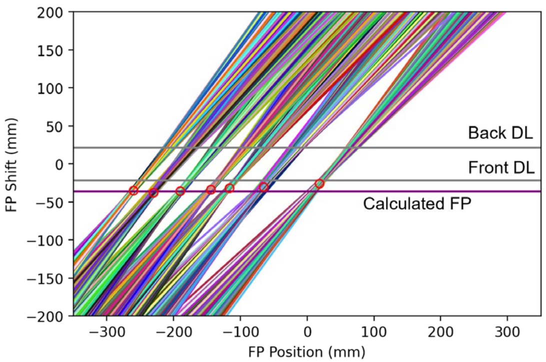




$$B\rho = \frac{\sqrt{2mE_{kin}}}{q}$$

Position resolution to identify excited states.

Ionization chamber with two anode wires, each inductively connected to pick-up pads, which are connected to delay-line chips.

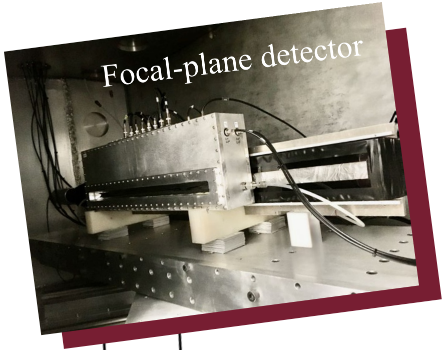


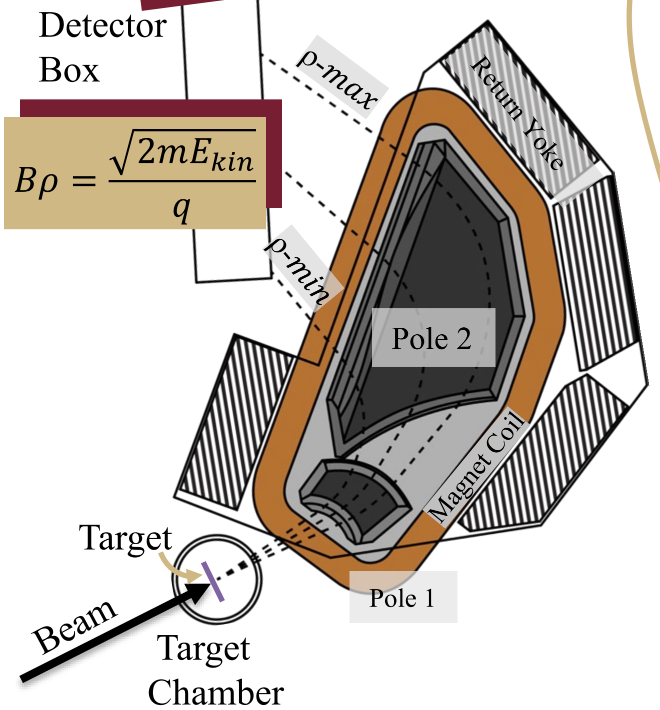
[Focal-plane figures courtesy of C. Benetti (FSU alumni; S. Tabor)]

We keep our focal plane detector position fixed and calculate the real focal plane position offline.

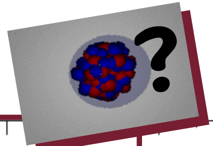
The Super-Enge Split-Pole Spectrograph @ FSU

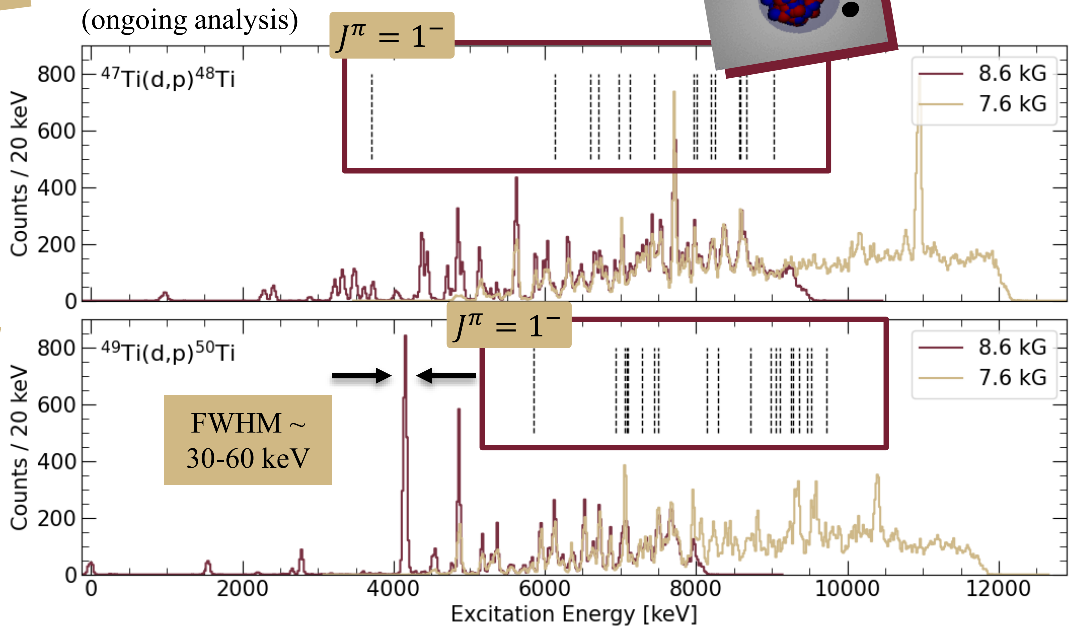
Position resolution to identify excited states.





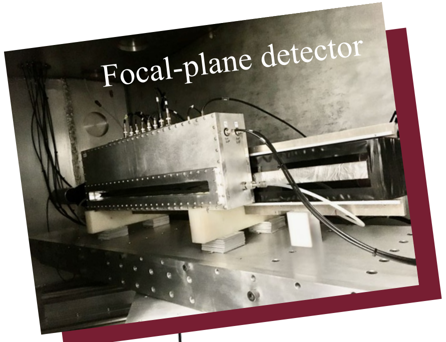
$$B\rho = \frac{\sqrt{2mE_{kin}}}{q}$$

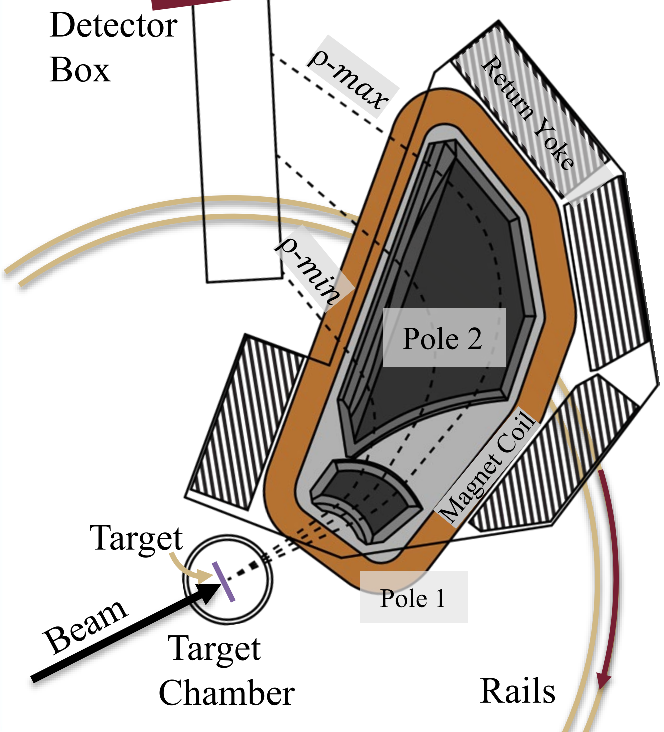


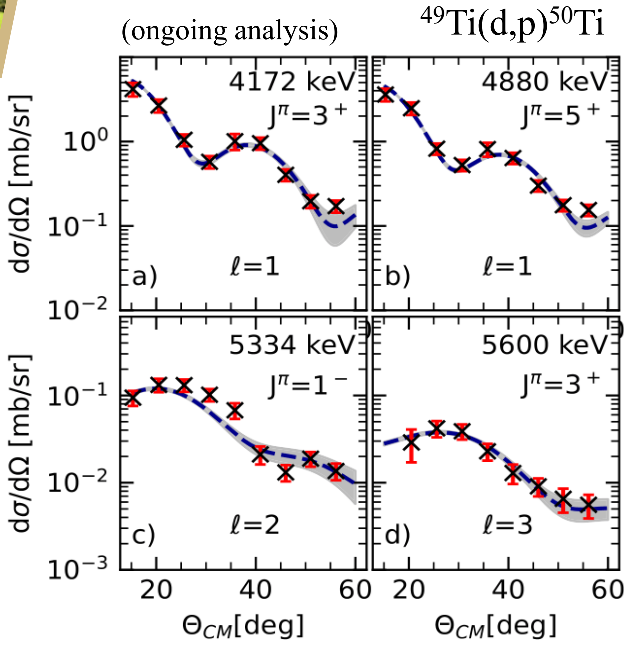


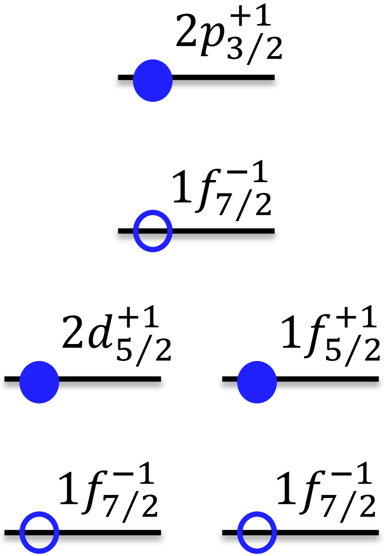
= 1⁻ states observed in real-photon scattering off ^{48,50}Ti at HIγS@Duke University.

The Super-Enge Split-Pole Spectrograph @ FSU





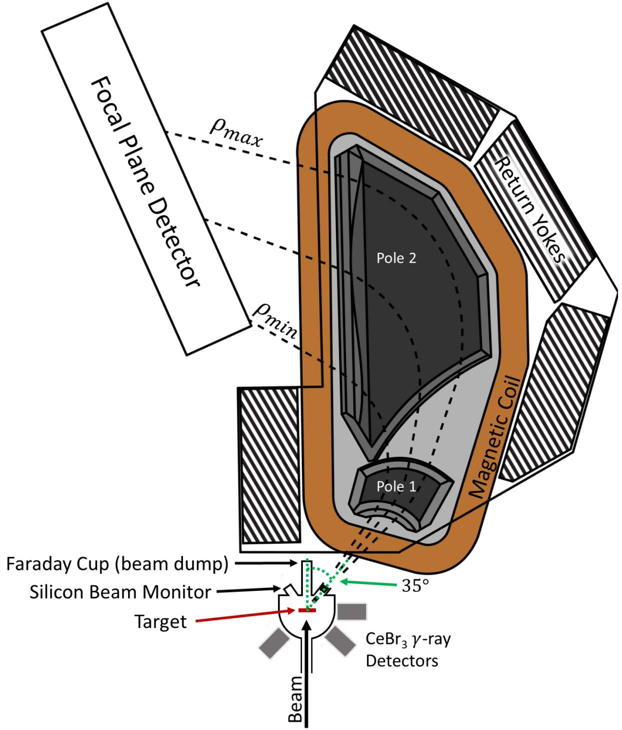


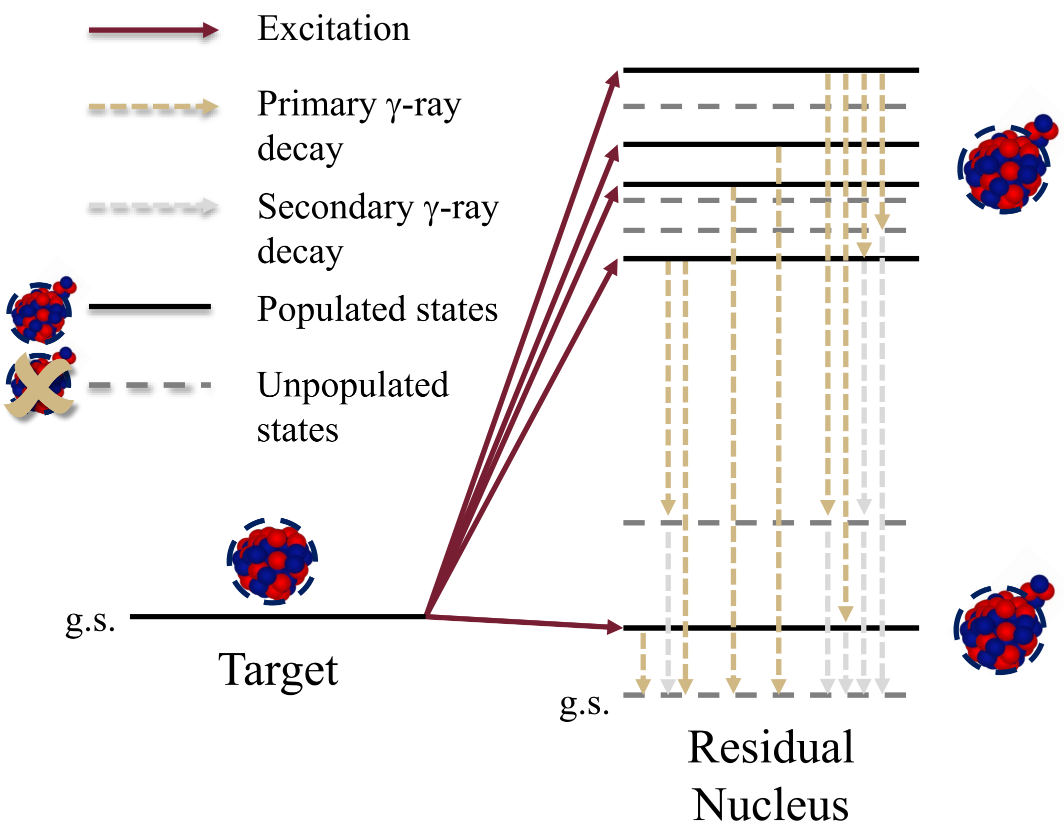


Measure reaction yields at different scattering angles (angular distributions) and identify neutron 1p-1h components of the state’s wave function by comparison to theory.

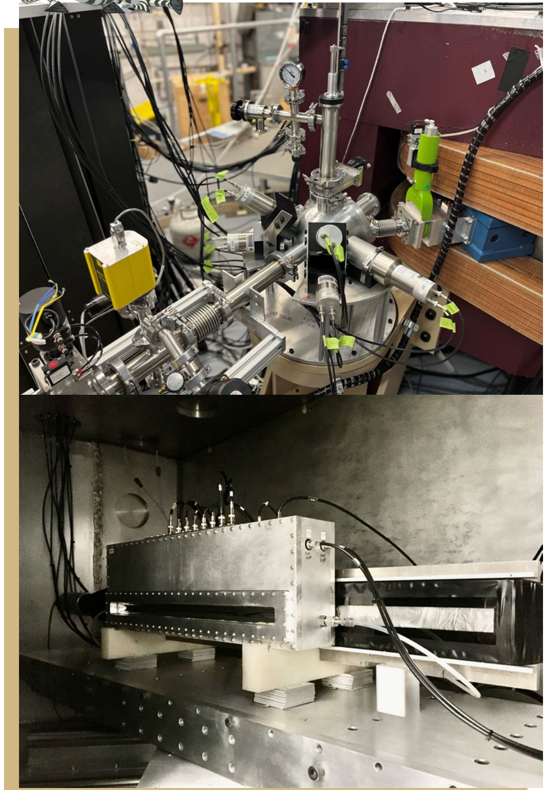
Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

Combining reaction and decay selectivity to study the structure of excited states.

