Nuclear-structure studies via direct reactions

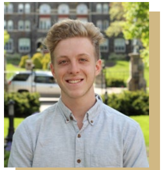
Detailed studies of the Pygmy Dipole Resonance, α clustering, and octupole as well as hexadecapole collectivity in atomic nuclei

Mark-Christoph Spieker

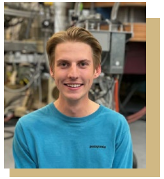
NSF Site Visit, John D. Fox Laboratory, Florida State University

My Research Group

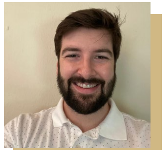
(3 grads, 1 (2) undergrads)



Bryan Kelly
Graduate Student
Supported on NSF grant

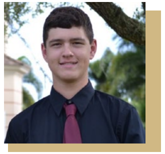


Alex L. Conley
Graduate Student
Supported on NNSA grant



Dennis Houlihan
Graduate Student
Supported on NSF grant

Ramiro Renom
Undergraduate Student
2021-2022 (Applied Mathematics)



Scott Baker
Undergraduate Student
Working on Honors Thesis
Applied for Graduate School

Proposed Science Projects

- **Study of octupole and hexadecapole collectivity in the Ge-Kr mass region at FRIB**

  → (p,p‘), (p,2p), and (p,pn) experiments in inverse kinematics using GRETINA and the S800 at FRIB

- **The microscopic structure of the Pygmy Dipole Resonance (PDR)**

  → Particle-transfer, (d,p) and (t,p), as well as particle-γ coincidence experiments, (d,pγ), with the CeBrA demonstrator and Super-Enge Split-Pole Spectrograph at Florida State University

- **α clustering and its possible implications for p-process nucleosynthesis**

  → (^{6}Li,d) α-transfer and particle-γ coincidence experiments, (^{6}Li,dγ), with the CeBrA demonstrator (CeBrA) and the Super-Enge Split-Pole Spectrograph at Florida State University

Connected Detector Development Projects

FRIB

- **Study of inorganic crystals for a new heavy-ion calorimeter for the S800 and HRS**
  → Energy resolution of better than 0.4% needed for charge state identification and experiments with heavy isotopes.

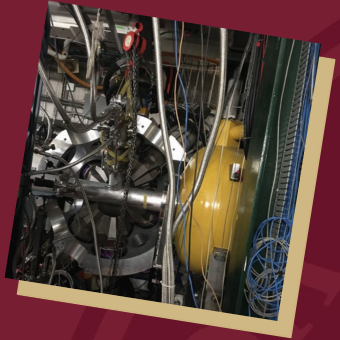
- **A sub-millimeter resolution focal-plane detector for the SE-SPS**
  → Use new multi-layer thick gaseous electron multiplier (M-THGEM) technology + Micromegas pioneered at FRIB and successfully tested at S800.

- **Construction of the full CeBrA+SE-SPS setup for particle-γ coincidence experiments**
  → 14 $CeBr_3$ detector array. Major upgrade with addition of 3 × 4 inches and 3 × 6 inches detectors. MRI in collaboration with Ursinus College and Ohio University has been submitted.

FLORIDA STATE UNIVERSITY

Project #1

Study of octupole and hexadecapole collectivity in the Ge-Kr mass region at FRIB



Propose experiments with GRETINA+S800 and liquid hydrogen target at FRIB

PHYSICAL REVIEW C **106**, 054305 (2022)

Investigation of octupole collectivity near the $A = 72$ shape-transitional point

M. Spieker,[1,*] L. A. Riley,[2] P. D. Cottle,[1] K. W. Kemper,[1] D. Bazin,[3,4] S. Biswas,[3] P. J. Farris,[3,4] A. Gade,[3,4] T. Ginter,[3] S. Giraud,[3] J. Li,[3] S. Noji,[3] J. Pereira,[3] M. Smith,[3] D. Weisshaar,[3] and R. G. T. Zegers[3,4]
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ELSEVIER

Hexadecapole strength in the rare isotopes ^{74,76}Kr

M. Spieker[a,*], S.E. Agbemava[b], D. Bazin[b,c], S. Biswas[b], P.D. Cottle[a], P.J. Farris[b,c], A. Gade[b,c], T. Ginter[b], S. Giraud[b], K.W. Kemper[a], J. Li[b], W. Nazarewicz[b,c], S. Noji[b], J. Pereira[b], L.A. Riley[d], M. Smith[b], D. Weisshaar[b], R.G.T. Zegers[b,c]
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PHYSICAL REVIEW C **109**, 014307 (2024)

Proton removal from ^{73,75}Br to ^{72,74}Se at intermediate energies

M. Spieker,[1,*] D. Bazin,[2,3] S. Biswas,[2] P. D. Cottle,[1] P. J. Farris,[2,3] A. Gade,[2,3] T. Ginter,[2] S. Giraud,[2] K. W. Kemper,[1] J. Li,[2] S. Noji,[2] J. Pereira,[2] L. A. Riley,[4] M. K. Smith,[2] D. Weisshaar,[2] and R. G. T. Zegers[2,3]
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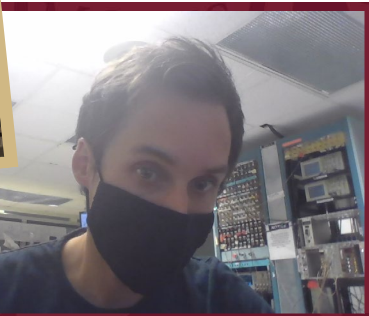
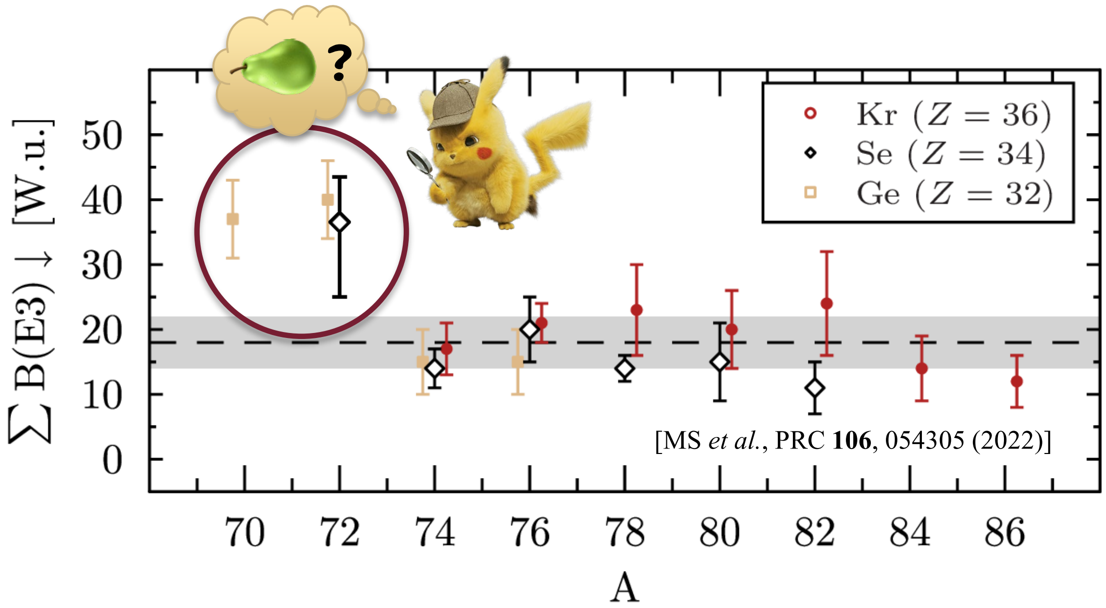
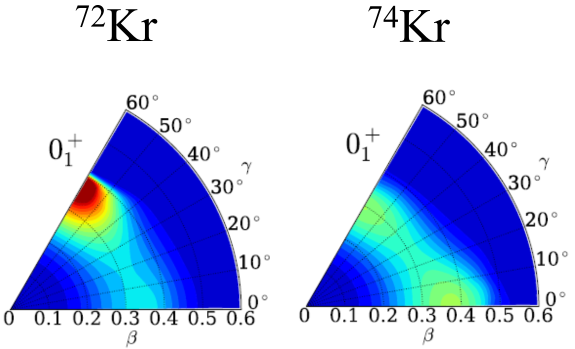
(Received 12 August 2023; accepted 13 December 2023; published 3 January 2024)



Increase in octupole collectivity might be linked to shape change





Sudden shape change from rather γ-soft to oblate deformation.

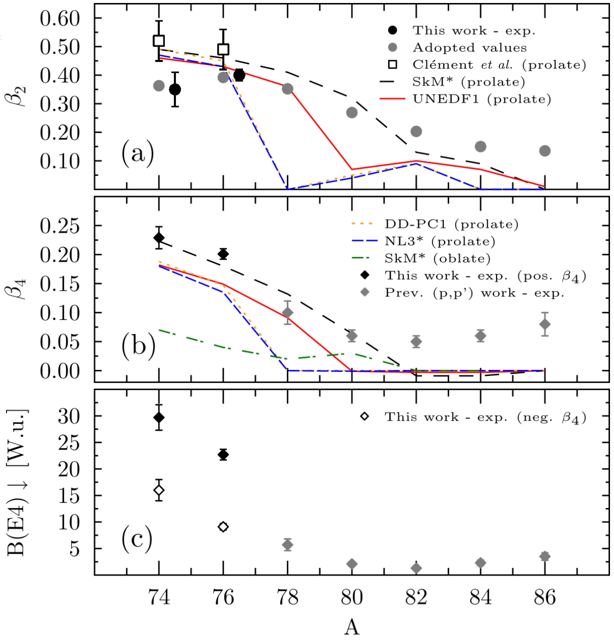
[K. Sato and N. Hinohara, Nuclear Physics A **849**, 53 (2011)]

Still an open question what causes this sudden strength increase.

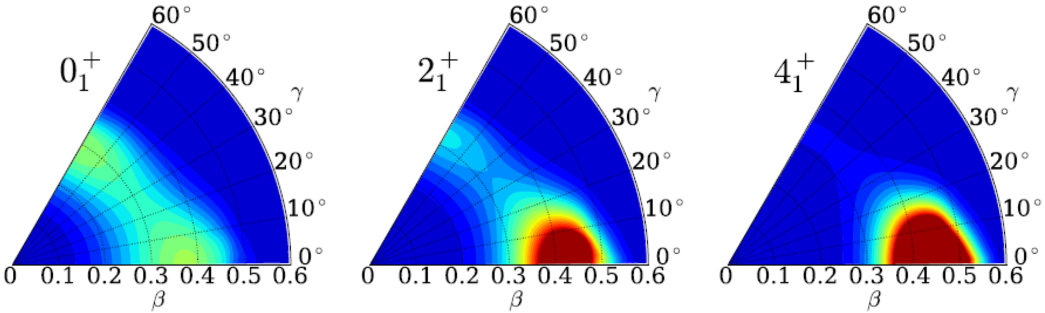
- For reference, ^{224}Ra, which we believe to be statically octupole deformed, has $B(E3; 3_1^- \rightarrow 0_1^+) = 42(3)$ Weisskopf Units (W.u.).
- Mass $A = 70 - 80$ nuclei are not believed to be octupole deformed.

Prolate-oblate shape transition in Kr isotopes & hexadecapole collectivity

[In collaboration with S. Agbemava and W. Nazarewicz (FRIB/MSU)]



^{74}Kr (CHFB+LQRPA)

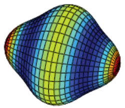


Squared vibrational wave functions in $\beta\gamma$ plane

[K. Sato and N. Hinohara, Nuclear Physics A **849**, 53 (2011)]

- We were able to determine β_2, β_3, and β_4 from our inverse kinematics (p,p') experiments on ^{74,76}Kr.
- Mixing between oblate and prolate configuration influences $B(E2; 2_1^+ \rightarrow 0_1^+)$ but appears to have only minor influence on $B(E4; 4_1^+ \rightarrow 0_1^+)$ strength. The latter is linked to prolate configuration.

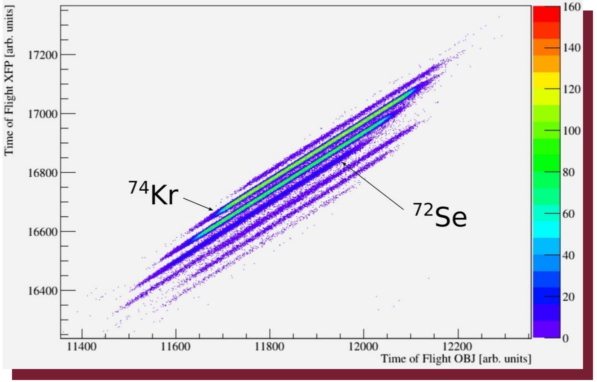
→ In agreement with CHFB+LQRPA predictions?

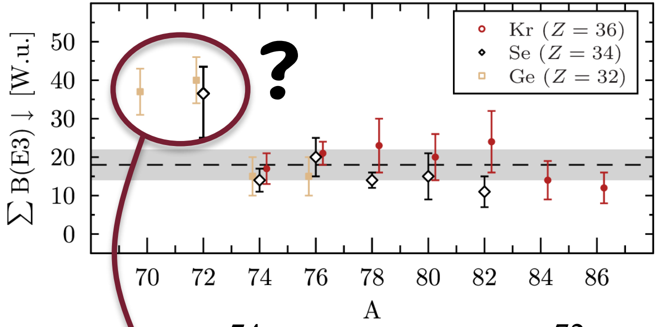


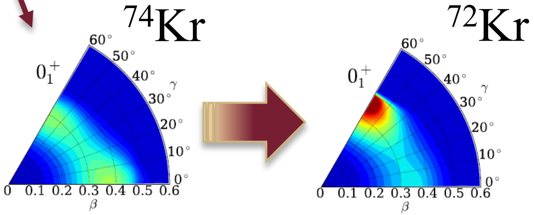
= *axially symmetric hexadecapole deformation*

[Data from MS *et al.*, PLB **841**, 137932 (2023) and E. Clement *et al.*, Phys. Rev. C **75**, 054313 (2007)]

Continue program at FRIB [proposal ready; not PAC approved]







- We will continue mining the existing data set.

→ Currently analyzing ^{74}Kr(p,pn) and ^{72}Se(p,pn). The latter is analyzed by undergraduate student Alyssa Himmelreich at Ursinus College working with Professor Riley. I am a co-advisor for her project.

[^{73,75}Br(p,2p): MS *et al.*, PRC **109**, 014307 (2024)]

- Propose (p,p') experiments with ^{70,72}Kr and ^{70}Se with GRETINA+S800+LH$_2$ target

→ Proposal was submitted to PAC-2, rated highly, but not recommended for beamtime.

- Possibly extend program to neutron-rich side, i.e., ^{90}Se (Z=34, N=56) which is supposedly a doubly octupole magic nucleus.

