RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

Nuclear Reaction Studies with rare isotope beams for Stewardship Science NRS4SS

SSAP Symposium
February 21-22, 2024

Jolie A. Cizewski
Rutgers University

DOE SSAA DE-NA0003897
DOE SSAA DE-NA0004066

Goals of NRS4SS

- NRS4SS projects
  - DOE SSAA DE-NA0003897 start 4/1/2019
  - DOE SSAA DE-NA0004066 start 7/1/2022
- Builds on 16 years of Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science (RIBSS)

- NRS4SS projects
  - DOE SSAA DE-NA0003897 start 4/1/2019
  - DOE SSAA DE-NA0004066 start 7/1/2022
- Builds on 16 years of Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science (RIBSS)
- Rutgers Alumni of RIBSS Center and NRS4SS
  - Staff & Postdocs at LLNL and DOE labs
    - Rebecca Toomey (LLNL, PD) as of September 2022
    - Chad Ummel (LLNL, staff) as of September 2023
    - Heather Garland (PNNL, PD) as of January 2024
  - Staff members at LLNL
  - Staff members at LANL
  - Staff members at ORNL
  - Faculty member at University of Tennessee
  - Key collaborators on NRS4SS projects

Publications & Presentations 2023-24

- Peer reviewed publications
  - 2 published with Rutgers students, postdocs and PI as co-authors
  - 1 under review
  - 2 in preparation
- Invited talks:
  - 12, 6 by PhD students (3 at NNSA labs/sites)
  - Poster and contributed talk presentations at LLNL, DNP meetings
- PhD dissertations:

- **Single-neutron excitations in A=135 nuclei**, Chad Conrad Ummel, *Ph.D. Dissertation Rutgers University, May 2023 (defended March 2023)*.
- **Results from the 95Mo(d,p) reaction measurements: Informing the 96Mo level scheme with GODDESS and investigating the (d,p) reaction as a surrogate for the (n,n') reaction with STARLiTeR**, Heather Irene Garland, *Ph.D. Dissertation, Rutgers University January 2024 (defended December 2023)*.

List of all pubs & talks

Refereed publications (students, postdocs)

1. **First Direct Measurement Constraining the 34Ar(α,p)37K Reaction Cross Section for Mixed Hydrogen and Helium Burning in Accreting Neutron Stars**, J. Browne, K.A. Chipps , Konrad Schmidt, H. Schatz, S. Ahn, S. D. Pain, F. Montes, W. J. Ong, U. Greife, J. Allen, D. W. Bardayan, J. C. Blackmon, D. Blankstein, S. Cha, K. Y. Chae, M. Febbraro, M.R. Hall, K. L. Jones, A. Kontos, Z. Meisel, P. D. O'Malley, K. T. Schmitt, K. Smith, M. S. Smith, P. Thompson, R. Toomey, M. Vostinar, and D. Walter, *Phys. Rev. Lett* ***130****, 212701 (2023)*, DOI: 10.1103/PhysRevLett.130.212701
2. **58Ni(3He,t)58Cu*(γ) Measurements with GODDESS to constrain the astrophysical rate of 57Ni(p,γ)58Cu**, S R Carmichael, S D Pain, M Siciliano, J Allen, D W Bardayan, C Boomershine, C M Campbell, M P Carpenter K A Chipps, J A Cizewski, P A Copp, J Forson, H Garland, R Ghirmire, J Kovoor, T Lauritsen, C Müller-Gatermann, P D O'Malley, A Ratkiewicz, W Reviol, D Seweryniak, H Sims, C C Ummel, G Wilson, J. Phys.: Conf. Ser. **2586** 012109. doi:10.1088/1742-6596/2586/1/012109
3. **Neutron-capture cross sections for Sm and Dy nuclei obtained using the Oslo method**, A. Simon, C.S. Reingold, M. Guttormsen, R.O. Hughes, J.T. Burke, K.A. Chipps, S.P. Burcher, S. Ahn, D.T. Blankstien, J.A. Cizewski, N. Cooper, M. Hall, S. Ota, A. Saastamoinen, B. Schroeder, and S. Upadhyayula, submitted to Phys. Rev C (under review).

Invited Talks (students, postdocs)

1. **Probing the Single-Neutron Structure of ^{135}Xe with GODDESS**, Chad Ummel, *Remote Sensing Laboratory Seminar, NNSS, February 23, 2023 (virtual)*
2. **Probing the Single-Neutron Structure of ^{135}Xe with GODDESS**, Chad Ummel, *ORNL Physics Division Seminar, March 21, 2023 (virtual)*
3. **Probing the Single-Neutron Structure of ^{135}Xe with GODDESS**, Chad Ummel, *LLNL WCI Seminar, April 6, 2023*
4. **Informing nucleosynthesis of heavy elements in stellar explosions through indirect neutron capture reaction measurements in inverse kinematics with GODDESS**, Heather Garland, *PNNL Seminar, April 2023*
5. **Probing the Single-Neutron Structure of ^{135}Xe with GODDESS**, Chad Ummel, *PNNL Seminar, April 28, 2023*
6. **Precision lifetime measurements of excited states in neutron-rich isotopes 38Si and 36Si,** Mara Grinder, *Nuclear Physics Seminar, Rutgers University, May 1, 2023.*
7. **Informing neutron capture for i-process nucleosynthesis via the (d,p) reaction with rare isotope beams**, Jolie A. Cizewski, Steven Pain, Andrew Ratkiewicz, Harrison Sims, and the GODDESS COLLABORATION , *i-process Nucleosynthesis Workshop, Limassol, Cyprus, May 2023*
8. **Probing the Single-Neutron Structure of ^{135}Xe with GODDESS**, Chad Ummel, LLNL Nuclear and Chemical Sciences Division Seminar, May 23, 2023 (virtual)
9. **Precision Lifetime Measurements of Excited States in 38Si and 36Si**, Mara Grinder, *Advances in Radioactive Ion Science (ARIS), Avignon, France, June 4-9, 2023*
10. **Introduction to Rutgers SSAA**, Mara Grinder, SSAA Rutgers and UC-Berkeley workshop, Lawrence Livermore National Laboratory, June 23, 2023.
11. **Neutron transfer (d,p) reactions to inform neutron capture,** Jolie A. Cizewski, Harrison Sims, *17th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Grenoble, France, July 17-21, 2023.*
12. **Using SABRE to Measure Near-threshold Proton Branching Ratios in ^{31}S Important for ONe Nova Nucleosynthesis**, Sudarsan Balakrishnan, *Nuclear Physics Seminar, Rutgers University, October 9, 2023.*

Current NRS4SS Students & Postdocs

- Who supported and their positions
  - Graduate students:
    - Heather Garland (Ph.D. January 2024)
    - Chad Ummel (Ph.D. May 2023): SSGF & NNSA Fellow
  - Postdocs:
    - Mara Grinder (Start 9/22)
    - Sudarsan Balakrishnan (Start 1/23)
  - Undergraduate student: Gabriel Cruz, Pacific Islander summer 2023 student
- NNSA-student interactions

NNSA-student interactions

- Grad students: Heather Garland, Chad Ummel (NNSA); Postdocs: Mara Grinder, Sudarsan Balakrishnan; Undergrad: Cruz
- Andrew Ratkiewicz (LLNL) key to realizing experiments & collaborator on subsequent analyses and interpretation
  - Member of GODDESS Management Committee
  - Member, Garland Ph.D. Dissertation committee
  - Hosted Garland at LLNL for 3 weeks of collaborative discussions
- June 2023 LLNL collaboration meeting and workshop (joint w/ UC-Berkeley SSAA)
- August 2023 collaboration meeting in Oak Ridge, TN
- Experiments at HIGS and TAMU
- Bi-weekly GODDESS collaboration analysis meetings (hosted by LLNL)
- Planning for future FRIB & ATLAS GODDESS experiments
  - LLNL exp and thy critical to developing proposals
  - Mara Grinder (RU) PI on proposal; Sudarsan Balakrishnan co-PI on proposal

NNSA-student interactions

- LLNL collaboration meeting & SSAA workshop (joint w/ UC-Berkeley) June 2023
  - Organized by Andrew Ratkiewicz
- Day 1: NRS4SS collaboration meeting with LLNL experimentalists
- Day 2: Applied nuclear physics talks by LLNL scientists:
  - Overview of Nuclear Physics & Accelerator Technology Group: Nick Scielzo
  - Overview of work at WCI: Jo Ressler
  - Recent results from NIF: Annie Kritcher
  - Enhanced particle identification with water-based liquid scintillator: Tomi Akindele
  - Measurements of Fission product yields using monoenergetic neutron and gamma-ray beams: Jack Silano
  - Session Chairs: Peter Bedrossian, Darren Bleuel
  - Tour of NIF
- Poster session over lunch; Rutgers posters:
  - Heather Garland: Using the (d,pγ) Reaction with 95Mo Beams and GODDESS to Inform Gamma-Decay Probabilities,
  - Mara Grinder: 80Ge(d,p) Measurements at FRIB to Inform (n,γ) Reaction Rates in Weak r-Process Nucleosynthesis
  - Sudarsan Balakrishnan: Measuring Near-Threshold Proton Branching Ratios in 31S Important for Nucleosynthesis in Nuclei,

