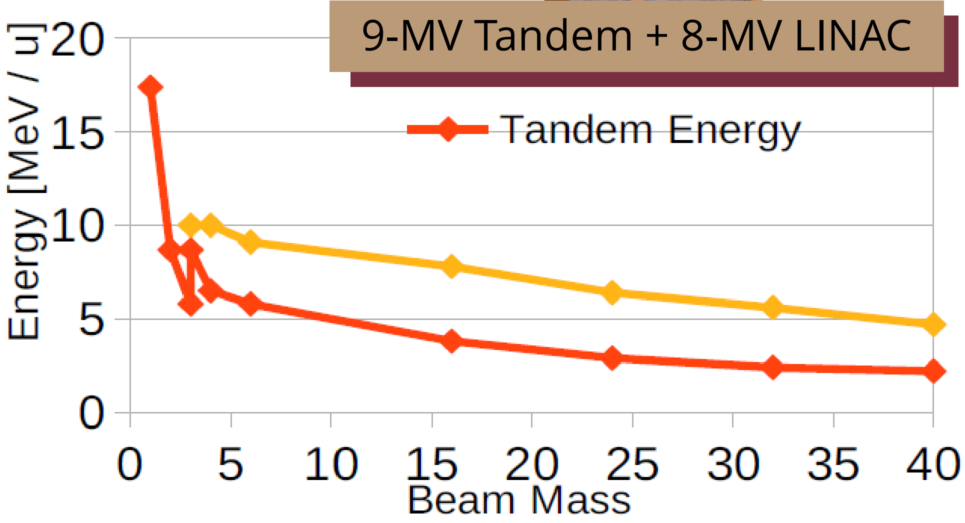
Nuclear structure and reaction studies at the FSU John D. Fox Laboratory

M. Spieker

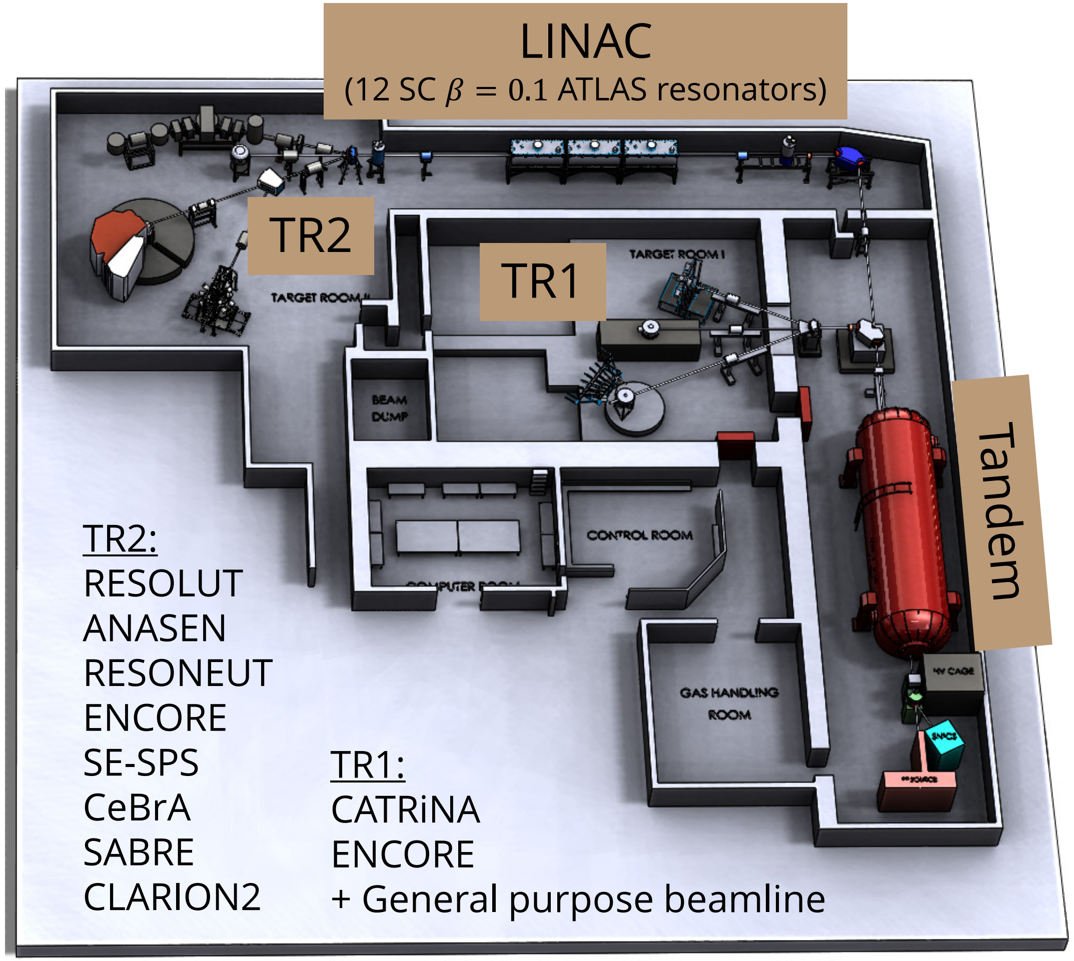
Nucleus-Nucleus Collisions 2024, Whistler, BC Canada

The John D. Fox Superconducting Linear Accelerator Laboratory



Four main experimental programs:

- In-flight radioactive beams with RESOLUT
- High-resolution spectroscopy with Super-Enge Split-Pole Spectrograph (SE-SPS)
  - Resonance spectroscopy with SABRE
  - γ-ray spectroscopy with CeBrA
- CLARION2 Clover γ-ray array (in collaboration with ORNL)
- Neutron detection with CATRiNA



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Outline

Recent science highlights

- Study of proton and neutron resonances in ^{11}B (RESOLUT and SE-SPS)
- Single-particle states studied with the SE-SPS (N=20 and N=28)
- Single-particle character of the Pygmy Dipole Resonance (SE-SPS)
- Particle-γ coincidences with CeBrA+SE-SPS
- Sub-barrier CoulEx with CLARION2+TRINITY and suppression of E2 collectivity in ^{49}Ti

Published results:

E. Lopez-Saavedra et al., PRL **129**, 012502 (2022)
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CeBrA+SE-SPS

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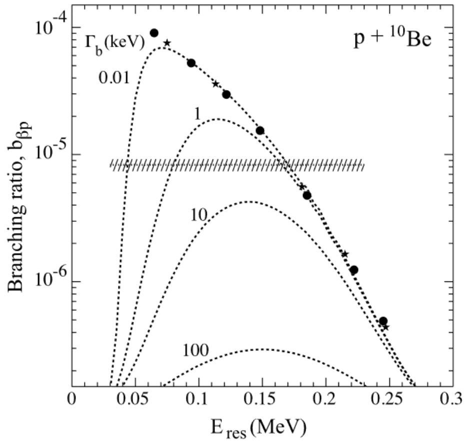
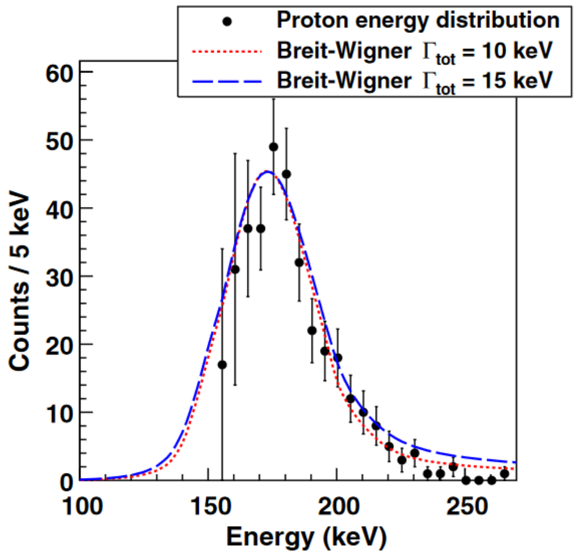
CeBrA+SE-SPS

Study of proton and neutron resonances in ^{11}B

How it started…





Riisager et al., PLB **732**, 205 (2014)

- Studied β^- decay of ^{11}Be indirectly by detecting decay product ^{10}Be.
- Measured enhanced β^-p branching ratio of (8.3±0.9)*10^{-6} in β^- decay of ^{11}Be with AMS technique.
- Suggested quasi-free decay of ^{11}Be halo neutron into a single-proton state.
  → Alternative explanations included a dark decay of the neutron (BSM physics).

Ayyad et al., PRL **123**, 082501 (2019)

- Measured the proton after β^- decay of ^{11}Be directly with prototype AT-TPC.
- Confirmed unexpectedly large branching ratio measured by Riisager et al.
- Suggested the existence of narrow proton resonance just above the proton-emission threshold in line with Riisager's preferred explanation.

Based on these studies, a narrow proton resonance at 11425(20) keV with Γ=12(5) keV and $J^\pi=(1/2,3/2)^+$ was the favored explanation for the observed β^-p branching ratio. What remained missing was the direct population and detection of this resonance in a nuclear reaction.

Study of proton and neutron resonances in ^{11}B

How the proton resonance was confirmed at FSU

PHYSICAL REVIEW LETTERS **129,** 012502 (2022)

Observation of a Near-Threshold Proton Resonance in ^{11}B

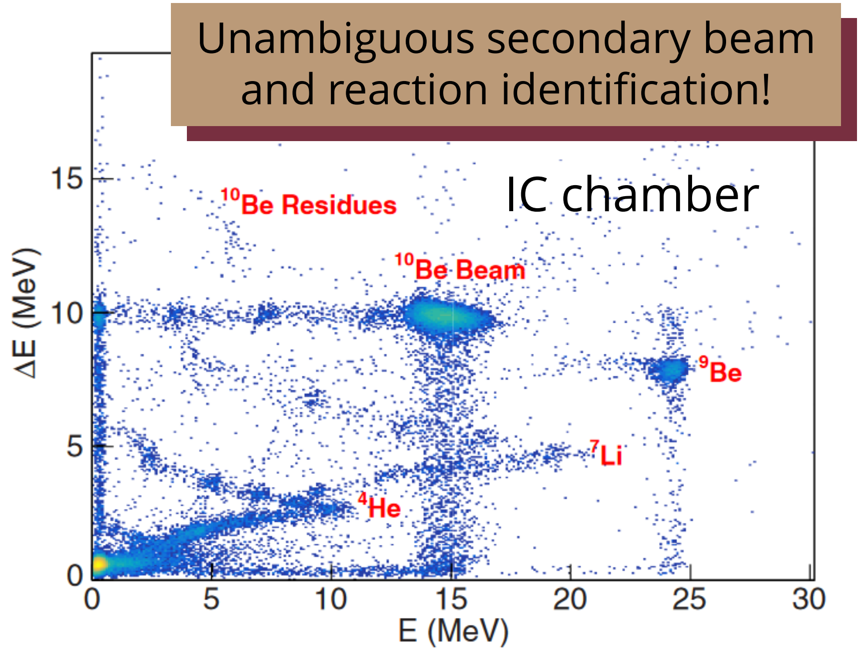
E. Lopez-Saavedra,[1,*] S. Almaraz-Calderon,[1,†] B. W. Asher,[1] L. T. Baby,[1] N. Gerken,[1] K. Hanselman,[1] K. W. Kemper,[1] A. N. Kuchera,[2] A. B. Morelock,[1] J. F. Perello,[1] E. S. Temanson,[1] A. Volya,[1] and I. Wiedenhöver[1]

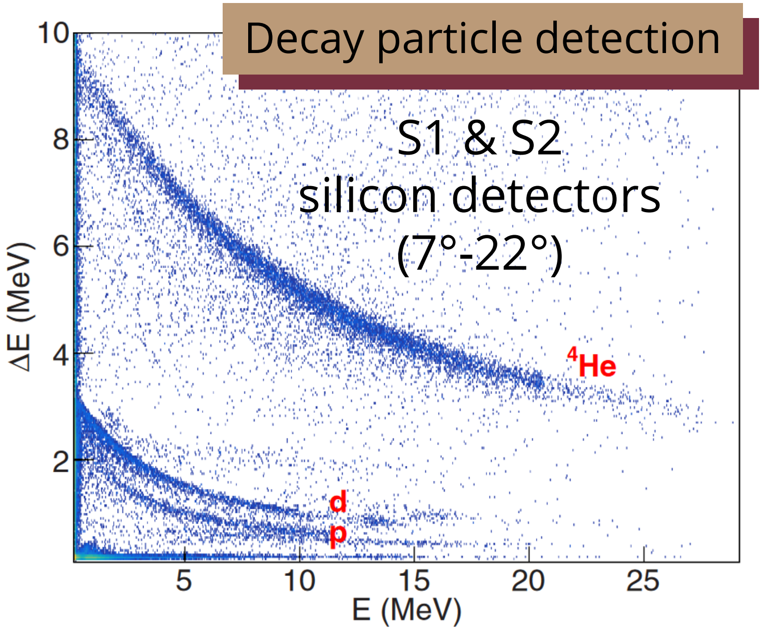
[1]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[2]*Department of Physics, Davidson College, Davidson, North Carolina 28035, USA*

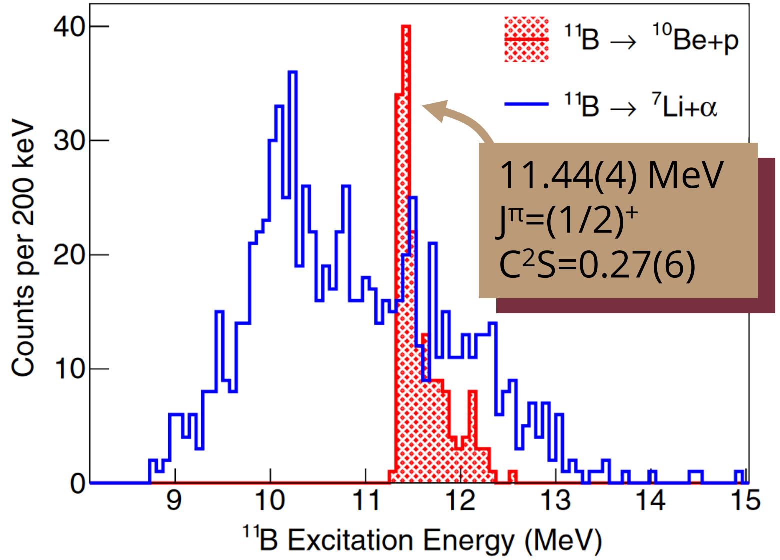
(Received 7 February 2022; revised 26 April 2022; accepted 1 June 2022; published 28 June 2022; corrected 16 November 2022)

- A ^{10}Be beam was produced in $^{9}Be(d,p)^{10}Be$ reaction at 40.9 MeV at the FSU RESOLUT radioactive beam facility and selected in flight.
- After the reaction, the secondary ^{10}Be beam had an energy of 39 MeV and was focused into the RESOLUT reaction chamber (~6000 pps, ≥90% purity).
- The $^{10}Be(d,n)^{11}B$ reaction on 517-μg/cm² CD_2 target was used to populate the possible proton resonance.