FLORIDA STATE UNIVERSITY

Project #2

The microscopic structure of the Pygmy Dipole Resonance (PDR)

Continue program with experiments at FSU

PHYSICAL REVIEW LETTERS **125,** 102503 (2020)

Accessing the Single-Particle Structure of the Pygmy Dipole Resonance in ^{208}Pb

M. Spieker,[1,*] A. Heusler,[2] B. A. Brown,[3,4] T. Faestermann,[5] R. Hertenberger,[6] G. Potel,[7] M. Scheck,[8,9] N. Tsoneva,[10] M. Weinert,[11] H.-F. Wirth,[6] and A. Zilges[11]
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(Received 9 June 2020; accepted 28 July 2020; published 2 September 2020)

PHYSICAL REVIEW LETTERS **127,** 242501 (2021)

Microscopic Structure of the Low-Energy Electric Dipole Response of ^{120}Sn

M. Weinert,[1,*] M. Spieker,[2] G. Potel,[3] N. Tsoneva,[4] M. Müscher,[1] J. Wilhelmy,[1] and A. Zilges[1]
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PHYSICAL REVIEW C **108,** 014311 (2023)

Experimental study of excited states of ^{62}Ni via one-neutron (d,p) transfer up to the neutron-separation threshold and characteristics of the pygmy dipole resonance states

M. Spieker,[1,*] L. T. Baby,[1] A. L. Conley,[1] B. Kelly,[1] M. Müscher,[2] R. Renom,[1] T. Schüttler,[2] and A. Zilges[2]
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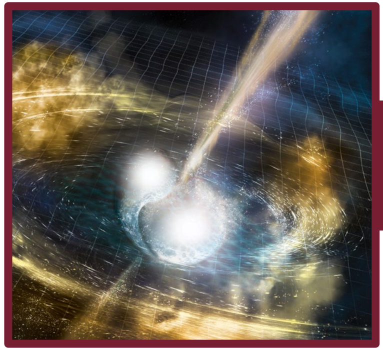
… and how we can possibly perform similar experiments at FRIB.

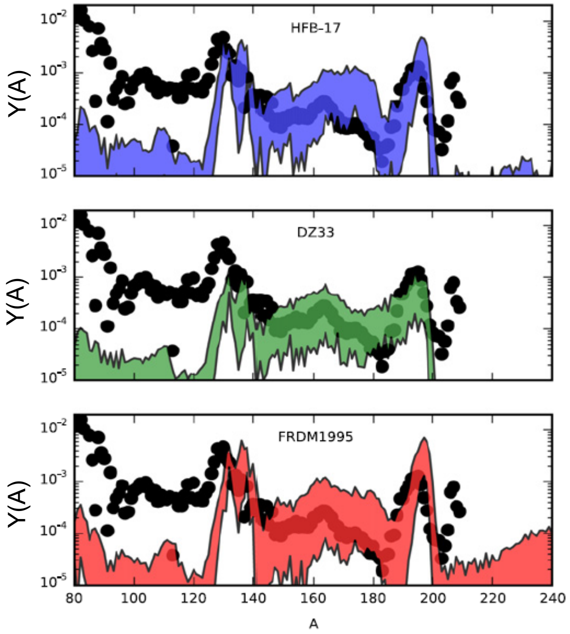
The r process and neutron capture (n,γ) rates

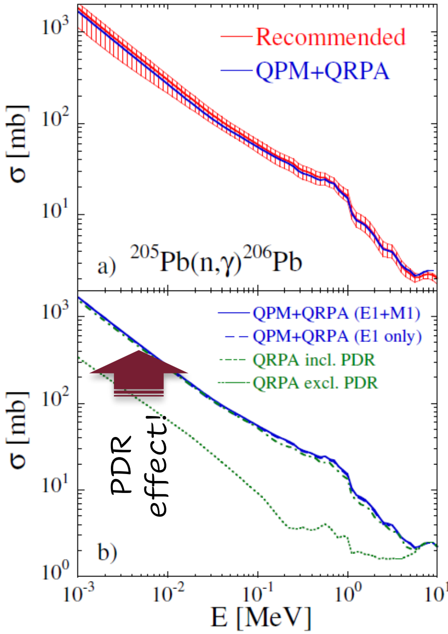


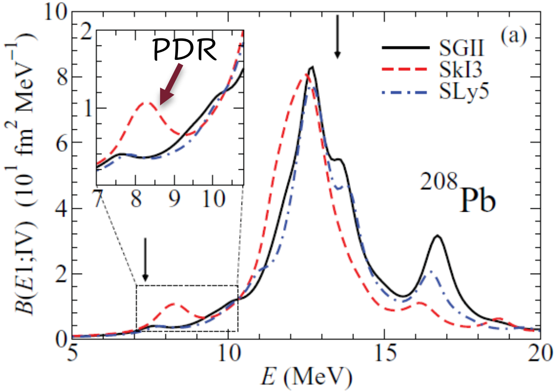
How and where are the elements heavier than iron synthesized?

[A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science]

[**Figure 1:** https://www.ligo.org/science/Publication-GW170817MMA/]
[**Figure 2**: M. Mumpower *et al.*, PPNP **86**, 86 (2016)]
[**Figure 3**: H. Lenske and N. Tsoneva, EPJA **55**, 238 (2019)]
[**Figure 4:** X. Roca-Maza *et al.*, PRC **85**, 024601 (2012)]



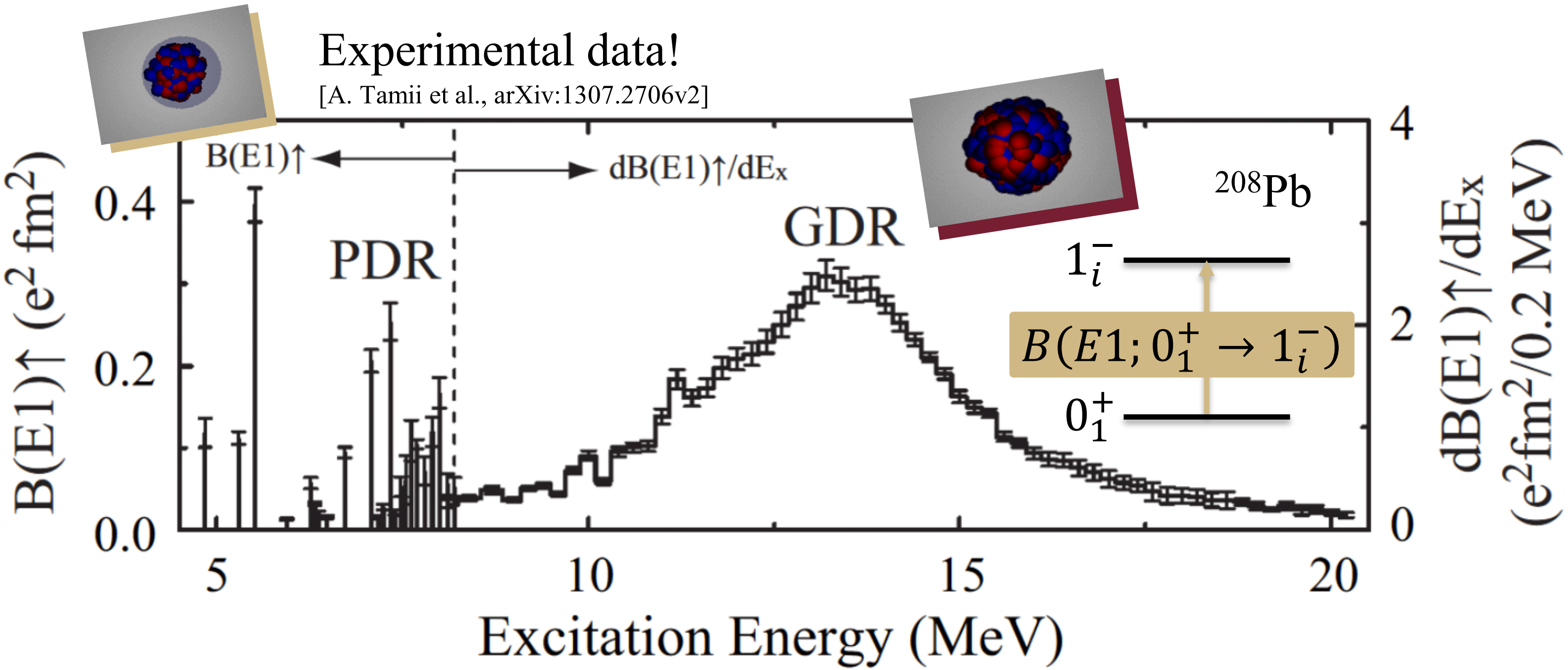




Appearance of PDR is also strongly model-dependent!

The electric dipole response of atomic nuclei [Example of ^{208}Pb and isovector response]

Data from ^{208}Pb(p,p') at ~0° and 295 MeV

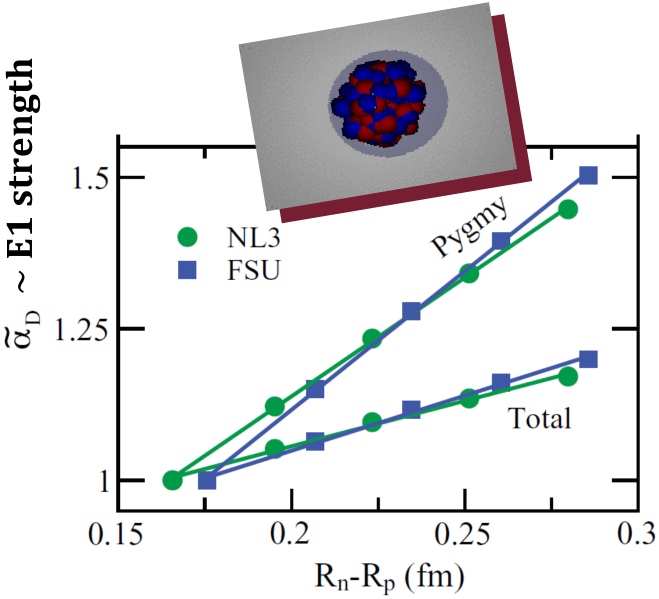


Pygmy Dipole Resonance (PDR)	Isovector Giant Dipole Resonance (IVGDR)
The **valence** neutrons (light blue) oscillate against the N = Z core = **smaller** (pygmy) dynamic dipole moment	**All** protons (red) oscillate against **all** neutrons (blue) = **large** (giant) dynamic dipole moment

From the PDR to the neutron skin to neutron-star radii

What can we expect at FRIB?

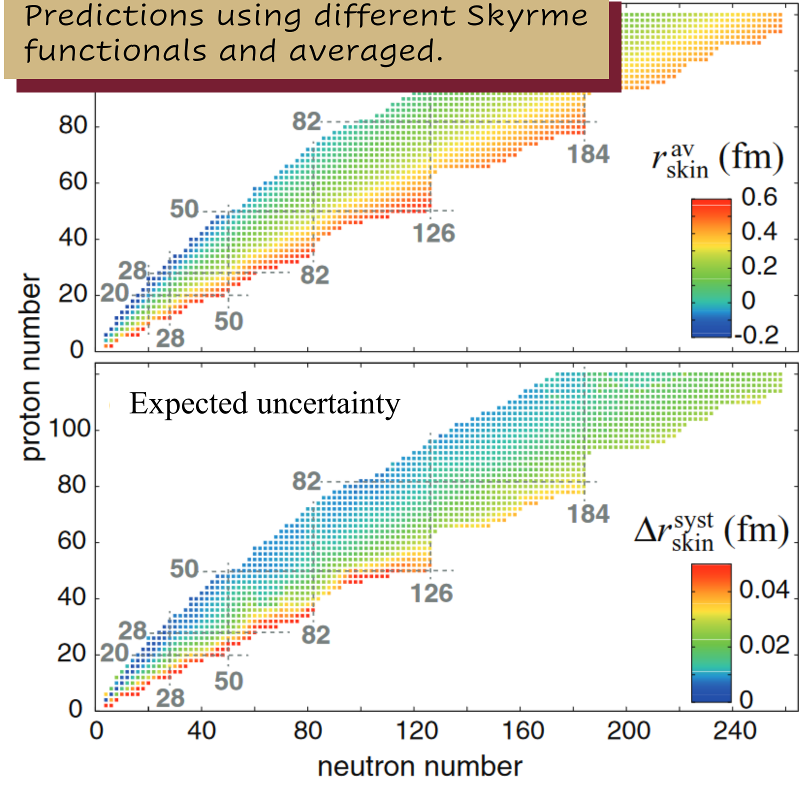
Neutron skins in neutron-rich isotopes



= neutron – skin thickness

[**Figure 1:** J. Piekarewicz, PRC **83**, 034319 (2011)]

Predictions using different Skyrme functionals and averaged.



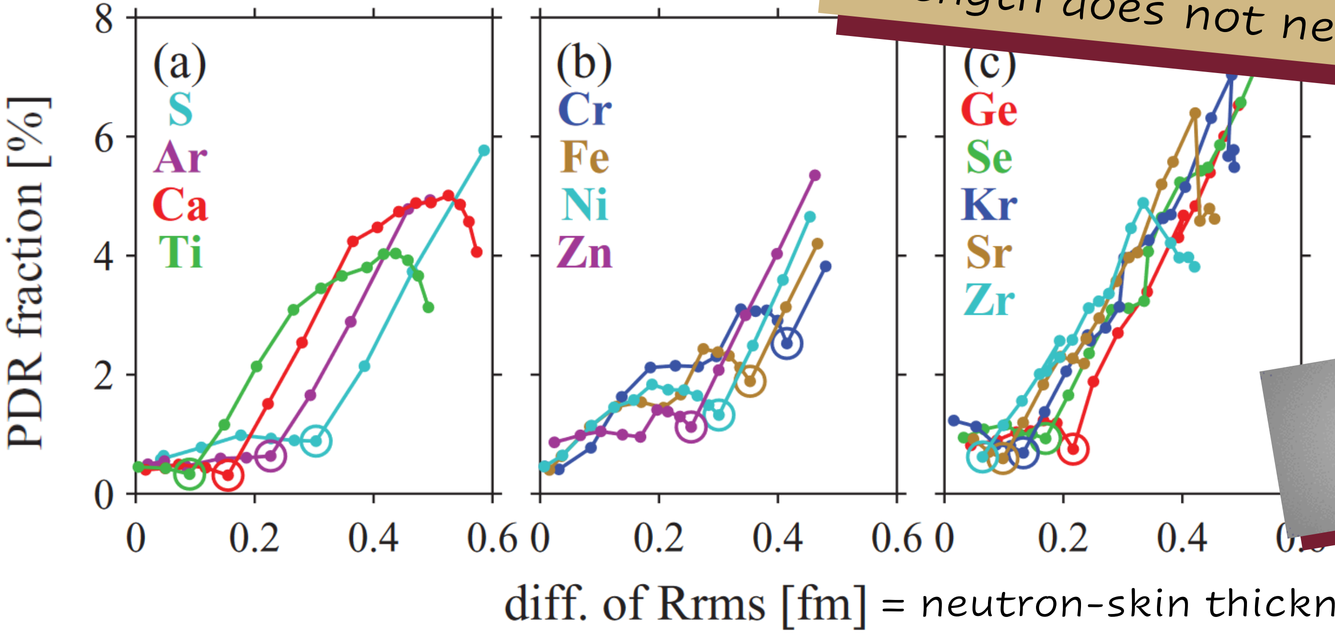
Massive neutron skins expected in neutron-rich isotopes (~ 0.4 – 0.6 fm). Reminder PREX result indicates ~ 0.28 fm for ^{208}Pb.