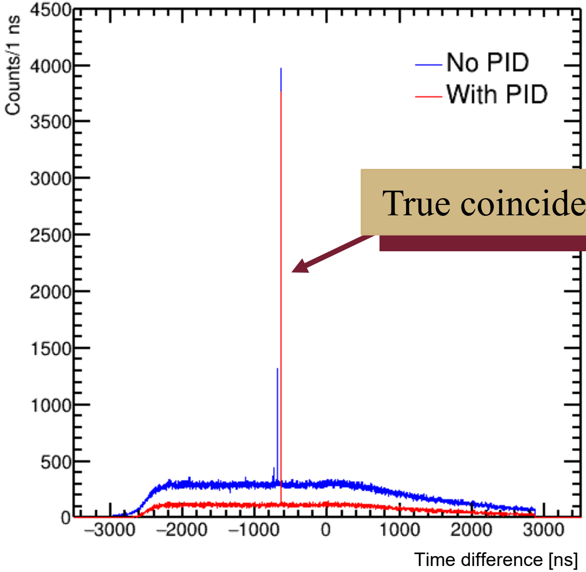




Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS



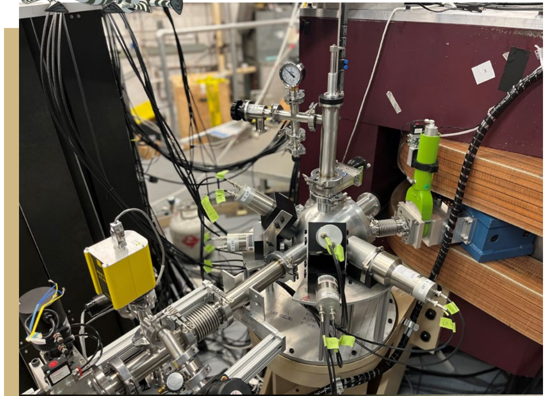
Coincidence timing between $CeBr_3$ γ-ray detectors and focal-plane scintillator.

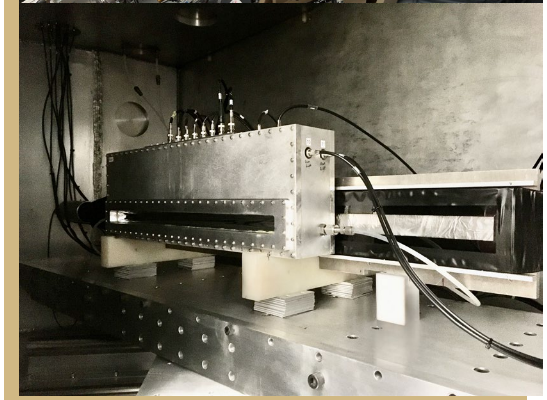


PID eliminates prompt events resulting from other reactions. To eliminate random background, further timing gates are needed.

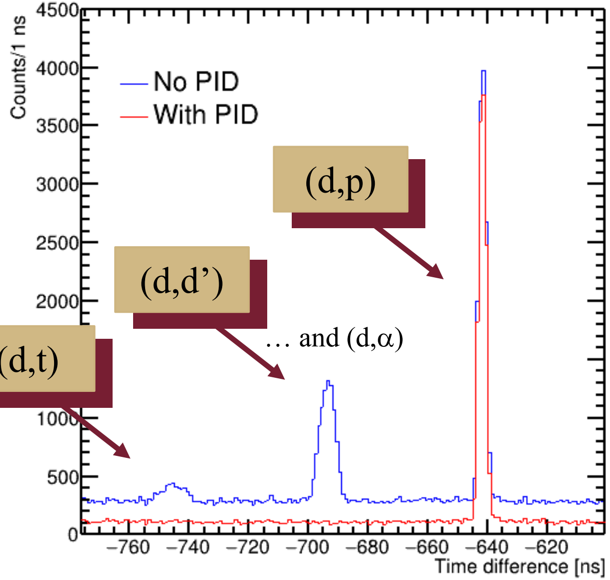
Heureka! [Archimedes]

Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS





Coincidence timing between $CeBr_3$ γ-ray detectors and focal-plane scintillator.



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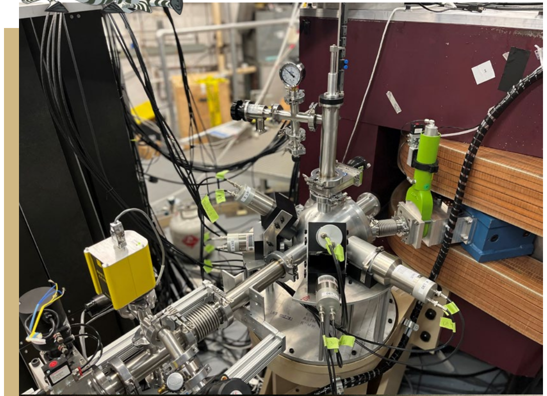
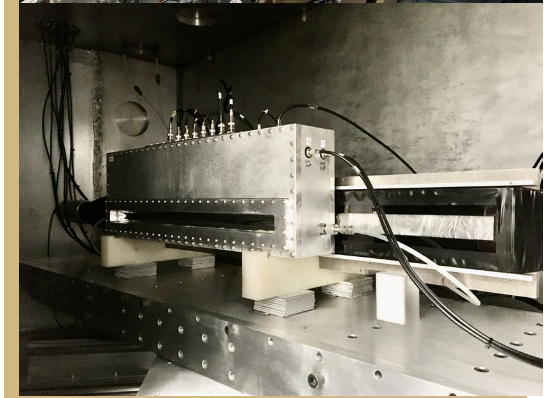
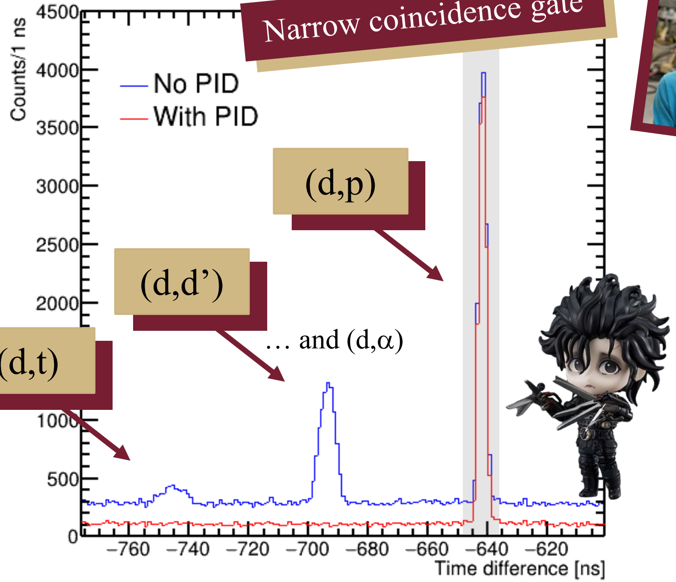
Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS



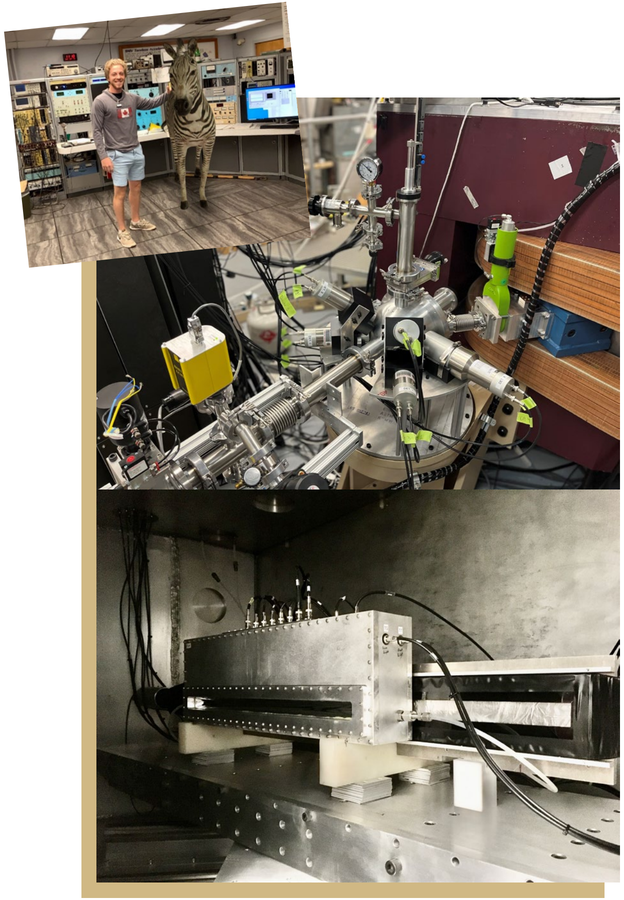


Coincidence timing between $CeBr_3$ γ-ray detectors and focal-plane scintillator.



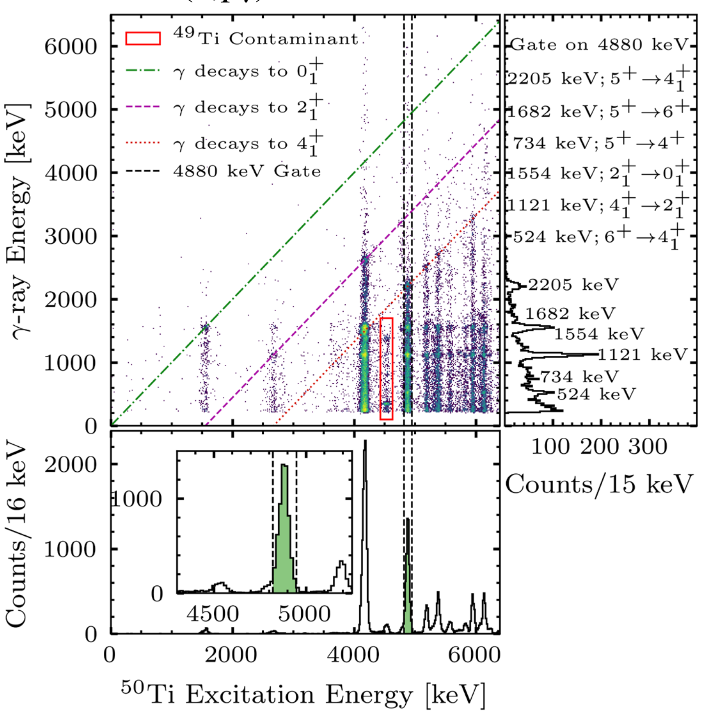
PID eliminates prompt events resulting from other reactions. To eliminate random background, further timing gates are needed.

Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS



Particle-γ coincidence matrix for selecting the excitation and decay of specific excited states.

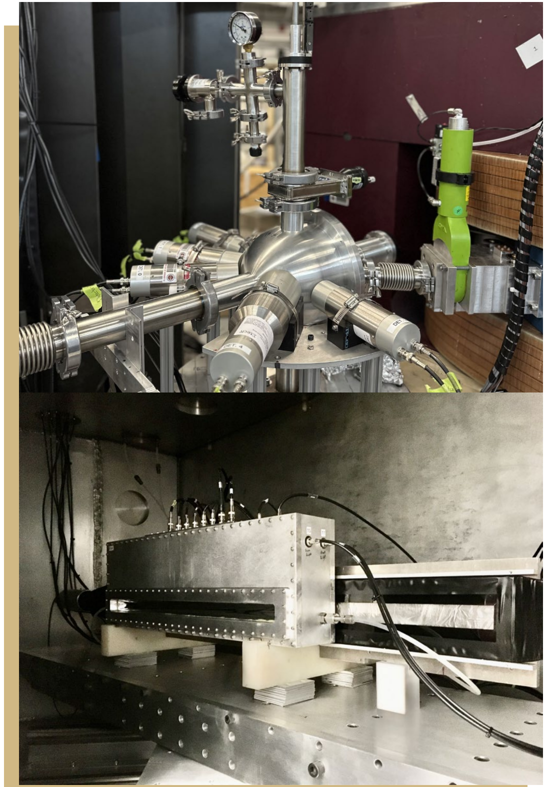
^{49}Ti(d,pγ)^{50}Ti



Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

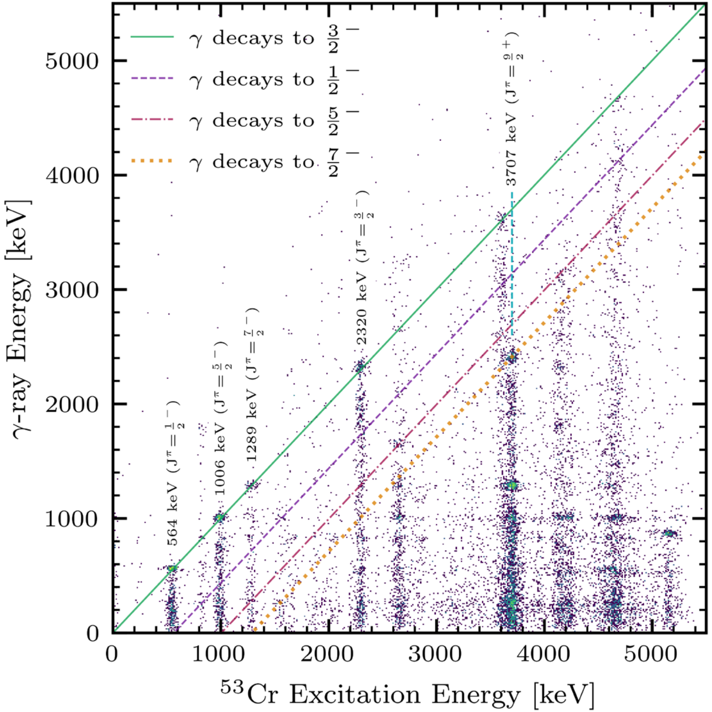
Measured during 2023 REU at Fox Lab

In collaboration with L.A. Riley [Ursinus College]



Particle-γ coincidence matrix for selecting the excitation and decay of specific excited states.