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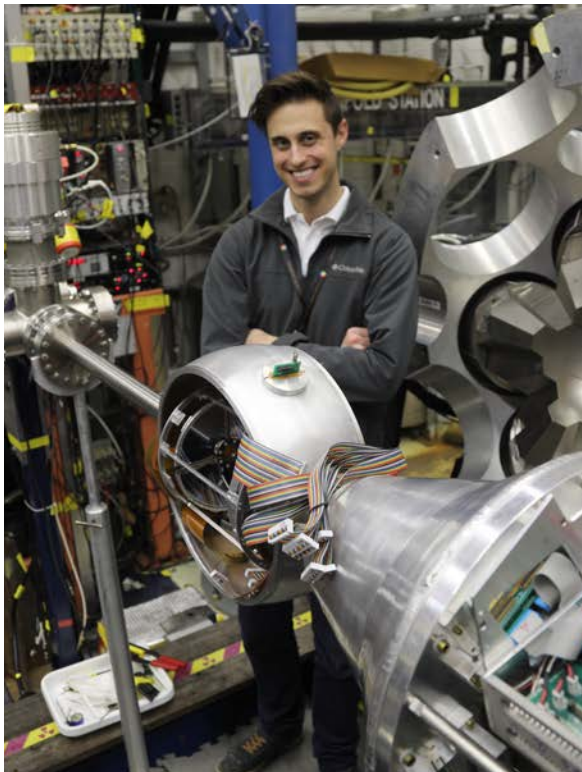
Informing level structure of ^{135}Xe with (d,p) reaction and GODDESS



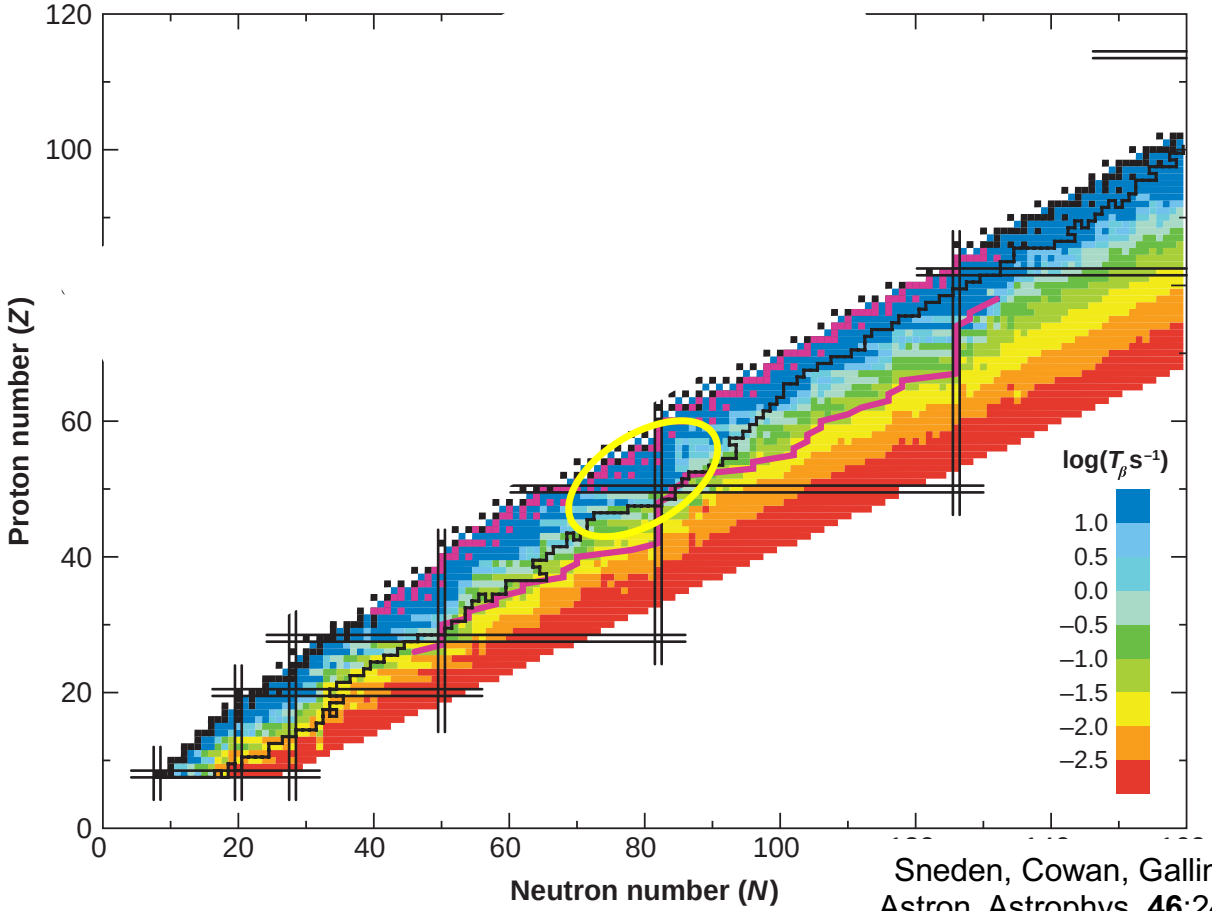
Chad Ummel:

PhD Dissertation (5/23) and to be published

Thank you Chad for providing material

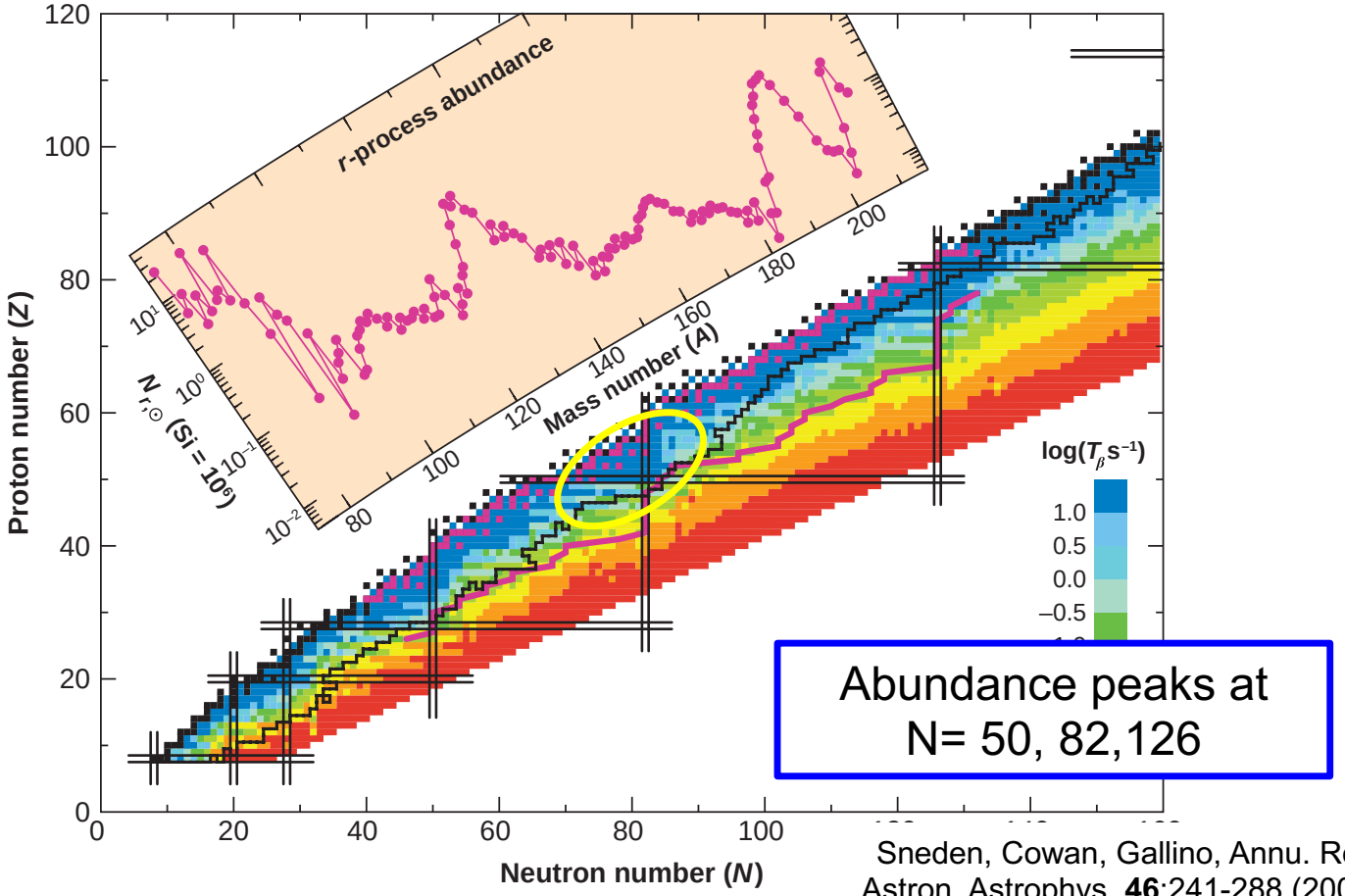
Chad C. Ummel, Ph.D. Dissertation, Rutgers University (2023)
Stewardship Science Graduate Fellow (2018-22)
NNSA Graduate Fellow (2022-23)
LLNL Staff (2023-present