[M. Kortelainen *et al.*, PRC **88**, 031305(R) (2013)]

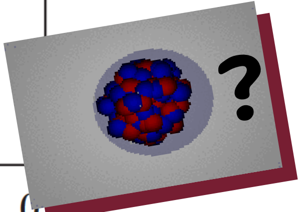
Are the PDR strength and neutron-skin thickness correlated?

Strength "not" correlated with neutron skin?

Theory



Neutron skin increases but strength does not necessarily!



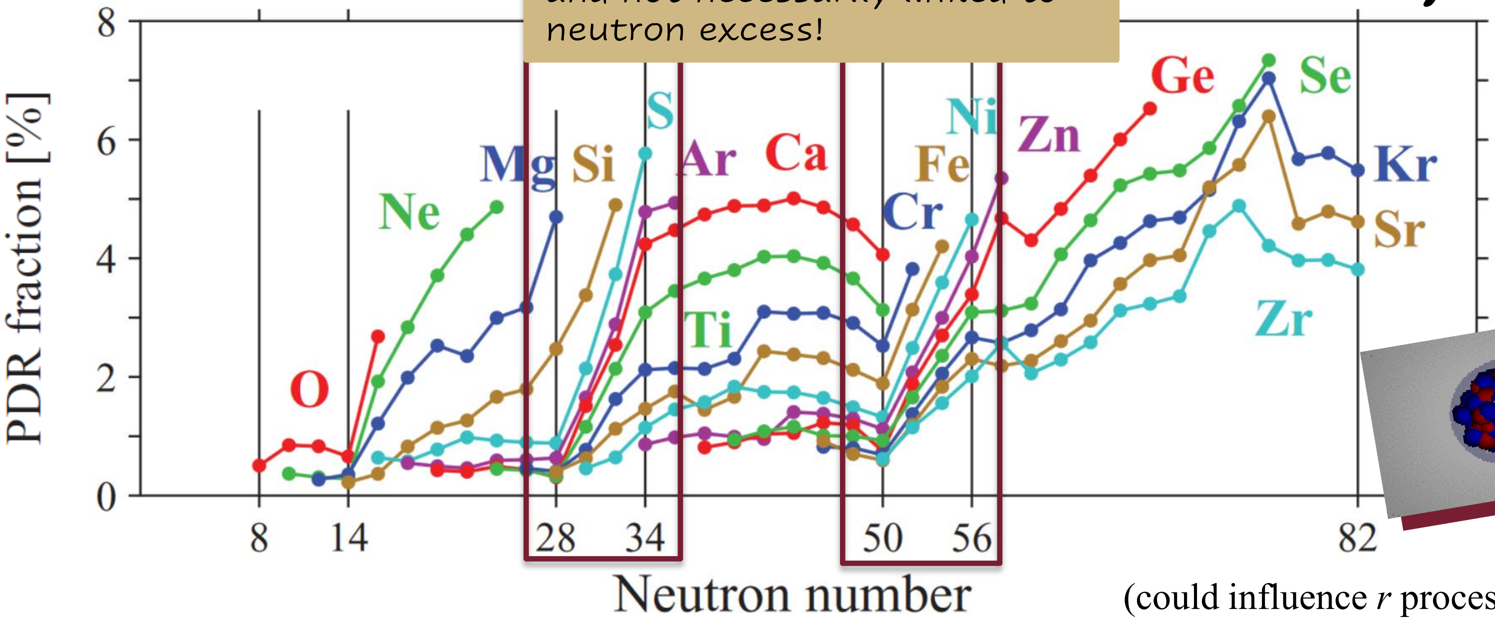
[T. Inakura *et al.*, PRC **84**, 021302(R) (2011)]

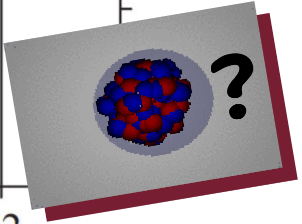
The microscopic structure of the PDR and its influence on the B(E1) distribution

The *E*1 strength of the PDR strongly depends on the position of the Fermi level and **shows a clear correlation with the occupation of the orbits with the orbital angular momenta less than 3ℏ ($l \leq 2$).** We also found a strong correlation between the isotopic dependence of the neutron skin thickness and the pygmy dipole strength. [T. Inakura *et al.*, PRC **84**, 021302(R) (2011)]

Strength increase is predicted and not necessarily linked to neutron excess!

Theory





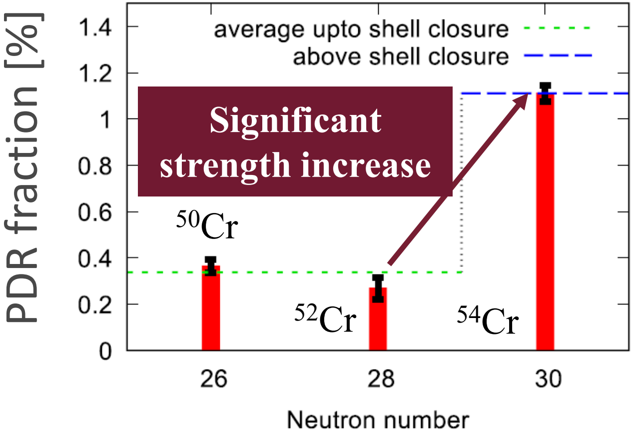
(could influence *r* process here…)

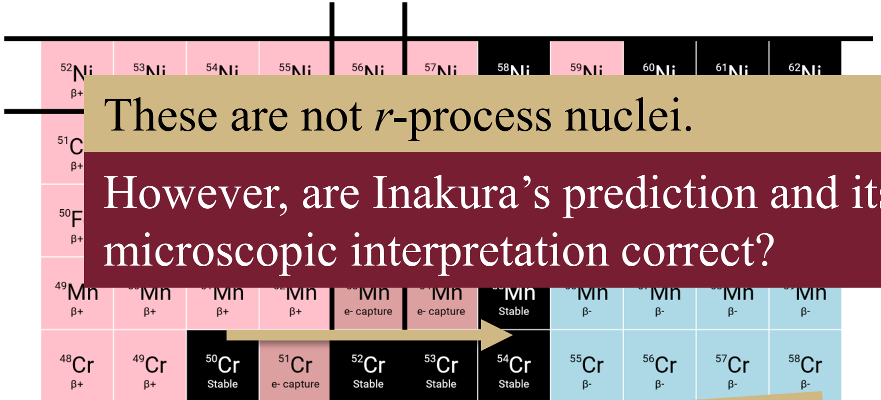
Strength increase has microscopic origin?

Significant strength increase observed above N=28 for Cr isotopes

Experiment

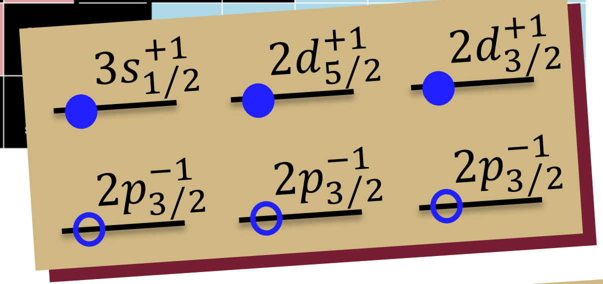
[P. Ries *et al.*, PRC **100**, 021301(R) (2019)]





These are not *r*-process nuclei.

However, are Inakura's prediction and its microscopic interpretation correct?



Possible cause: Change of single-particle structure

^{49}**Cr:** $J^{\pi}_{gs} = {}^{5}/_{2}^{-} \rightarrow (1f_{5/2})^{-1}(2d_{5/2})^{+1}, (1f_{5/2})^{-1}(2d_{3/2})^{+1}$

^{51}**Cr:** $J^{\pi}_{gs} = {}^{7}/_{2}^{-} \rightarrow (1f_{7/2})^{-1}(2d_{5/2})^{+1}, (1f_{7/2})^{-1}(1g_{9/2})^{+1}$

^{53}**Cr:** $J^{\pi}_{gs} = {}^{3}/_{2}^{-} \rightarrow (2p_{3/2})^{-1}(2d_{5/2})^{+1}, (2p_{3/2})^{-1}(2d_{3/2})^{+1}, (2p_{3/2})^{-1}(3s_{1/2})^{+1}$

All these neutron one-particle one-hole (1p-1h) configurations can contribute to $J^{\pi}=1^{-}$ states' (PDR) wave functions

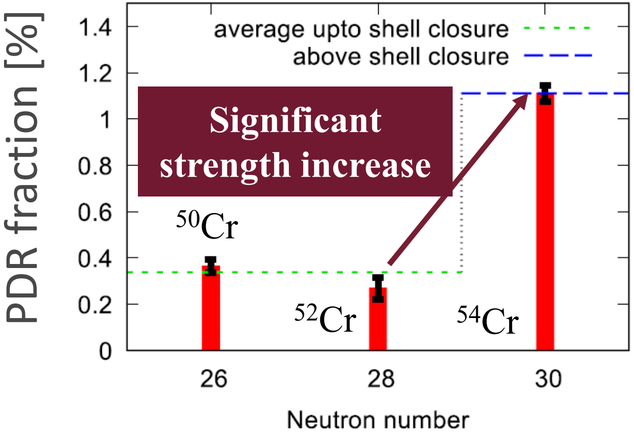
[https://people.physics.anu.edu.au/~ecs103/chart/]

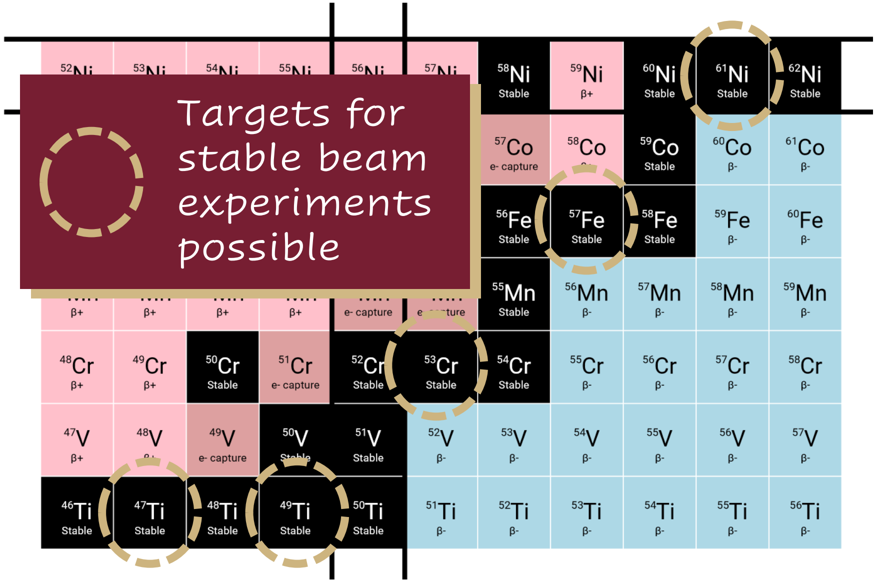
Motivation

Map possible microscopic change with (d,p) reactions on highlighted nuclei

Experiment

[P. Ries *et al.*, PRC **100**, 021301(R) (2019)]





Possible cause: Change of single-particle structure

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^{51}Cr: $J^{\pi}_{gs} = {}^{7}/_{2}^{-} \rightarrow (1f_{7/2})^{-1}(2d_{5/2})^{+1}, (1f_{7/2})^{-1}(1g_{9/2})^{+1}$

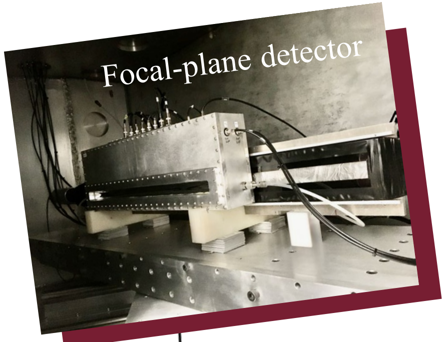
^{53}Cr: $J^{\pi}_{gs} = {}^{3}/_{2}^{-} \rightarrow (2p_{3/2})^{-1}(2d_{5/2})^{+1}, (2p_{3/2})^{-1}(2d_{3/2})^{+1}, (2p_{3/2})^{-1}(3s_{1/2})^{+1}$

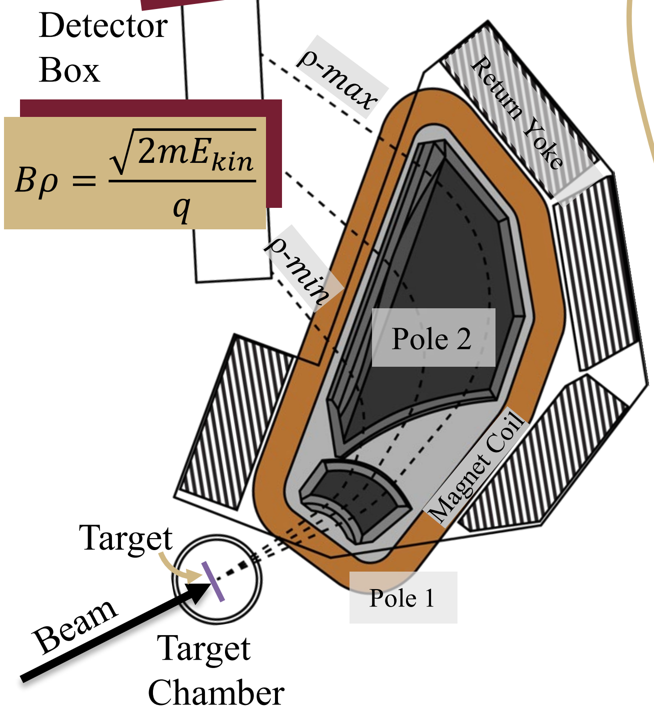
All these neutron one-particle one-hole (1p-1h) configurations can contribute to $J^{\pi}=1^{-}$ states' (PDR) wave functions

[https://people.physics.anu.edu.au/~ecs103/chart/]

Motivation

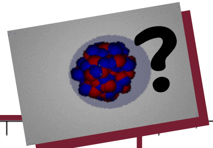
Populate PDR states through (d,p) reaction