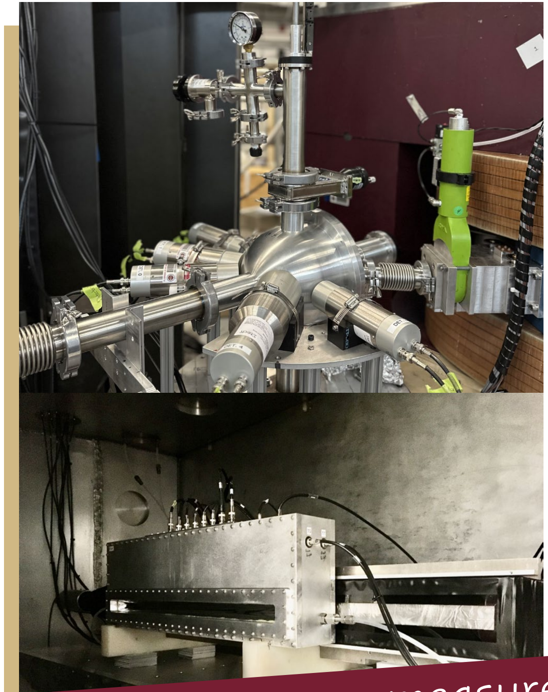
^{52}Cr(d,pγ)^{53}Cr



Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

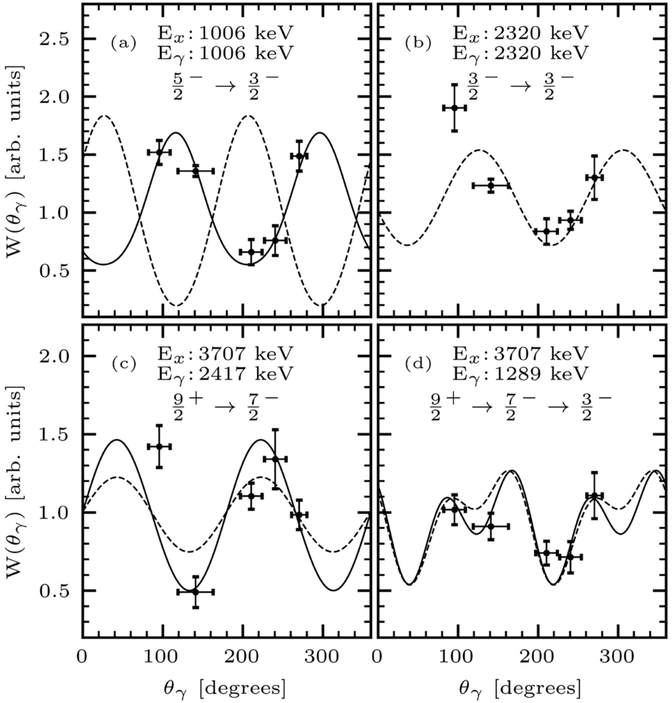
Angular correlations

In collaboration with L.A. Riley [Ursinus College]



Particle-γ angular correlations for spin-parity assignments and determination of multipole mixing ratios.

$^{52}Cr(d,p\gamma)^{53}Cr$

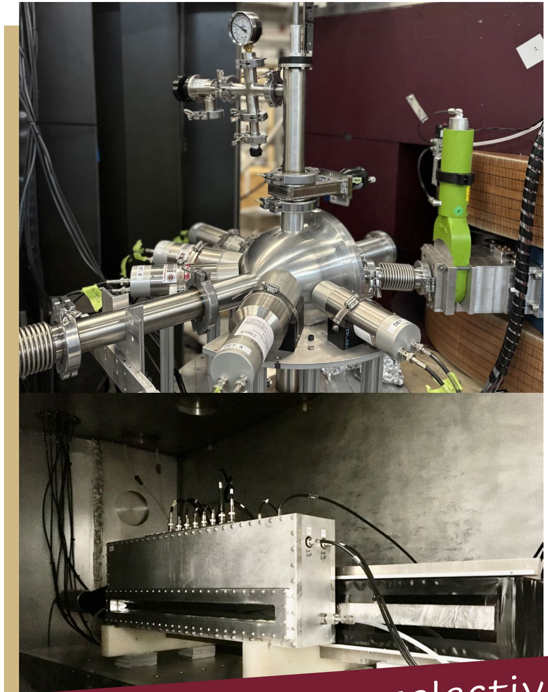


Bottom line: We can measure particle-γ angular correlations in (d,pγ) with SE-SPS+CeBrA!

Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

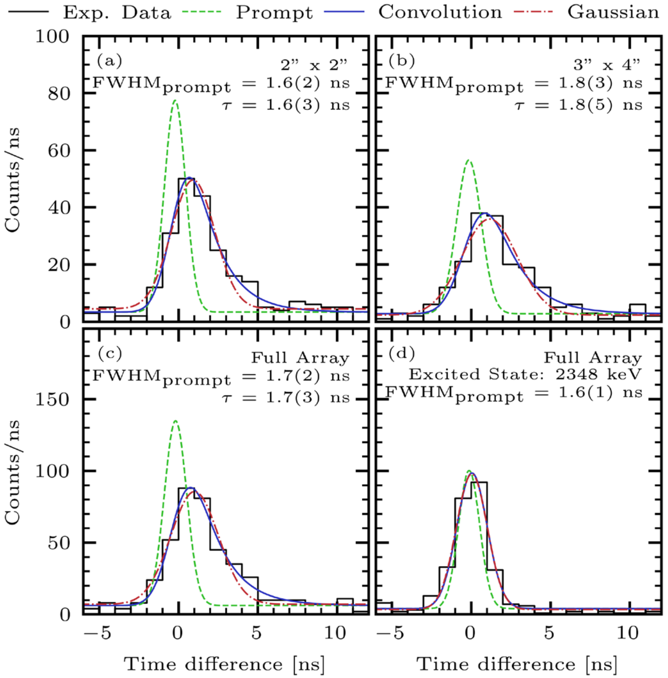
Nuclear level lifetimes

In collaboration with A. Kuchera [Davidson College]



Time difference between γ-ray detection with CeBrA and particle detection with SE-SPS to determine level lifetimes.

$^{34}S(d,p\gamma)^{35}S$

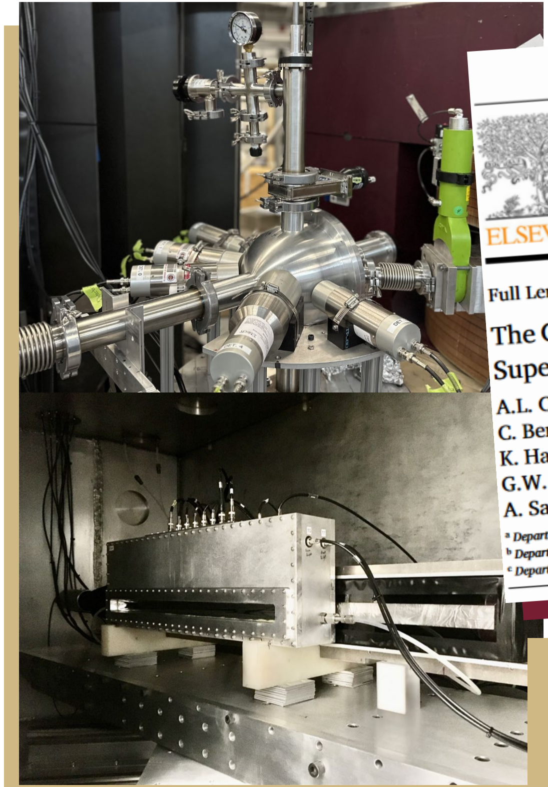


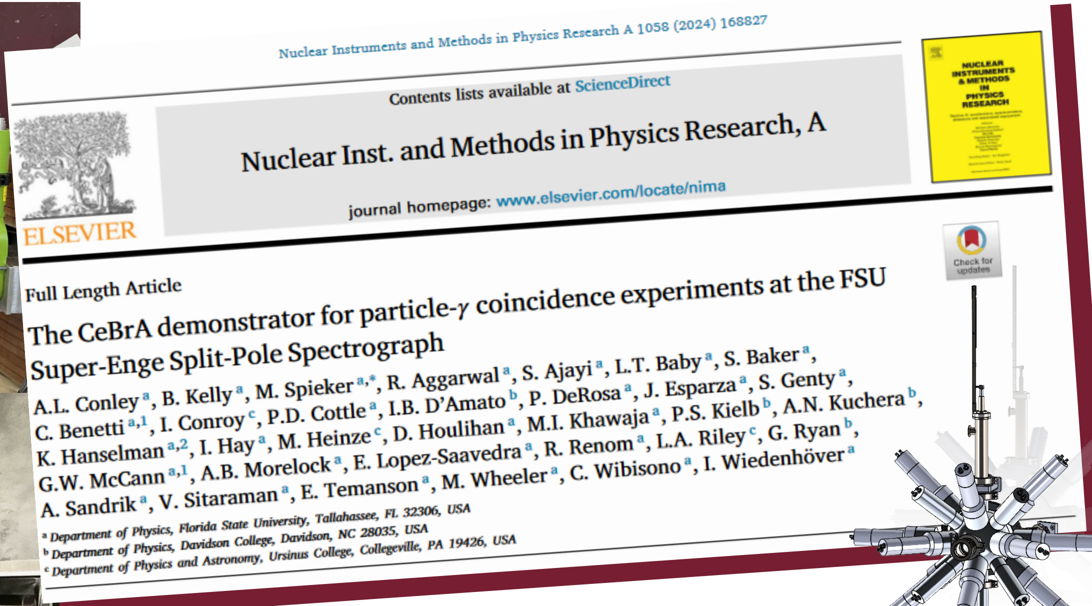
Bottom line: We can selectively measure nanosecond lifetimes and exclude feeding.

Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

We have big plans!

In collaboration with L.A. Riley [Ursinus College] and A. Richard [Ohio University]





Nuclear Instruments and Methods in Physics Research A 1058 (2024) 168827

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Full Length Article

The CeBrA demonstrator for particle-γ coincidence experiments at the FSU Super-Enge Split-Pole Spectrograph

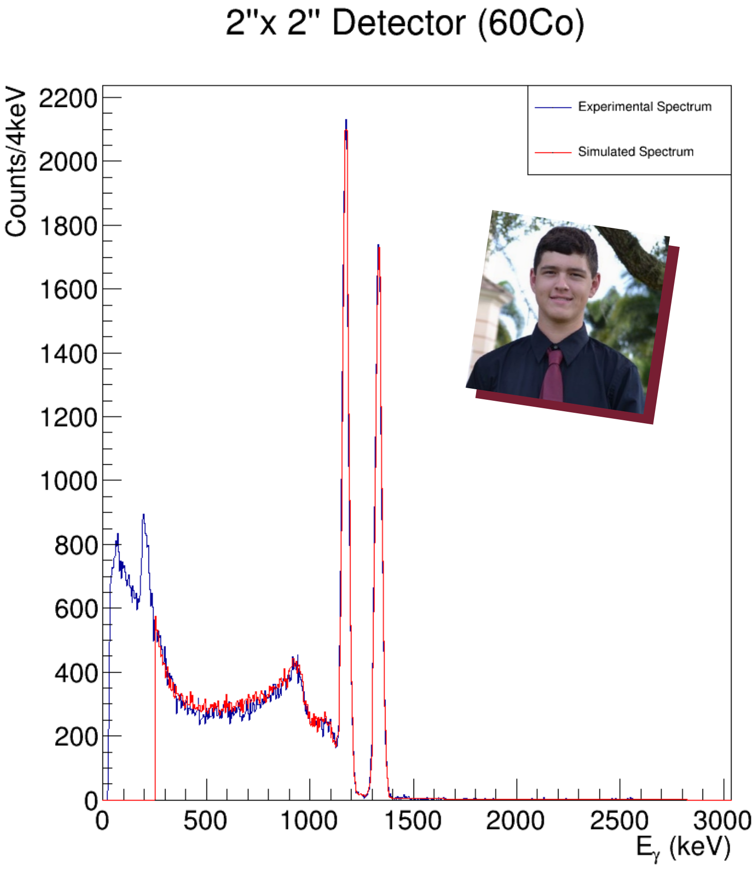
A.L. Conley[a], B. Kelly[a], M. Spieker[a,*], R. Aggarwal[a], S. Ajayi[a], L.T. Baby[a], S. Baker[a], C. Benetti[a,1], I. Conroy[c], P.D. Cottle[a], I.B. D'Amato[b], P. DeRosa[a], J. Esparza[a], S. Genty[a], K. Hanselman[a,2], I. Hay[a], M. Heinze[c], D. Houlihan[a], M.I. Khawaja[a], P.S. Kielb[b], A.N. Kuchera[b], G.W. McCann[a,1], A.B. Morelock[a], E. Lopez-Saavedra[a], R. Renom[a], L.A. Riley[c], G. Ryan[b], A. Sandrik[a], V. Sitaraman[a], E. Temanson[a], M. Wheeler[a], C. Wibisono[a], I. Wiedenhöver[a]

[a] Department of Physics, Florida State University, Tallahassee, FL 32306, USA
[b] Department of Physics, Davidson College, Davidson, NC 28035, USA
[c] Department of Physics and Astronomy, Ursinus College, Collegeville, PA 19426, USA

Submitted MRI to NSF in collaboration with Ursinus College and Ohio University to build and use full CeBrA detector array at FSU (Oct. 2023) [~$750k]

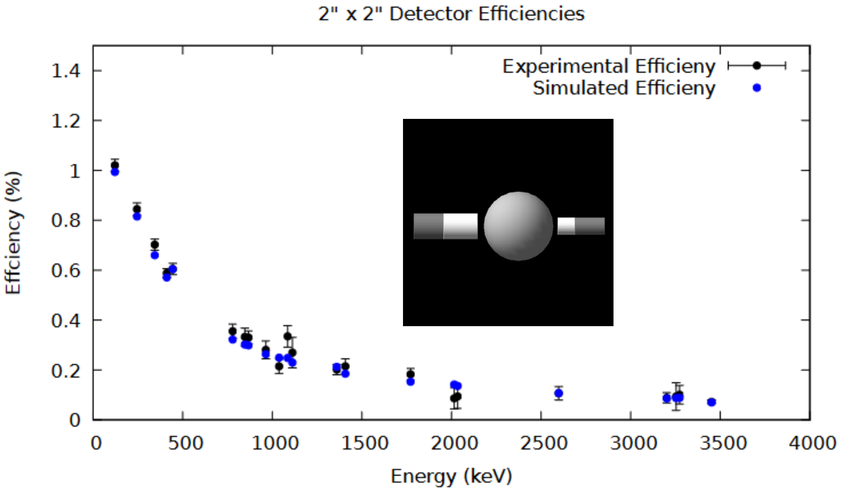
Undergraduate Research

GEANT4 simulation of $CeBr_3$ detectors



- FSU undergraduate student Scott Baker working on simulation of our $CeBr_3$ detectors using GEANT4 as part of his honors thesis.

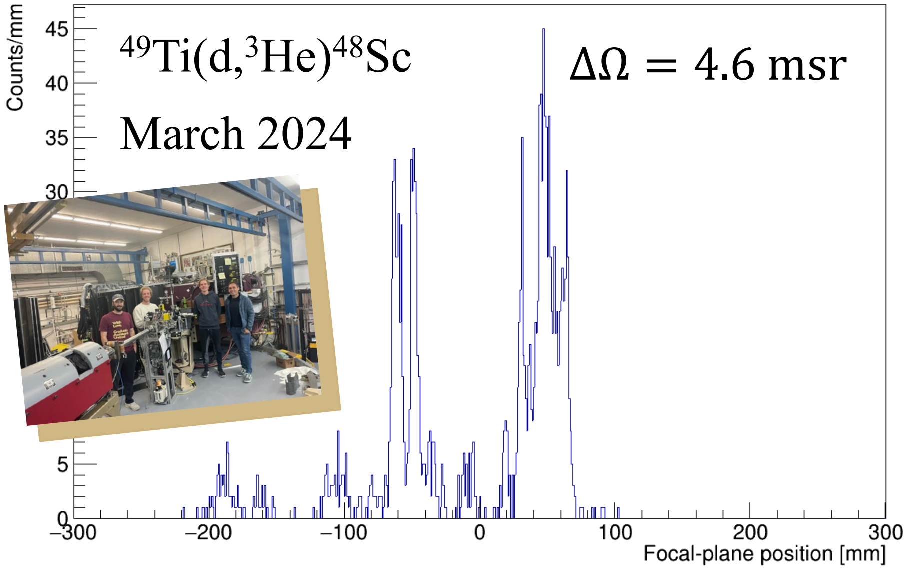
→ Benchmark of simulation against data measured with standard calibration sources.