Nuclei A≈130, N≈82: Heavy fission fragments & r-process nucleosynthesis



Sneden, Cowan, Gallino, Annu. Rev. Astron. Astrophys. **46**:241-288 (2008)

Nuclei A≈130, N≈82: Heavy fission fragments & r-process nucleosynthesis

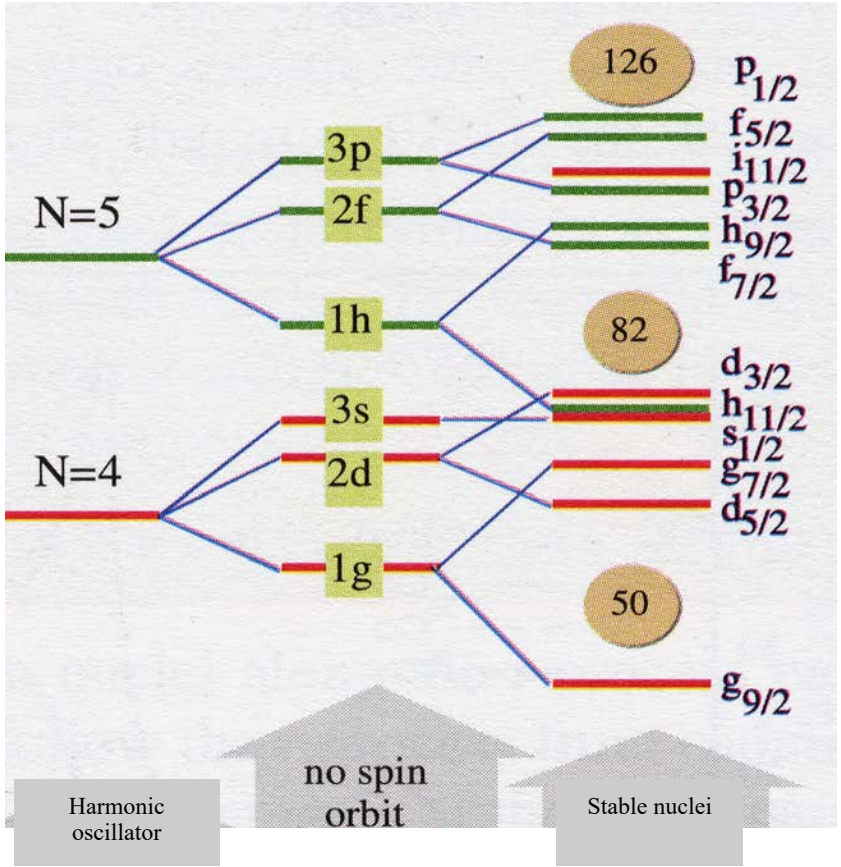


Abundance peaks at
N= 50, 82,126

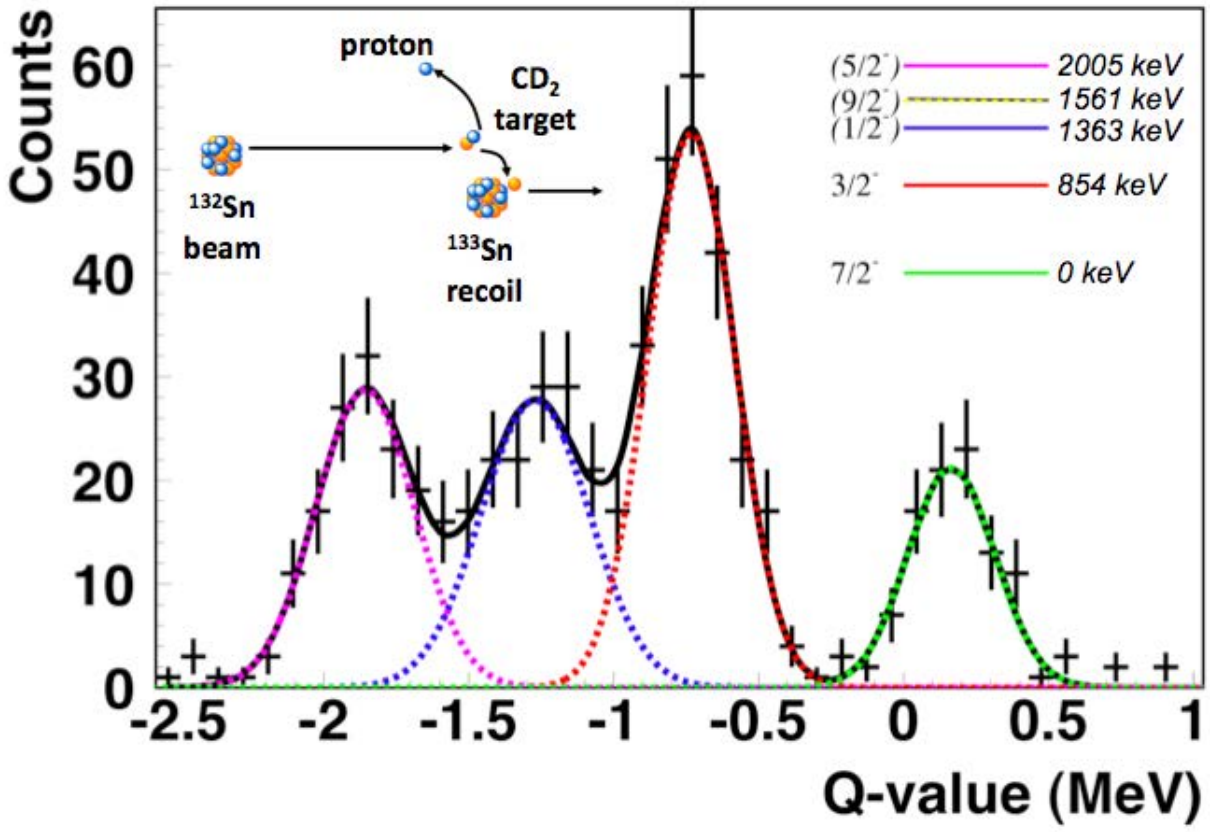
Sneden, Cowan, Gallino, Annu. Rev. Astron. Astrophys. **46**:241-288 (2008)

Shell closures 50, 82, 126

"Flat" harmonic oscillator potential with positive spin-orbit interaction



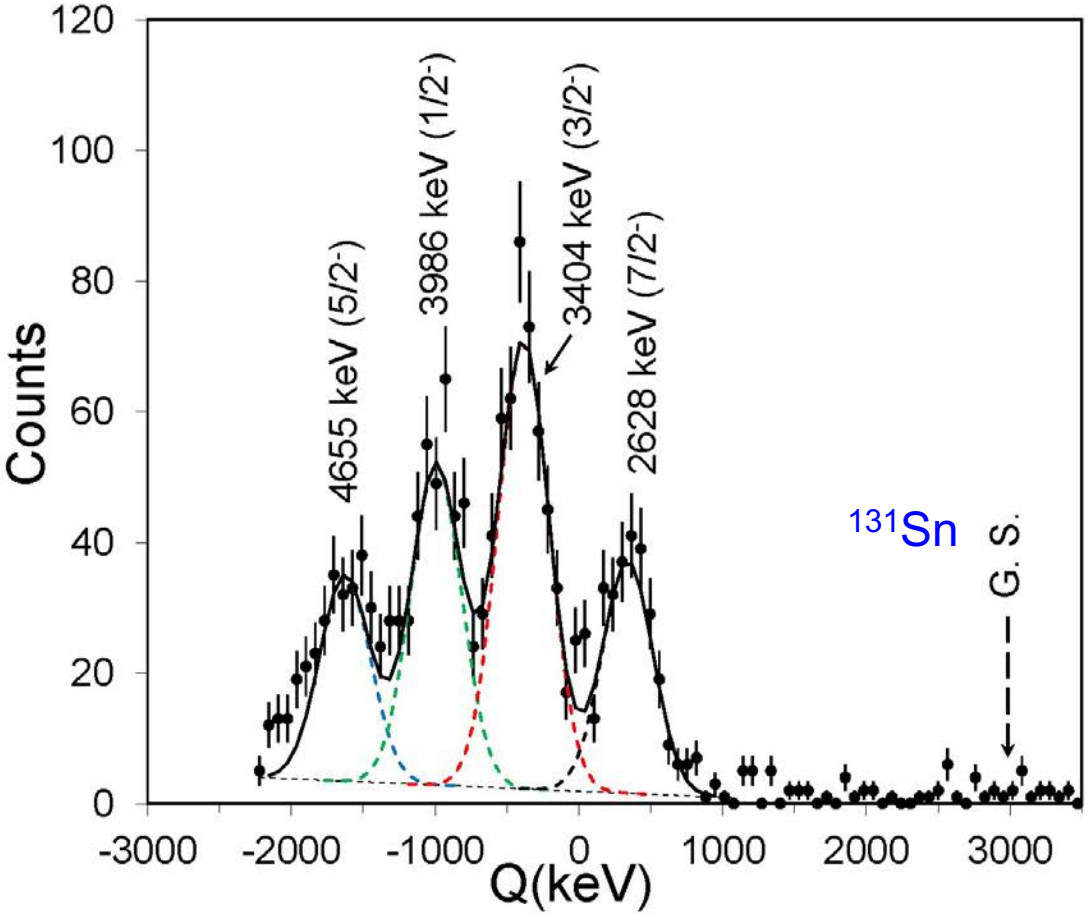
^{132}Sn(d,p): N=83 single neutron states