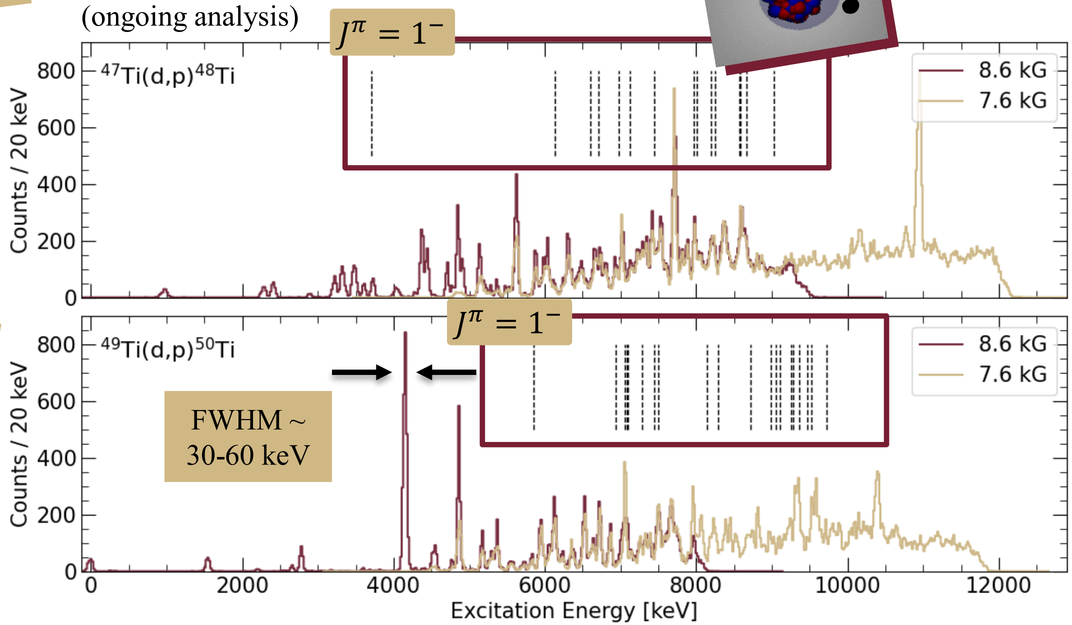




$$B\rho = \frac{\sqrt{2mE_{kin}}}{q}$$

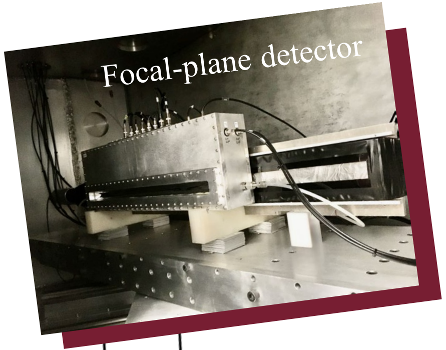
Identify PDR and other excited states with SE-SPS.

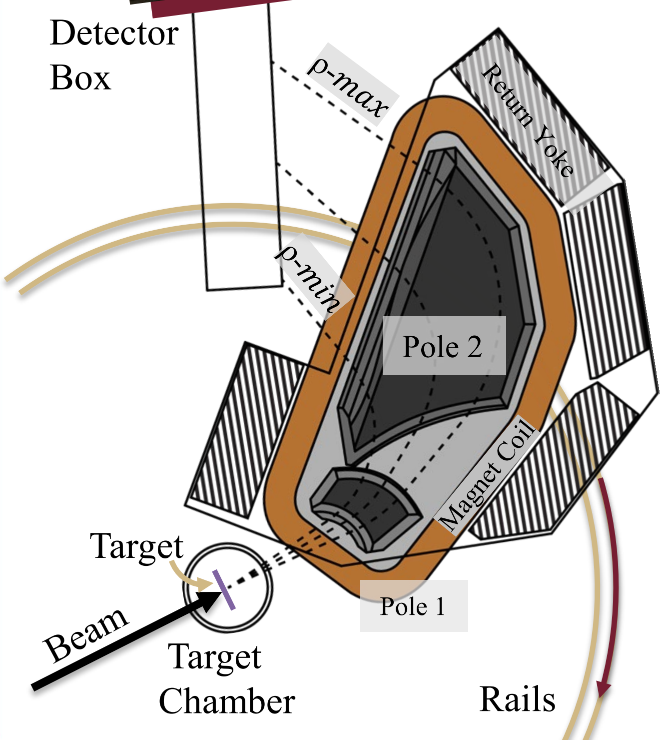


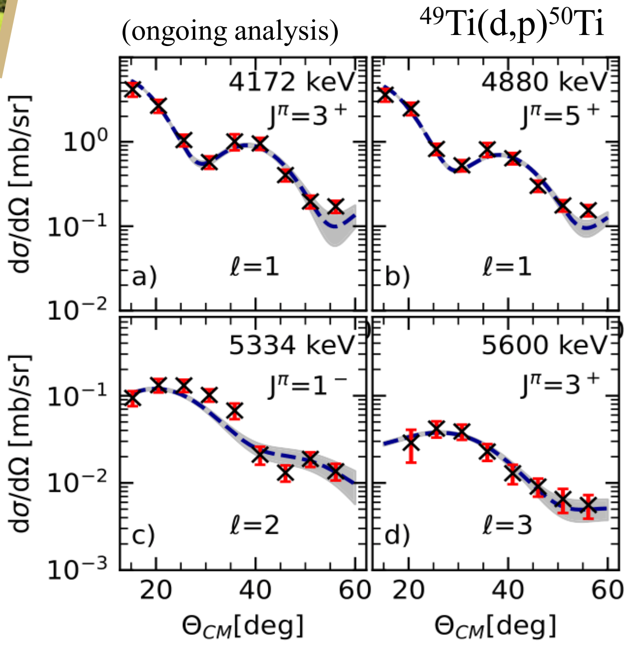


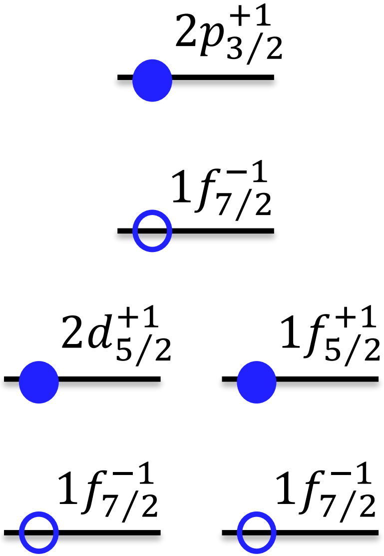
= 1^- states observed in real-photon scattering off ^{48,50}Ti at HIγS@Duke University.

Populate PDR states through (d,p) reaction









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.

Results for possible PDR states populated in ^{61}Ni(d,p)^{62}Ni

Undergraduate Research

Early hands-on research experience for both Ramiro Renom and Scott Baker. Ramiro is co-author on <u>five</u> peer-reviewed publications!

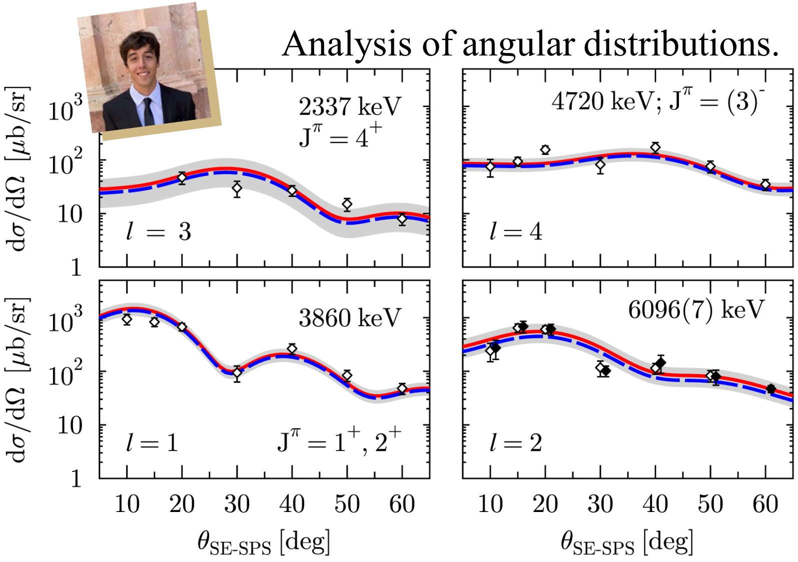
PHYSICAL REVIEW C **108**, 014311 (2023)

Experimental study of excited states of ^{62}Ni via one-neutron (d, p) transfer up to the neutron-separation threshold and characteristics of the pygmy dipole resonance states

M. Spieker,[1,*] L. T. Baby,[1] A. L. Conley,[1] B. Kelly,[1] M. Müscher,[2] R. Renom,[1] T. Schüttler,[2] and A. Zilges[2]
[1]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[2]*Institute for Nuclear Physics, University of Cologne, 50937 Köln, Germany*

(Received 5 May 2023; accepted 28 June 2023; published 10 July 2023)

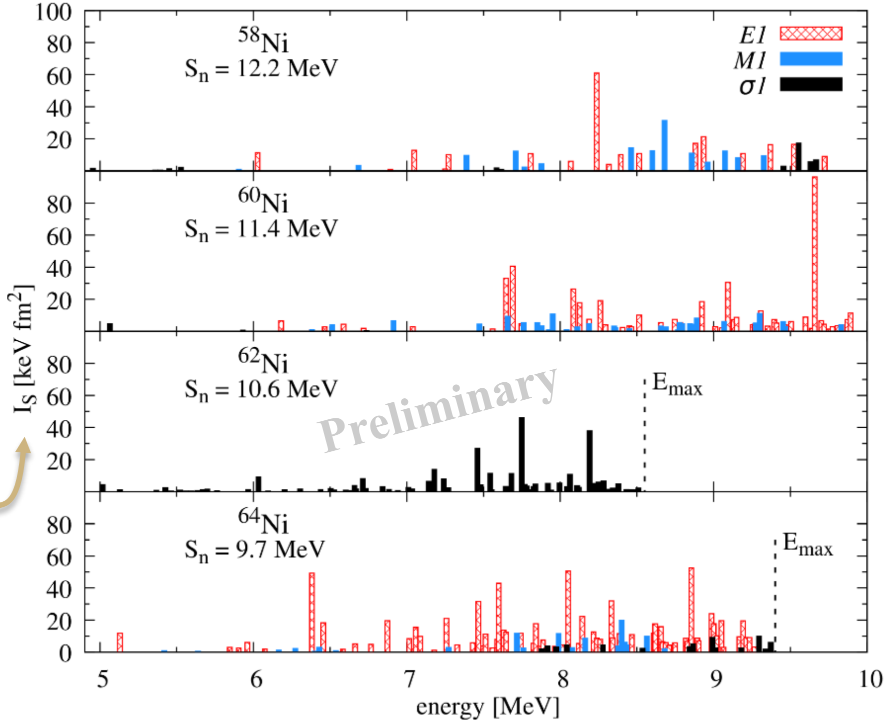
Analysis of angular distributions.



Research Experience

“PDR” E1 strength increases with increasing neutron excess in Ni isotopes

$\sim B(E1; 0_1^+ \rightarrow 1_i^-)$ strength



F. Bauwens *et al.*, Phys. Rev. C **62** (2000) 024302

M. Scheck *et al.*, Phys. Rev. C **87** (2013) 051304R
M. Scheck *et al.*, Phys. Rev. C **88** (2013) 044304

T. Schüttler, Bachelor’s thesis, Cologne (2023)

NRF experiments on ^{62}Ni up to S_n already performed at γELBE and HIγS

M. Müscher, to be published

Is this E1 strength increase linked to the low-*l* single-particle strength shifting down in energy?

[M. Müscher, A. Zilges (University of Cologne, Germany), private communication (2023)]

"PDR" E1 strength increases with increasing neutron excess in Ni isotopes

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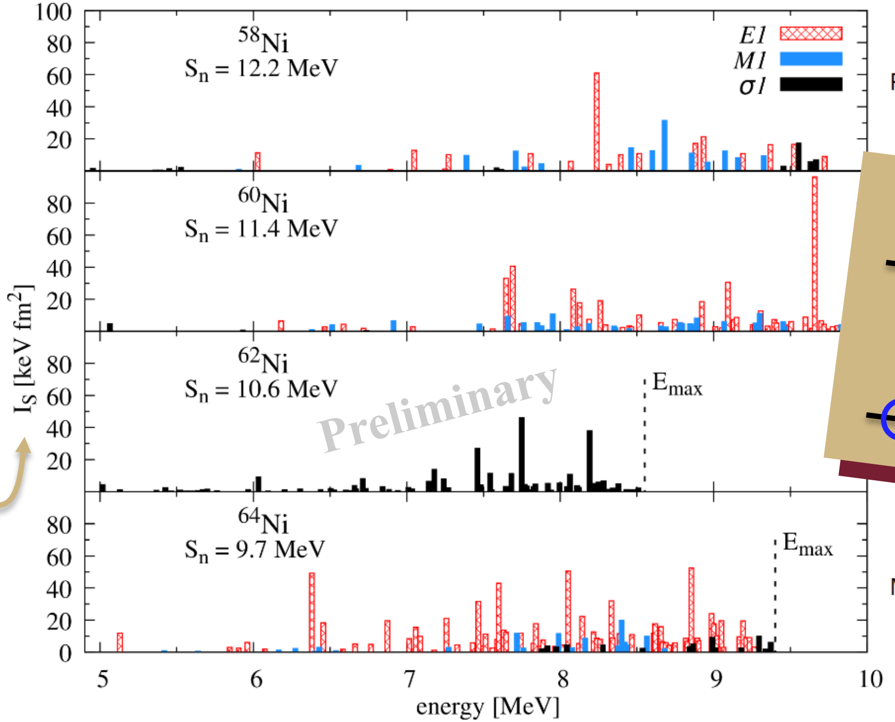

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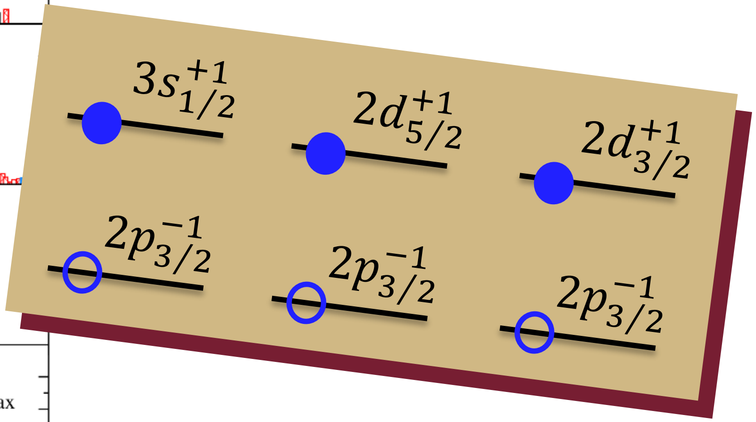