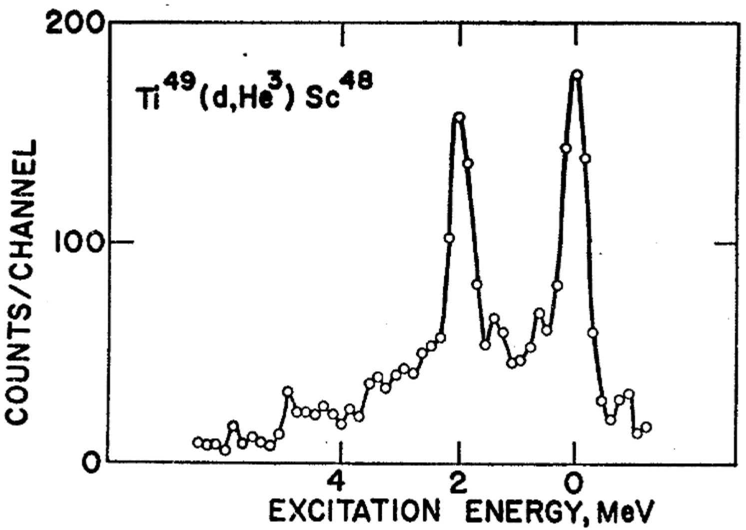


Why don't you just simulate your data?

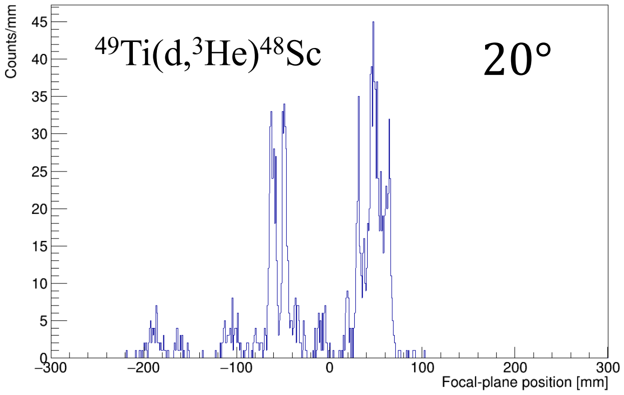
Spectra from source commissioning with deuterium beam – (d,^{3}He) and (d,t)

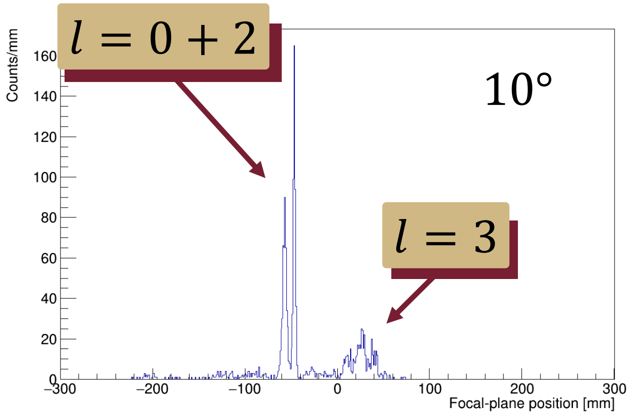
Only published spectrum from J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964) measured at scattering angle of 20°.

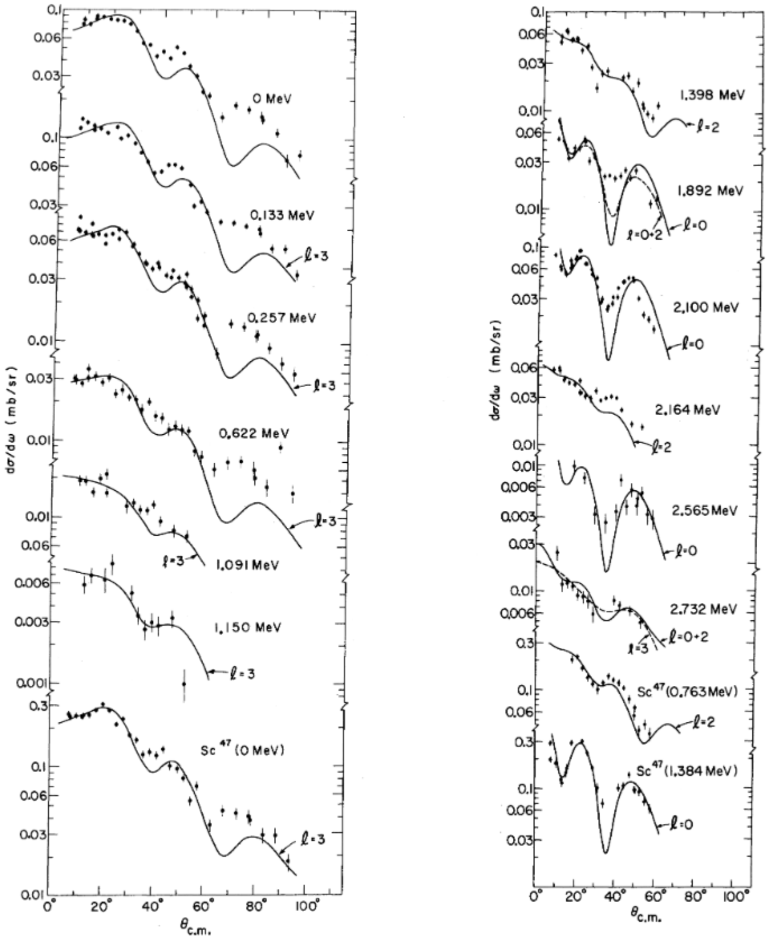




Spectra from source commissioning with deuterium beam – (d,^{3}He) and (d,t)



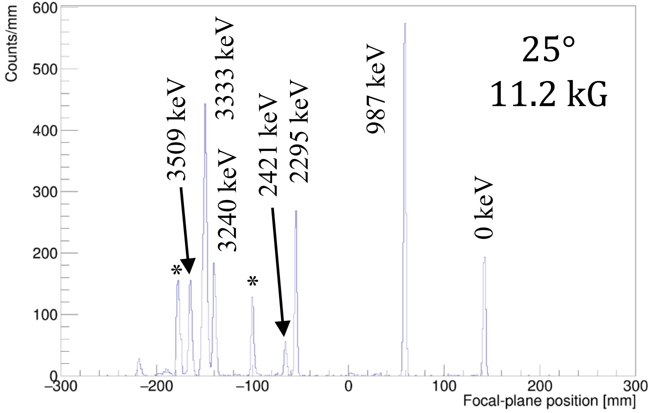


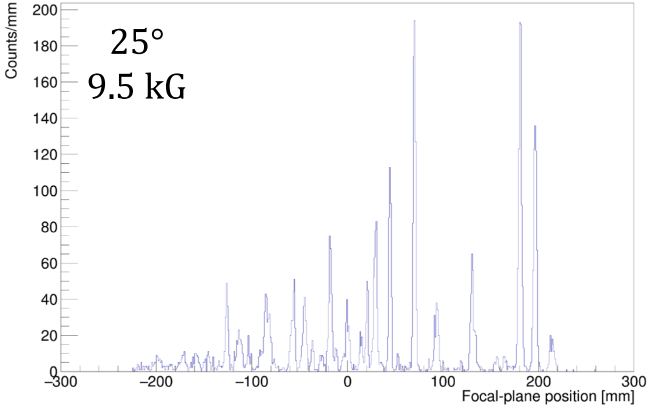


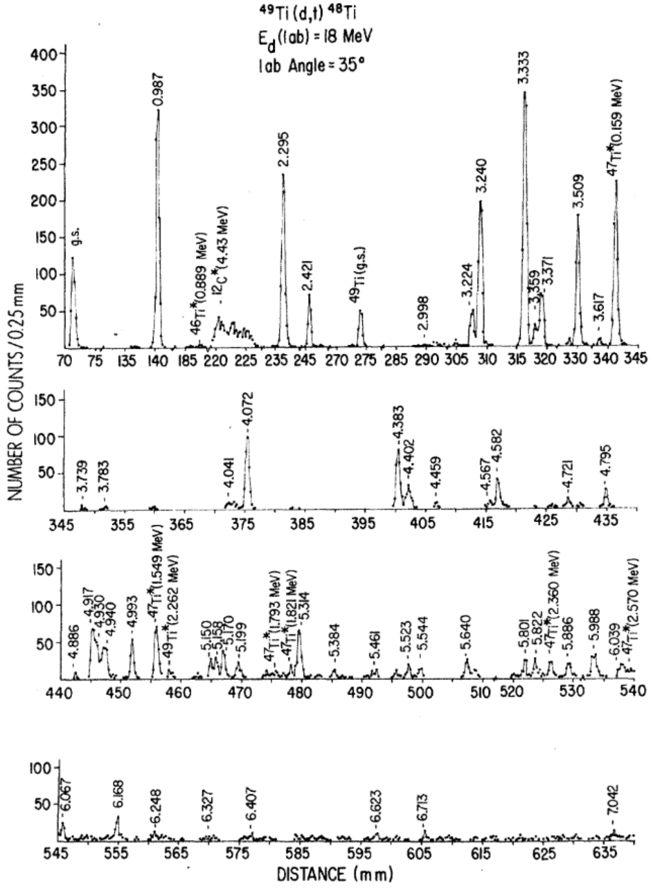
[Angular distributions: H. Ohnuma and J. L. Yntema, Phys. Rev. C **2**, 1725 (1970)]

Spectra from source commissioning with deuterium beam – (d,^{3}He) and (d,t)

March 2024

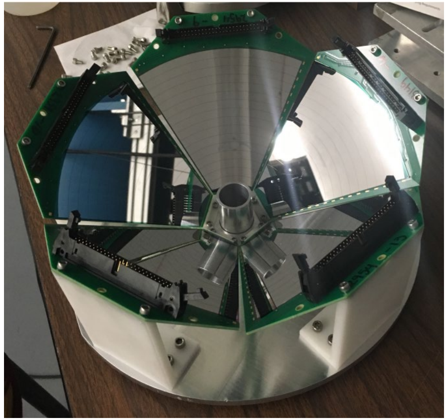


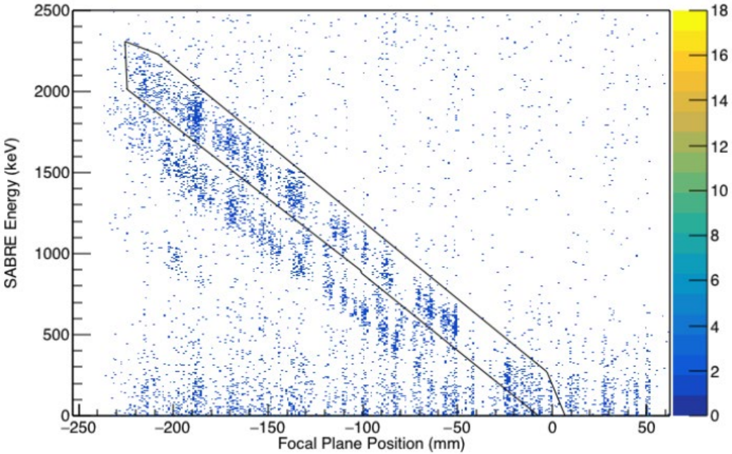




[A. Jamshidi and W. P. Alford, Phys. Rev. C **8**, 1796 (1973)]

Silicon Array for Branching Ratio Experiments (SABRE)

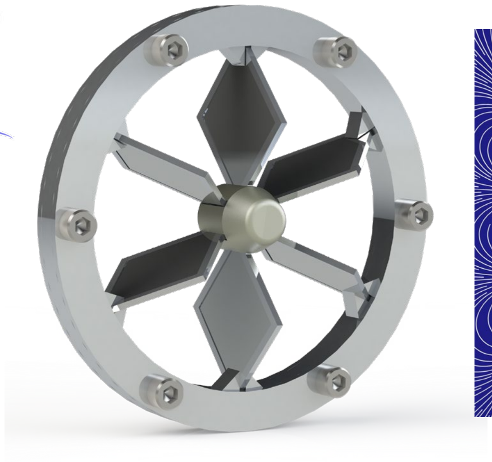


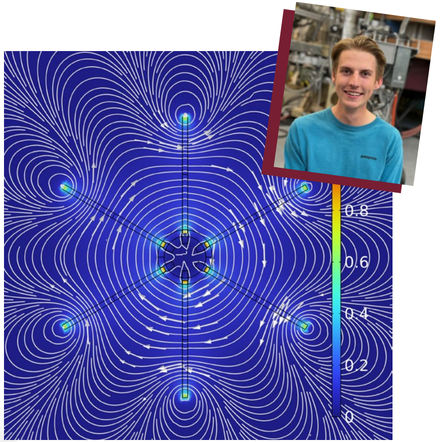


- In collaboration with LSU (C. Deibel)
- 5 Micron Semiconductor Ltd. MMM Silicon strip detectors with thin deadlayers in lampshade configuration.
- Fully digital data acquisition based on CAEN V1725 and V1730 digitizers and DPP-PHA firmware.
- Array primarily used for studying the decay of unbound particle resonances relevant for Nuclear Astrophysics.
- Decay-particle-particle angular correlations with SABRE and SE-SPS can be measured to test wave functions in great detail.
- Exemplary science cases: Synthesis of ^{26}Al, isotope production in classical novae, super-radiance in ^{13}C.

Reference: E.C. Good *et al.*, Nuclear Instruments and Methods in Physics Research, A **1003**, 165299 (2021)

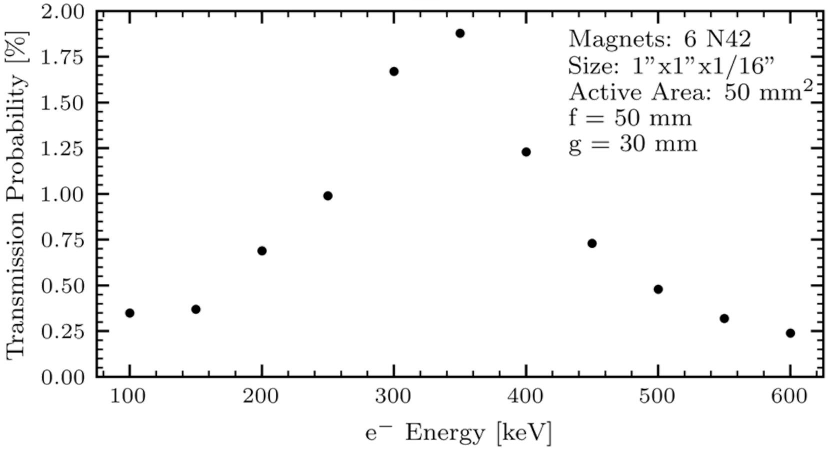
Future detector developments

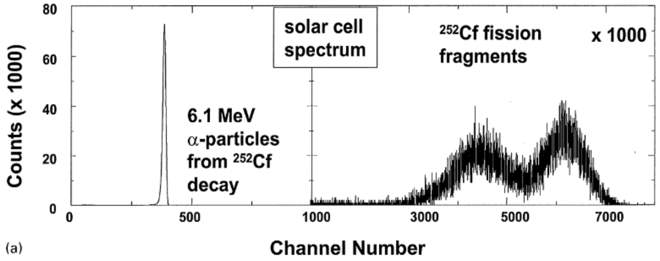




- Development of conversion electron spectrometer in Mini-Orange Design using PIPS detectors

- Fission detector (cube design) using silicon photodiodes similar to SCARY design used at WNSL.