[For NSCL $^{10}Be(p,p')$ experiment, see Ayyad et al., PRL **129**, 012501 (2022)]







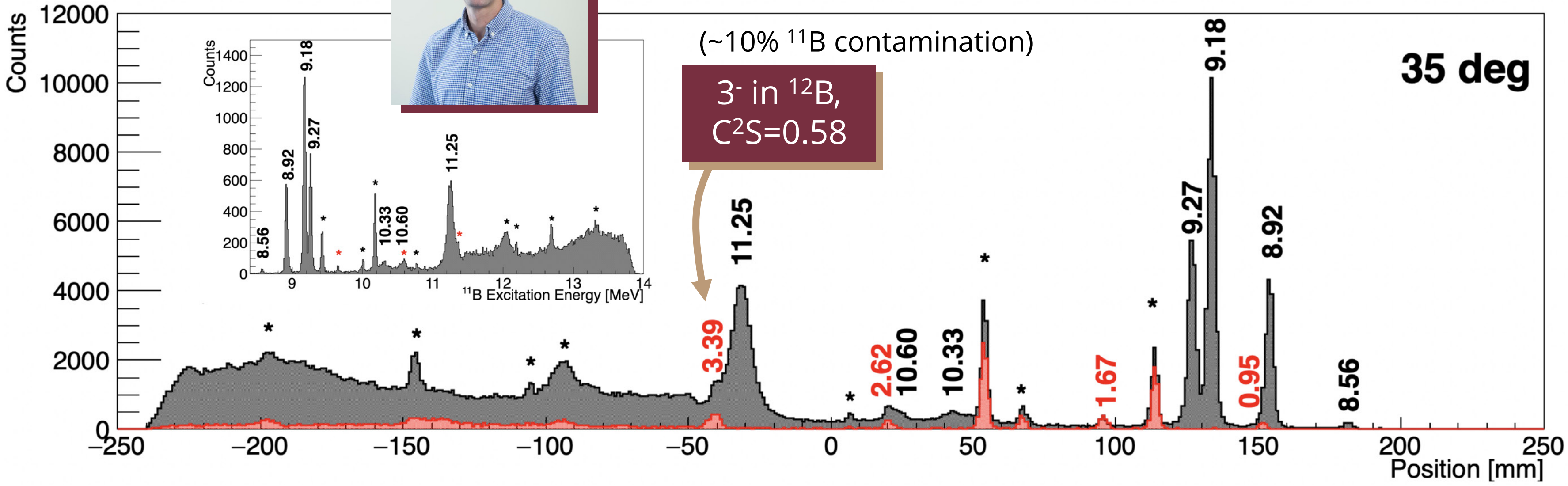
Study of proton and neutron resonances in ^{11}B

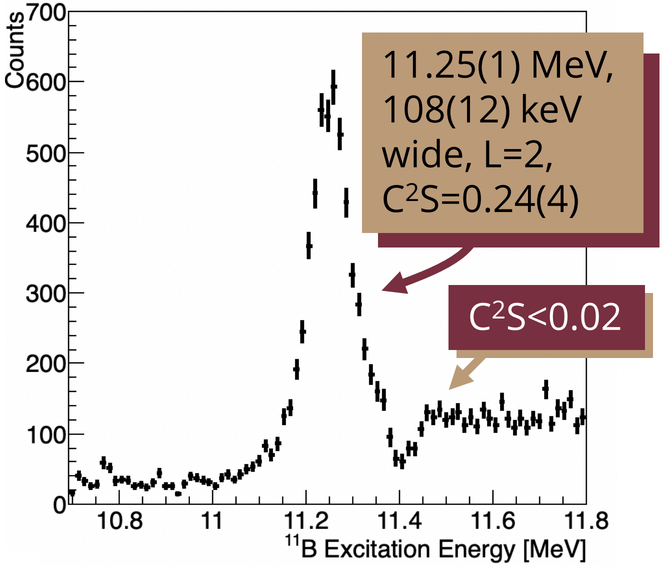
The 11.44-MeV resonance is rather close to S_n=11.45 MeV

An open question prior to our ^{10}B(d,p)^{11}B experiment: Could the 11.44-MeV resonance have a ^{10}B(3^+)+n contribution? Theoretically not expected, but experimentally possible. Also, Okolowicz et al. predicted existence of L=2 dominated, narrow ^{10}B(3^+)+n resonance, analogous to the proton resonance.

^{10}B(d,p)^{11}B at FSU SE-SPS [complementary ^{11}B(d,p)^{12}B measurement]

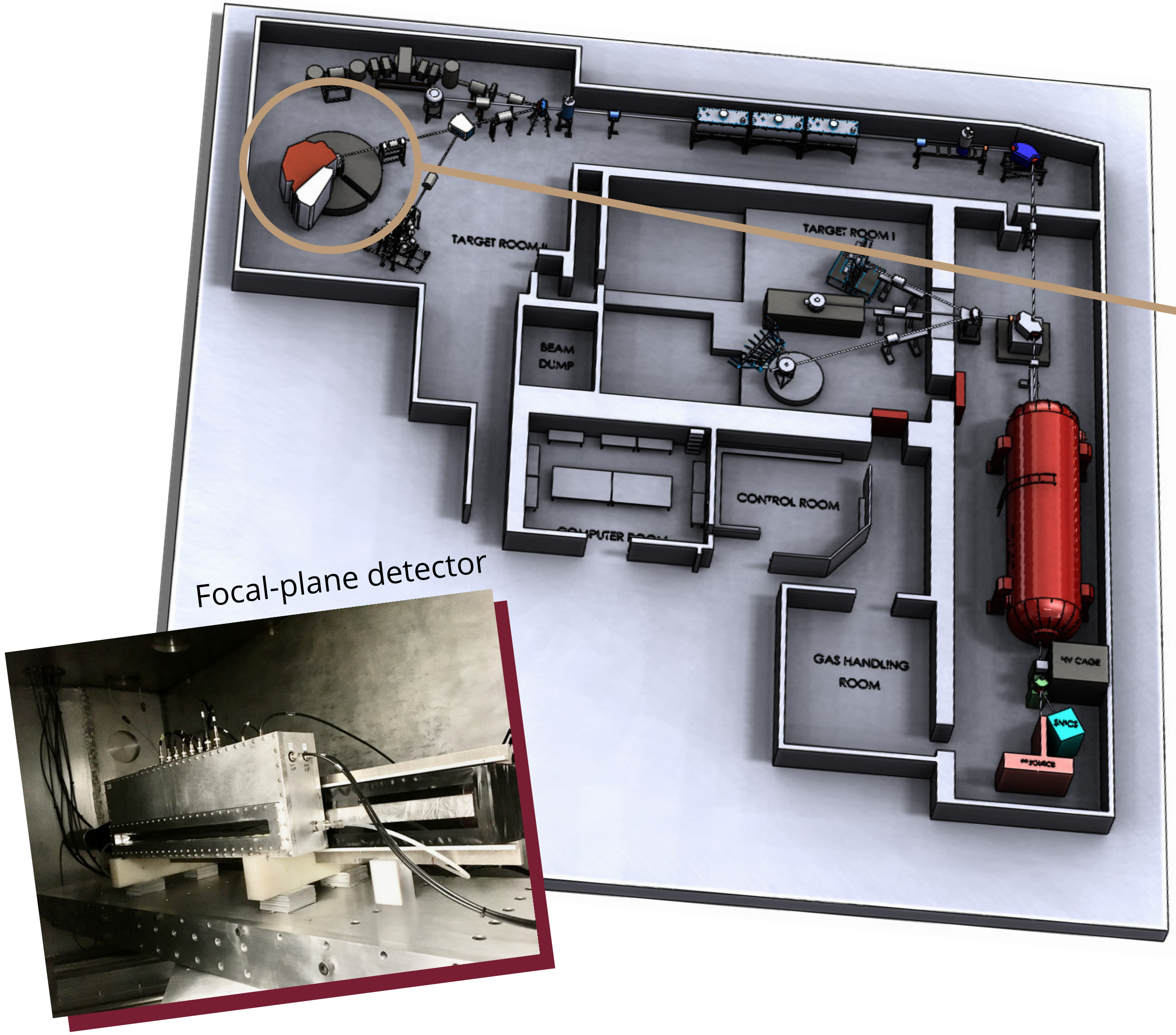
[A.N. Kuchera et al., submitted for publication (2024)]



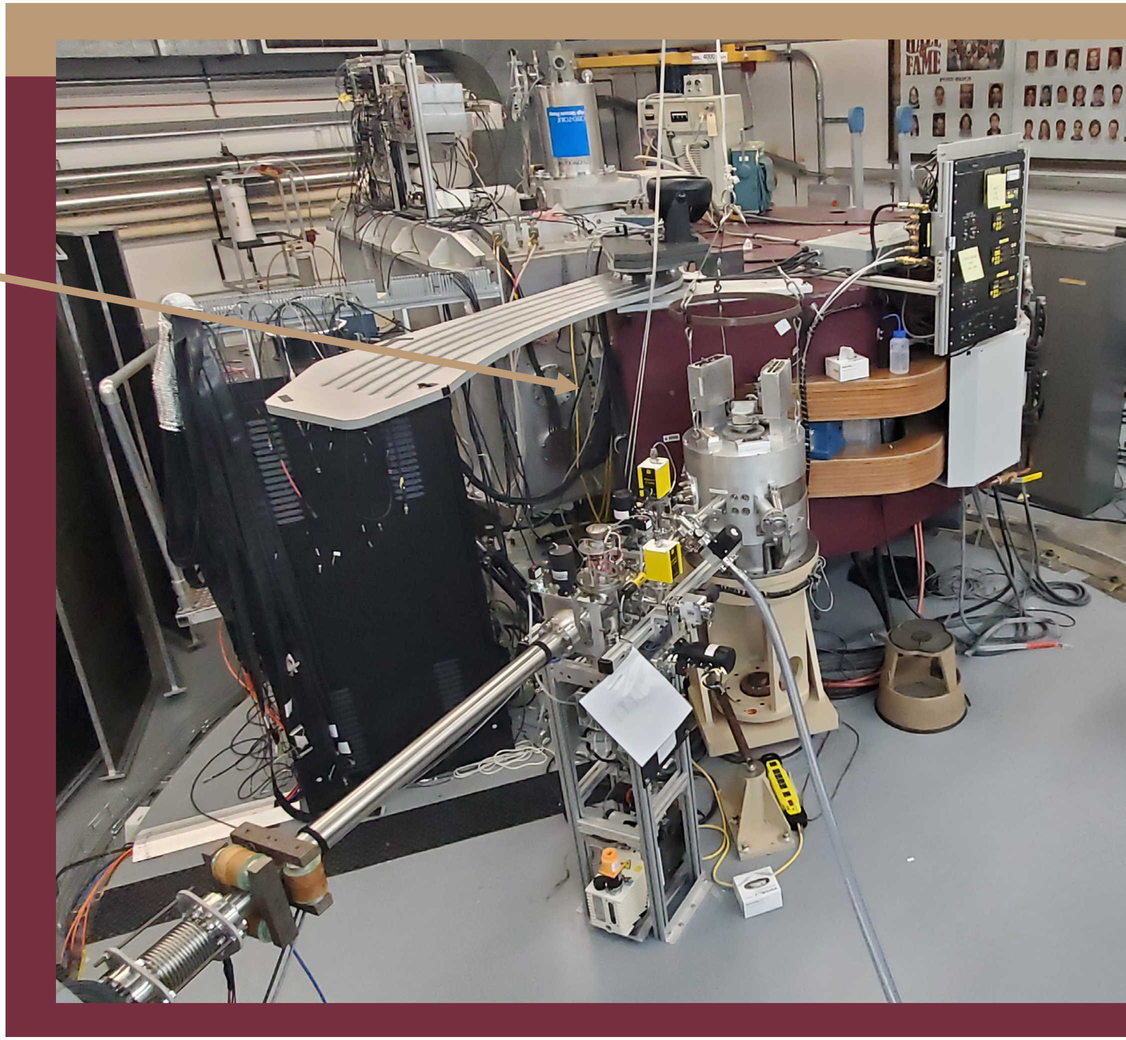


No indication of significant ^{10}B(3^+)+n contribution to 11.44-MeV resonance and, overall, no narrow ^{10}B(3^+)+n resonance detected above S_n! Why would the predicted neutron resonance be significantly broader or have a much smaller ^{10}B(3^+)+n spectroscopic factor?

The FSU Super-Enge Split-Pole Spectrograph



Focal-plane detector



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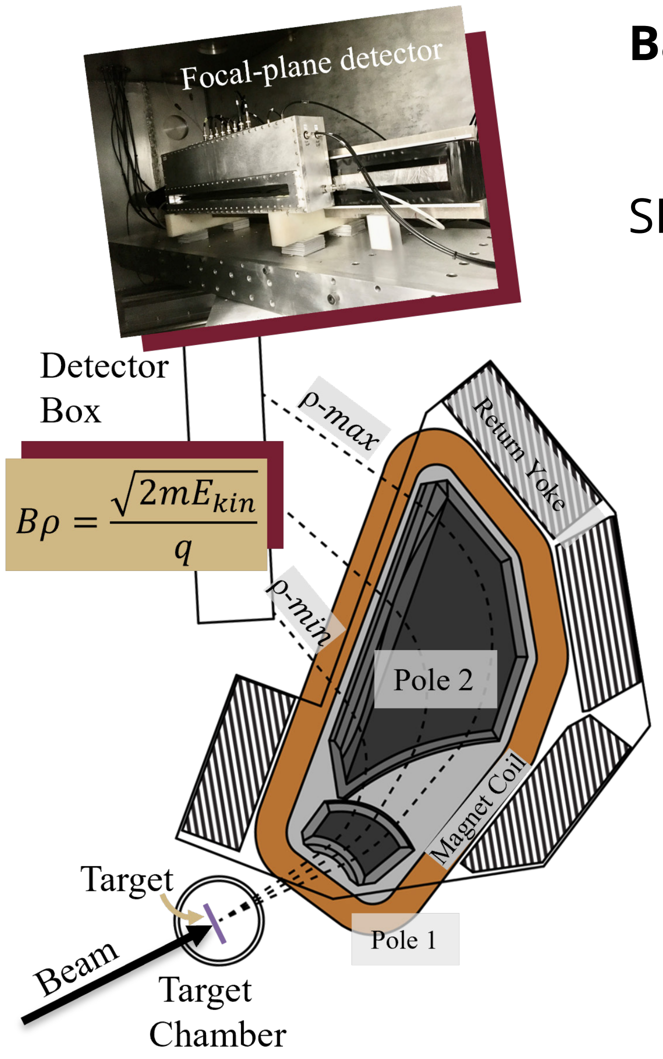
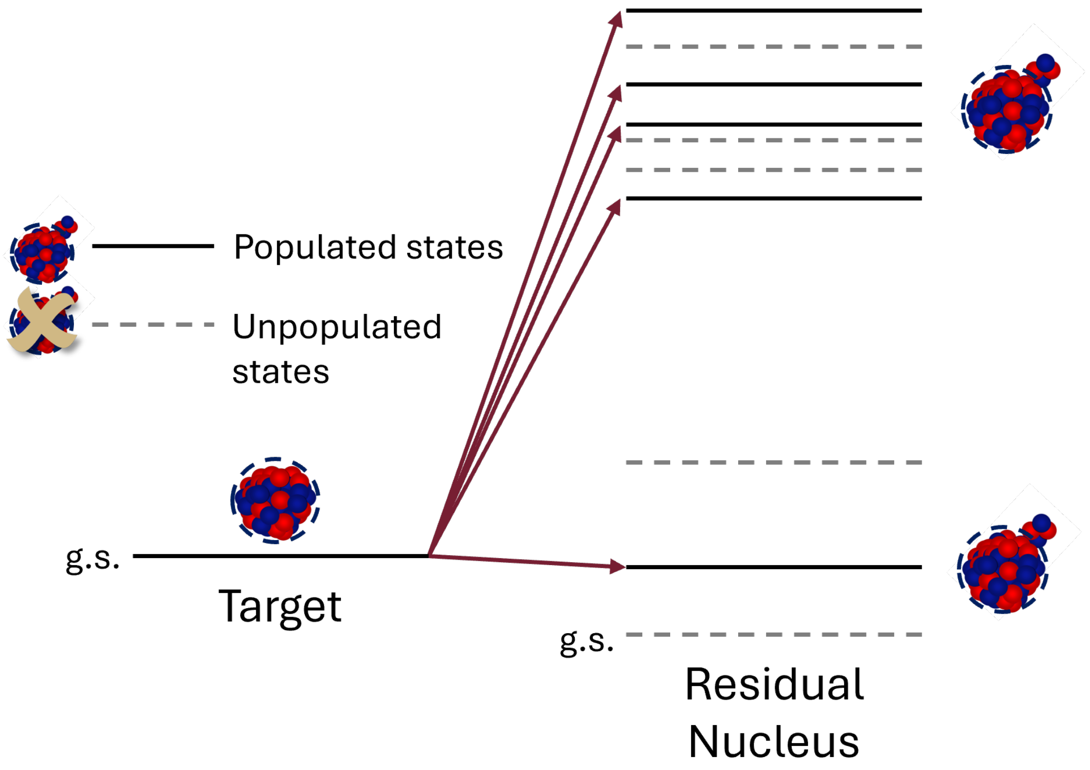


Basic idea: Use direct nuclear reactions to selectively populate excited states of atomic nuclei.

SE-SPS acts as momentum (or Bρ) and reaction filter.