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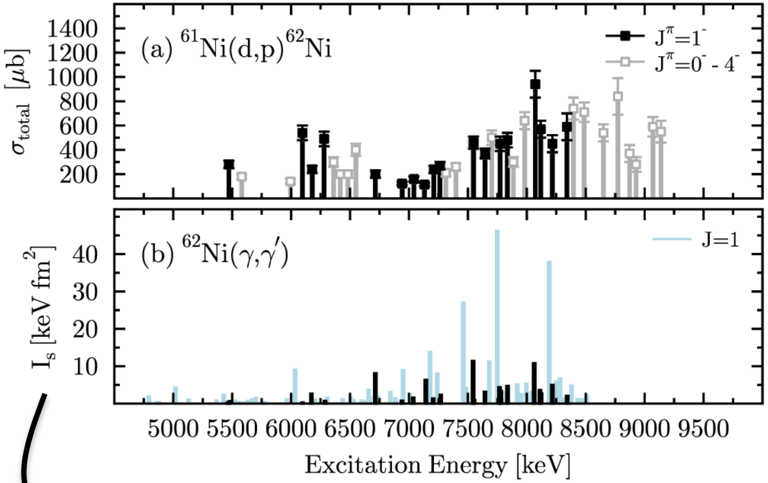
Results for possible PDR states populated in ^{61}Ni(d,p)^{62}Ni

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



$\sim B(E1; 0_1^+ \rightarrow 1_i^-)$ strength

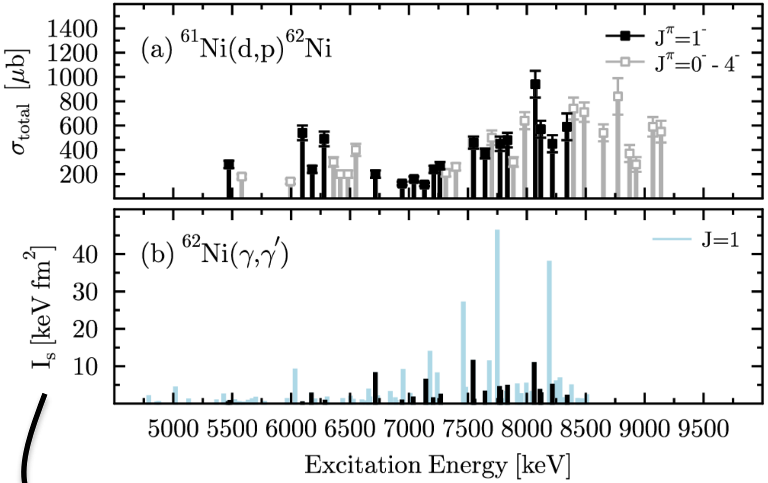
- Intensity ratios from ^{62}Ni(γ,γ') were used to identify $J = 1$ states up to 8.5 MeV.
  [T. Schüttler, M. Müscher, A. Zilges, *et al.*]
- 17 $J^\pi = 1^-$ candidates populated in ^{61}Ni(d,p)^{62}Ni through $l = 2$ angular momentum transfers.

→ No $l = 0$ transfers were observed below S_n!
→ Consequently, neutron $(2p_{3/2})^{-1}(2d_{5/2})^{+1}$ and $(2p_{3/2})^{-1}(2d_{3/2})^{+1}$ 1p-1h configurations need to be responsible for E1 strength increase in ^{62}Ni (N=34) if Inakura's predictions are correct.

- ^{62}Ni(γ,γ') up to threshold will show whether strength increases further and whether more 1^- states, populated in (d,p) and (γ,γ'), can be identified. (HIγS experiment up to S_n performed)
- Detailed theoretical calculations will then be needed (LSSM, SSRPA, RQTBA+PVC, QPM, …).

Results for possible PDR states populated in ^{61}Ni(d,p)^{62}Ni

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



$\sim B(E1; 0_1^+ \rightarrow 1_i^-)$ strength

Ongoing project in collaboration with UoC, UNC, and ELI-NP.

- Intensity ratios from ^{62}Ni(γ,γ') were used to identify $J = 1$ states up to 8.5 MeV.
  [T. Schüttler, M. Müscher, A. Zilges, *et al.*]
- 17 $J^{\pi} = 1^{-}$ candidates populated in ^{61}Ni(d,p)^{62}Ni through $l = 2$ angular momentum transfers.

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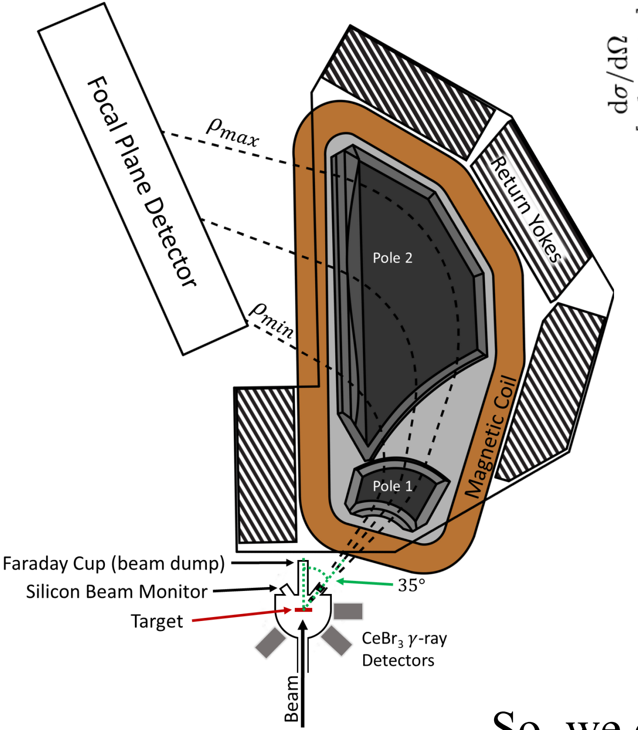
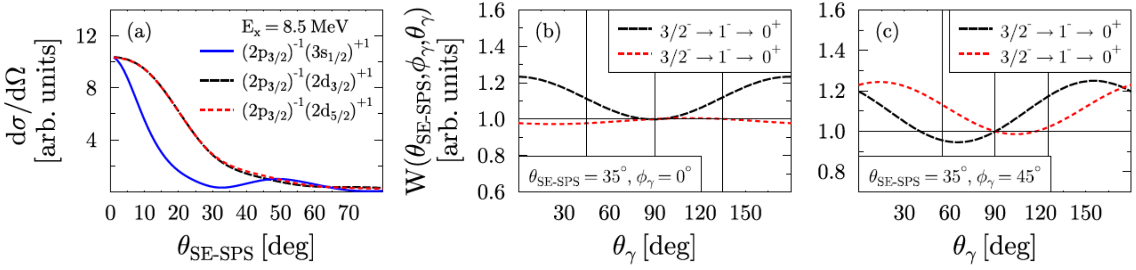
Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

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

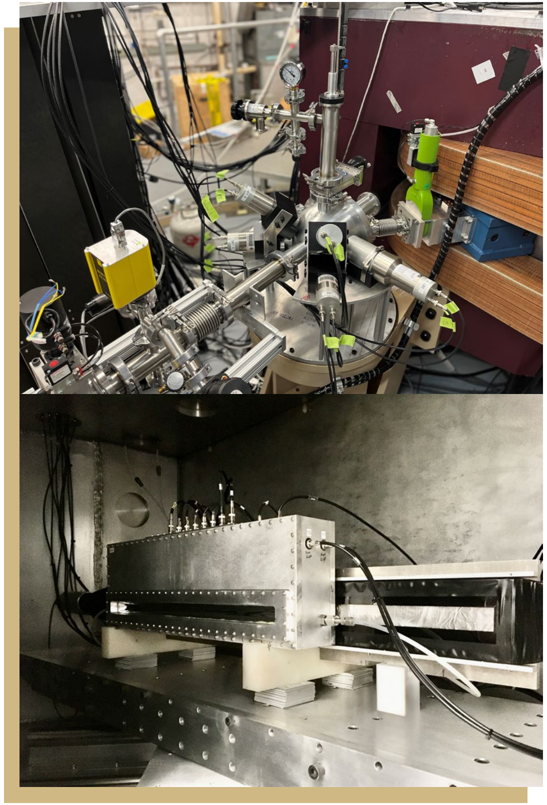




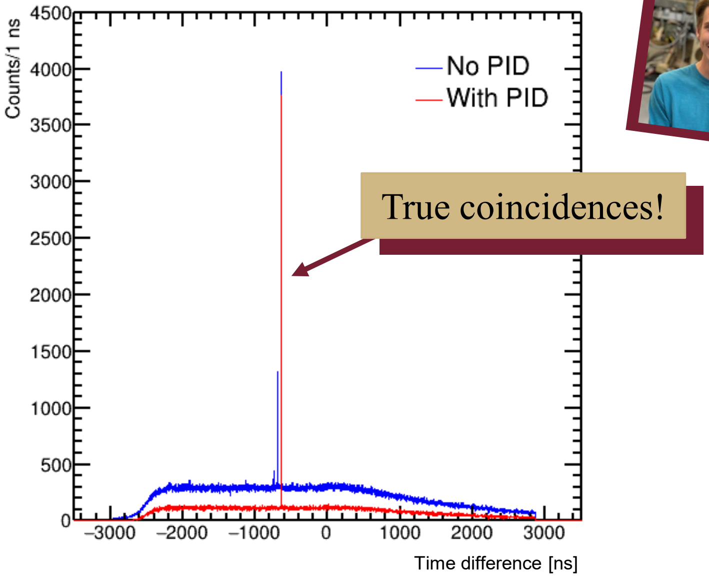
… and we can use particle-γ angular correlations to distinguish 1p-1h configurations, which were populated through the same angular momentum transfer!

So, we decided to build the $CeBr_3$ Array (CeBrA) demonstrator.

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

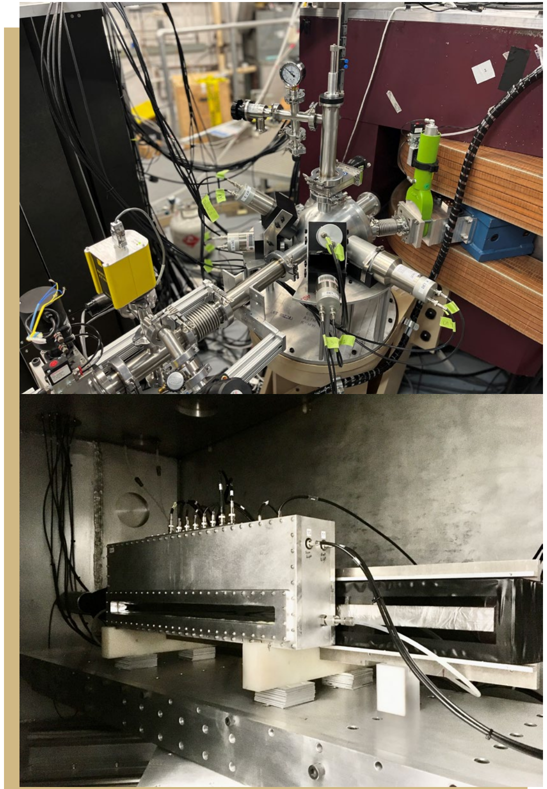


Coincidence timing between $CeBr_3$ γ-ray detectors and focal-plane scintillator.

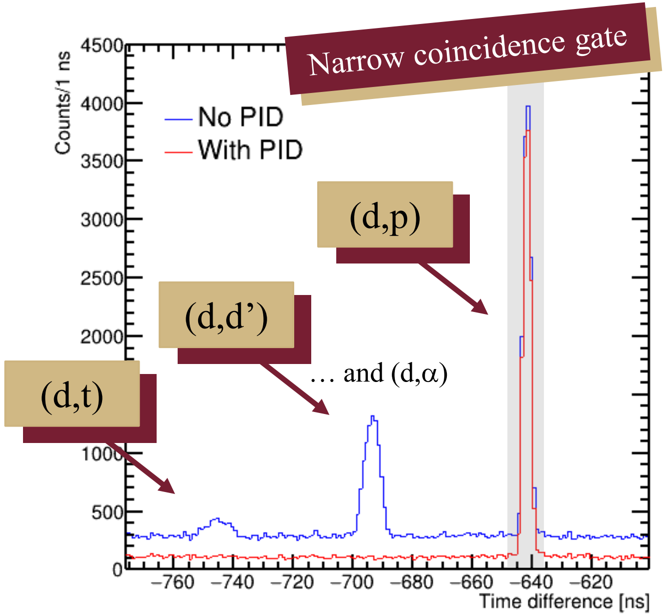


PID eliminates prompt events resulting from other reactions. To eliminate random background, further timing gates are needed.

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



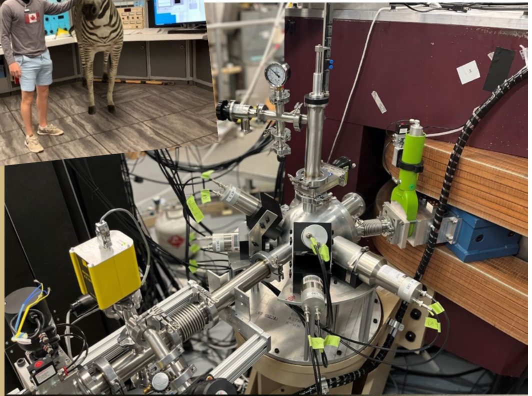
Coincidence timing between $CeBr_3$ γ-ray detectors and focal-plane scintillator.

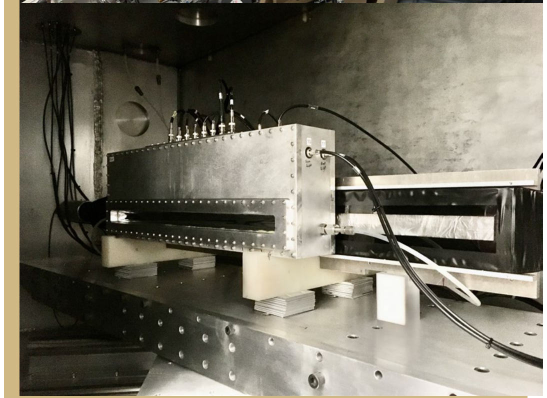


PID eliminates prompt events resulting from other reactions. To eliminate random background, further timing gates are needed.