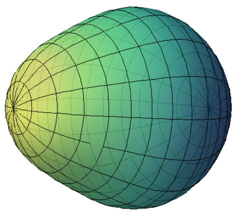


[WNSL/SCARY: C.W. Beausang *et al.*, Nucl. Instr. Meth. A **452**, 431 (2000)]

FLORIDA STATE UNIVERSITY

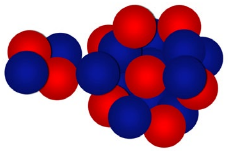
A very brief review of what we learned from (p,t) and why (t,p) might provide additional insights…

Phenomena influencing structure of low-lying excited states



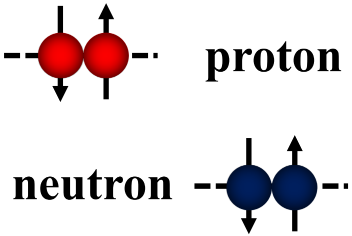
Octupole Correlations ($\Delta j = \Delta l = 3$)

- Octupole deformation and excitations in the actinides (ground state and excited states)



α Clustering

- An alternative way to cause reflection asymmetry in the actinides



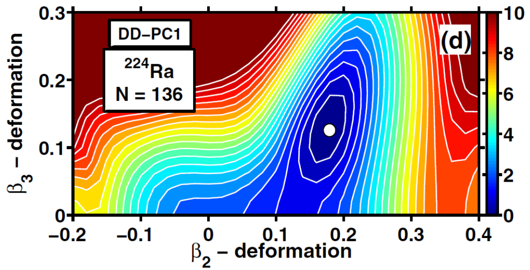
Pairing

- Pairing probed in (p,t) and (t,p) reactions (neutrons only; $\Delta s = 0$)

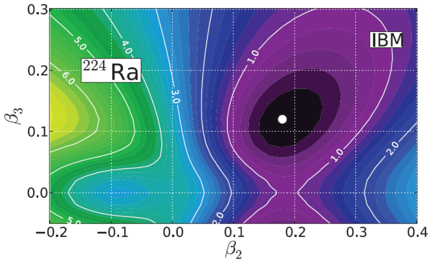
[M. Spieker *et al.*, PRC **97**, 064319 (2018)]

Octupole deformation in light actinides

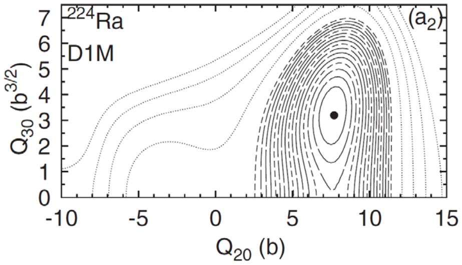
- Covariant density functional theory



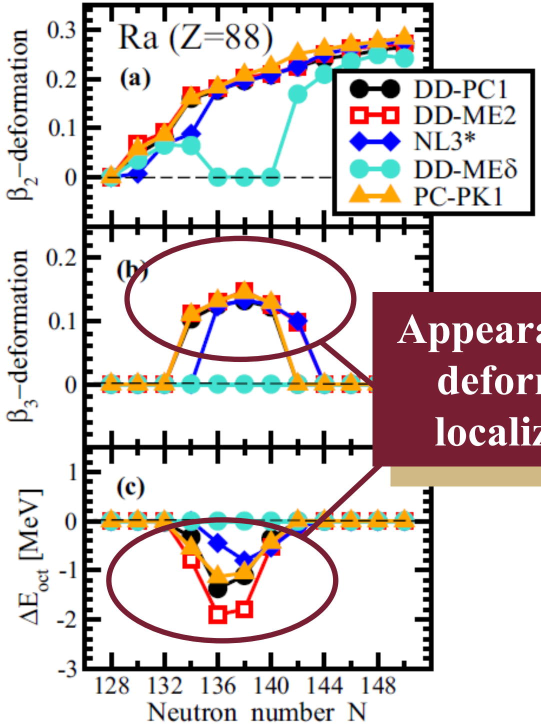
- DFT constrained *sdf* IBM-1 PES



- HFB+Gogny(D1M)+GCM



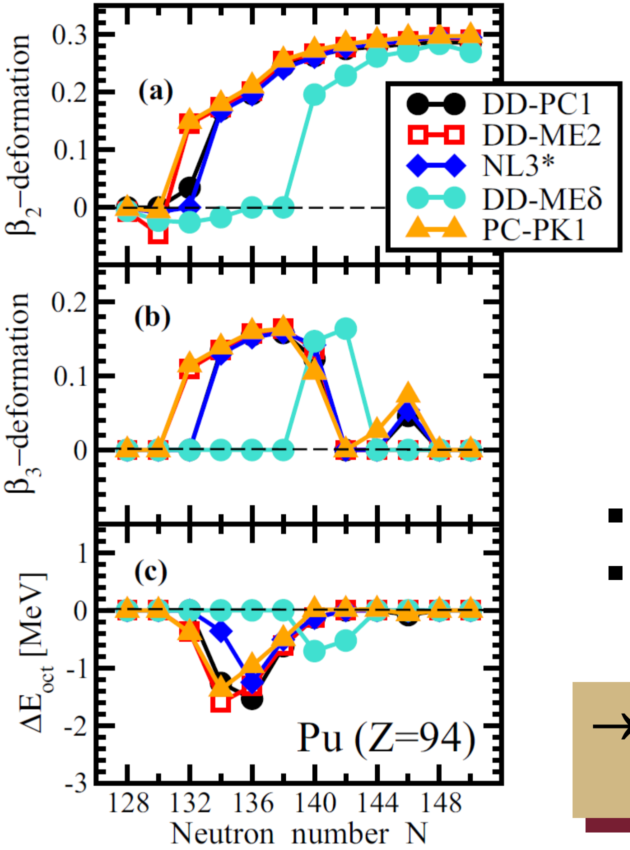
Static octupole deformation in light actinides?

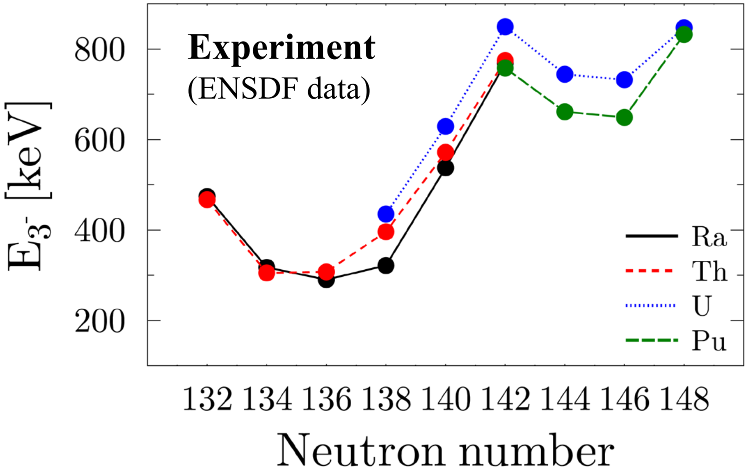


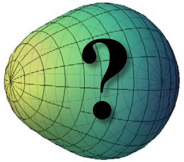
Appearance of octupole deformation rather localized at N ~ 136

[**Figures:** S.E. Agbemava *et al.*, PRC **93**, 044304 (2016); K. Nomura *et al.*, PRC **89**, 024312 (2014); L.M. Robledo and P.A. Butler, PRC **88**, 051302(R) (2013)]
[**Similar conclusions:** E. Olsen *et al.*, JoP: Conference Series **402**, 012034 (2012)]

Octupole excitations in heavier actinides



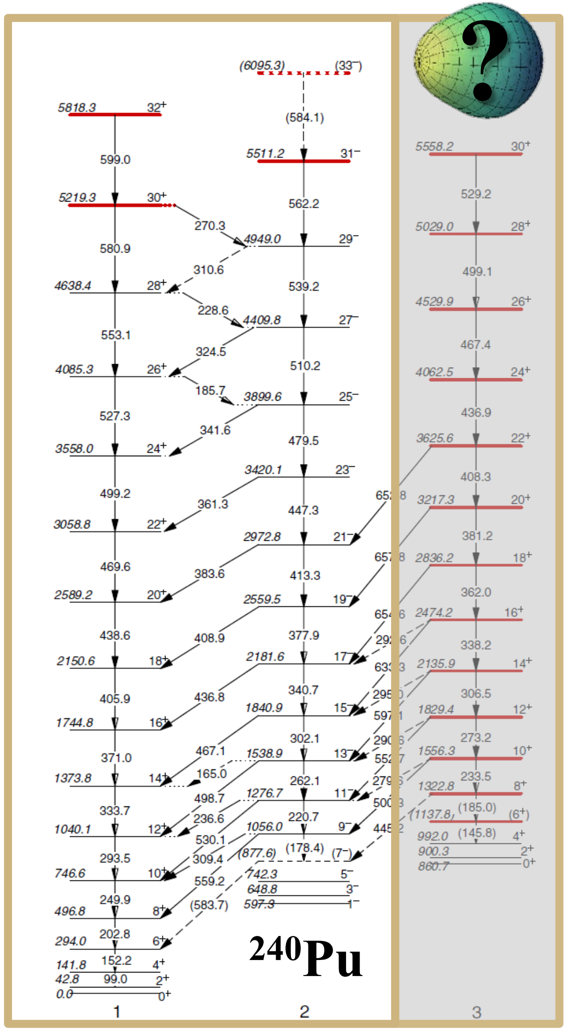




- Second octupole minimum exists around N ~ 146
- No significant gain in binding energy due to octupole correlations predicted by theory

→ **No static octupole deformation in nuclear ground state of more neutron-rich actinides**

[**Figure:** S.E. Agbemava *et al.*, PRC **93**, 044304 (2016)]



[**Figure:** X. Wang *et al.*, PRL **102**, 122501 (2009)]

Octupole excitations in actinides

Appearance of octupole deformation at high spins?

(… stabilization of octupole shape with rotation?)

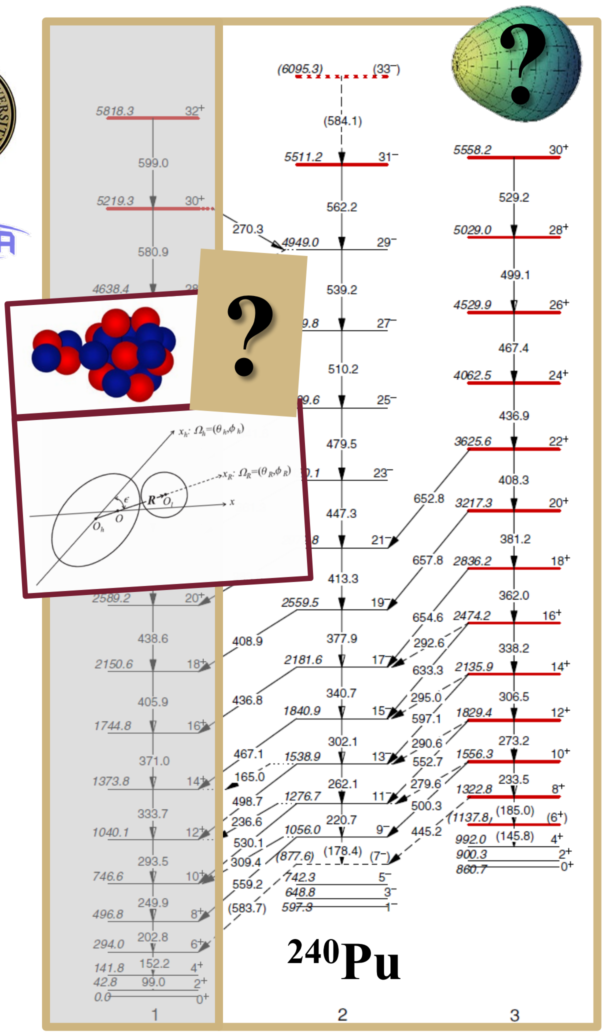
- $B(E3; 3_1^- \rightarrow 0_1^+) = 17(3)$ W.u. in ^{240}Pu
- No alternating-parity band at low spins
- Instead build-up of alternating-parity band at $J \geq 20$
- Induced intrinsic dipole moment $D_0 = 0.2$ efm (e.g., $D_0 = 0.2 - 0.3$ efm in light, octupole-deformed Th isotopes)

[I. Wiedenhöver *et al.*, PRL **83**, 2143 (1999)]

→ Second-order phase transition to an octupole-deformed shape at high spins

[R.V. Jolos and P. von Brentano, PRC **84**, 024312 (2011); R.V. Jolos *et al.*, PRC **86**, 024319 (2012)]

Octupole excitations in actinides



[**Figure:** X. Wang *et al.*, PRL **102**, 122501 (2009)]

- **Band 3 ($K^\pi = 0_2^+$)** was proposed to be either of

  → **double-octupole phonon character**

  [X. Wang *et al.*, PRL **102**, 122501 (2009); R.V. Jolos *et al.*, PRC **88**, 034306 (2013)]

  or

  → to be lowest-lying **α-cluster excitation** in mass-asymmetry coordinate

  [T.M. Shneidman *et al.*, PRC **92**, 034302 (2015)]

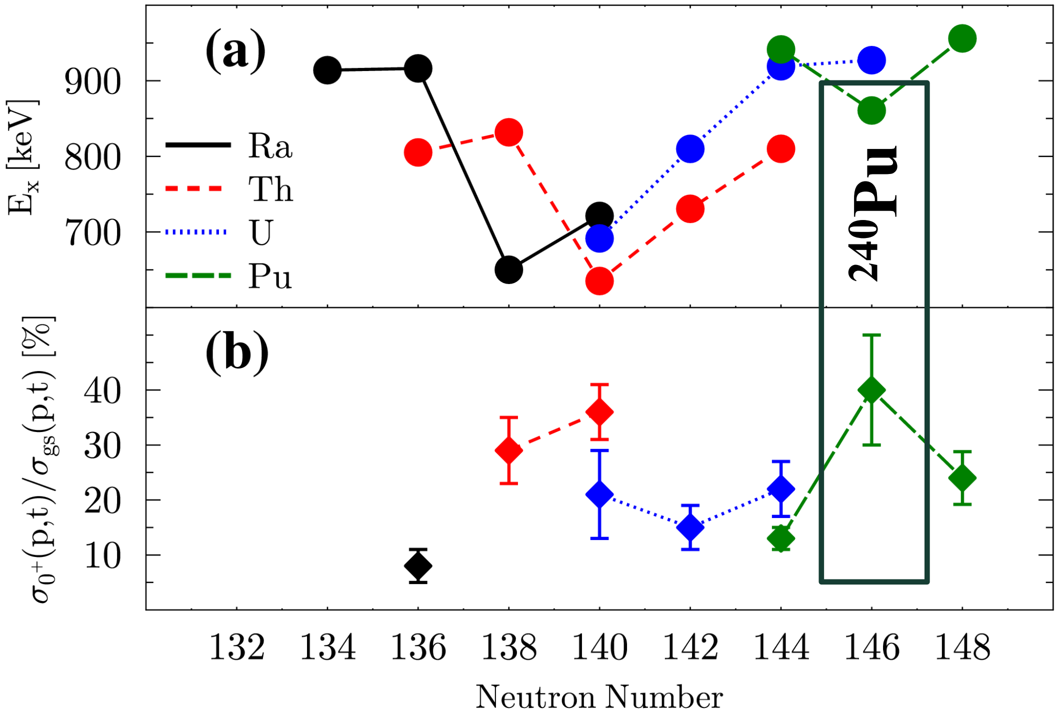
Problem:
Both approaches can describe the properties of the ground-state, $K^\pi = 0_1^-$ and $K^\pi = 0_2^+$ band.