Identified $2f_{7/2}$, $3p_{3/2}$, $(3p_{1/2})$, $2f_{5/2}$ neutron states in ^{133}Sn

K.L. Jones et al.
Nature, **465**,454 (2010)
Phys. Rev. C **84**, 034601 (2011)

^{130}Sn(d,p): N=81 and N>82 configurations



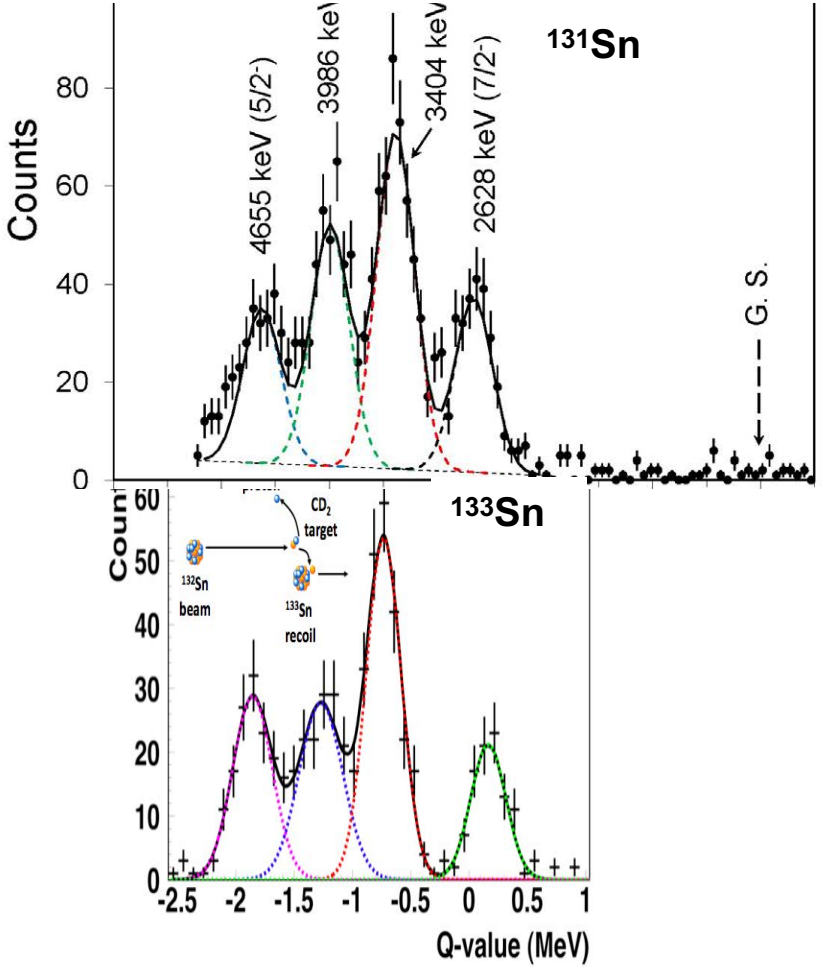
Candidates for

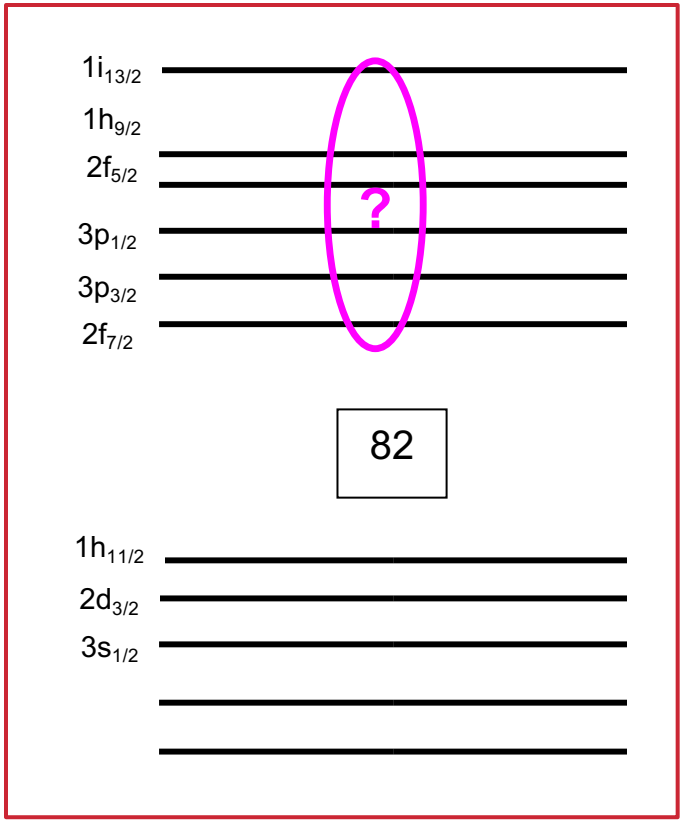
$2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$

neutron states in ^{131}Sn

R.L. Kozub, et al. PRL **109**, 172501 (2012)

N>82 configurations in Z>50, N=81 isotones?

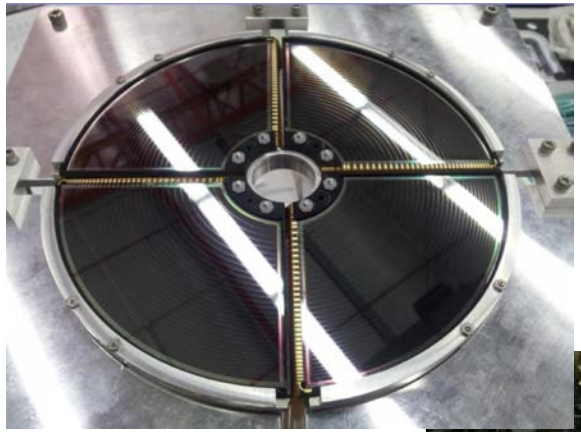


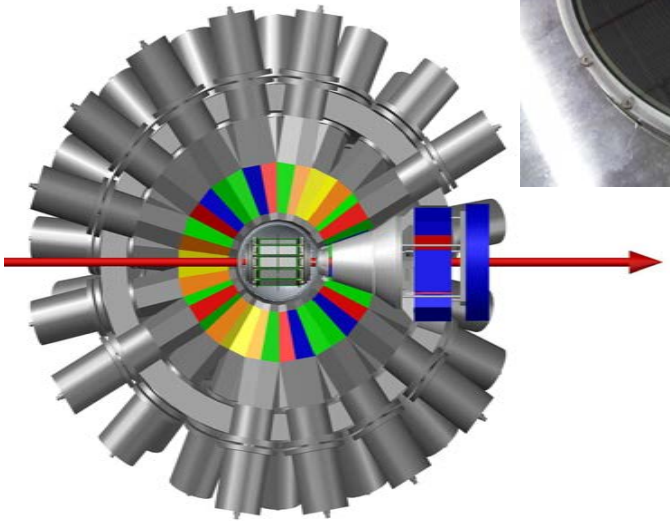


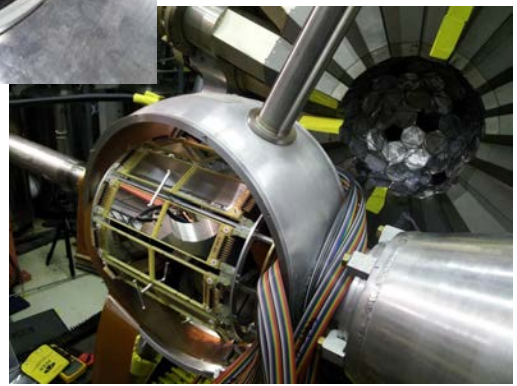
(d,pγ) with ^{134}Xe (N=80) beams

GODDESS: Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies

S.D. Pain et al.,
Phys. Procedia **90**, 455 (2017)