Heureka! [Archimedes]

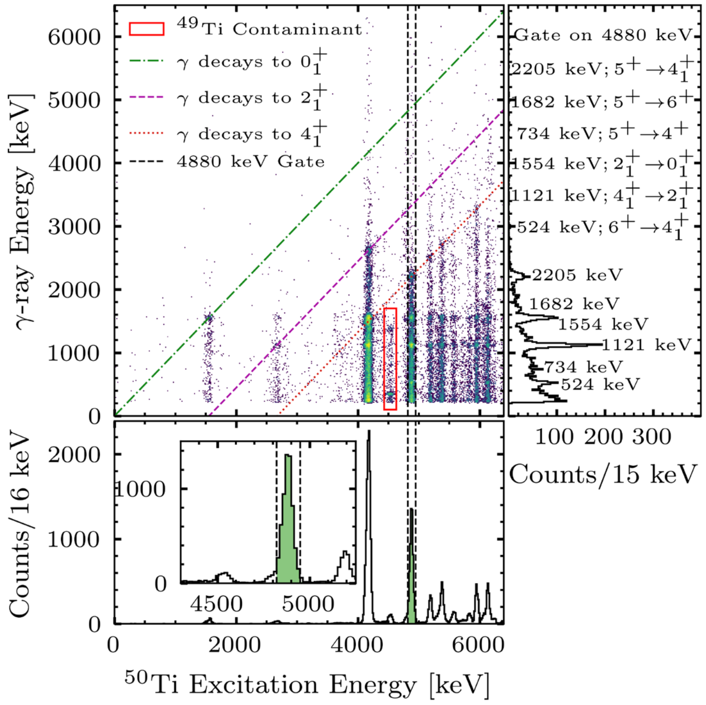
Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS



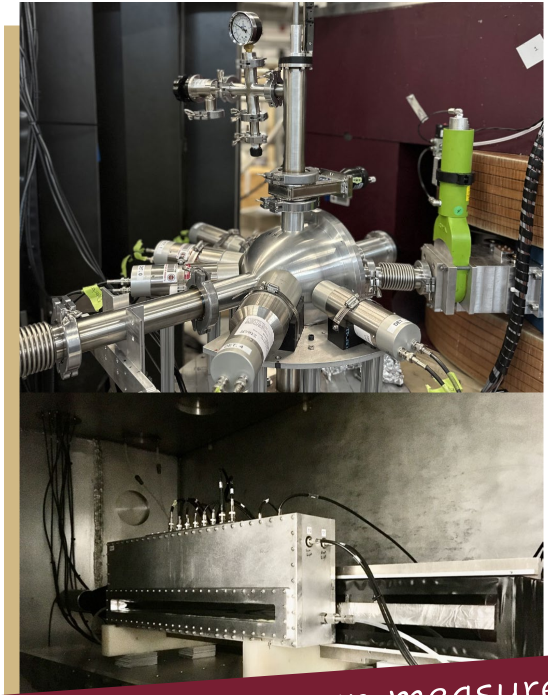


Particle-γ coincidence matrix for selecting the excitation and decay of specific excited states.

^{49}Ti(d,pγ)^{50}Ti



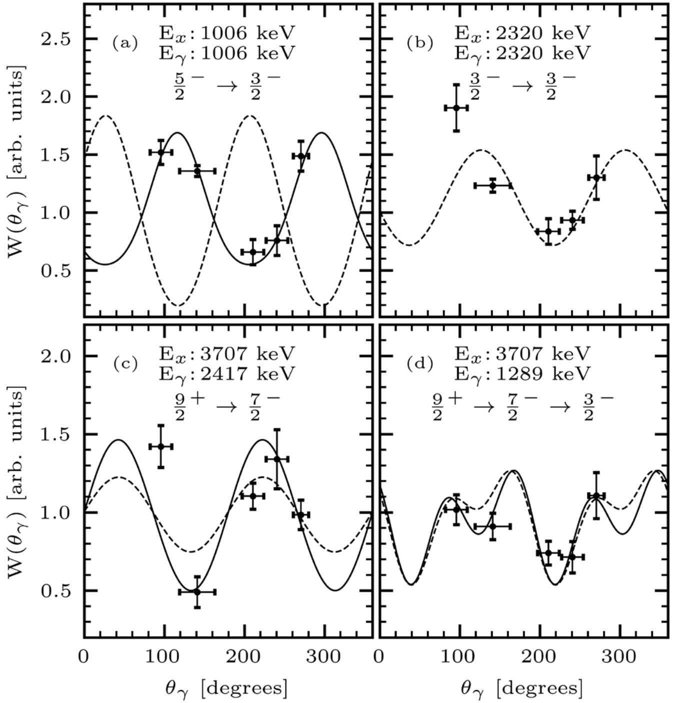
Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS



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

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

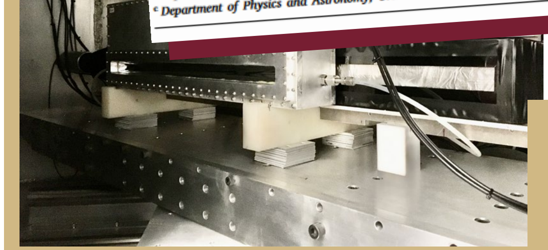
$^{52}Cr(d,p\gamma)^{53}Cr$

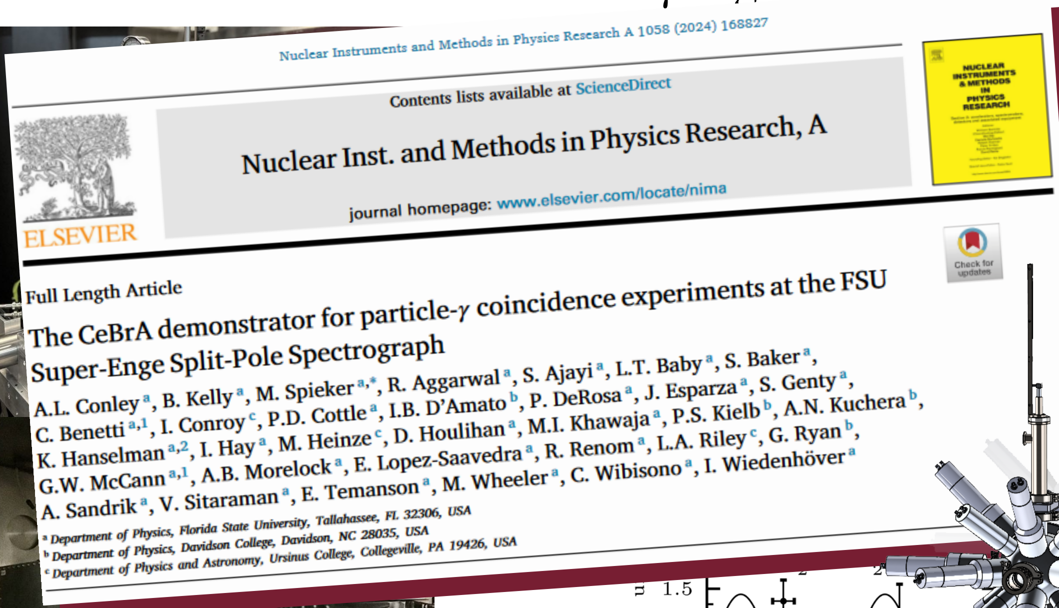


Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

We have big plans!

Particle-γ angular correlations for spin-parity ... n of multipole




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

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

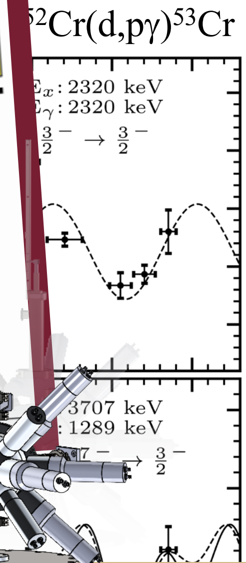
journal homepage: www.elsevier.com/locate/nima

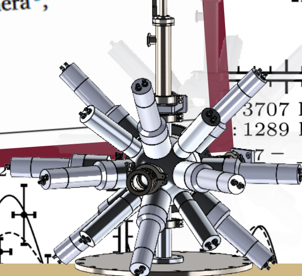
Full Length Article

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]

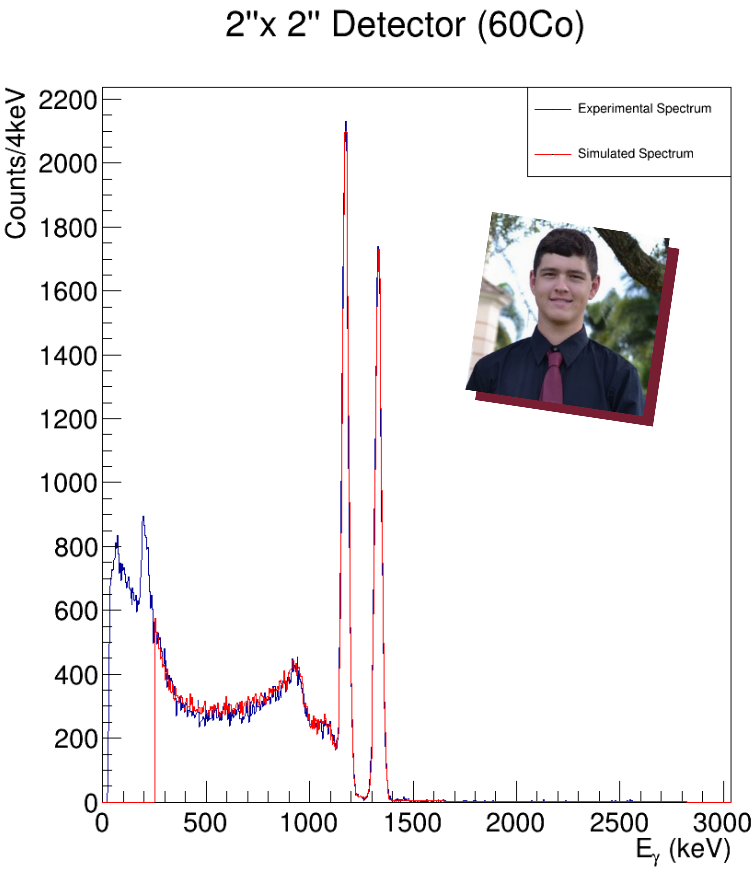
Honors Thesis Work

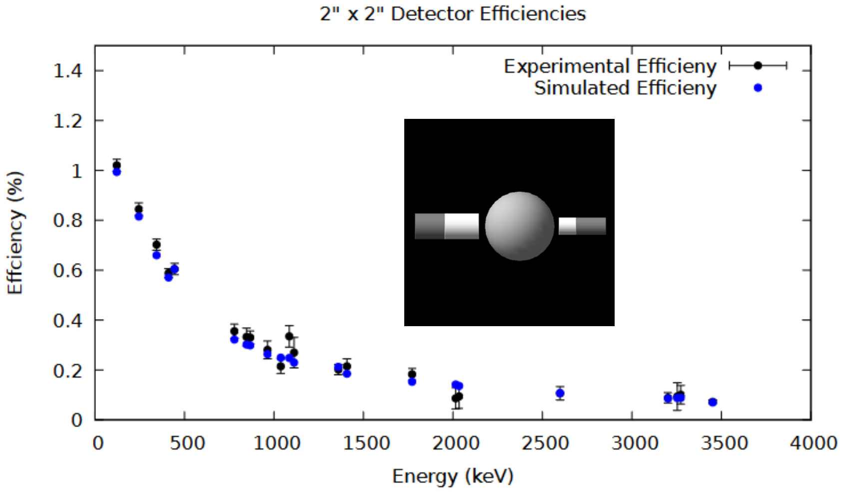
Undergraduate Research

GEANT4 simulation of $CeBr_3$ detectors

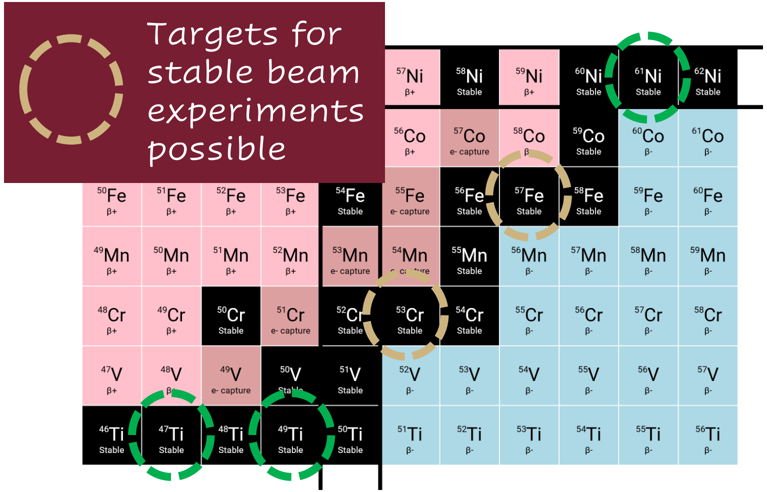
- FSU undergraduate student Scott Baker working on simulation of our $CeBr_3$ detectors using GEANT4 as part of his honors thesis.

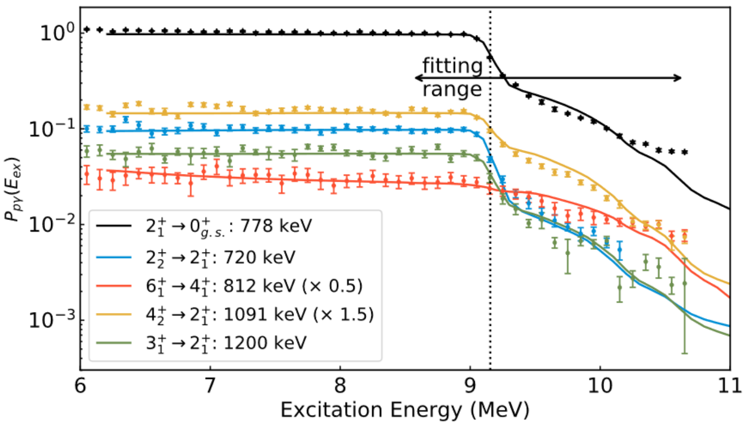
→ Benchmark of simulation against data measured with standard calibration sources.





Future plans for PDR studies at FSU





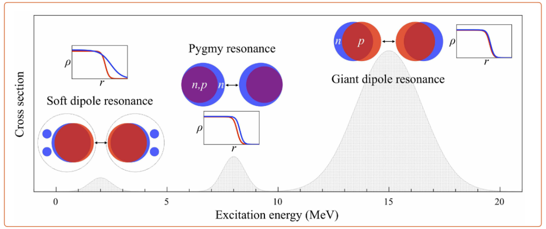
[Figure 2: A. Ratkiewicz *et al.*, PRL **122**, 052502 (2019)]

- Measure γ-ray strength function in ^{62}Ni via ^{61}Ni(d,pγ)^{62}Ni using surrogate method and CeBrA demonstrator.
  [Thesis experiment for B. Kelly]
- Continue (d,p) program to study PDR in fp-sd shell.
  [new grad student after B. Kelly graduation]
- Study neutron 2p-2h structure of PDR in ^{62}Ni via ^{60}Ni(t,p)^{62}Ni.
  [new grad student after B. Kelly graduation]
- Study γ decay of PDR states directly if CeBrA MRI gets funded.
  (higher FEP of array needed!)