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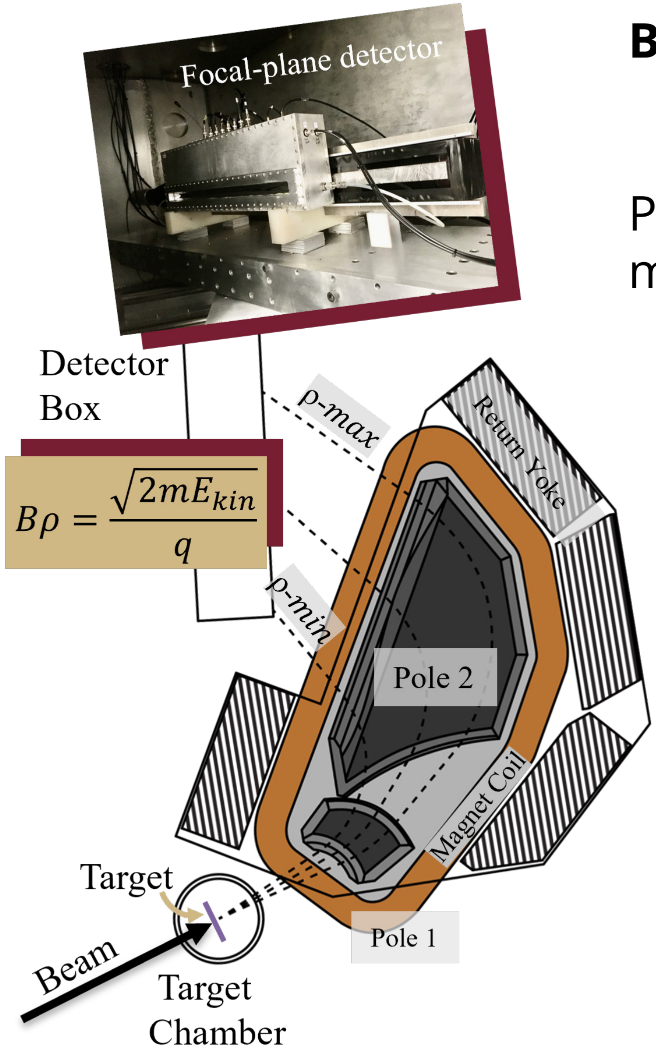

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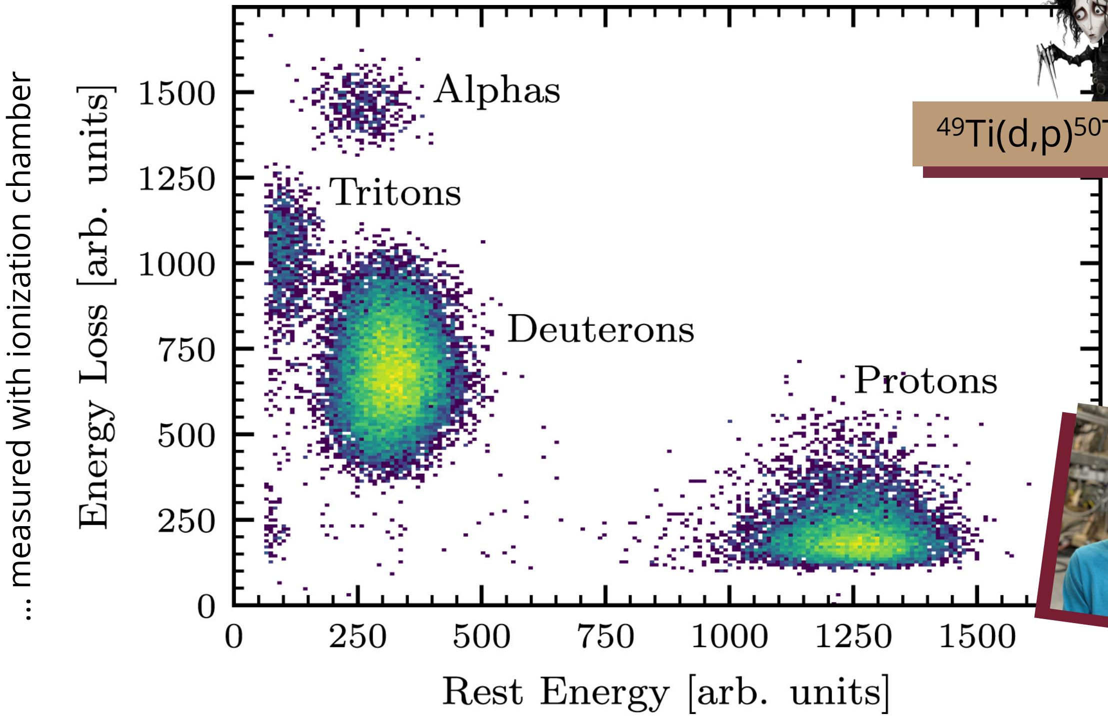
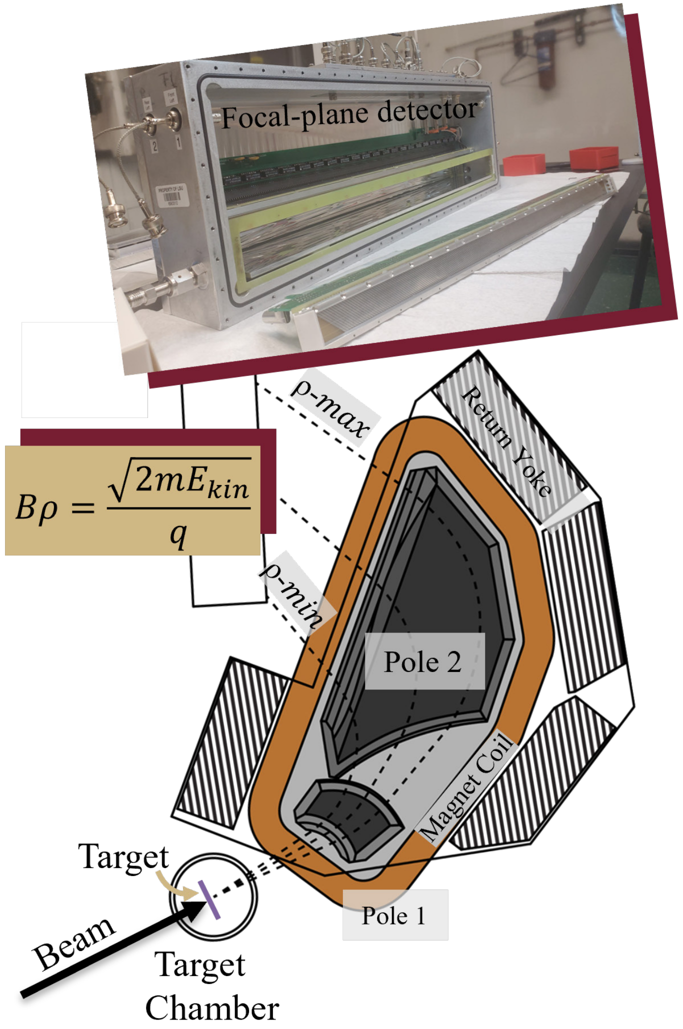
Particle identification with energy loss ΔE and remaining energy E measurements.



… measured with plastic scintillator

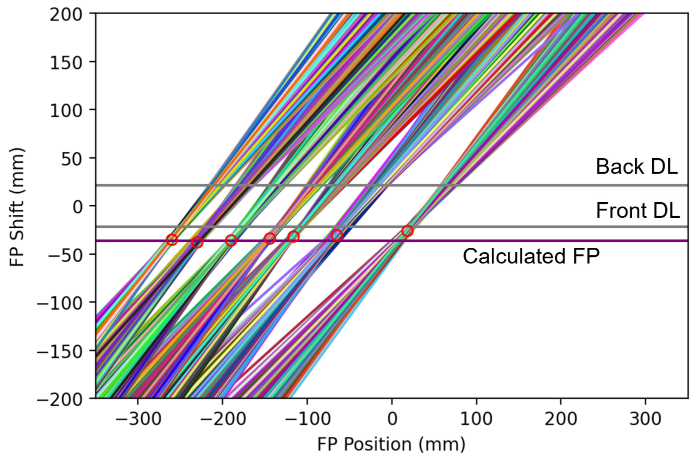
The FSU Super-Enge Split-Pole Spectrograph



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

Basic idea: Position resolution to identify excited states.

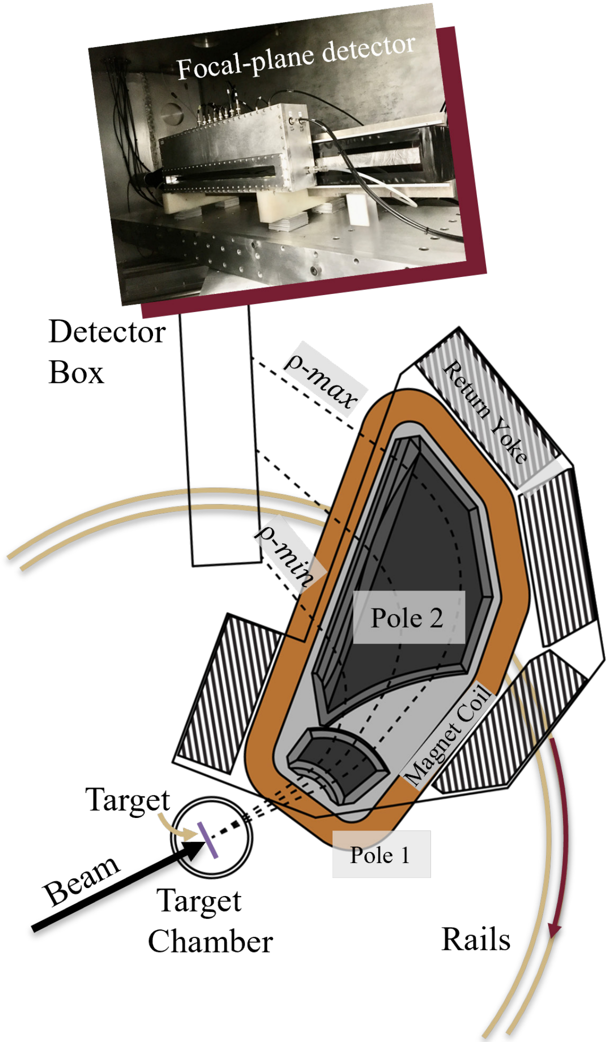
Ionization chamber with two anode wires, each inductively connected to pick-up pads, which are connected to delay-line chips.



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

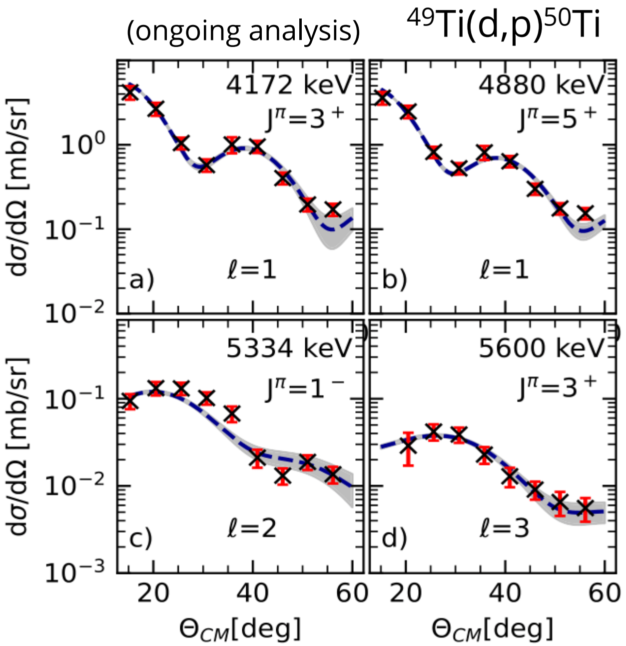
We keep our focal plane detector position fixed and calculate the real focal plane position offline.

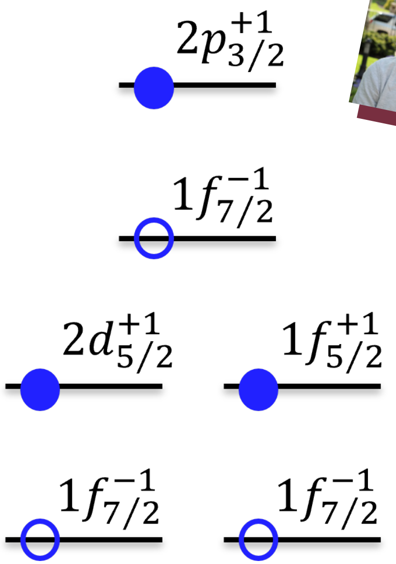
The FSU Super-Enge Split-Pole Spectrograph



Basic idea: Measure angular distributions, i.e., particle yields at different scattering angles, to determine angular momentum transfer.

SE-SPS on rails and sliding seal scattering chamber to facilitate measurements at different scattering angles.





This project focuses primarily on the single-particle character of the Pygmy Dipole Resonance. More later in this talk.

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T.J. Gray et al., PLB **855**, 138856 (2024)

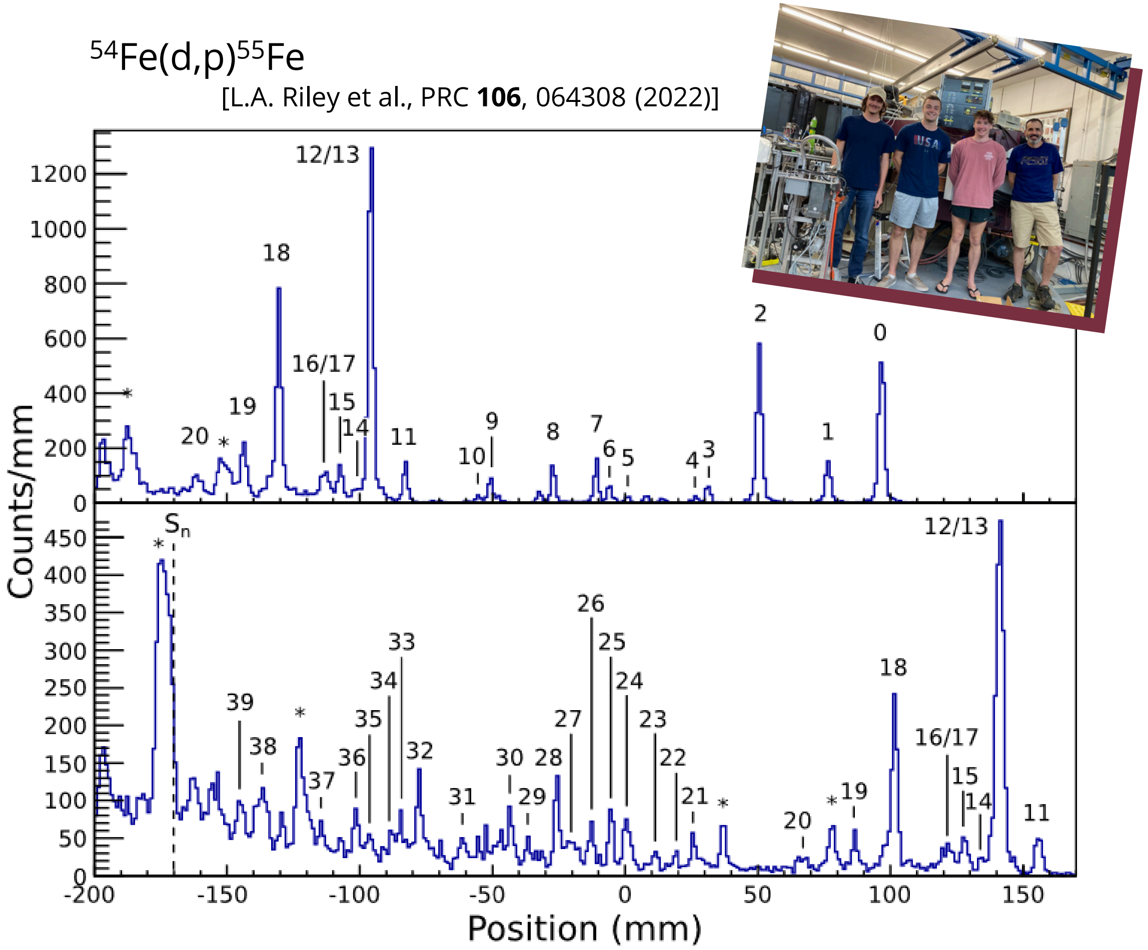
CeBrA+SE-SPS

Single-particle strengths around N=28

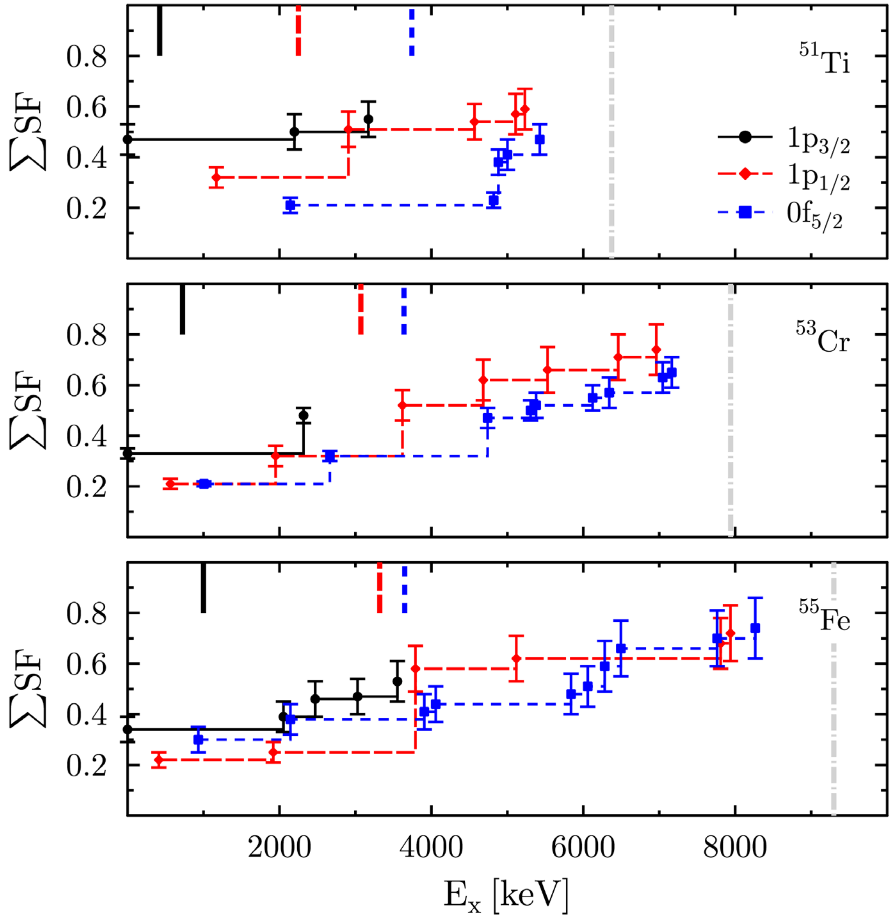
Collaboration with L.A. Riley (Ursinus College) as part of Research Experience for Undergraduate Students (REU) at FSU John D. Fox Laboratory. Measured single-particle strengths for N=29 isotones.