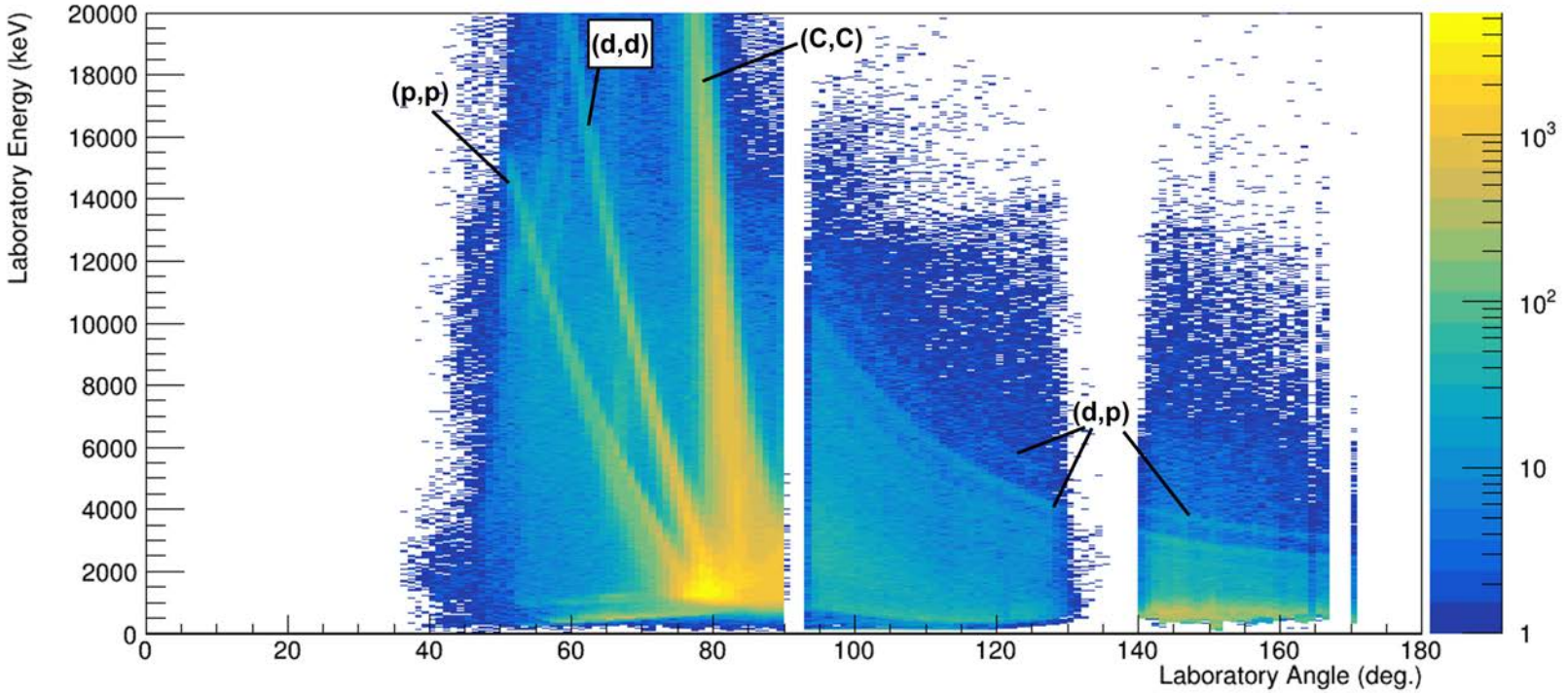






(Oak Ridge Rutgers University Barrel Array) ORRUBA+ endcap annular detectors

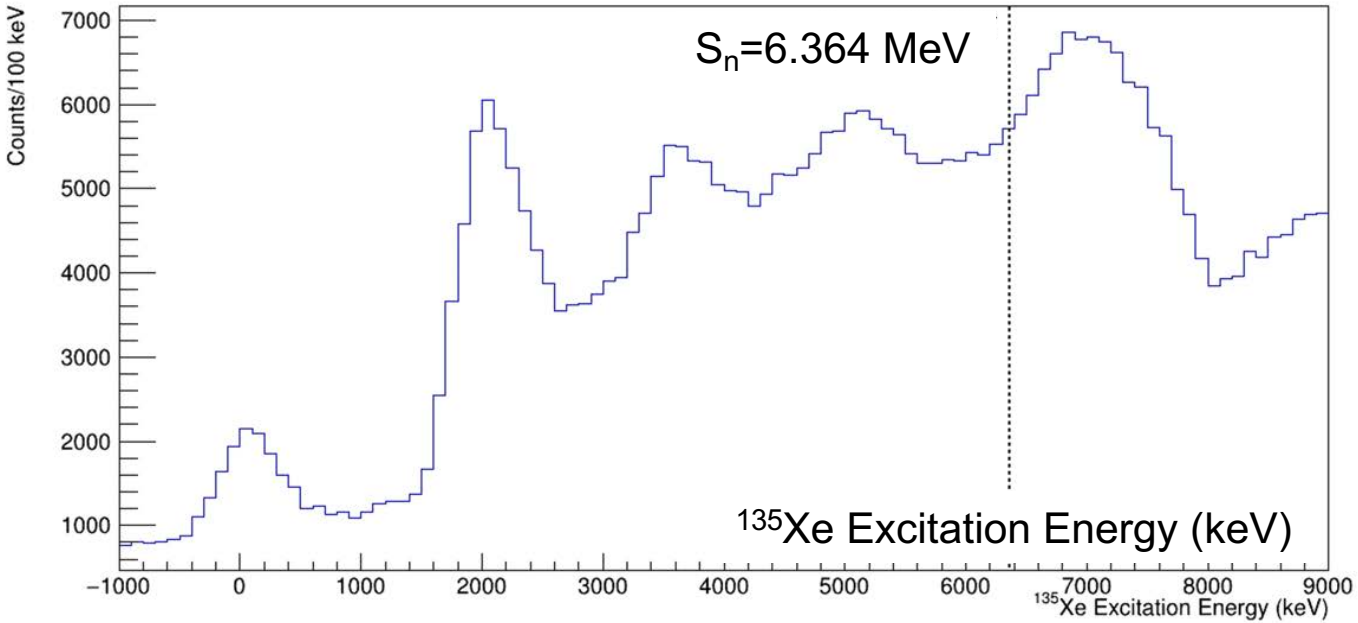
$^{134}Xe + CD_2$: Particle singles vs Lab angle



Next: transform data to center of mass

Chad C. Ummel, Ph.D. Dissertation, Rutgers University (2023)

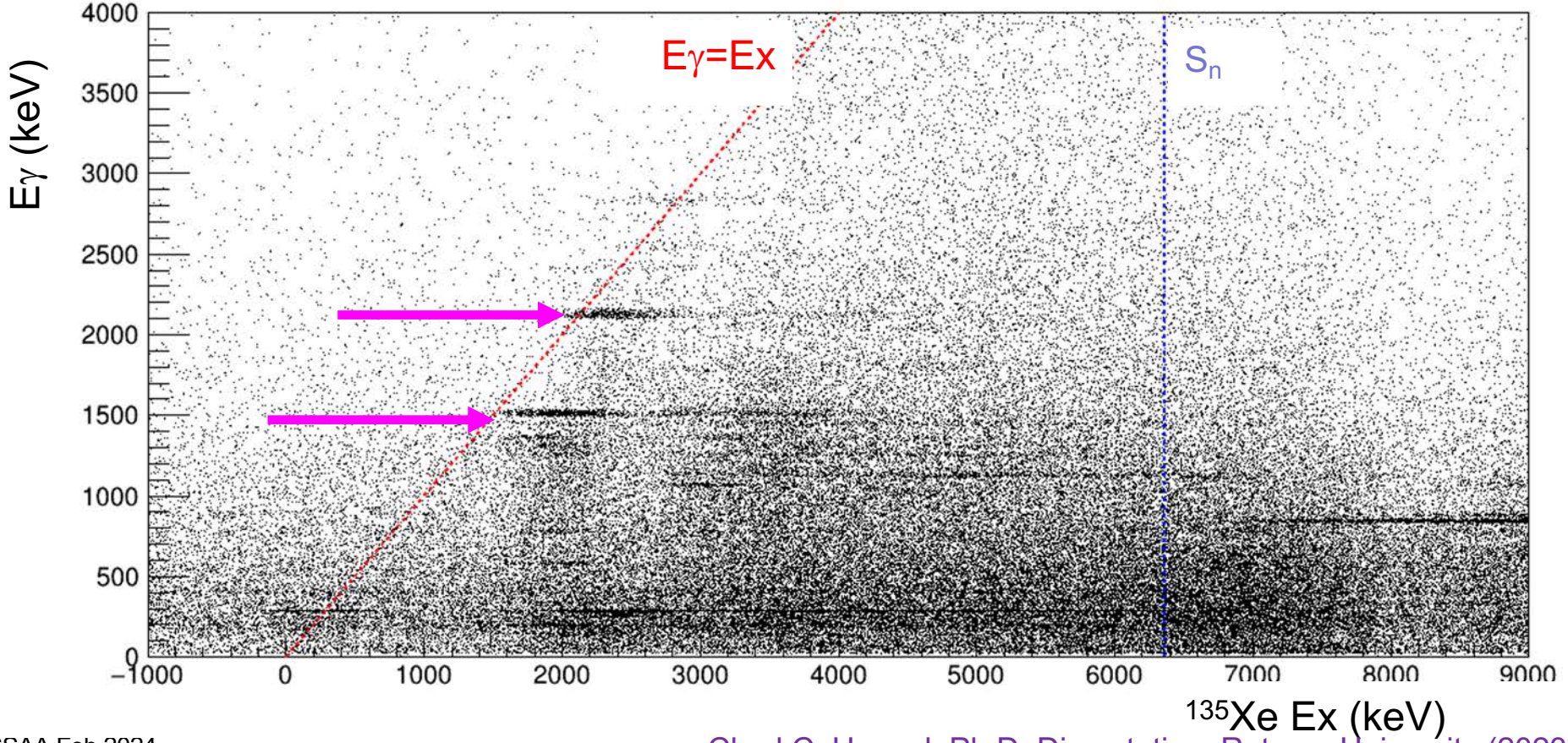
Proton singles counts vs ^{135}Xe Ex energy