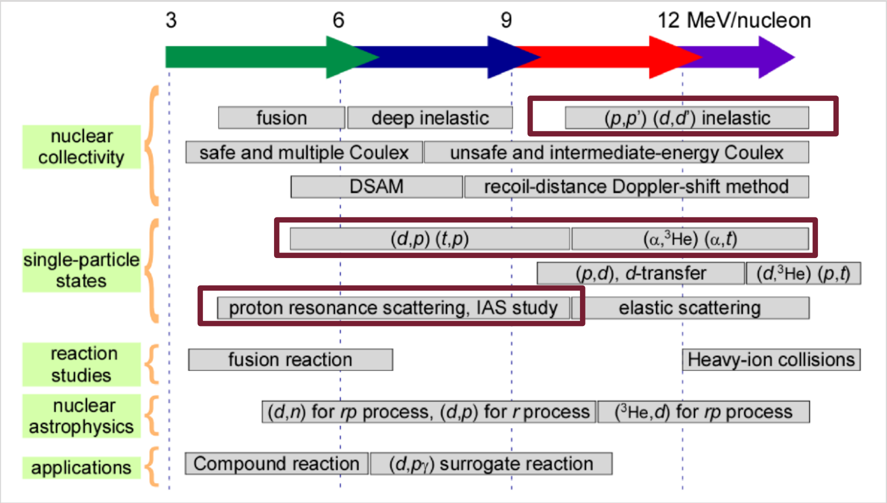
Single-particle structure studies of PDR with SOLARIS at FRIB [^{49}Ca(d,pγ)^{50}Ca]

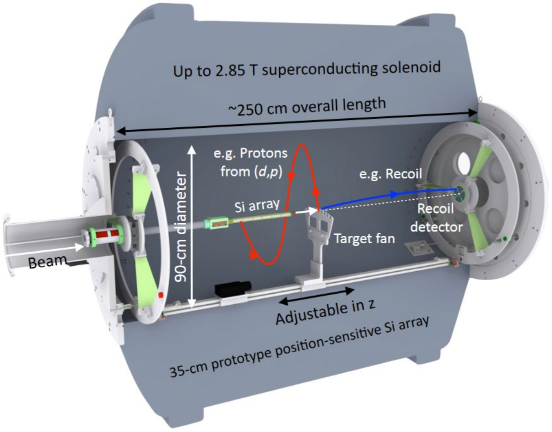
PAC proposal is being developed.

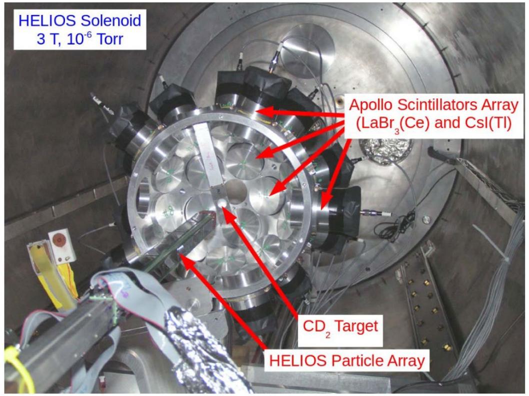
FRIB



ReA stages @ FRIB [SOLARIS White Paper (2018)]







of interest for PDR studies

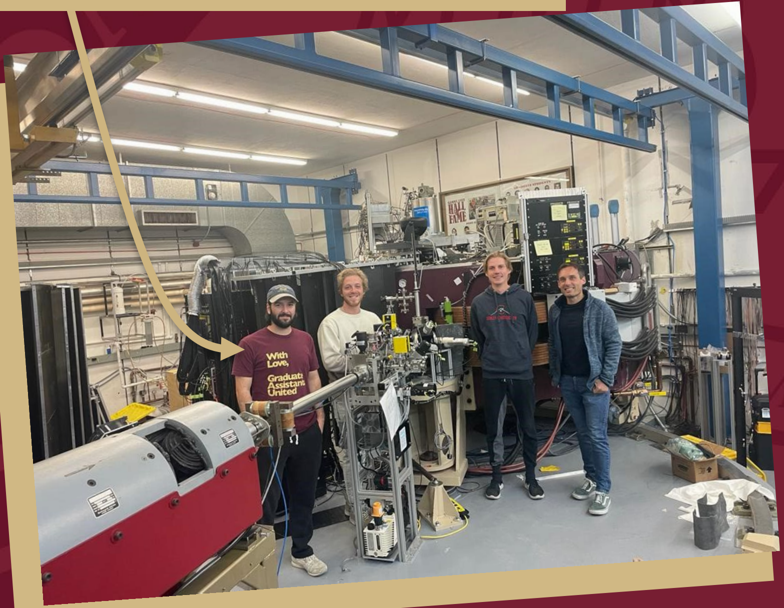
In collaboration with T.L. Tang (FSU), A. Couture (LANL), B. Kay (ANL).

FLORIDA STATE UNIVERSITY

Project #3

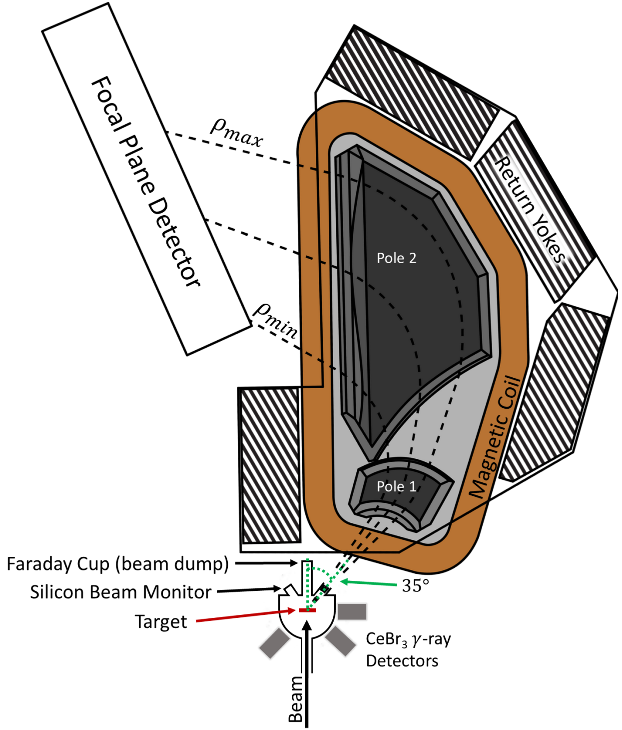
α clustering and its possible implications for p-process nucleosynthesis

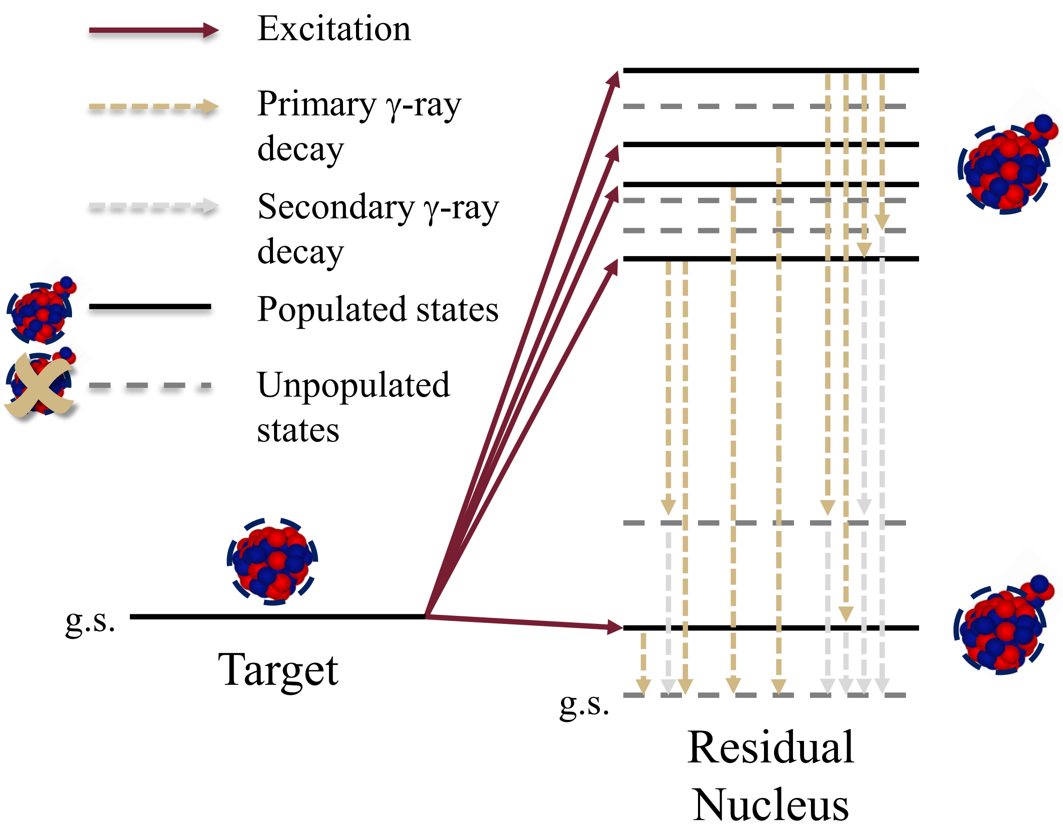
[Thesis experiments for D. Houlihan]



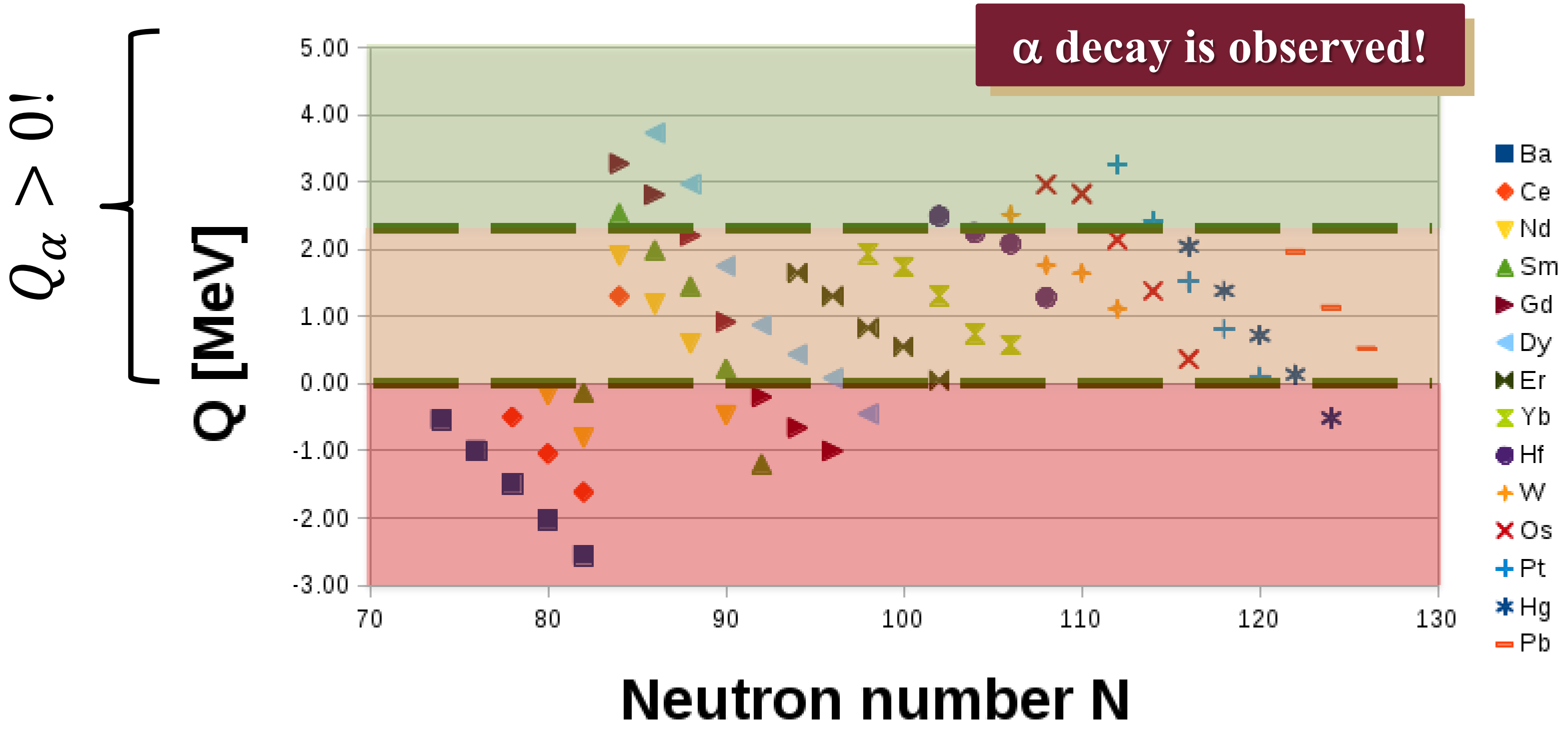
Coincident γ-ray detection with the CeBrA demonstrator at SE-SPS

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



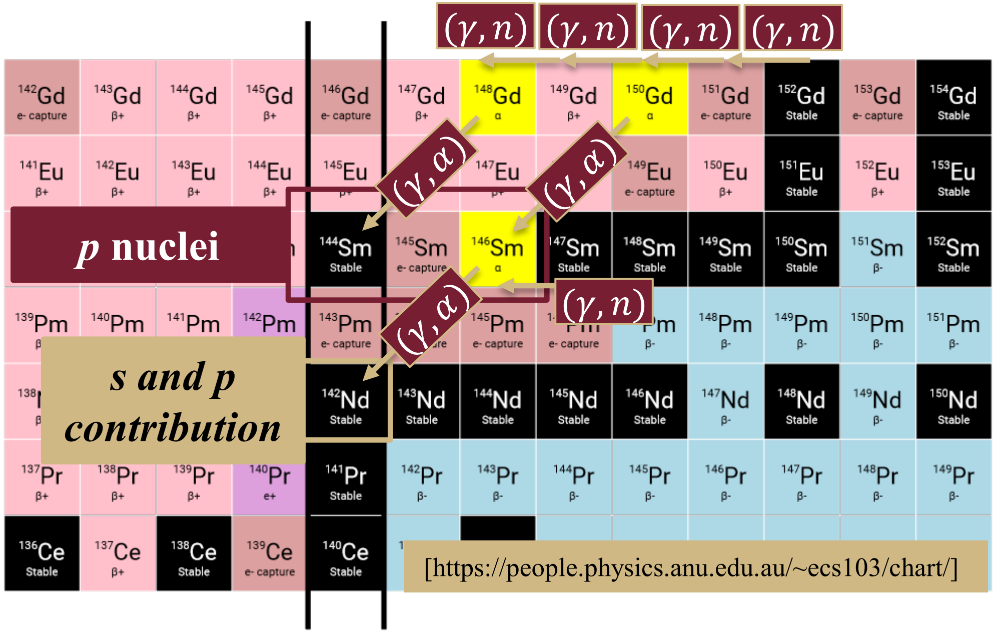


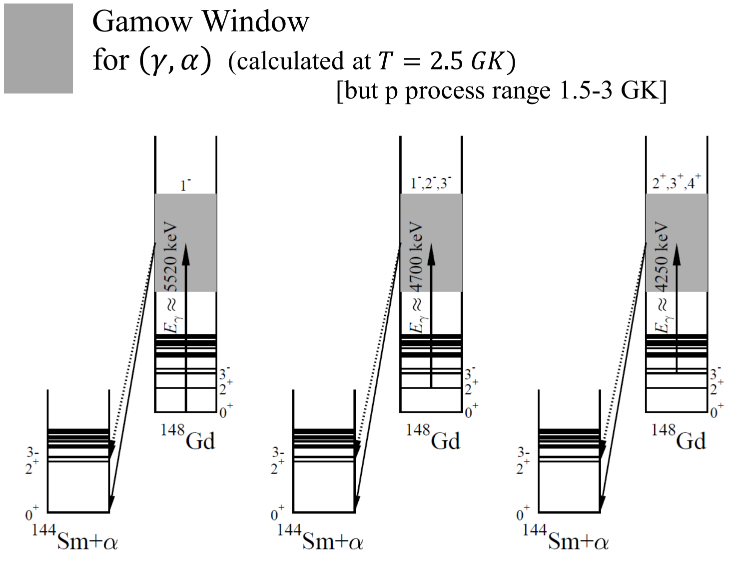
Q_α values from Ba to Pb



Cluster strength expected at comparably low excitation energy!