(relative motion between clusters was previously missing in order to describe B($E3$) in ^{224}Ra)

(p,t) reaction and the nature of the first excited 0^+ state

Uniformly strong (*p,t*) population of first-excited 0^+ state

→ Collective excitation? Pairing vibration? Pairing isomer?



[J.V. Maher *et al.*, PRL **25**, 302 (1970); J.V. Maher *et al.*, PRC **5**, 1380 (1972); A.M. Friedman *et al.*, PRC **9**, 760 (1974)]

Experimental data from Q3D campaign

(… may it rest in peace, wherever it is now.)

We decided to revisit some (p,t) measurements a while ago…

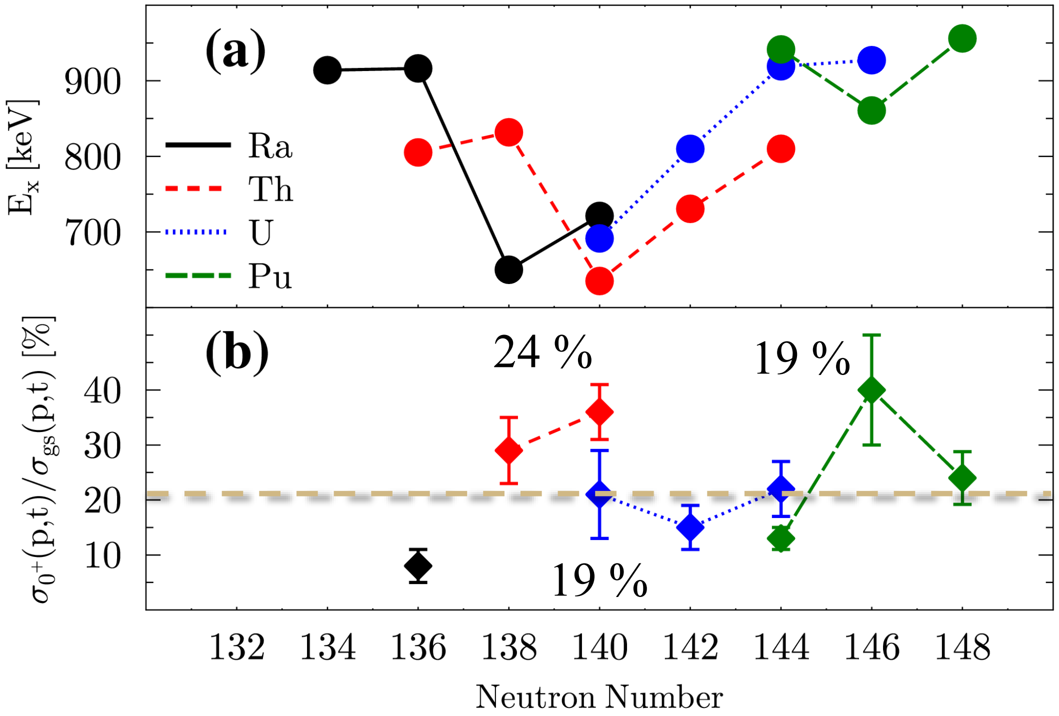
^{230,228}Th, ^{232}U: H.-F. Wirth *et al.*, PRC **60**, 044310 (2004)
^{230}Th: A.I. Levon *et al.*, PRC **79**, 014318 (2009)
^{228}Th: A.I. Levon *et al.*, PRC **88**, 014310 (2013)
^{240}Pu: M. Spieker *et al.*, PRC **88**, 041303(R) (2013)
^{232}U: A.I. Levon *et al.*, PRC **92**, 064319 (2015)
^{240}Pu: M. Spieker *et al.*, PRC **97**, 064319 (2018)

… time flies if you are having fun.

(p,t) reaction and the nature of the first excited 0^+ state

Uniformly strong (*p*,*t*) population of first-excited 0^+ state

→ Collective excitation? Pairing vibration? Pairing isomer?

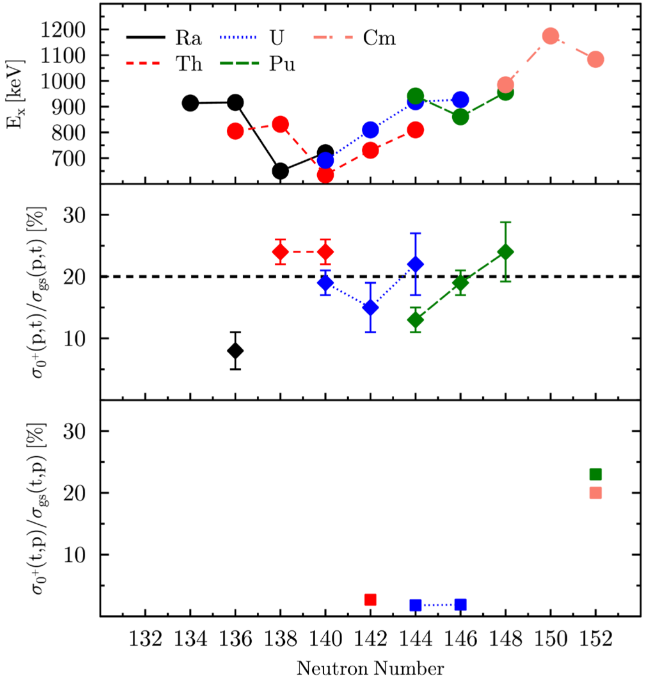


[J.V. Maher *et al.*, PRL **25**, 302 (1970); J.V. Maher *et al.*, PRC **5**, 1380 (1972); A.M. Friedman *et al.*, PRC **9**, 760 (1974)]

What we thought (think?) we learned from (t,p) reactions…

The (t,p) reactions from ^{230,232}Th and ^{234,236,238}U were studied at 15-20 MeV bombarding energy. The known excited 0^+ states in ^{232}Th, ^{236,238}U were not observed nor was any excited 0^+ strength located in ^{234}Th or ^{234}U. The previously reported strong $L = 0$ (p,t) transitions in this region as well as the weak $L = 0$ (t,p) strengths reported here constitute a strong indication of the existence of quadrupole pairing correlations in deformed superfluid nuclei.

[R.F. Casten *et al.*, PLB **40**, 333 (1972); B.B. Back *et al.*, NPA **217**, 116 (1973)]



- Strong (p,t) and weak (t,p) cross section supported pairing isomer interpretation of 0_2^+ states favored by Ragnarsson and Broglia.

[I. Ragnarsson and R.A. Broglia, NPA **263**, 315 (1976)]

- Strong population of 0_2^+ in ^{239}Pu(d,p)^{240}Pu did already question pairing isomer interpretation.

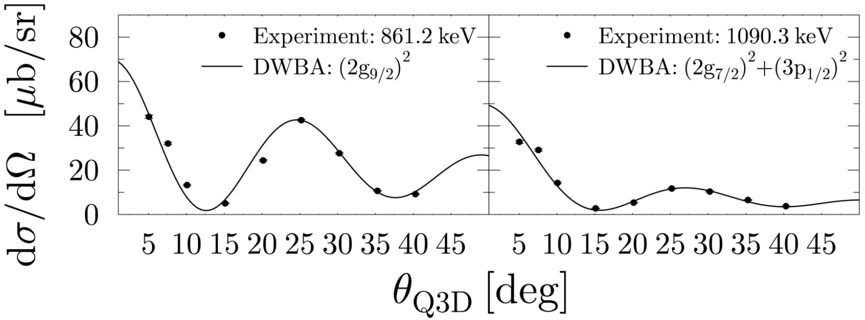
[A. Friedman and K. Katori, PRL **30**, 102 (1973)]

How does the double octupole phonon structure fit into this story?

We learned that we are dealing with at least two different structures!

- **(*p*,*t*) observables**

Nucleus	n	E_x [keV]	$R_{0_n^+/0_1^+}(5°/25°)$
^{228}Th	2	831.9	1.5
	3	938.7	2.5
^{230}Th	2	635.1	2.1
	3	1297.1	1.2
^{232}U	2	691.4	2.1
	3	927.2	1.7
^{240}Pu	2	861.2	1.1
	3	1090.3	2.9



- **γ-decay behavior [B(*E1*)/B(*E2*)]**

Nucleus	n	E_x [keV]	$J^\pi_{f,E1}$	$J^\pi_{f,E2}$	$R_{E1/E2}$ [10^{-6}fm^{-2}]
^{224}Ra	2	916.4	1_1^-	2_1^+	≈ 0.2
^{226}Ra	2	824.6	1_1^-		[a]
^{228}Ra	2	721.2	1_1^-	2_1^+	2.7(4)
^{226}Th	2	805.2	1_1^-		[a]
^{228}Th	2	831.9	1_1^-	2_1^+	5.1(4)
^{230}Th	(3)	1297.1	1_1^-	2_1^+	0.71(4)
^{232}Th	(3)	1078.6	1_1^-	2_1^+	[b]
^{232}U	3	927.3	1_1^-	2_1^+	44(7)
^{234}U	3	1044.5	1_1^-	2_1^+	3.9(3)
^{238}U	2	927.2		2_1^+	[c]
^{238}Pu	2	941.5	1_1^-	2_1^+	$\leqslant$0.5
^{240}Pu	2	861.2	1_1^-	2_1^+	13.7(3)

N=140,142

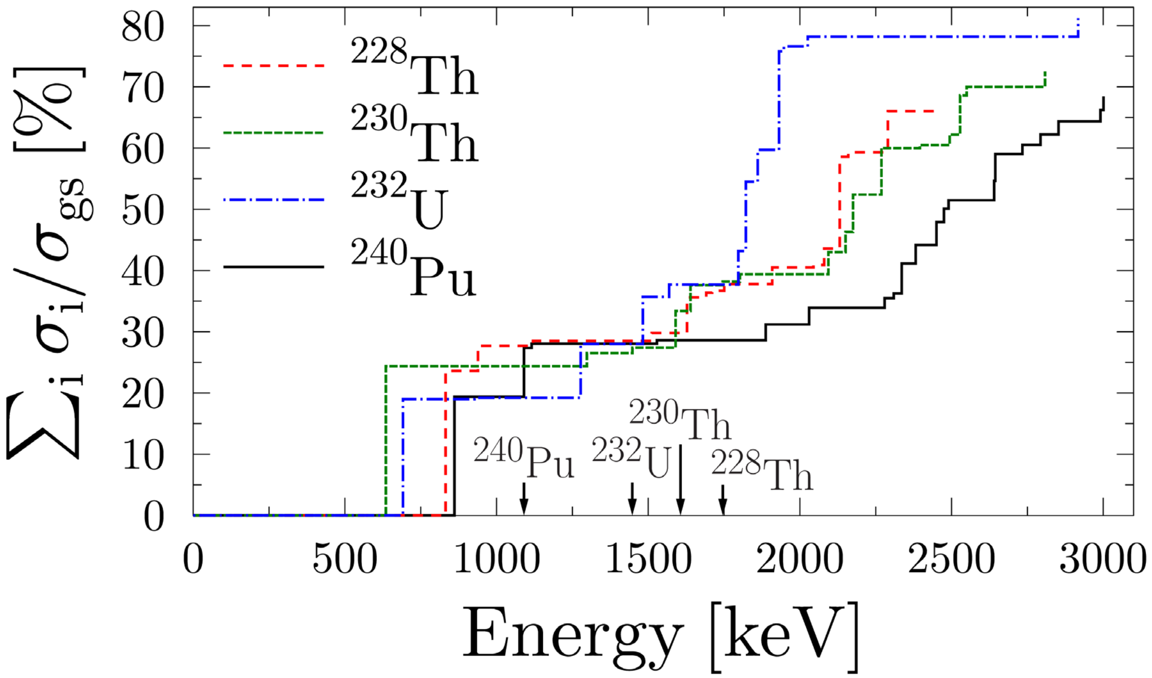
[a]No $E2$ transition observed.
[b]No γ-intensities measured.
[c]Assignment based on $R_{E1/E2}$ of $J^\pi = 2^+$ band member.

[M. Spieker *et al.*, PRC **97**, 064319 (2018)]

The two states have different angular distributions and a very different γ-decay behavior! (probably "double-octupole" component mixes with "pairing" state)

Nuclear structure is more complex…

Data for excited 0^+ states from Q3D campaign



Results:

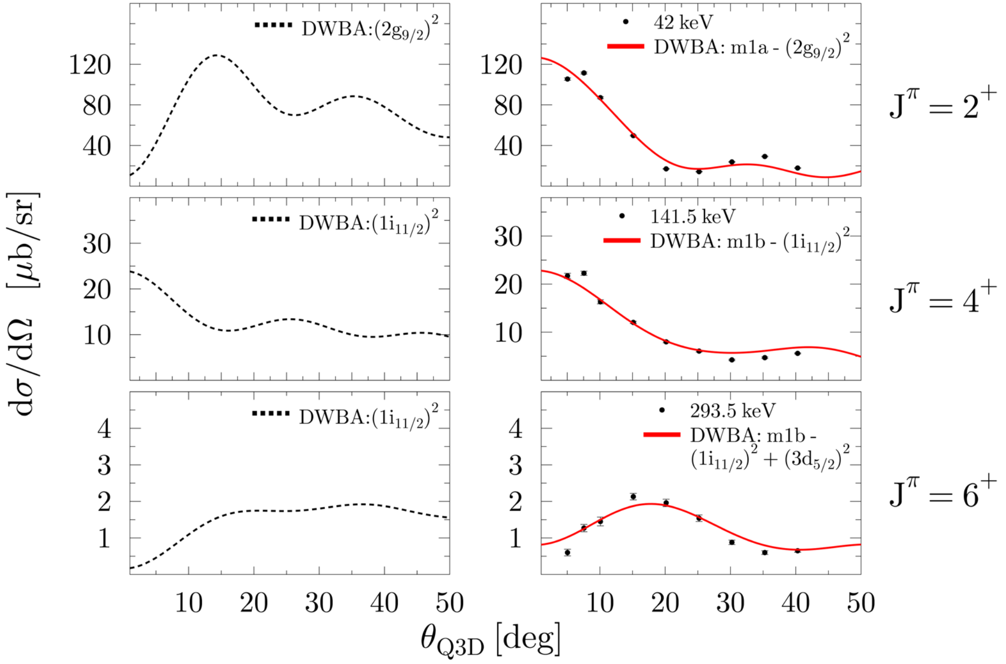
- $\frac{\sigma(0_2^+)}{\sigma(0_1^+)} = 18 - 25\,\%$ confirmed
- $\sum \sigma(0_i^+)/\sigma(0_1^+)$ jumps at $\sim 2\Delta_n$
- $\Delta E(0_2^+, 0_3^+)$ variation
- $\sum \sigma(0_i^+)/\sigma(0_1^+)$ comparable

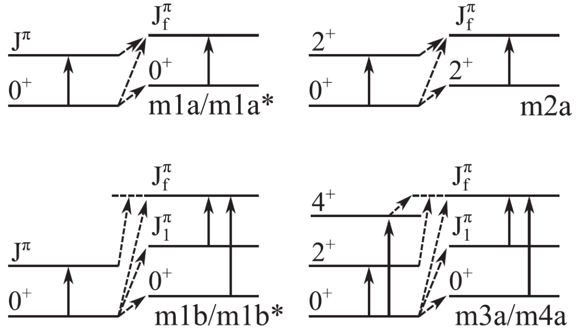
Expectations in 60s/70s were that one should observe strongly excited 0^+ states at higher excitation energies. We could search for these states.