- Low population of states <Ex≈2 MeV
- Relatively poor energy resolution
- ➢ Need gamma coincidences to improve resolution

Chad C. Ummel, Ph.D. Dissertation, Rutgers University (2023)

^{134}Xe (d,pγ) Gamma-proton coincidences



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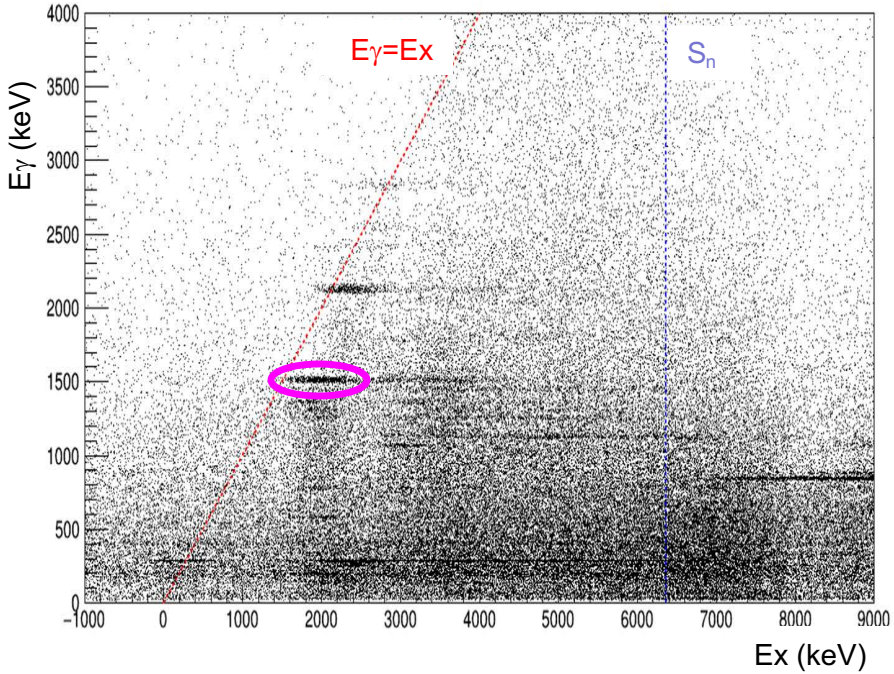
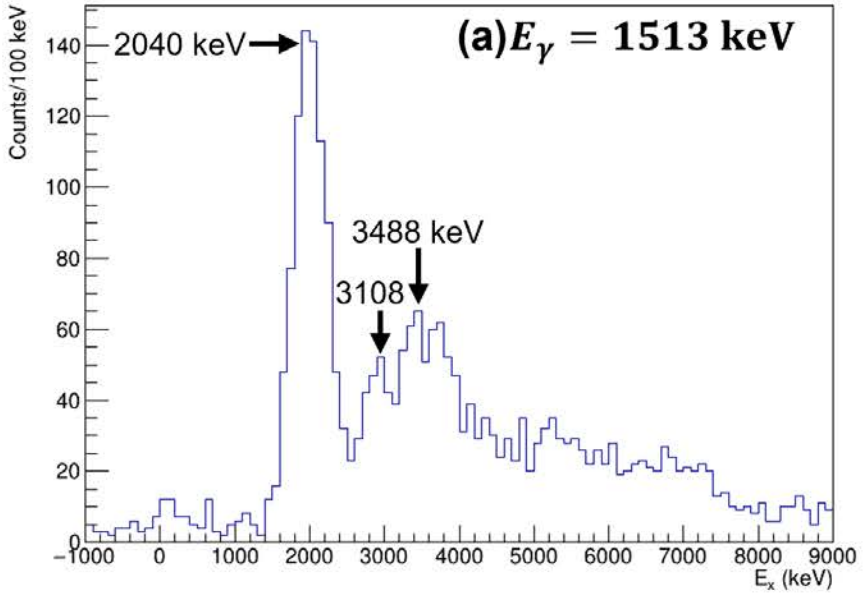
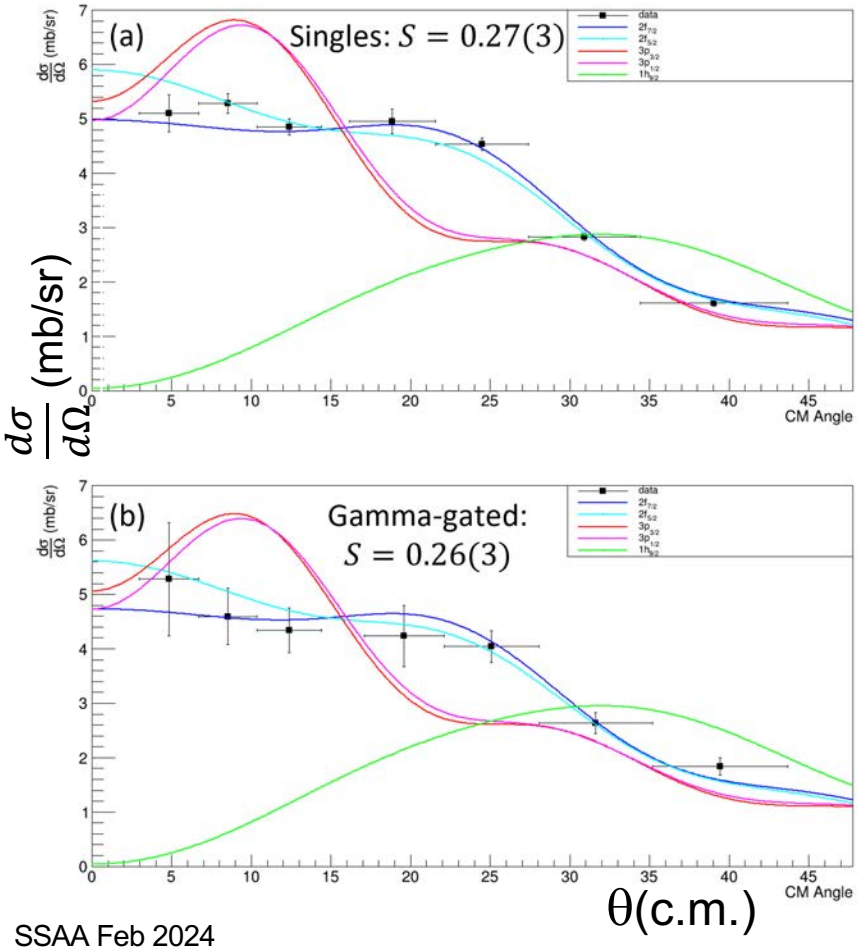
Gate on 1513 keV gamma => Ex=2040 keV





Chad C. Ummel, Ph.D. Dissertation, Rutgers University (2023)