^{54}Fe(d,p)^{55}Fe

[L.A. Riley et al., PRC **106**, 064308 (2022)]



fp orbitals



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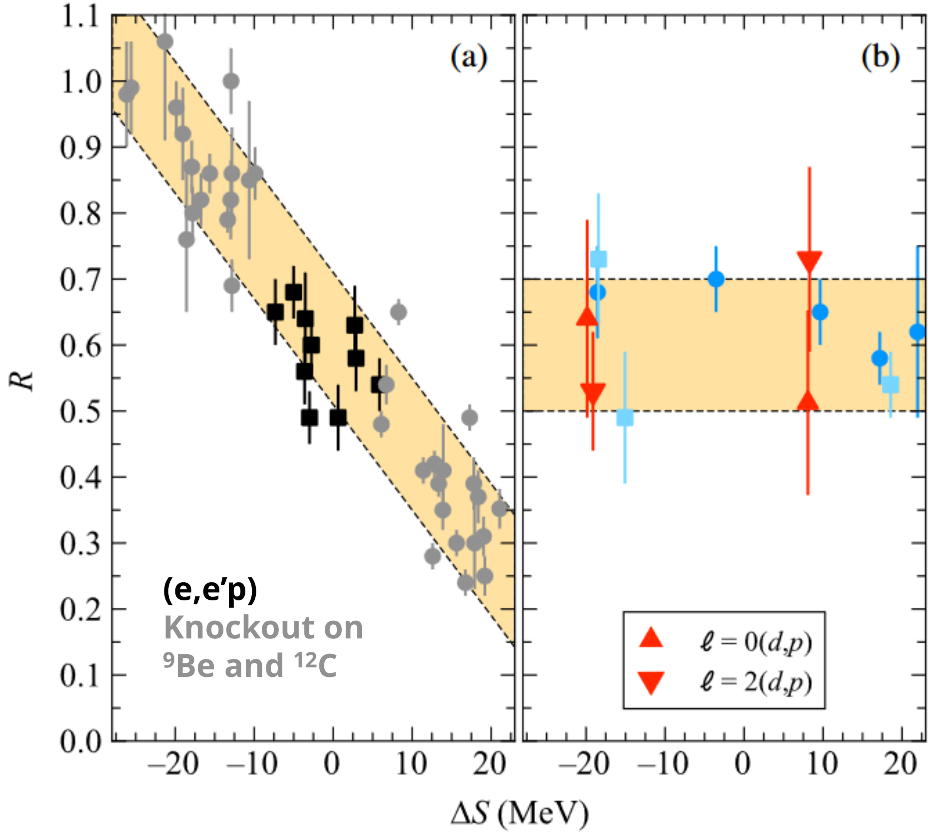
Quenching of single-particle strengths



[Kay et al., PRL **129**, 152501 (2022)]

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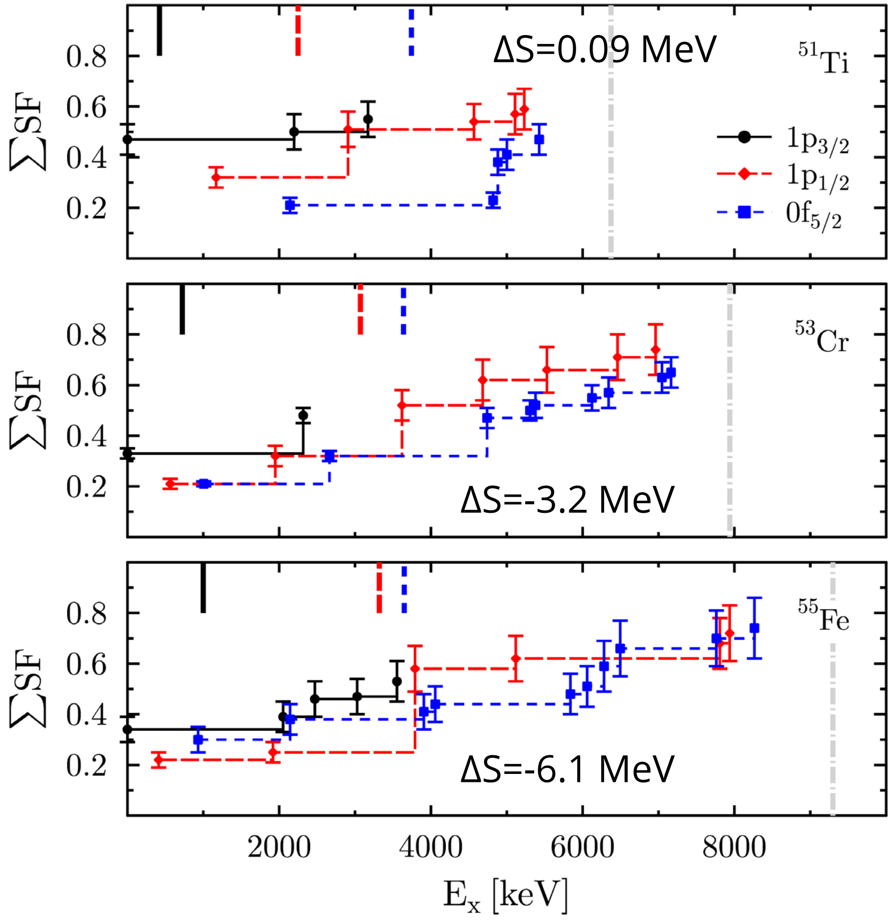
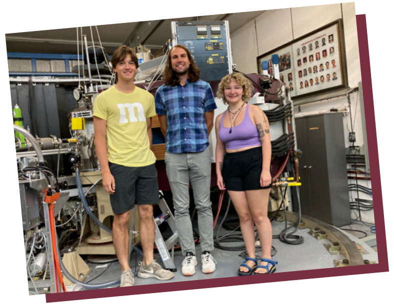
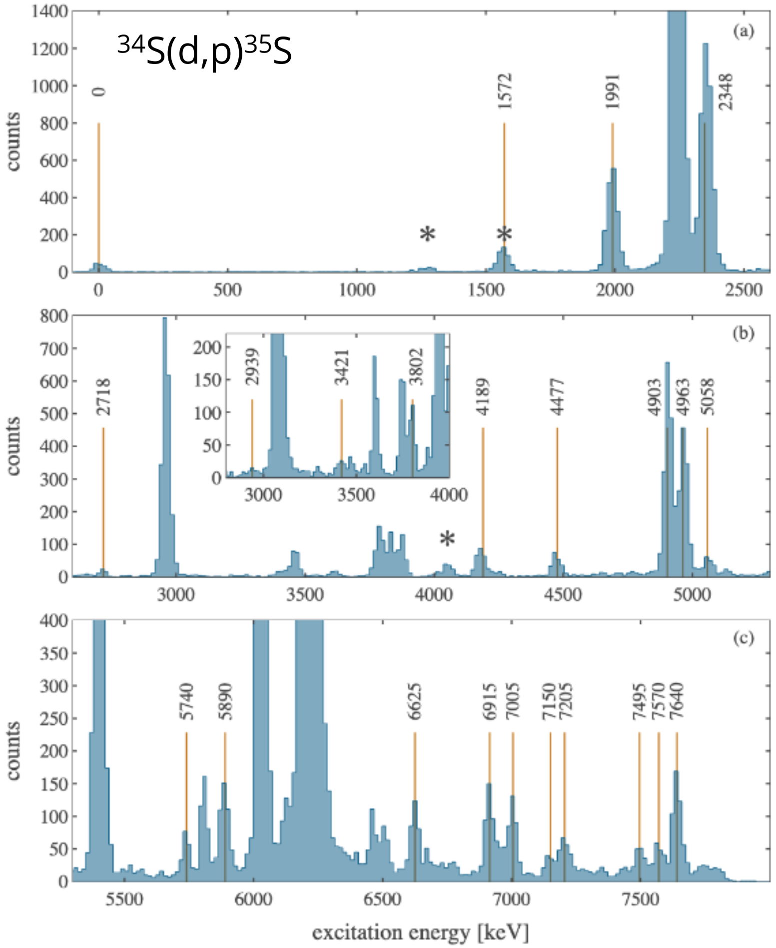
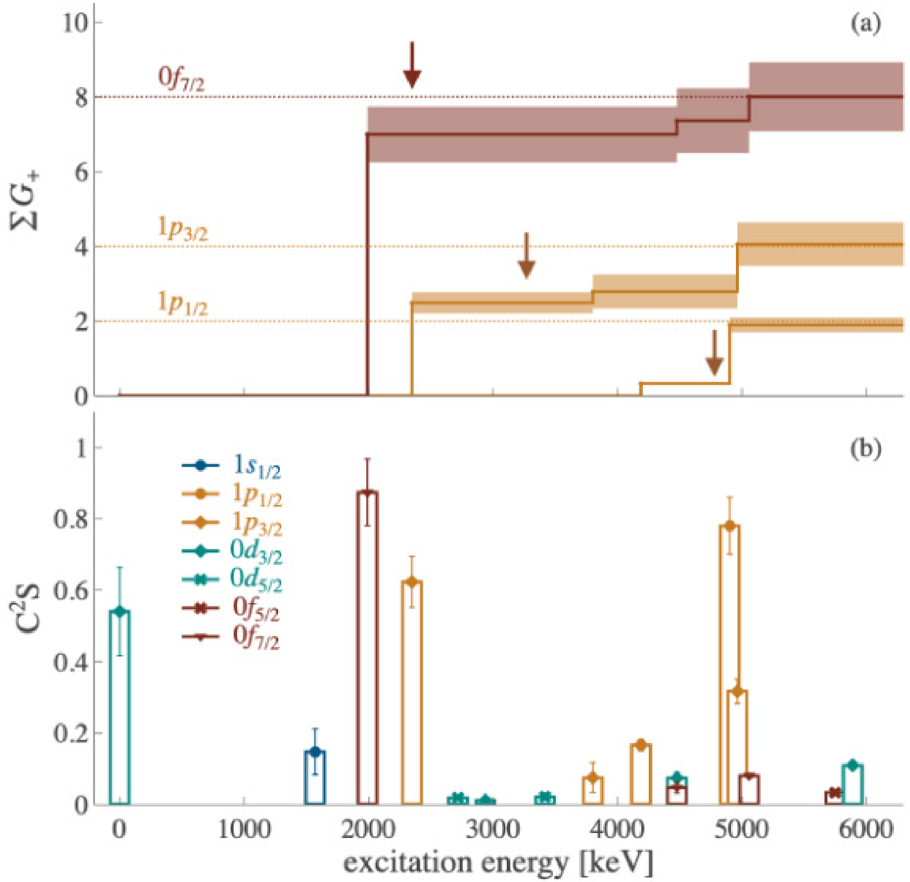


Single-particle strengths around N=20

Collaboration with A.N. Kuchera (Davidson College) as part of Research Experience for Undergraduate Students (REU) at FSU John D. Fox Laboratory. Measured single-particle strengths for ^{35}S.







arXiv:2407.06030v2 [nucl-ex]; submitted for publication (2024)

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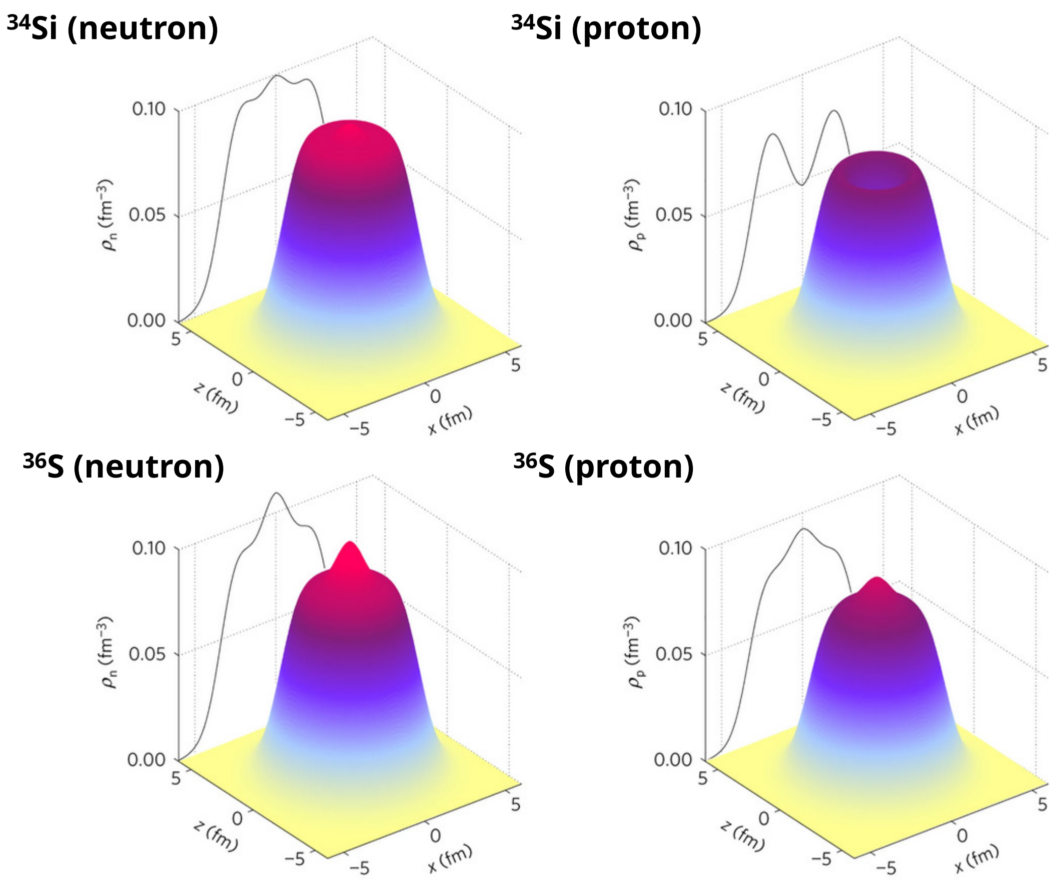
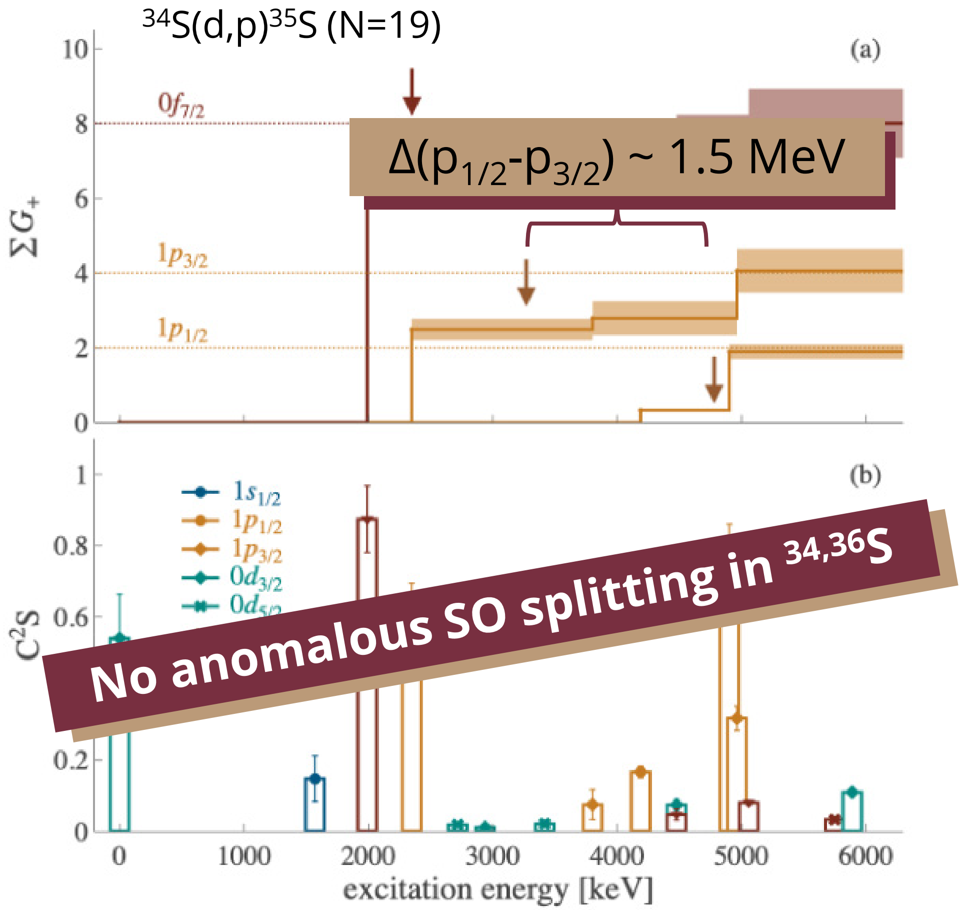