[**Data and results:** A.I. Levon *et al.*, PRC **79**, 014318 (2009); PRC **88**, 014310 (2013); PRC **92**, 064319 (2015); M. Spieker *et al.*, PRC **97**, 064319 (2018)]

A word of caution – Multistep contributions in deformed nuclei

In deformed nuclei, multistep contributions can be significant. (p,t) $l = 0$ transfer appears to be unaffected. We will need to see what happens in (t,p).





- **Direct transfer: (p,t)**
- **Inelastic transfer:** $(p,p') \rightarrow (p,t) \rightarrow (t,t')$

[M. Spieker *et al.*, PRC **97**, 064319 (2018)]

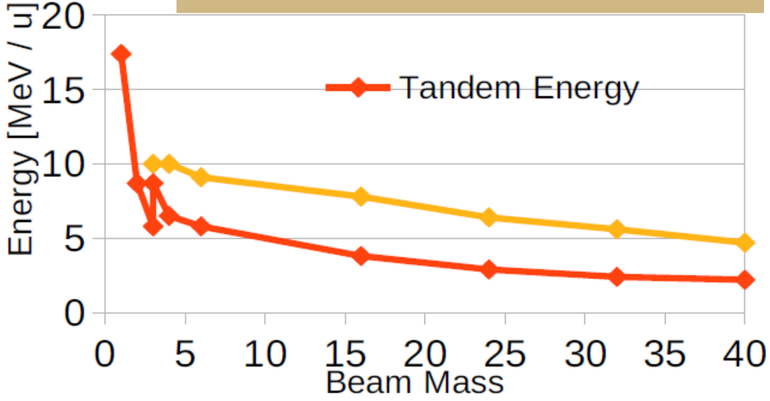
Back-Up

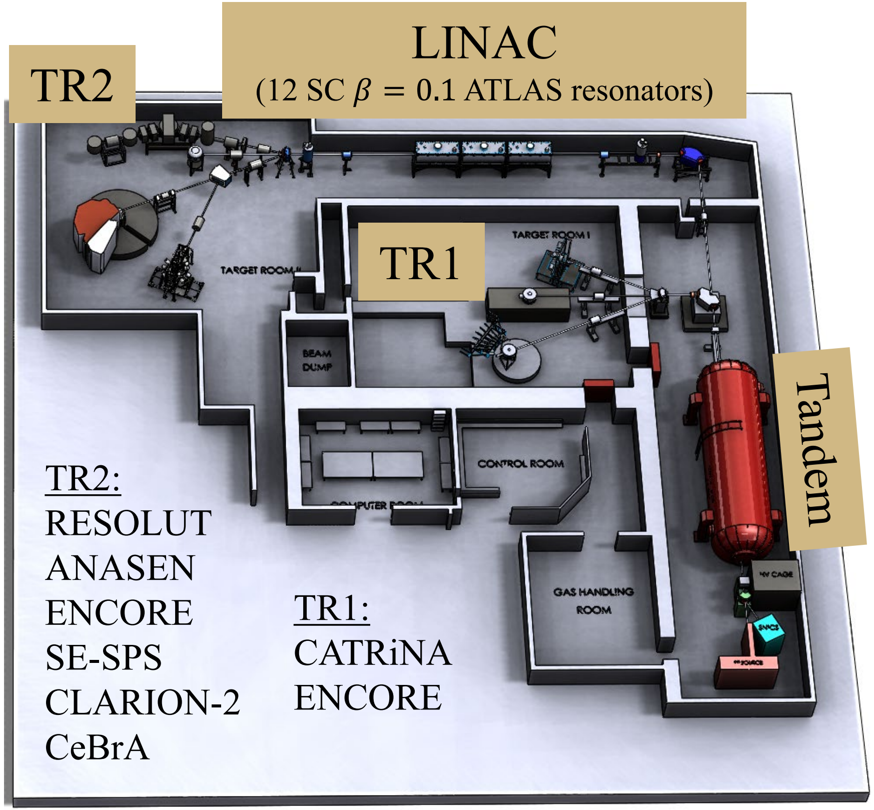
FLORIDA STATE UNIVERSITY

FSU Program

The John D. Fox Laboratory at Florida State University

9-MV Tandem + 8-MV LINAC

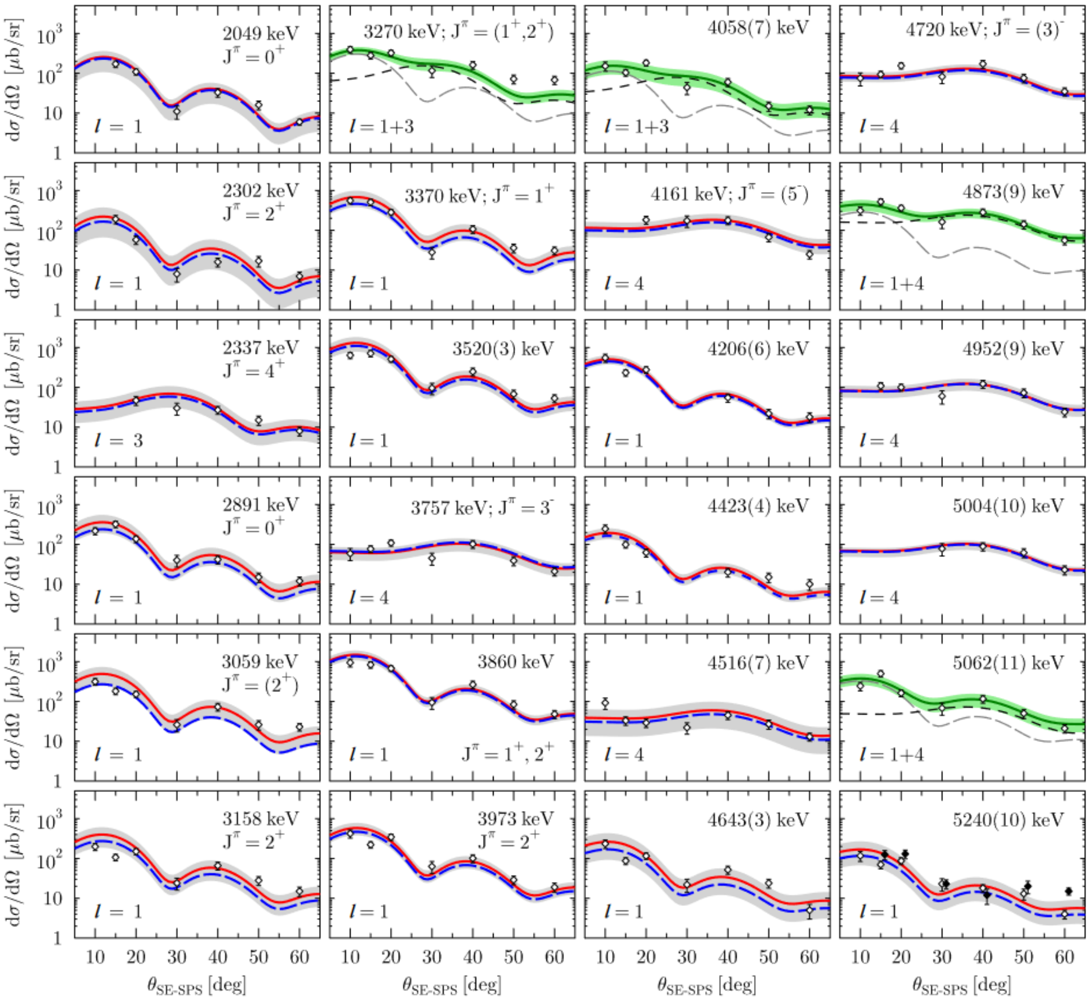




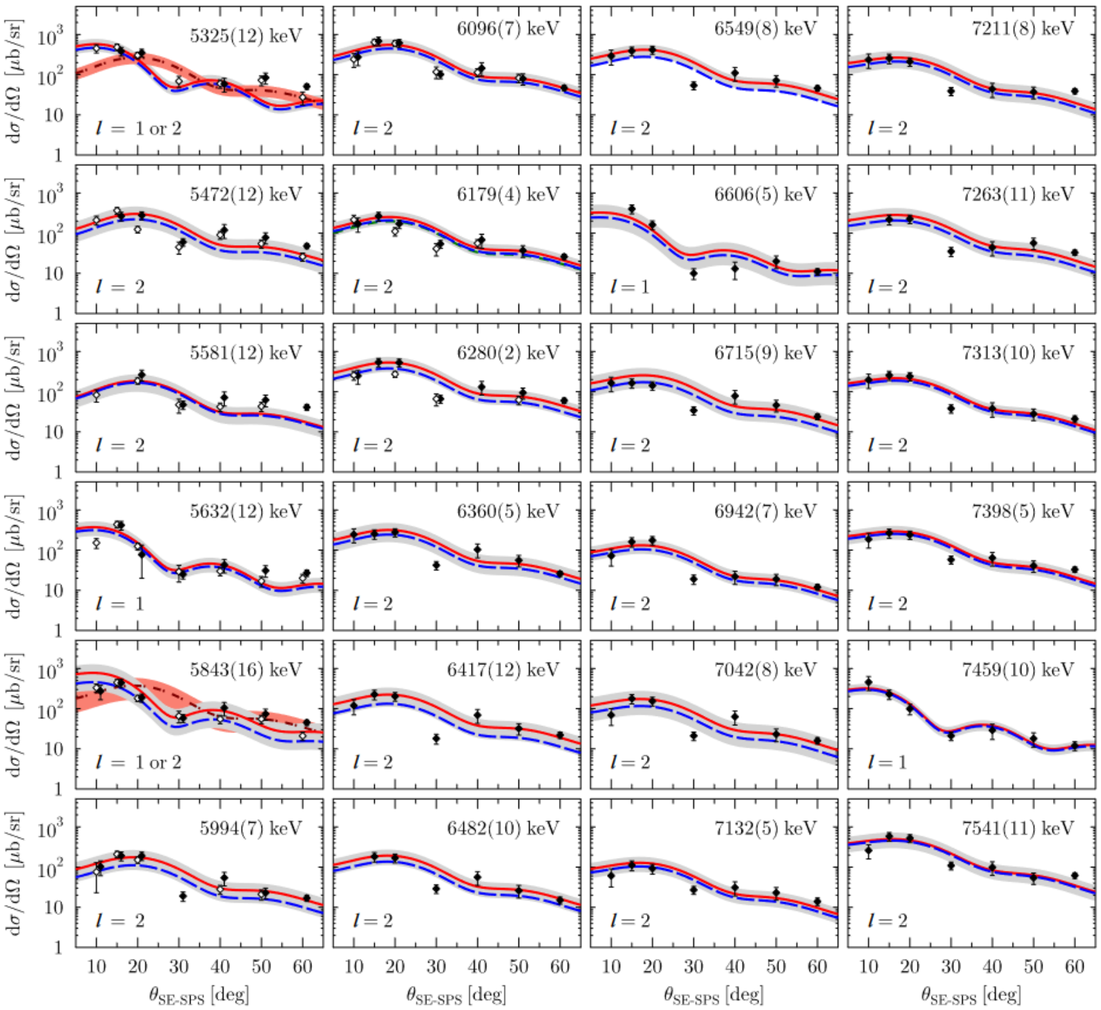
Four main experimental programs:

- In-flight radioactive beams with RESOLUT
- High-resolution spectroscopy with Super-Enge Split-Pole Spectrograph (SE-SPS)
- CLARION-2 Clover γ-ray array (w. ORNL)
- Neutron detection with CATRiNA

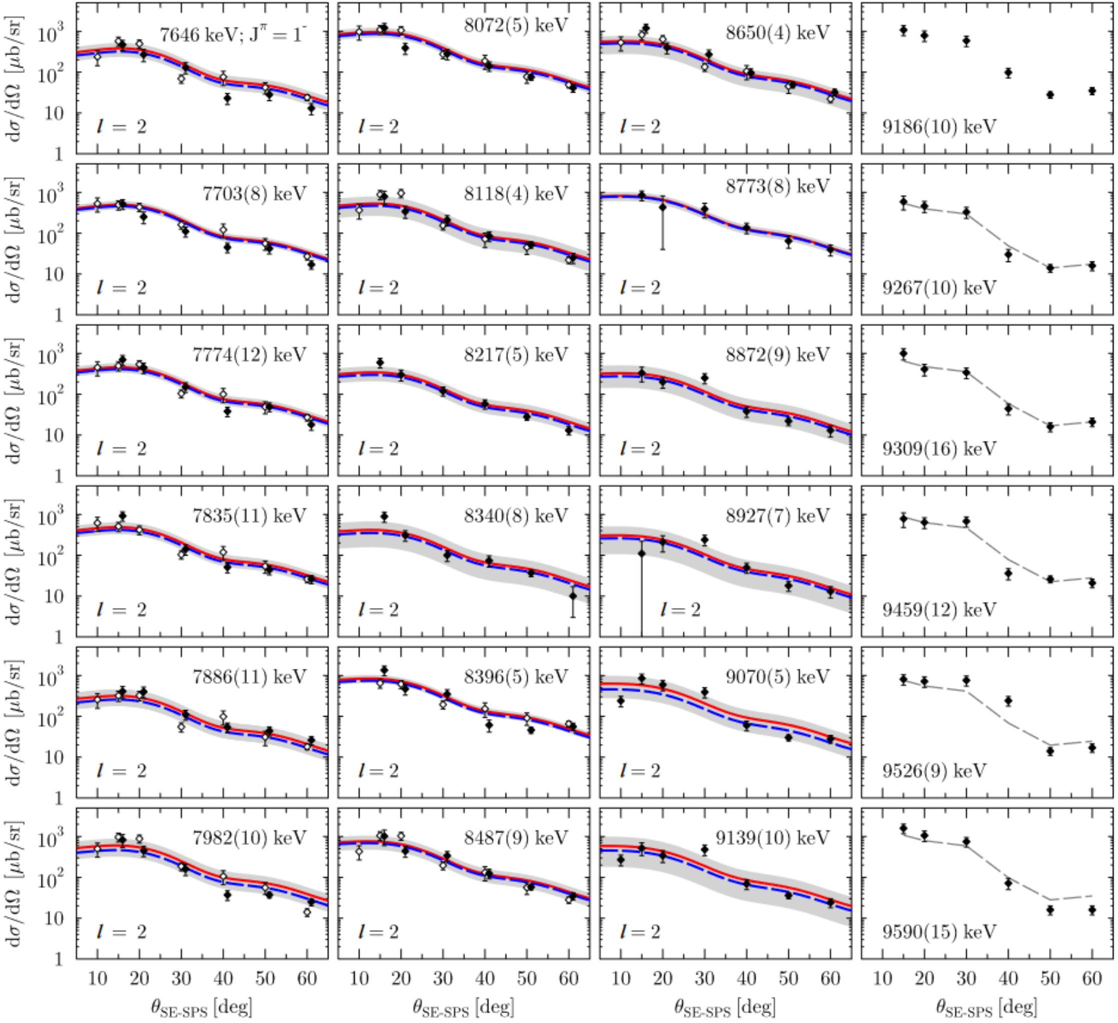
$^{61}Ni(d,p)^{62}Ni$ Angular Distributions