Deducing J^{π} of 2040 keV State

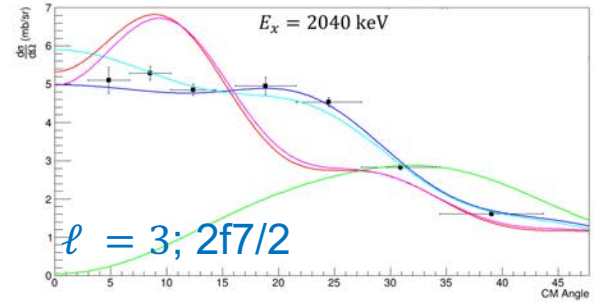


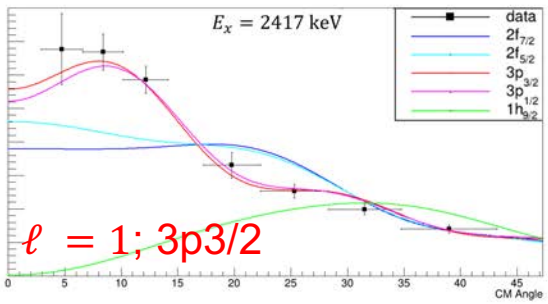
Differential cross sections vs θ_{cm}

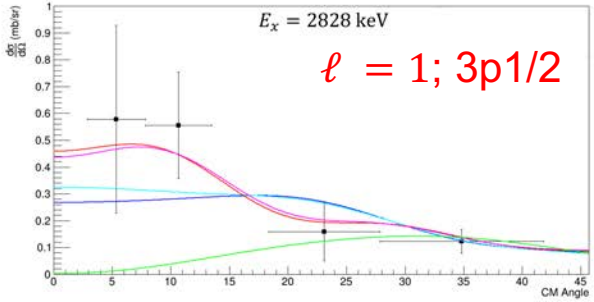
- Top: proton singles
  - $\ell = 3$ transfer
  - Decay to 11/2- isomer
  - ➢ J^{π}= 7/2-
  - 2f7/2 strength
- Bottom: $E_{\gamma} = 1513$ keV gate
  - $\ell = 3$ transfer, ≈same S
  - ➢ gamma-gated $^{d\sigma}/_{d\Omega}$ are valid

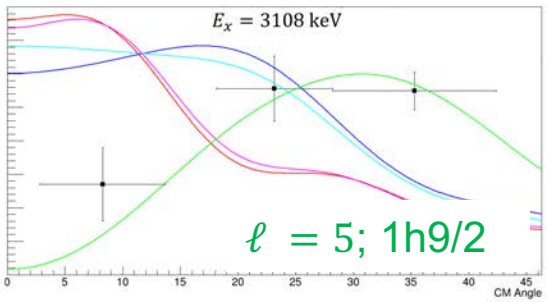
Chad C. Ummel, Ph.D. Dissertation, Rutgers University (2023)

^{135}Xe $d\sigma/d\Omega$ & N>82 configs



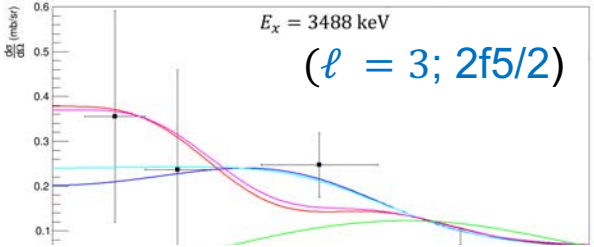






θ(c.m.)

$\frac{d\sigma}{d\Omega}$ (mb/sr)



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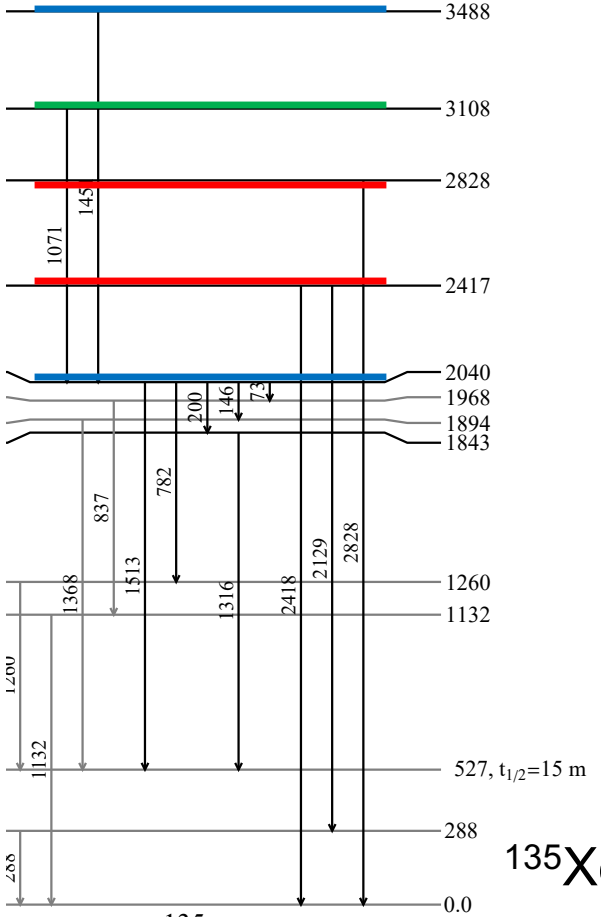

Summary NRS4SS 2023-24 Projects

- 2023-24 activities
  - Finalizing analysis of GODDESS 2015 data
    - ^{134}Xe(d,pγ): for rare isotope structure
      - Ummel dissertation defended; preliminary results for N>82 excitations in ^{135}Xe
    - ^{95}Mo(d,pγ): to help validate surrogate for (n,γ) with beams
      - Garland dissertation defended
  - LLNL-Rutgers collaboration meeting and workshop w/ UC-Berkeley
  - Extensive LLNL (Ratkiewicz)-Rutgers interactions
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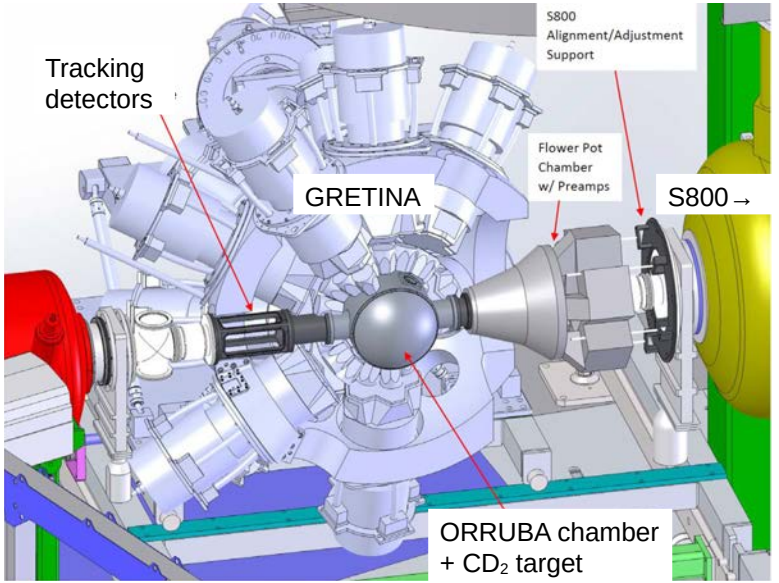
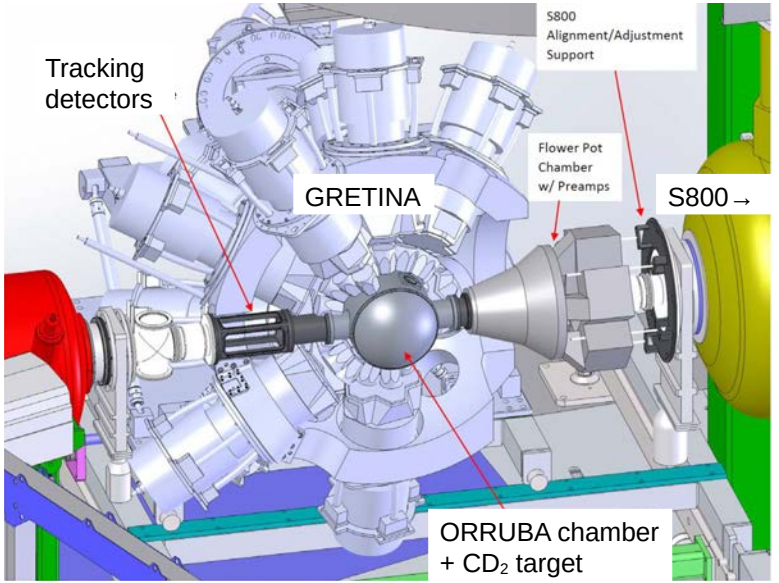
  - Preparing for FRIB GODDESS (April 2024)
    - Tracking detectors tested at TAMU
    - New QQQ6 endcap detectors
      - Received and tested
    - New ORRUBA chamber manufactured
    - DAQ coordination realized
    - ^{80}Ge and ^{75}Ga (d,pγ) scheduled April 22-May 6