The *p* process and the neutron-deficient Sm and Gd nuclei – (γ,α) reactions





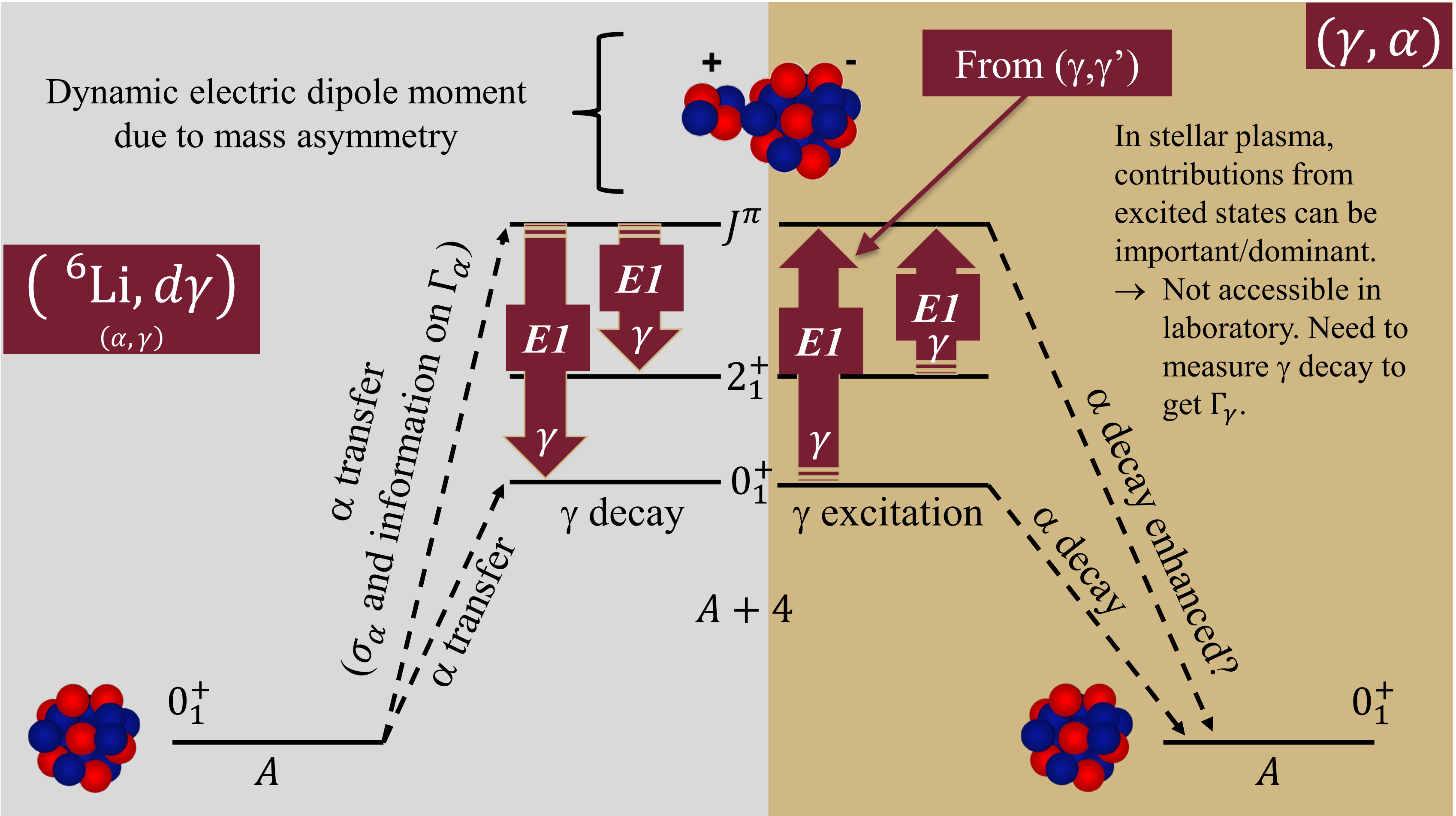
[P. Mohr, arXiV:nucl-ex/0405035v1 (2004)]

γ-induced reactions predominantly excite states via dipole transitions (E1 and M1).

If pre-clustered states have enhanced B(E1) strength, a (γ,α) enhancement might result.

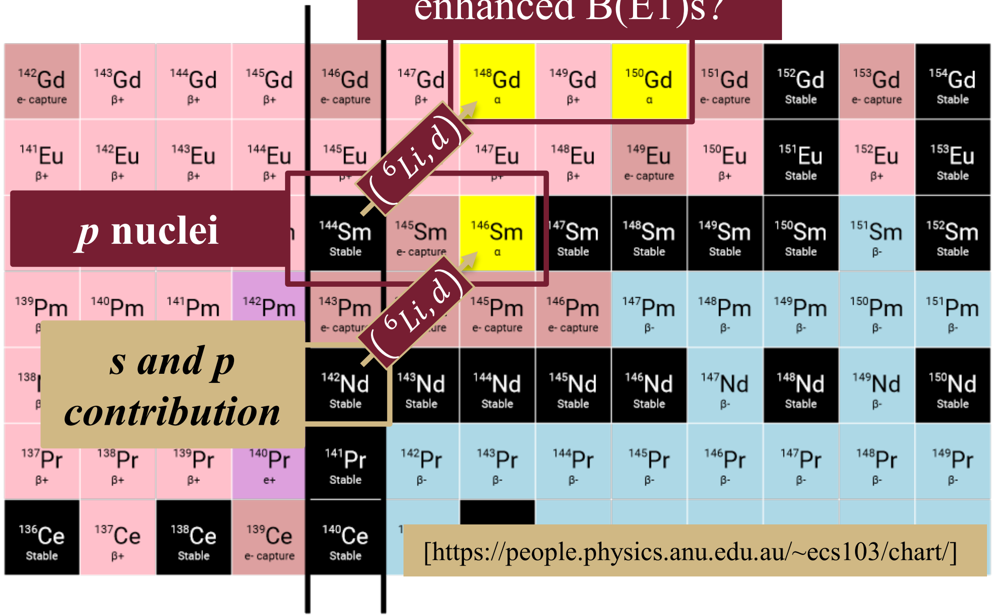
Possible influence on p process

The *p* process and the neutron-deficient Sm and Gd nuclei – (γ,α) reactions



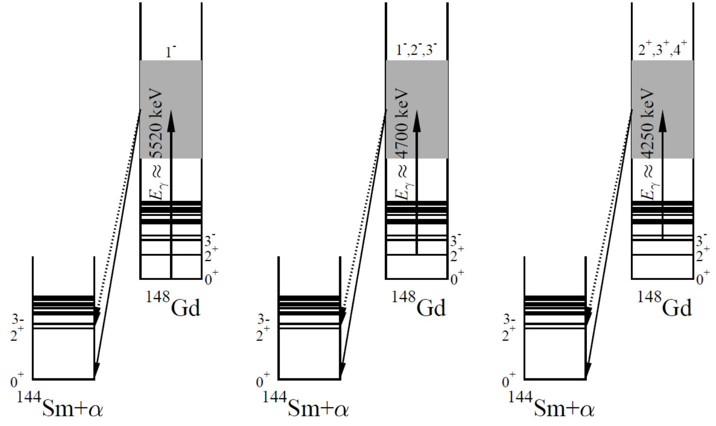
The *p* process and the neutron-deficient Sm and Gd nuclei – (γ,α) reactions

α-cluster states and enhanced B(E1)s?



[https://people.physics.anu.edu.au/~ecs103/chart/]

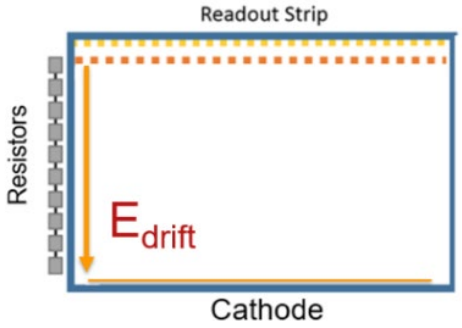
Gamow Window for (γ,α) (calculated at $T = 2.5\ GK$)
[but p process range 1.5-3 GK]

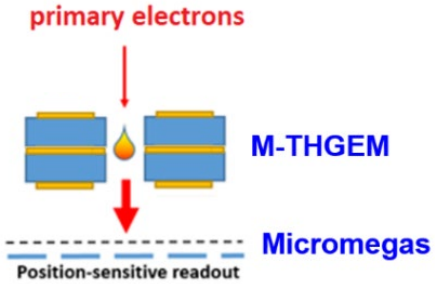


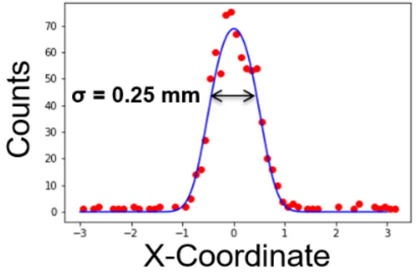
[P. Mohr, arXiV:nucl-ex/0405035v1 (2004)]

Perform (⁶Li,d) α-transfer experiments with SE-SPS and detect γ-ray transitions from excited states in coincidence with CeBrA.

A new focal plane detector for the SE-SPS







Needs

- Energy resolution of 15 keV or better (improve position resolution of ~ 2 mm by factor of ~ 4).
- Higher rate capabilities (currently limited to ~ 2kHz).

Solution: Piggyback on recent developments at S800 spectrograph for drift chambers

- New S800 Micro-Pattern Gaseous Detector (MPGD)-based readout of drift chamber improved position resolution from 0.5 mm to 0.25 mm.

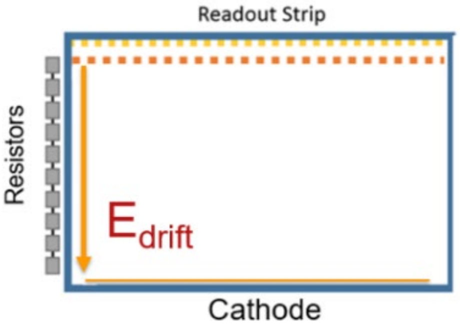
→ Factor 4 improvement achievable!

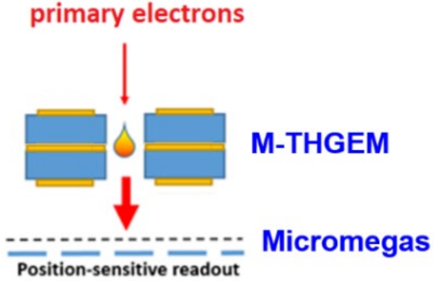
- New S800 drift chamber design allowed for rates as high as 20 kHz

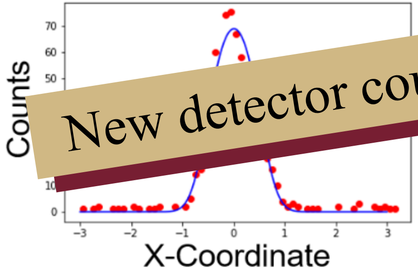
→ Factor 10 increase in rates achievable!

[Figures and information: M. Cortesi *et al.*, Journal of Instrumentation **15**, P03025 (2020)]

A new focal plane detector for the SE-SPS







Needs

- Energy resolution of 15 keV or better (improve position resolution of ~ 2 mm by factor of ~ 4).
- Higher rate capabilities (currently limited to ~ 2kHz).

Solution: Piggyback on recent developments at S800 spectrograph for drift chambers

- New S800 Micro-Pattern Gaseous Detector (MPGD)-based readout of … roved positi… 0.25 mm.
  … …provement achievable!
- New S800 drift chamber design allowed for rates as high as 20 kHz

→ Factor 10 increase in rates achievable!

New detector could be used as both light- and heavy-ion detector!

[Figures and information: M. Cortesi *et al.*, Journal of Instrumentation **15**, P03025 (2020)]

- **Study of octupole and hexadecapole collectivity in the Ge-Kr mass region at FRIB**

  → (p,p‘), (p,2p), and (p,pn) experiments in inverse kinematics using GRETINA and the S800 at FRIB

- **The microscopic structure of the Pygmy Dipole Resonance (PDR)**

  → Particle-transfer, (d,p) and (t,p), as well as particle-γ coincidence experiments, (d,pγ), with the CeBrA demonstrator and Super-Enge Split-Pole Spectrograph at Florida State University

- **α clustering and its possible implications for p-process nucleosynthesis**

  → (^{6}Li,d) α-transfer and particle-γ coincidence experiments, (^{6}Li,dγ), with the CeBrA demonstrator (CeBrA) and the Super-Enge Split-Pole Spectrograph at Florida State University

Project Timeline

Year 1	Year 2	Year 3	Year 4

^{72}Se(p,pn)^{71}Se
GRETINA+S800
A. Himmelreich
(Ursinus w. Riley)

^{74}Kr(p,pn)^{73}Kr
GRETINA+S800

^{70,72}Kr(p,pX)
GRETINA+S800@FRIB

^{61}Ni(d,pγ)^{62}Ni
CeBrA+SE-SPS
B. Kelly

^{53}Cr(d,p)^{54}Cr
SE-SPS
New student #1

^{57}Fe(d,p)^{58}Fe
SE-SPS
Undergraduate #1

^{60}Ni(t,p)^{62}Ni
SE-SPS
New student #1

^{49}Ca(d,pγ)^{50}Ca
SOLARIS+APOLLO@FRIB

^{142}Nd(^{6}Li,dγ)^{146}Sm
CeBrA+SE-SPS
D. Houlihan

^{144}Sm(^{6}Li,dγ)^{148}Gd
CeBrA+SE-SPS
D. Houlihan

^{92}Mo(^{6}Li,dγ)^{96}Ru
CeBrA+SE-SPS
New student #2

Planning of new FP detector (Spieker)

Construction of new FP detector (New student #1)

Commissioning of new FP detector