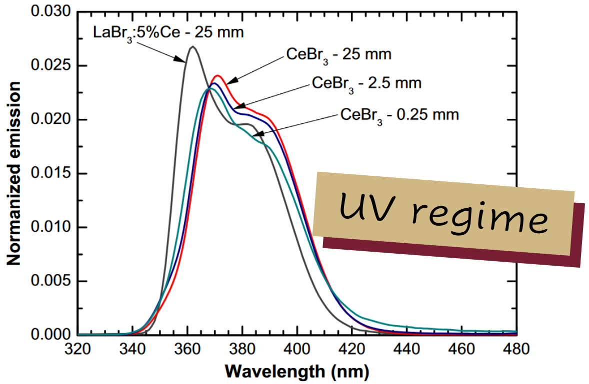
$^{61}Ni(d,p)^{62}Ni$ Angular Distributions

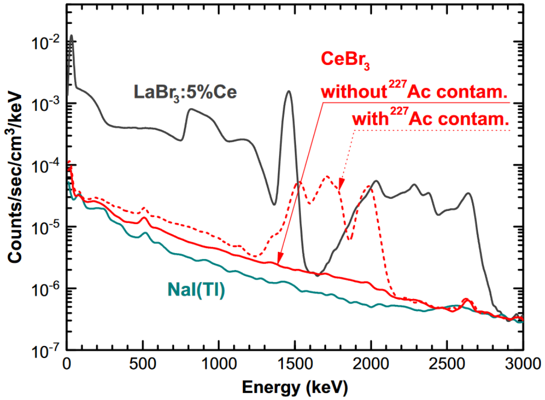


^{61}Ni(d,p)^{62}Ni Angular Distributions



$CeBr_3$ – An inorganic scintillator for γ-ray spectroscopy





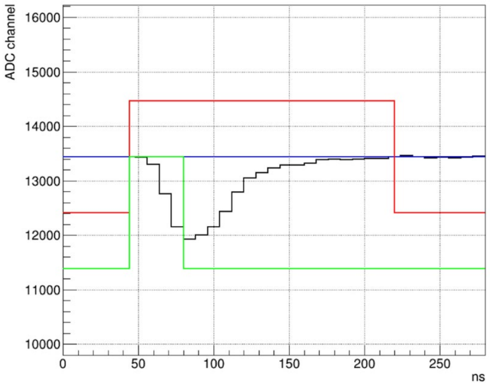
- Similar emission spectrum to $LaBr_3$(Ce) scintillator, which are widely used in low-energy nuclear physics.
  → Double emission band from lowest 5d level to the spin orbit split 4f ground state.

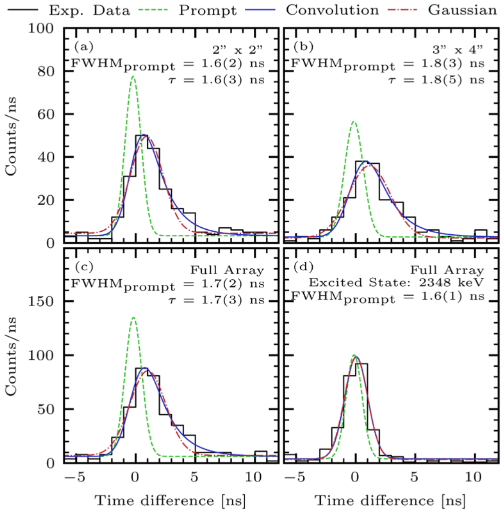
- Unlike $LaBr_3$(Ce), no intrinsic activity.
  → Contaminants can be separated and no radioactive Ce isotope in natural Ce.
  → Low background for spectroscopy applications between 0 and 3 MeV.

- Energy resolution is worse than for HPGe, but comparable to $LaBr_3$(Ce), i.e., ~ 4% at 662 keV.

[F.G.A. Quarati *et al.*, NIM A **729**, 596 (2013)]

$CeBr_3$ – An inorganic scintillator for γ-ray spectroscopy



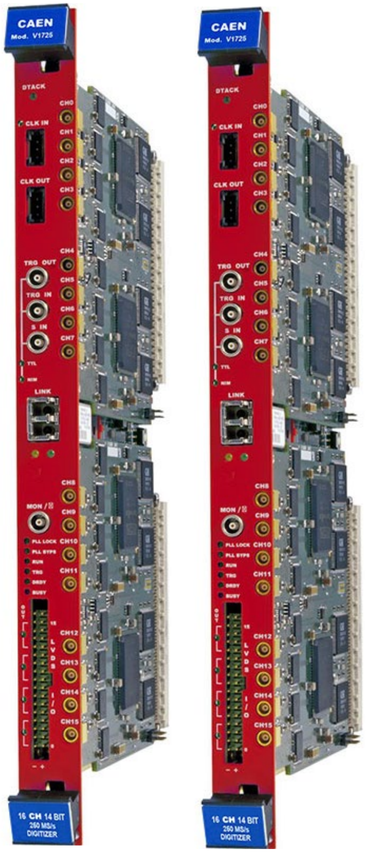


- As for LaBr3(Ce), emission is fast.
  → Because of this fast signal decay, $CeBr_3$ can be operated at much higher rates than slower detector types as, e.g., HPGe.
  → With suitable PMTs, $CeBr_3$ can be used for fast-timing applications, i.e., lifetime measurements of nuclear excited states.

- $CeBr_3$ is less prone to radiation damage by neutrons than HPGe and LaBr3(Ce).
  → Detectors can be used in "violent" environments; *e.g.*, light-ion induced reactions at spectrographs.

[A. Conley, B. Kelly, MS, *et al.*, NIM A **1058**, 168827 (2024)]

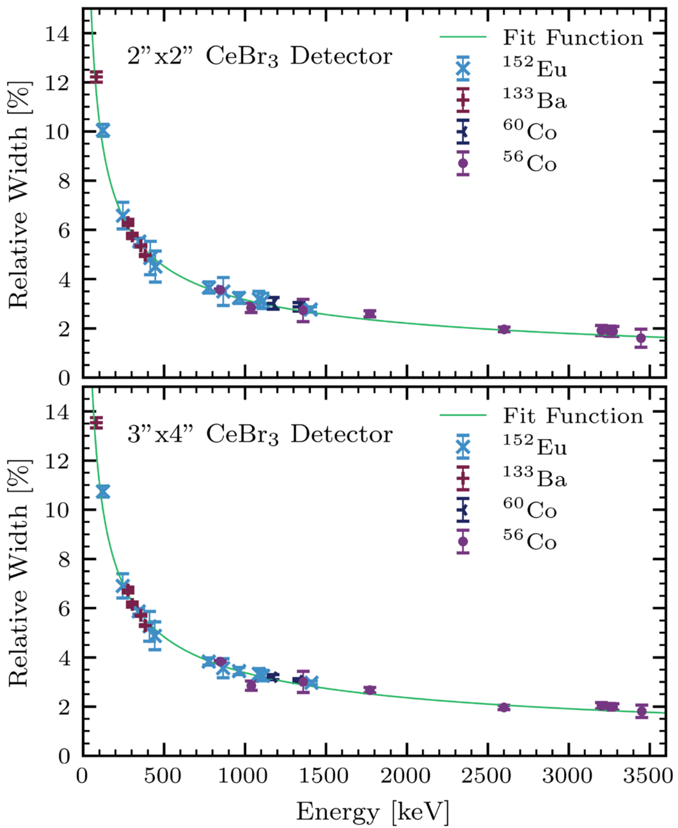
Digital data acquisition

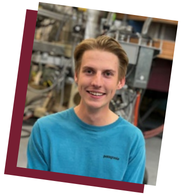


- CAEN V1725S digitizers
  - DPP-PSD firmware
  - 14-bit resolution
  - 250 MS/s sampling rate
  - Clock: 20 ns (50 MHz)
  - Digital CFD provides sub-ns resolution for timing.

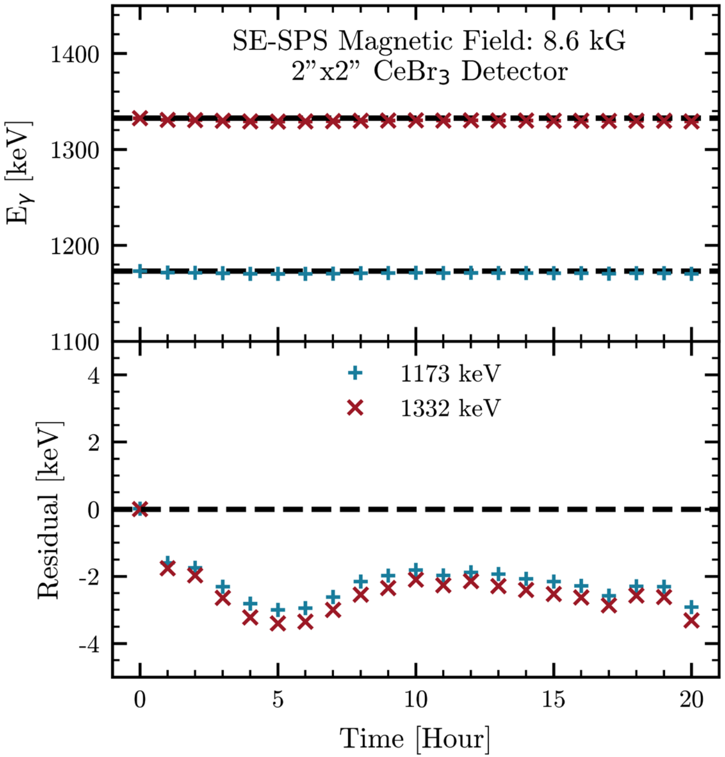
[Also see, *e.g.*, C.J. Prokop *et al.*, NIM A **792**, 81 (2015) for fast-timing with XIA digitizers and digital CFD algorithms]

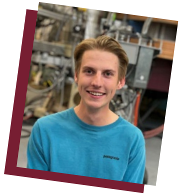
Characterization of $CeBr_3$ detectors – Energy resolution



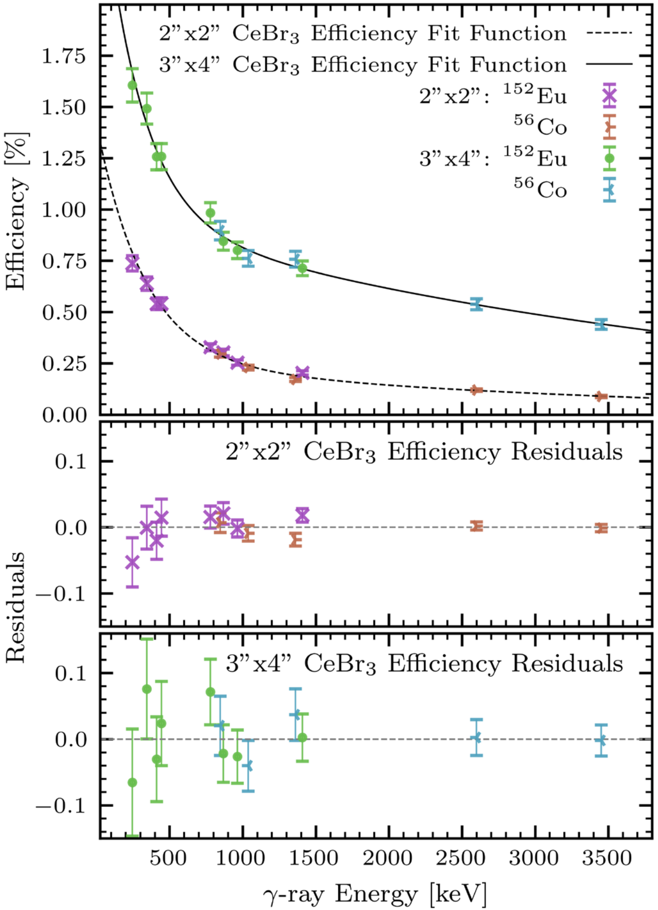


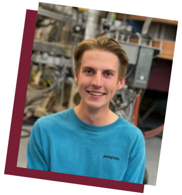
Characterization of $CeBr_3$ detectors – Gain stability close to magnetic field





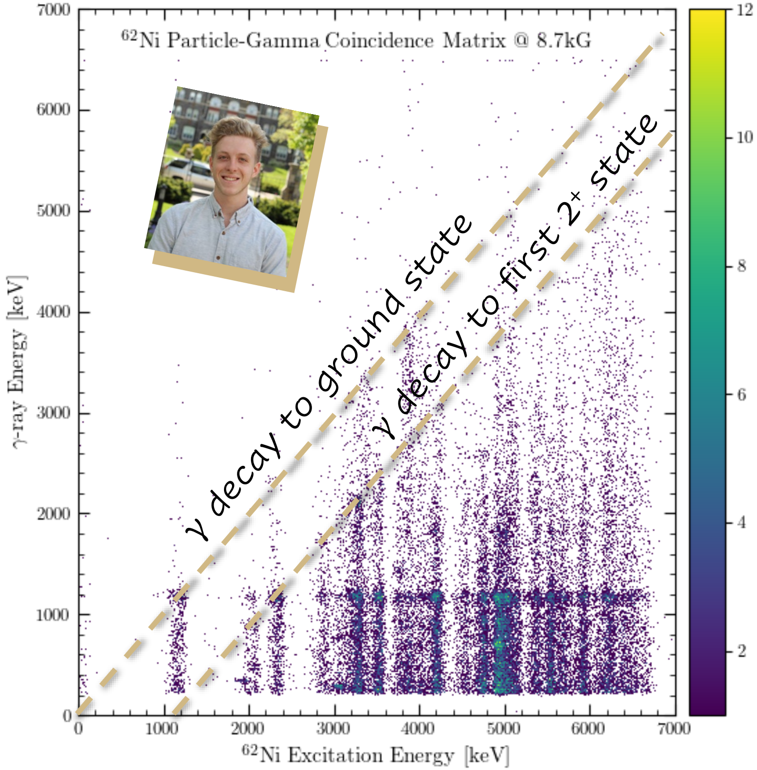
Characterization of $CeBr_3$ detectors – γ-ray detection efficiency

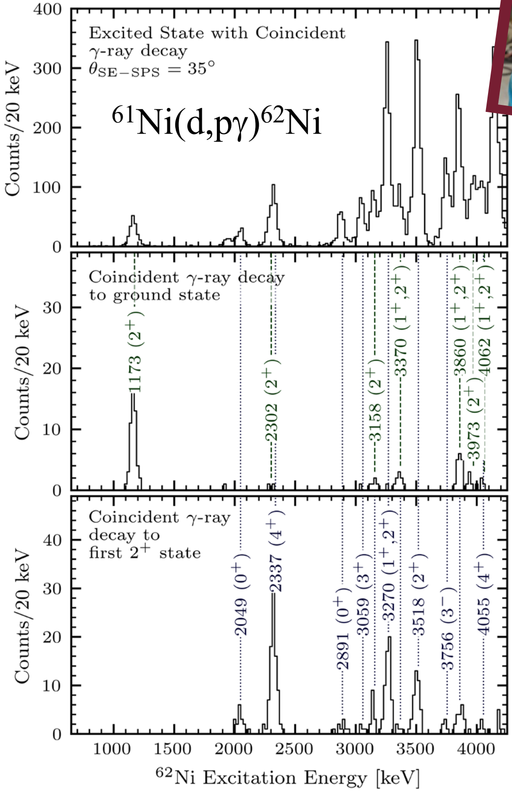




Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

Select decay to specific final state with particle-γ coincidence matrix.





Particle-γ coincidences at SE-SPS