Bubble or no bubble? [Mutschler et al., Nature Physics **13**, 152 (2017)]



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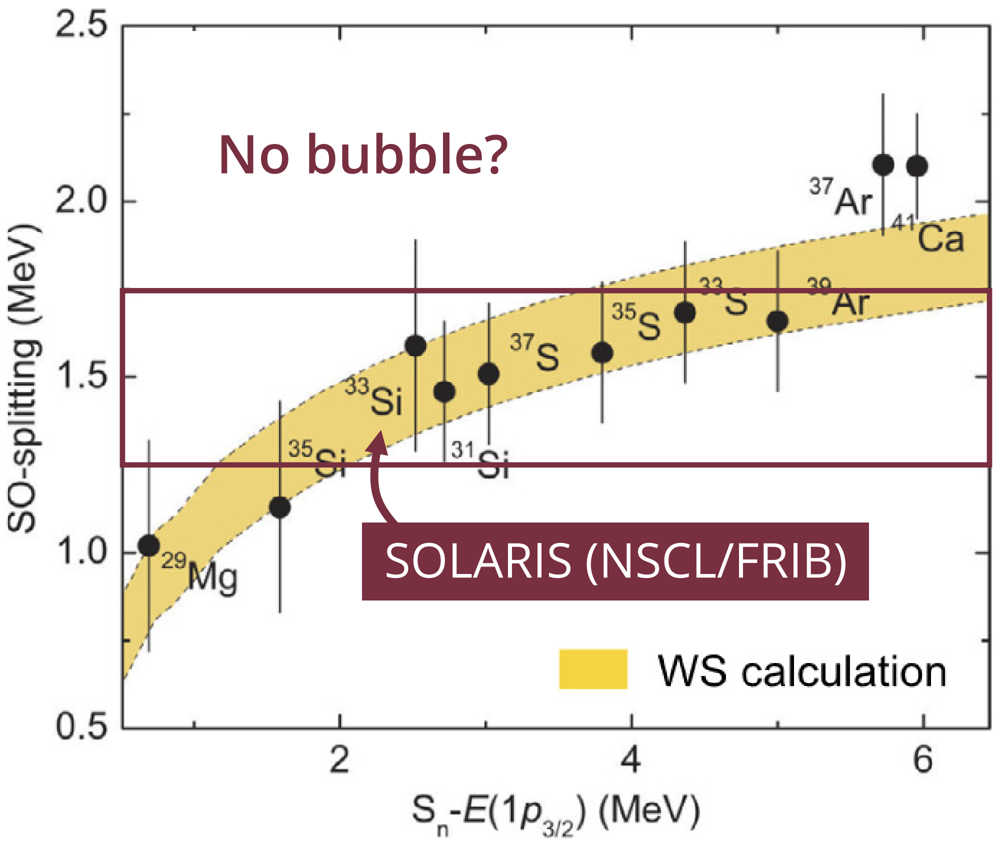
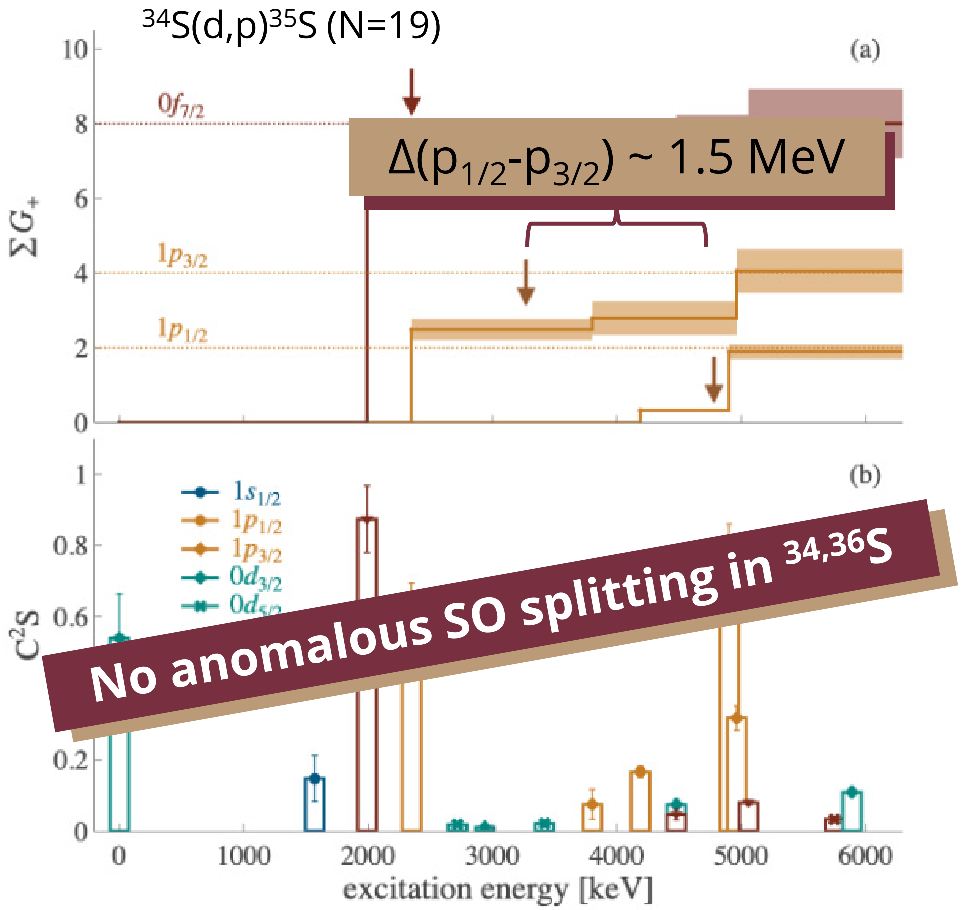


[J. Chen et al., PLB **853**, 138678 (2024)]



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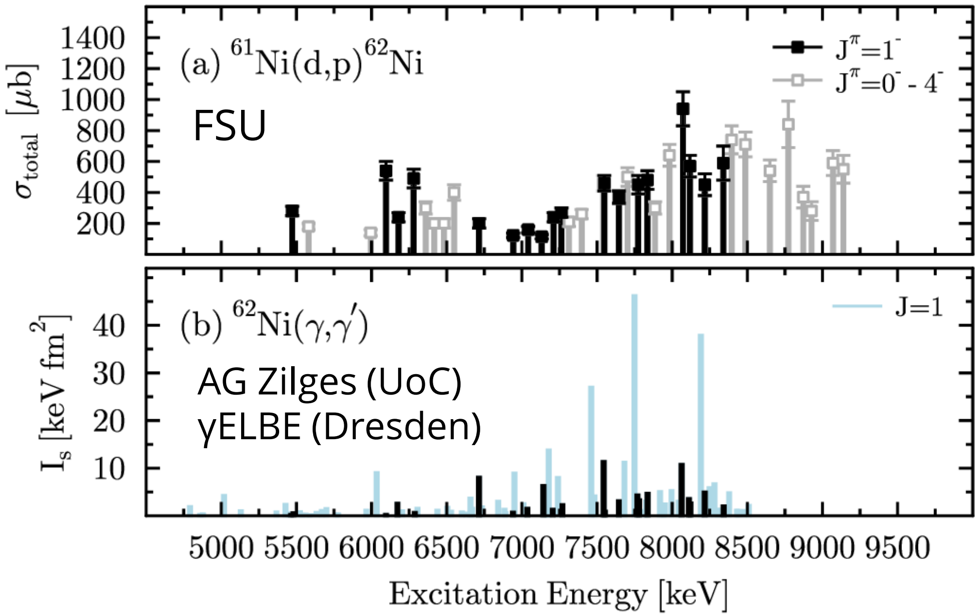
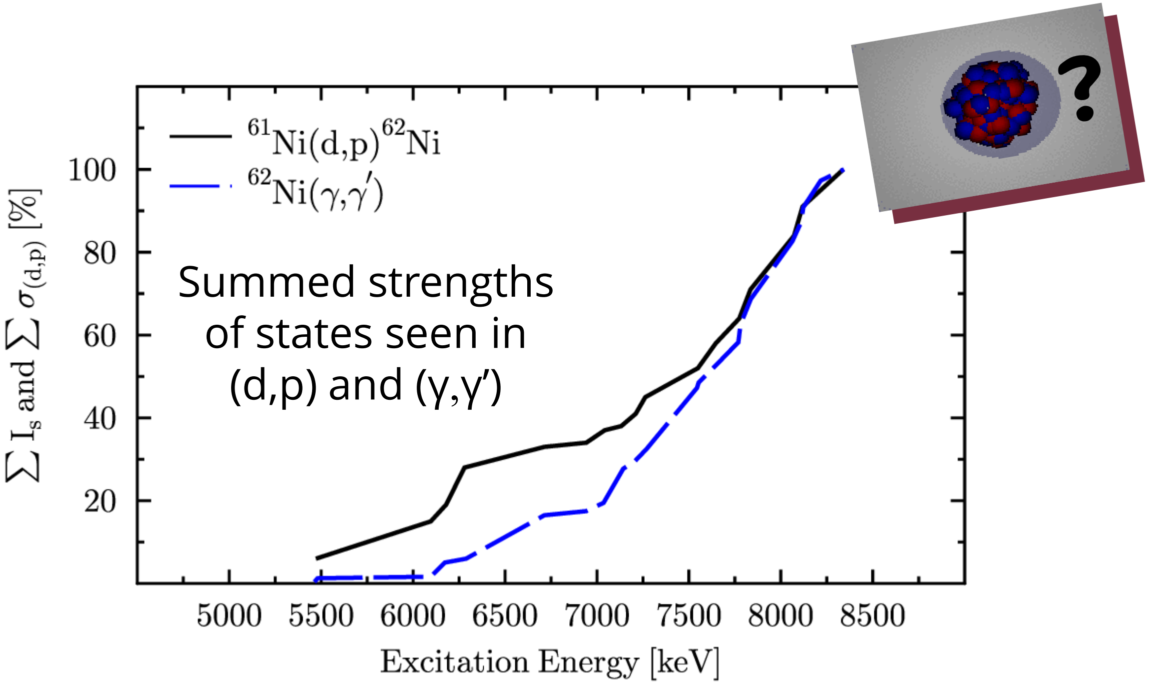
Single-particle character of the Pygmy Dipole Resonance

Theoretical prediction: $(2p_{3/2})^{-1}(2d_{5/2})^{+1}$, $(2p_{3/2})^{-1}(2d_{3/2})^{+1}$, and $(2p_{3/2})^{-1}(3s_{1/2})^{+1}$ neutron one-particle-one-hole contributions cause observed strength increase beyond N=28. [T. Inakura *et al.*, PRC **84**, 021302(R) (2011)]





Observations:

- Most strongly populated states in (γ,γ') not populated in (d,p).
- Only L=2 angular momentum transfers populated 1^- states below S_n in (d,p).
- Relative strength evolution does not follow the same trend in 5.5-7.5 MeV energy window.

→ **Systematic studies needed to test details of Inakura's theoretical predictions and other models!**

[MS et al., Phys. Rev. C **108**, 014311 (2023)]

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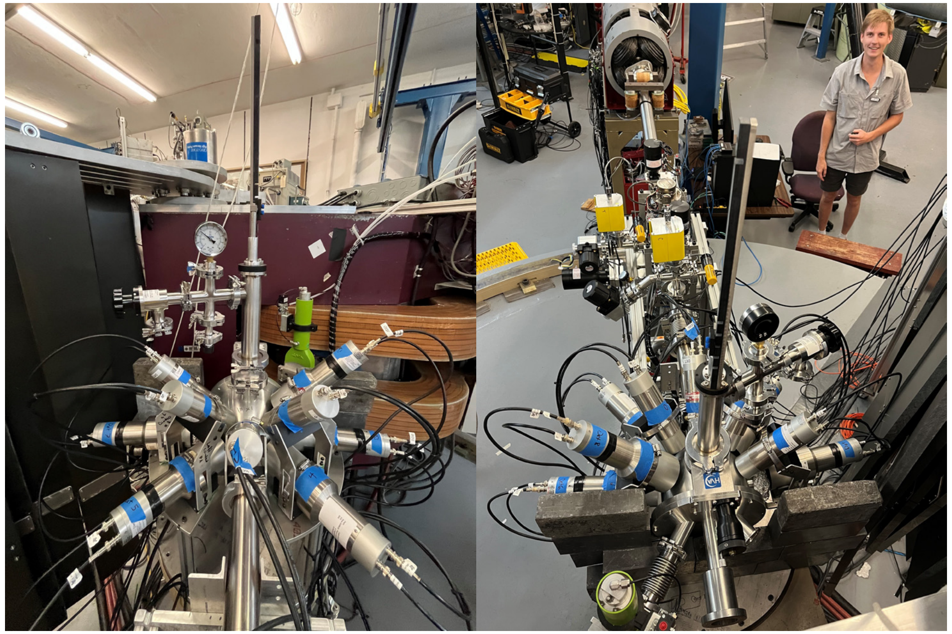
CeBrA+SE-SPS

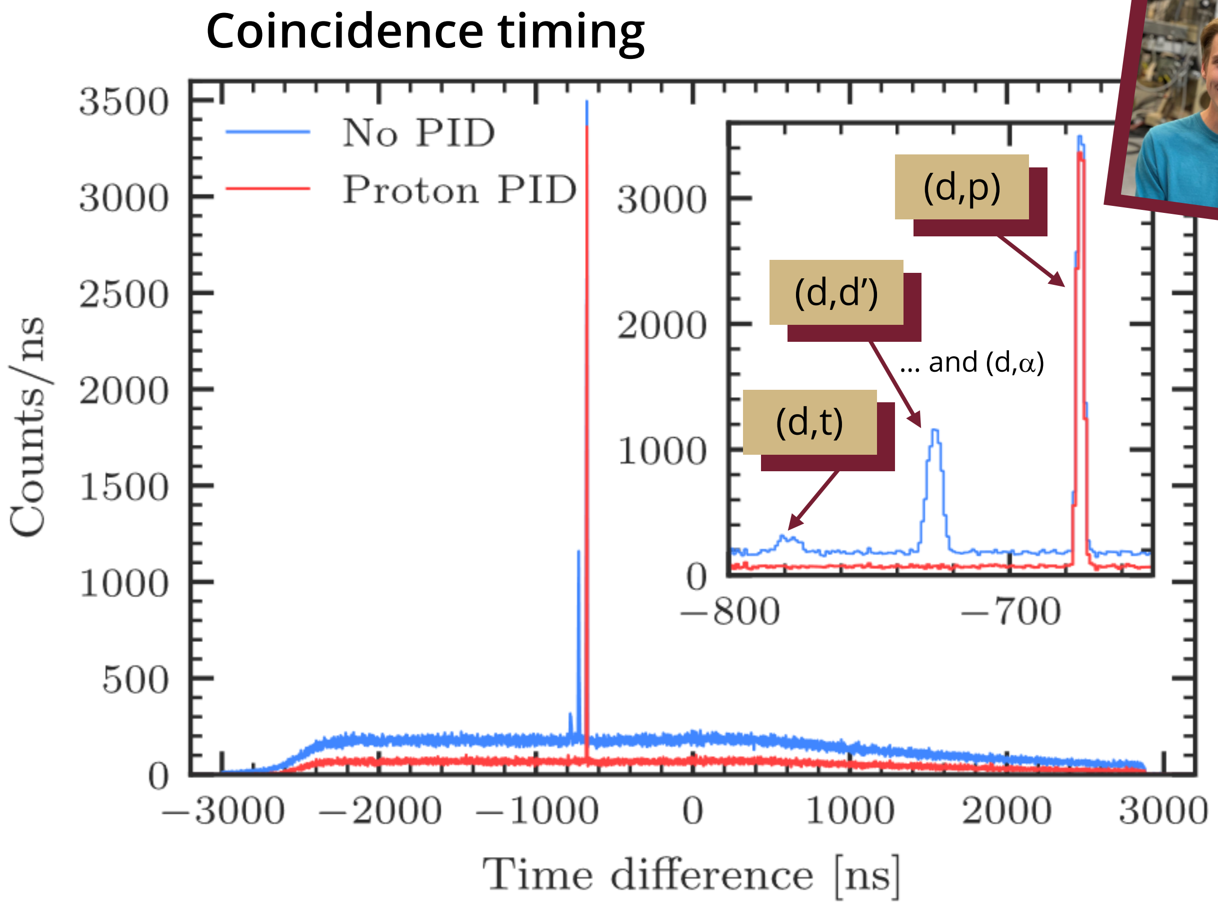
Particle-γ coincidences with CeBrA+SE-SPS



Extended CeBrA demonstrator
(with four $CeBr_3$ from MSS)

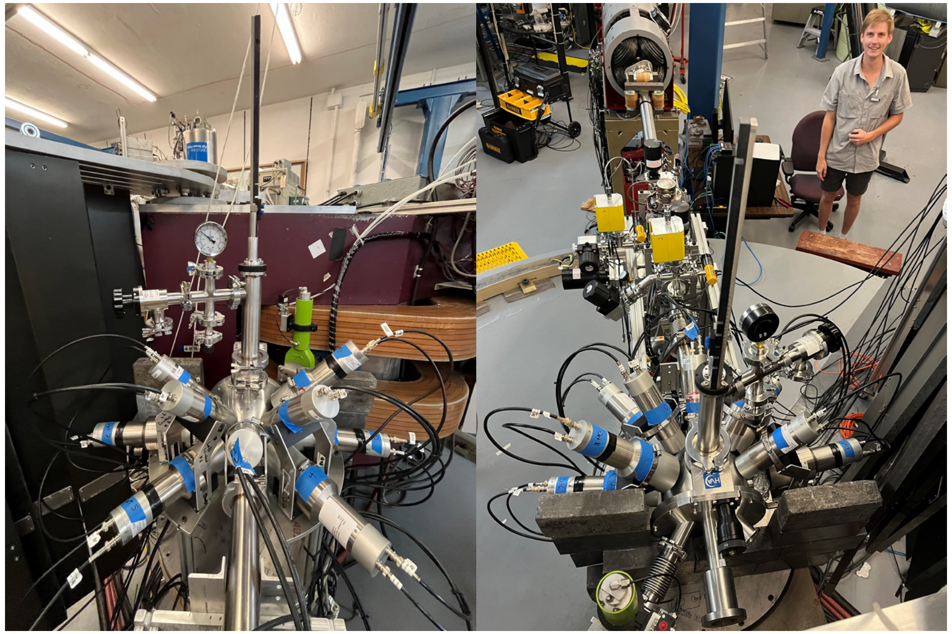
- 4x 2x2 inch, 1x 3x4 inch, 4x 3x3 inch $CeBr_3$ detectors
- CAEN V1725S based DAQ
- CeBrA run in triggered mode (3μs coincidence windows with SE-SPS scintillator)

A.L. Conley et al., NIMA **1058**, 168827 (2024)



(between CeBrA and FP scintillator)

Particle-γ coincidences with CeBrA+SE-SPS



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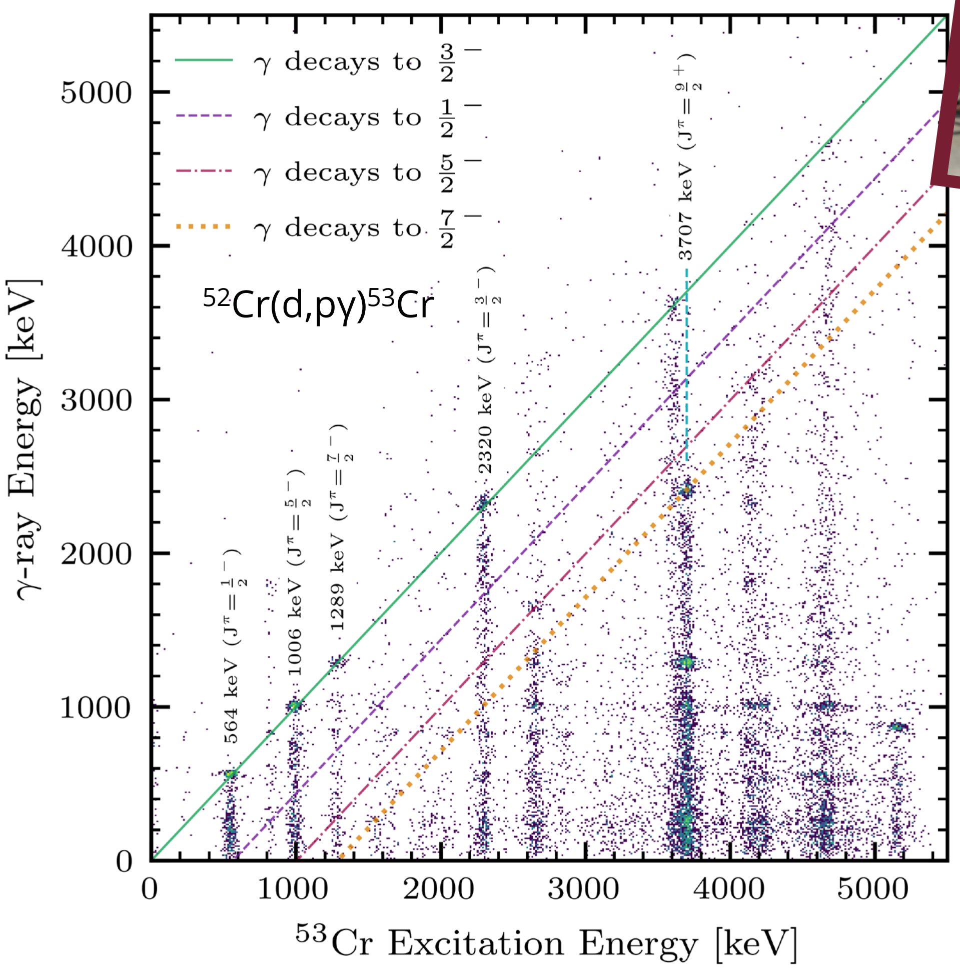
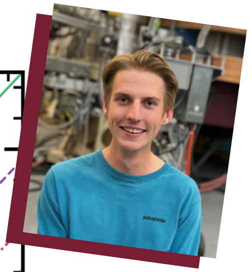
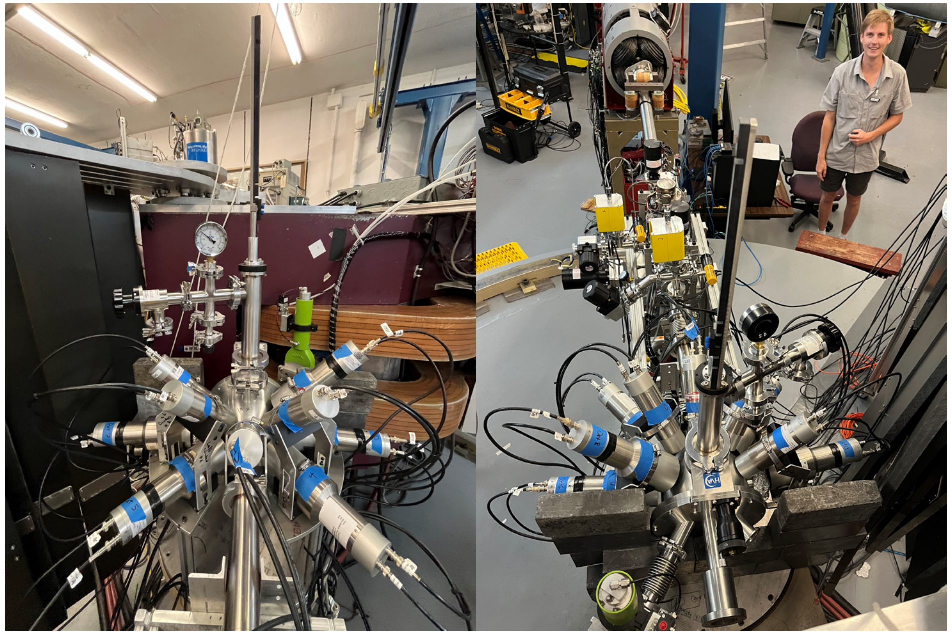
Particle-γ coincidence matrix





Particle-γ coincidences with CeBrA+SE-SPS



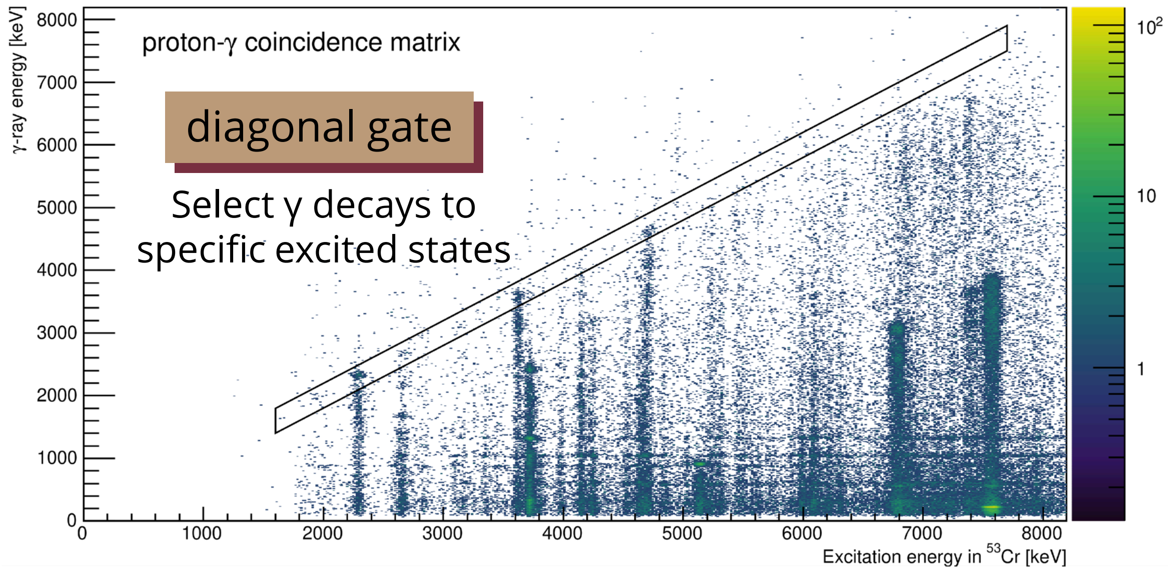
Extended CeBrA demonstrator

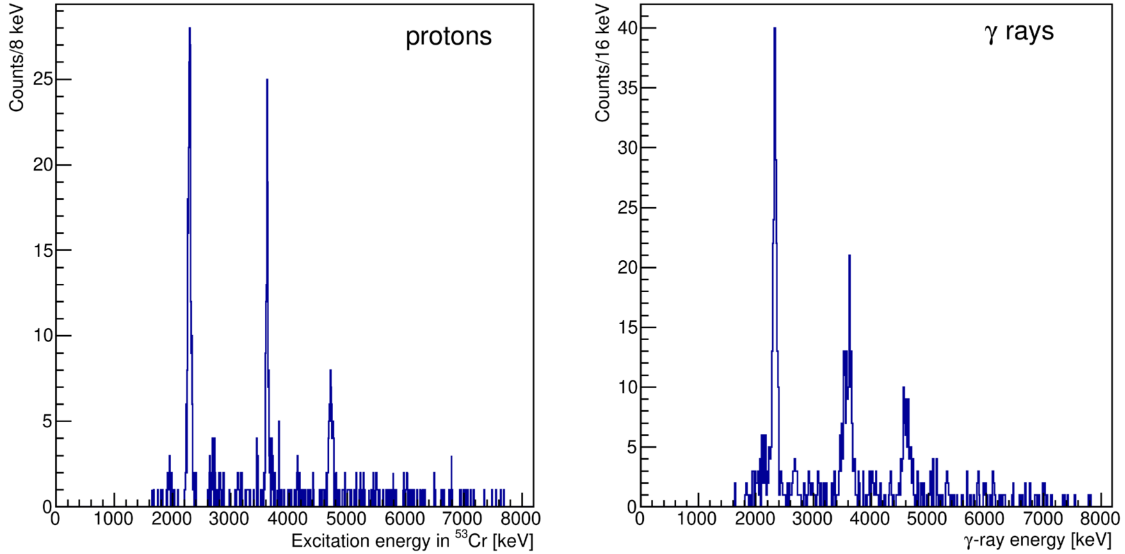
(with four $CeBr_3$ from MSS)

- 4x 2x2 inch, 1x 3x4 inch, 4x 3x3 inch $CeBr_3$ detectors
- CAEN V1725S based DAQ
- CeBrA run in triggered mode (3μs coincidence windows with SE-SPS scintillator)

A.L. Conley et al., NIMA **1058**, 168827 (2024)

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





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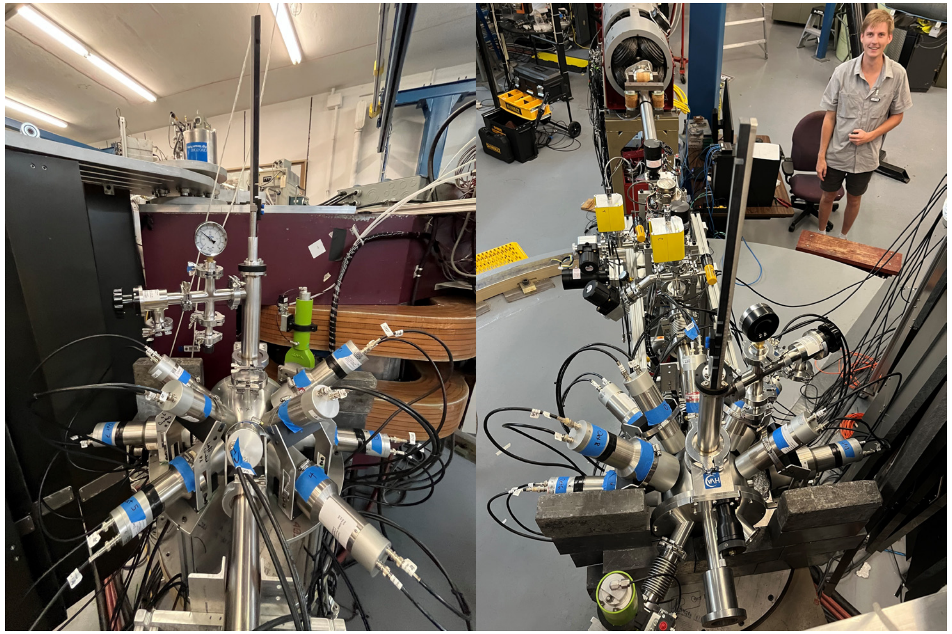

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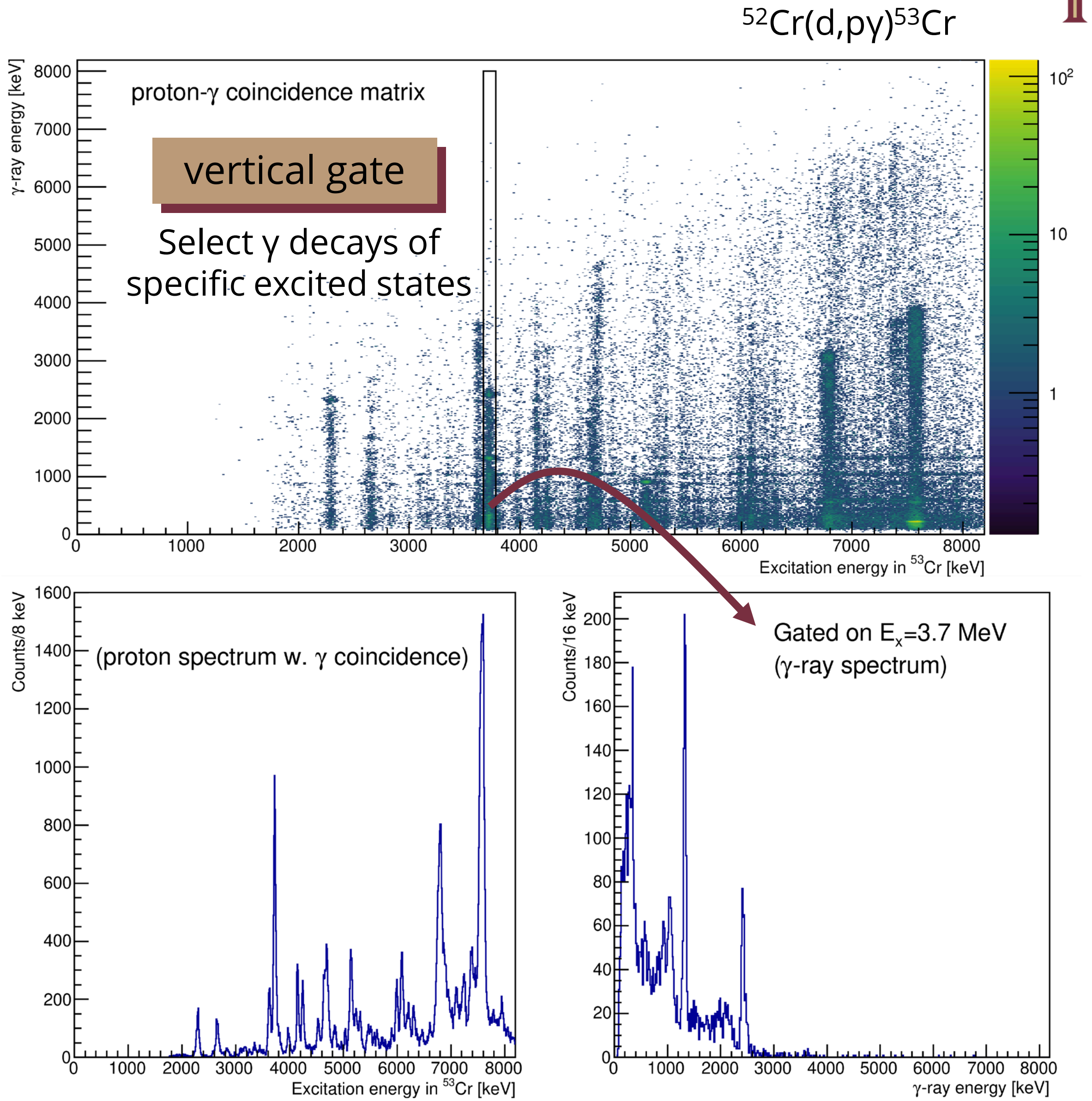

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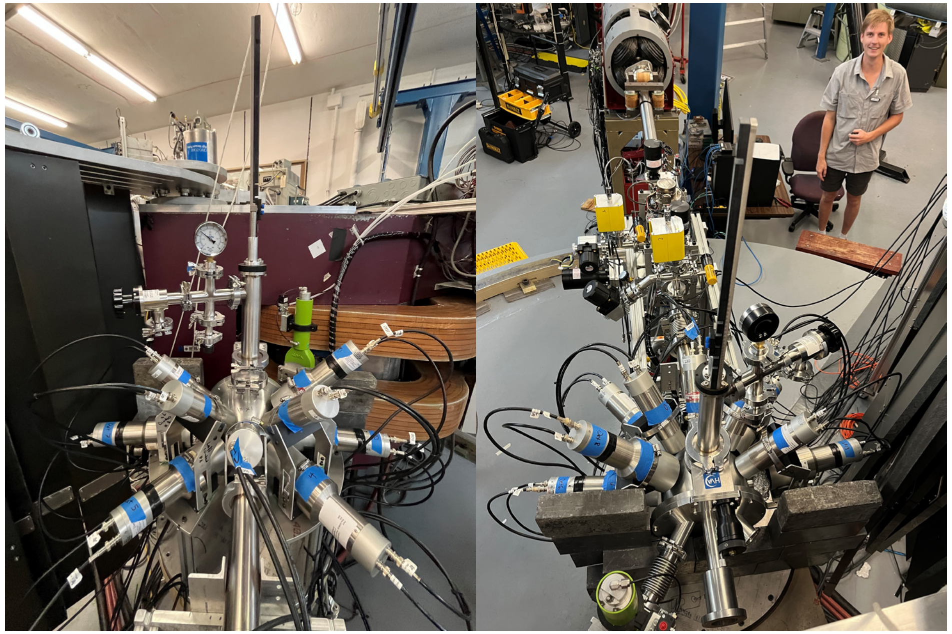

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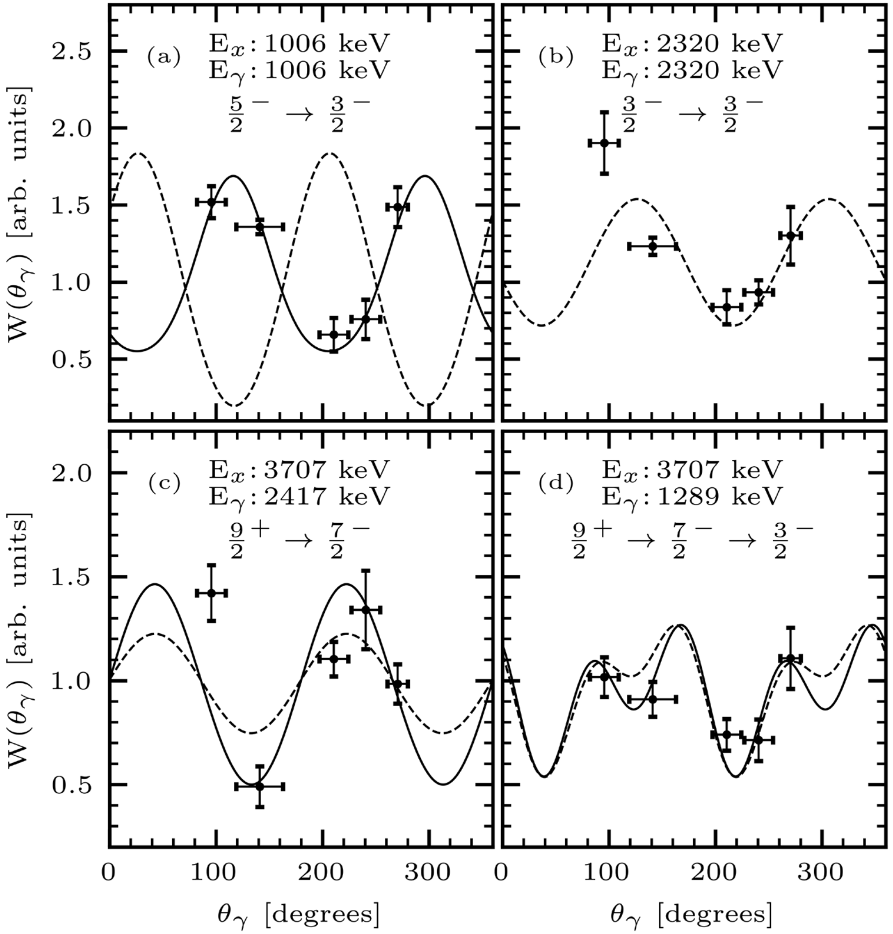
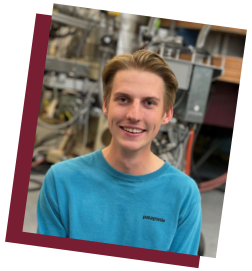
A.L. Conley et al., NIMA **1058**, 168827 (2024)

Particle-γ angular correlations

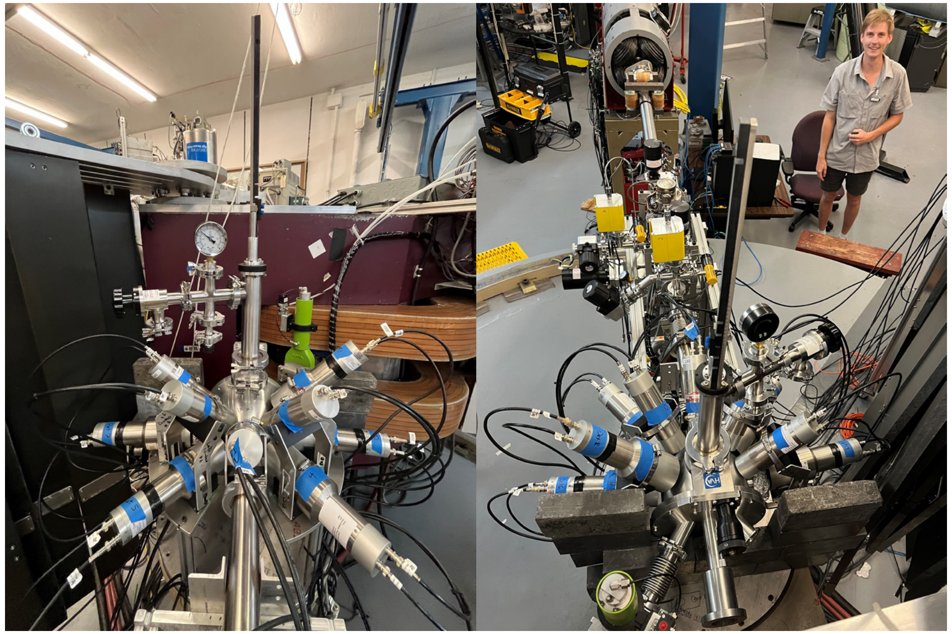
$^{52}Cr(d,p\gamma)^{53}Cr$





Particle-γ coincidences with CeBrA+SE-SPS

FSU



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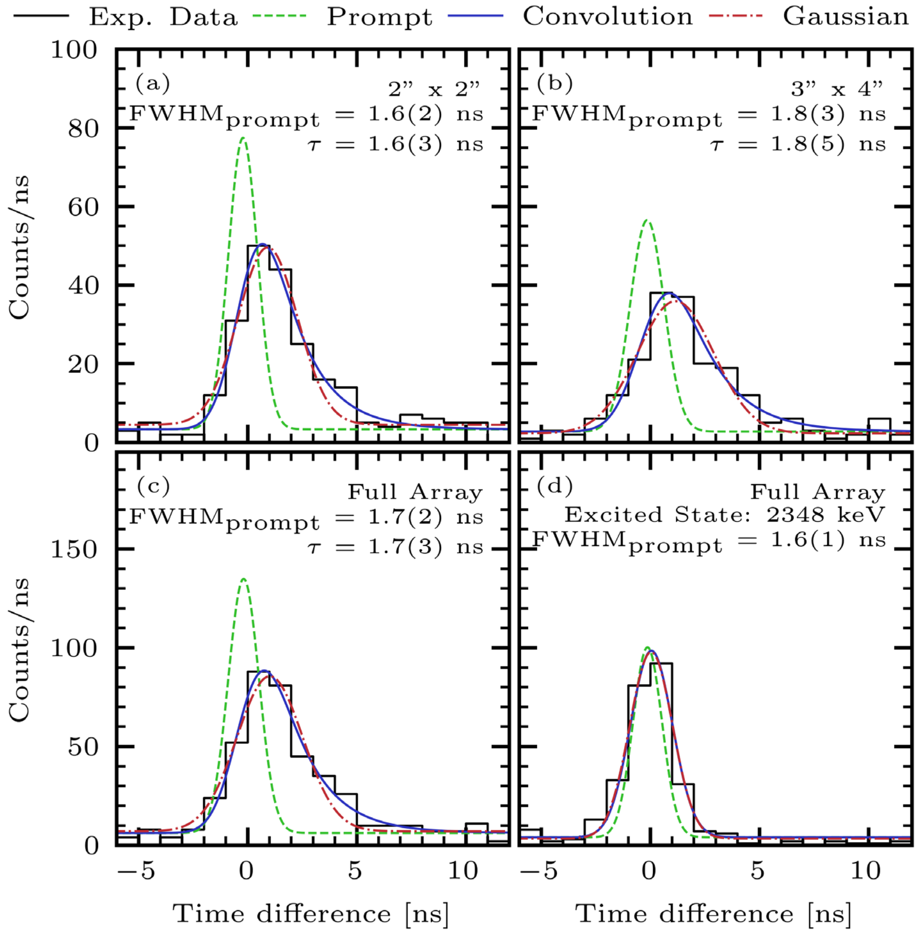
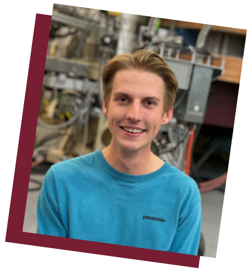
A.L. Conley et al., NIMA **1058**, 168827 (2024)

Lifetime determination

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





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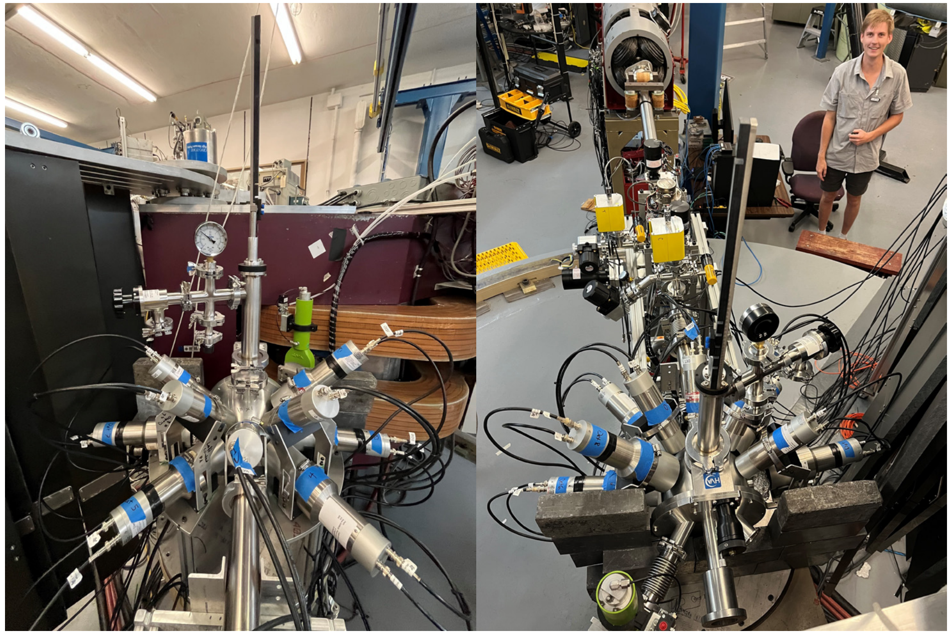

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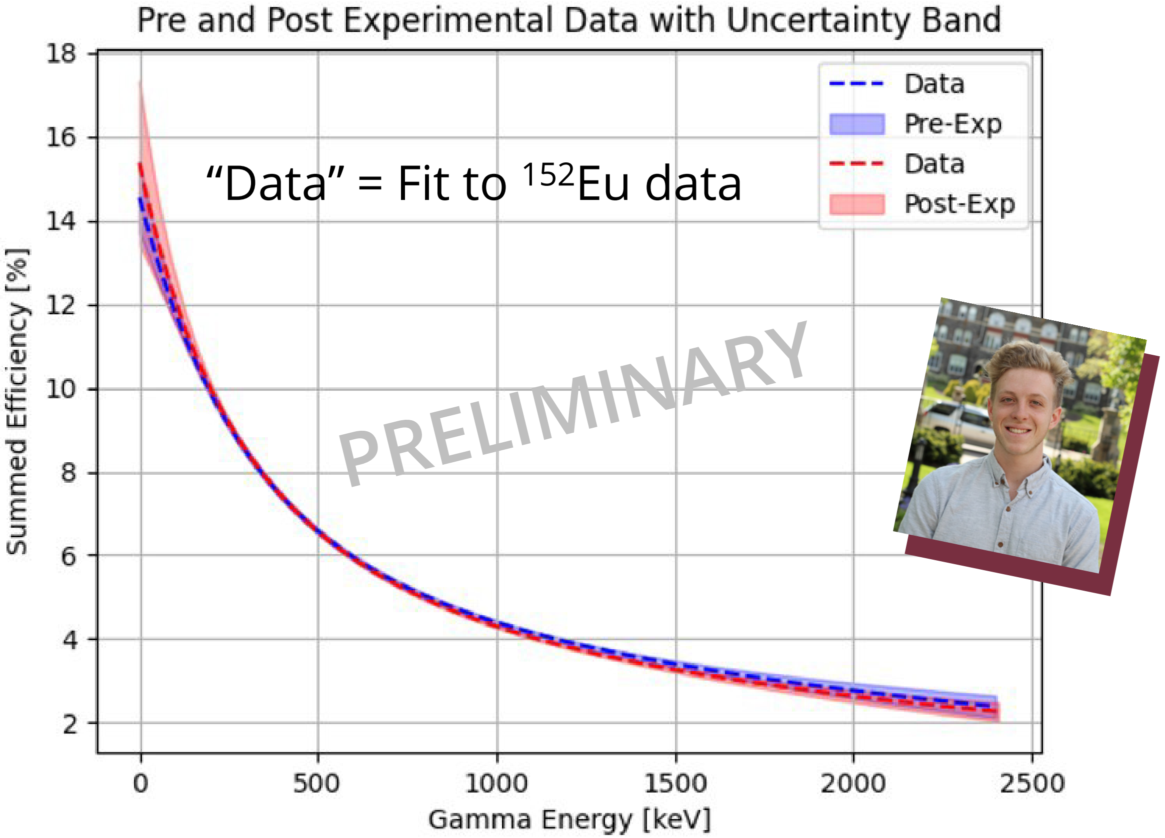
A.L. Conley et al., NIMA **1058**, 168827 (2024)

FEP efficiency



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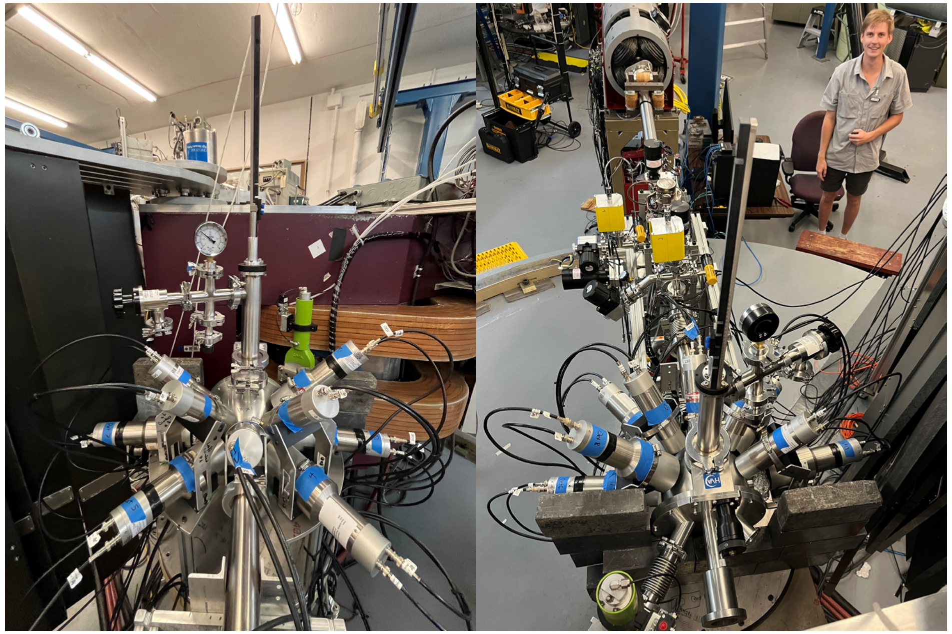

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A.L. Conley et al., NIMA **1058**, 168827 (2024)

MRI proposal accepted by NSF to build 14-detector array!
[PHY-2405485 with L.A. Riley (Ursinus College) & A. Richard (Ohio University)]

Outline

FSU

Recent science highlights

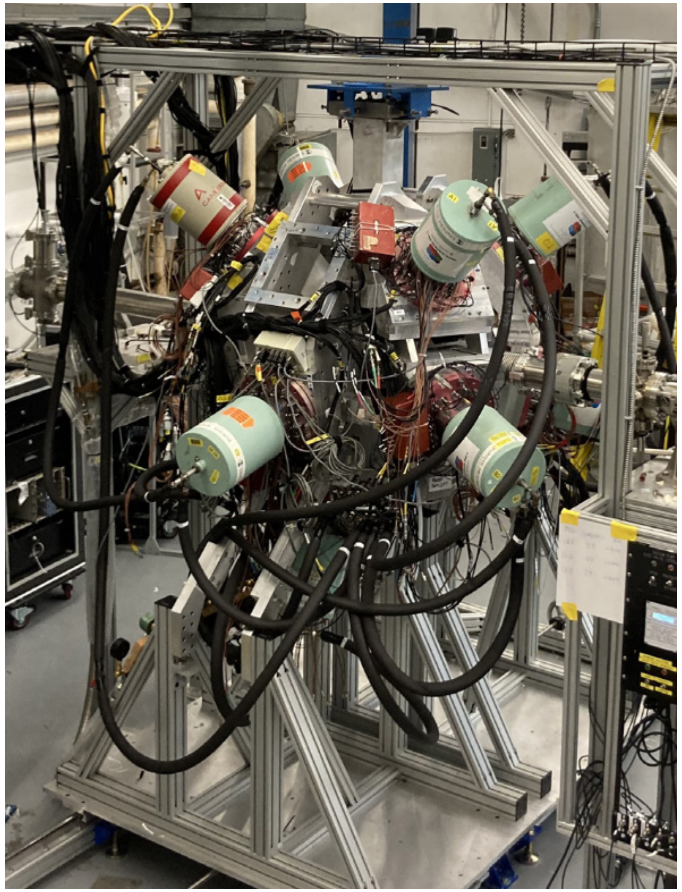
- Study of proton and neutron resonances in ^{11}B (RESOLUT and SE-SPS)
- Single-particle states studied with the SE-SPS (N=20 and N=28)
- Single-particle character of the Pygmy Dipole Resonance (SE-SPS)
- Particle-γ coincidences with CeBrA+SE-SPS
- Sub-barrier CoulEx with CLARION2+TRINITY and suppression of E2 collectivity in ^{49}Ti

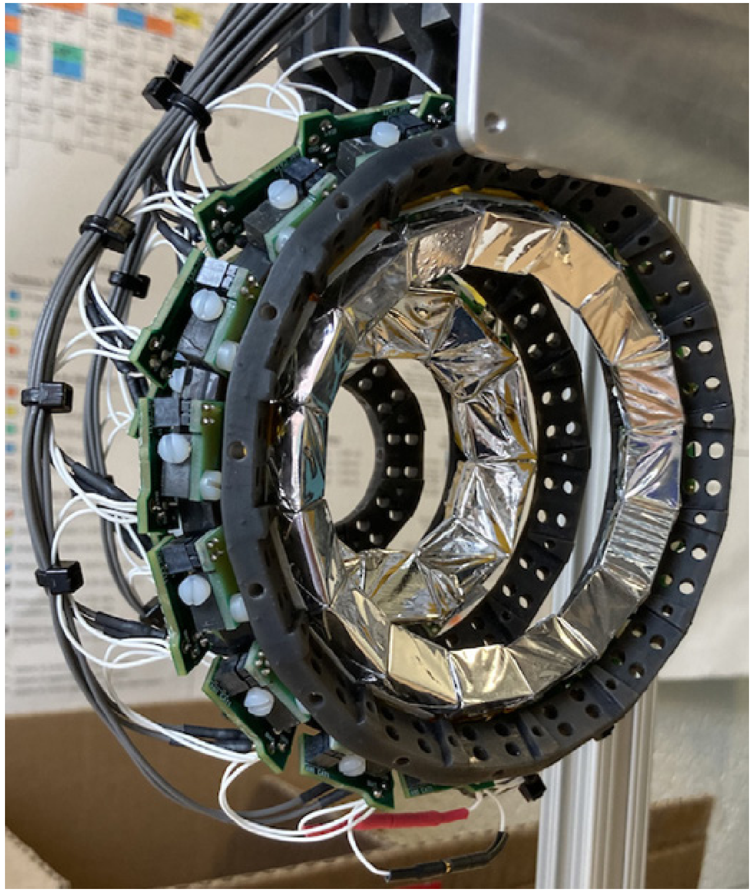
Published results:

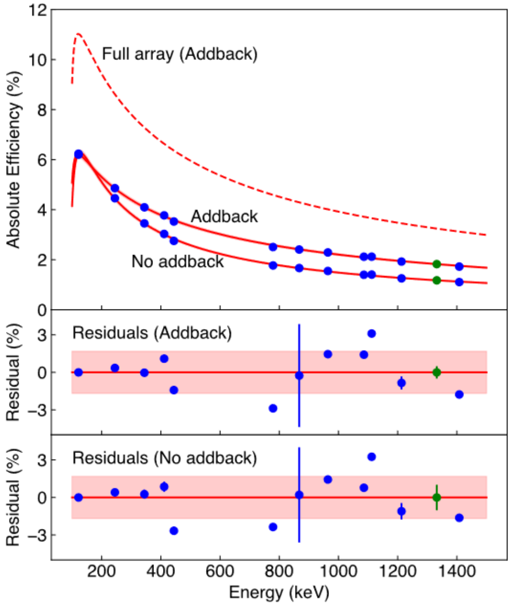
E. Lopez-Saavedra et al., PRL **129**, 012502 (2022)
T.J. Gray et al., NIMA **1041**, 167392 (2022)
L.A. Riley et al., PRC **106**, 064308 (2022)
M. Spieker et al., PRC **108**, 014311 (2023)
L.A. Riley et al., PRC **107**, 044306 (2023)
A.L. Conley et al., NIMA **1058**, 168827 (2024)
I.C.S. Hay et al., PRC **109**, 024302 (2024)
T.J. Gray et al., PLB **855**, 138856 (2024)

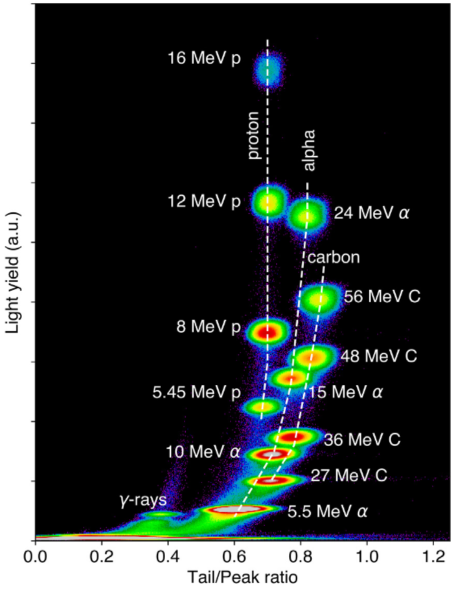
CeBrA+SE-SPS

CLARION2+TRINITY









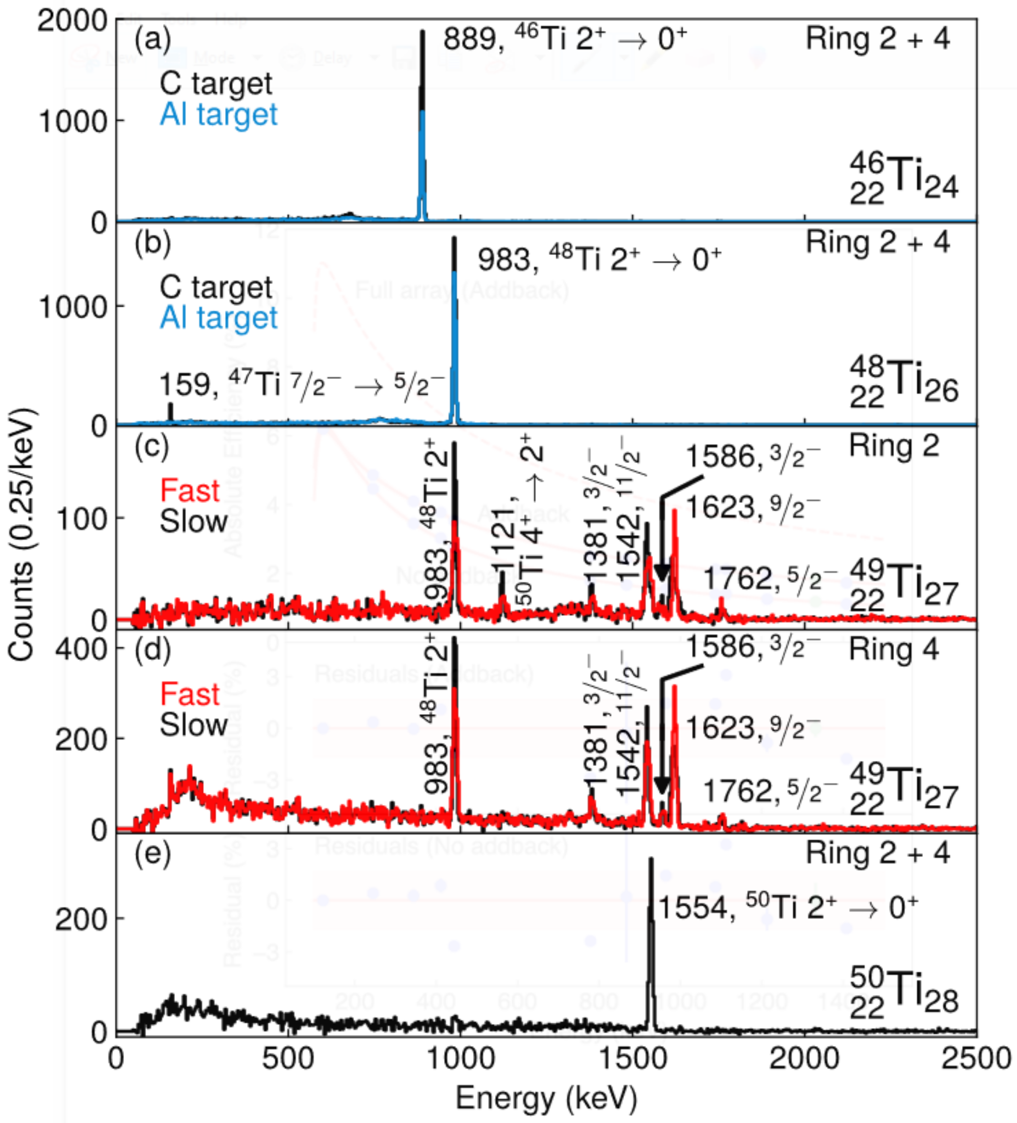
- CLARION2 with up to 16 Compton-suppressed Clover-type HPGe detectors
- TRINITY for particle/reaction-channel identification
  - Now, five rings of GAGG:Ce crystals with Si:PM and PSD capabilities.

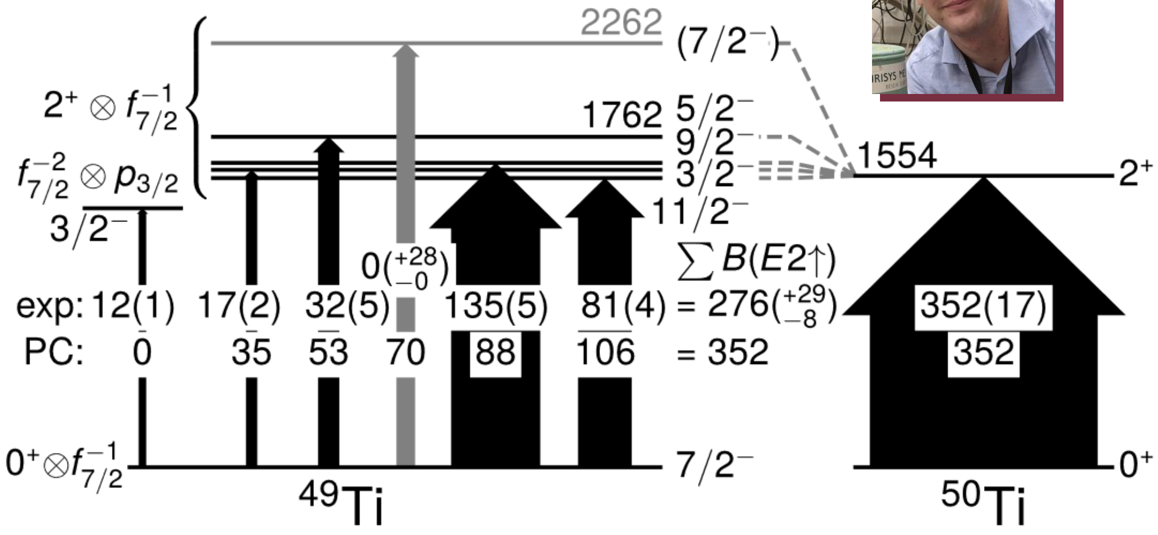
High-resolution γ-ray spectroscopy setup combined with particle identification and pulse-shape discrimination capabilities.

In collaboration with Oak Ridge National Laboratory (J.M. Allmond)

T.J. Gray et al., NIMA **1041**, 167392 (2022)

Suppressed electric quadrupole collectivity in ^{49}Ti





- Sub-barrier CoulEx campaign with CLARION2+TRINITY to study ^{46,48,49,50}Ti E2 collectivity.
- Prior to experiment, suppression of E2 strength in ^{49}Ti relative to semi-magic ^{50}Ti not expected.

Possible explanation: Mixing between $[0^+ \otimes \nu f_{7/2}]_{7/2-}$ and $[2^+ \otimes \nu f_{7/2}]_{7/2-}$ reduces collectivity.

T.J. Gray et al., PLB **855**, 138856 (2024)

Theoretical support at FSU

Kevin Fossez
(FRIB Bridge)

Open quantum systems, nuclear structure in light nuclei

EFT, DMRG, Berggren basis

Jorge Piekarewicz
(Full Professor)

Ground-state properties, neutron skins, neutron stars

CDFT, RMF, RPA, equation of state

Alexander Volya
(Full Professor)

Open quantum systems, clustering, nuclear structure

(Continuum) shell model++

Acknowledgments

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FSU – Sergio Almaraz-Calderon, Lagy T. Baby, Paul D. Cottle, Kevin Fossez, Kirby W. Kemper, Jorge Piekarewicz, Samuel Tabor, Tsz Leung (Ryan) Tang, Vandana Tripathi, Alexander Volya, Ingo Wiedenhoever, graduate & undergraduate students, postdoctoral researchers

Ursinus College – L.A. Riley and undergraduate students

Davidson College – A.N. Kuchera and undergraduate students

Oak Ridge National Laboratory – A.M. Allmond and T.J. Gray

Argonne National Laboratory – C.R. Hoffman

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Save the date!

8th International Conference on Collective Motion in Nuclei under Extreme Conditions