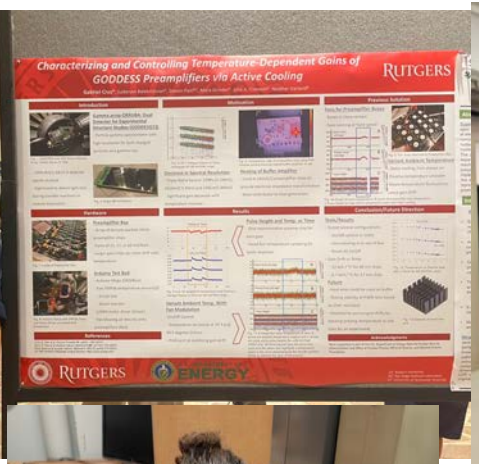


Plans NRS4SS 2024-25 Projects

- 2024-25 activities
  - Realizing FRIB GODDESS (April 2024)
    - ^{80}Ge and ^{75}Ga (d,pγ) scheduled April 22-May 6
  - Analyzing ^{80}Ge (Grinder) and ^{75}Ga (Balakrishnan) (d,pγ) GODDESS data
  - LLNL-Rutgers collaboration meeting and workshop w/ UC-Berkeley – June 2024?
  - Extensive LLNL (Ratkiewicz)-Rutgers interactions
  - Preparing for GODDESS at ATLAS campaign



Thank you to my team



Work supported in part DOE SSAA DE-NA0003897 & DE-NA0004066
and National Science Foundation

Summary NRS4SS Projects and Thank you

- 2023-24 activities
  - Finalizing analysis of GODDESS 2015 data: 2 dissertations
  - LLNL-Rutgers collaboration meeting and workshop w/ UC-Berkeley
  - Extensive LLNL (Ratkiewicz)-Rutgers interactions
  - Preparing for FRIB GODDESS (April 2024)
- 2024-25 activities
  - Realizing & Analyzing FRIB GODDESS (April 2024)
    - ^{80}Ge and ^{75}Ga (d,pγ) scheduled April 22-May 6
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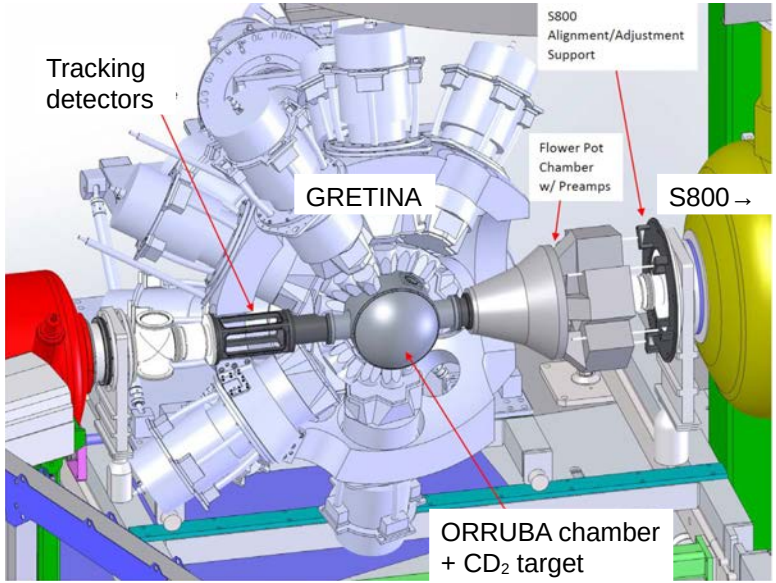
  - Extensive LLNL (Ratkiewicz)-Rutgers interactions
  - Preparing for GODDESS at ATLAS campaign



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DOE SSAA DE-NA0003897 & DE-NA0004066 and National Science Foundation

Backup slides

Summary of new levels in ^{135}Xe

E_{level} (keV)	J^{π}	E_{γ} (keV)	I_{γ} (relative)	E_{final} (keV)
1843(3)	$(7/2^{-}, 9/2^{\pm}, 11/2^{-})$	1316(3)	100	526.551
2039.5(7)	$7/2^{-}$	72.6(6)	3.4(13)	1968.323
		146.4(6)	25(3)	1894.45
		199.86(16)	14(3)	1843
		781.7(19)	8.9(18)	1260.416
		1512.9(7)	100	526.551
2417.2(18)	$3/2^{-}$	2128.8(18)	100	288.455
		2418(3)	7.3(18)	0
2828(4)	$1/2^{-}$	2828(4)	100	0
3108.4(16)	$9/2^{-}$	1070.7(14)	100	2039.5
3488.3(16)	$5/2^{-}$	1450.6(15)	100	2039.5

Table 4.1: Newly-observed levels in ^{135}Xe and their proposed spin-parities (see section 4.5). The initial gamma rays from each level are listed, along with their relative intensities. The 1843 keV level was not observed being populated directly by (d, p) reactions–it was only observed via the 199.86-keV gamma decay of the 2039.5-keV level.

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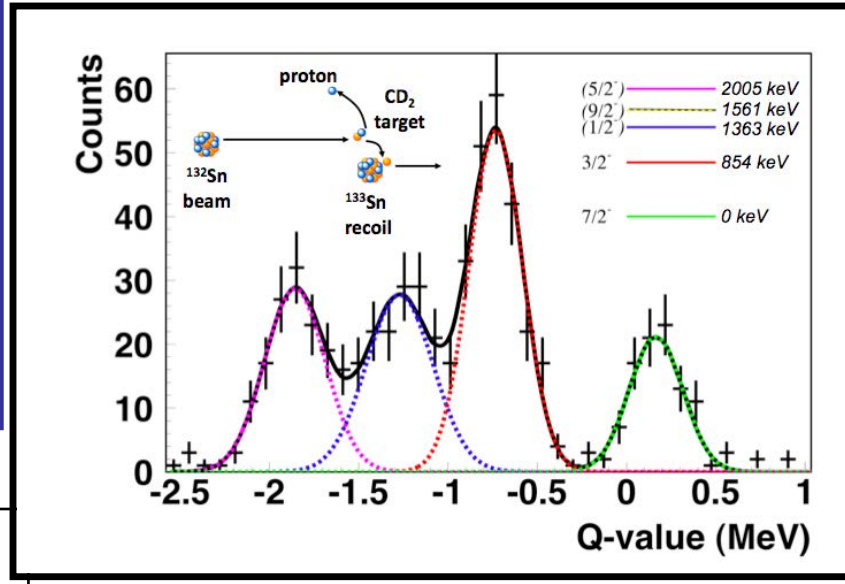
^{132}Sn(d,p): N=83 single neutron states

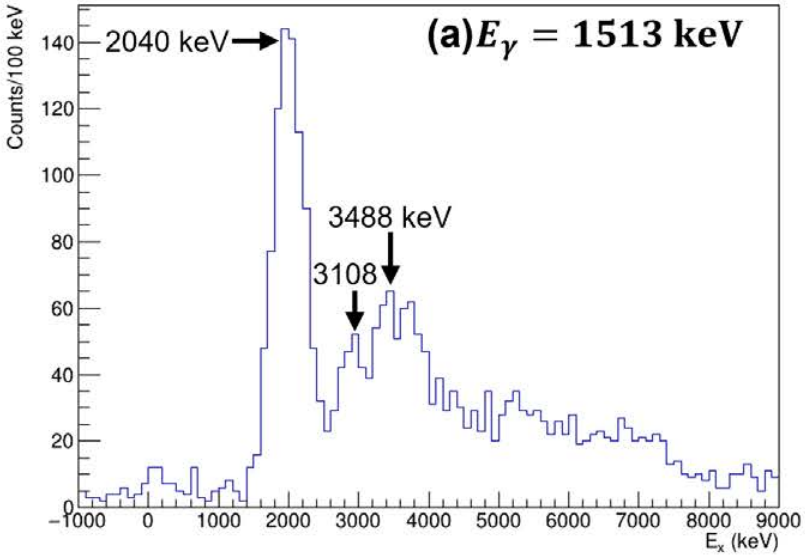
Identified $2f_{7/2}$, $3p_{3/2}$, $(3p_{1/2})$, $2f_{5/2}$ neutron strength in ^{133}Sn



E_x(keV)	J^π	Config	SF (DWBA)	SF (FR-ADWA)
0	$7/2^-$	$2f_{7/2}$	0.86(14)	1.00(8)
854	$3/2^-$	$3p_{3/2}$	0.92(14)	0.92(7)
1363(31)	$(1/2^-)$	$3p_{1/2}$	1.1(3)	1.2(2)
2005	$(5/2^-)$	$2f_{5/2}$	1.1(2)	1.2(3)

K.L. Jones et al.
Nature, **465**,454 (2010)
Phys. Rev. C **84**, 034601 (2011)

Gate on 1513 keV gamma => Ex=2040 keV



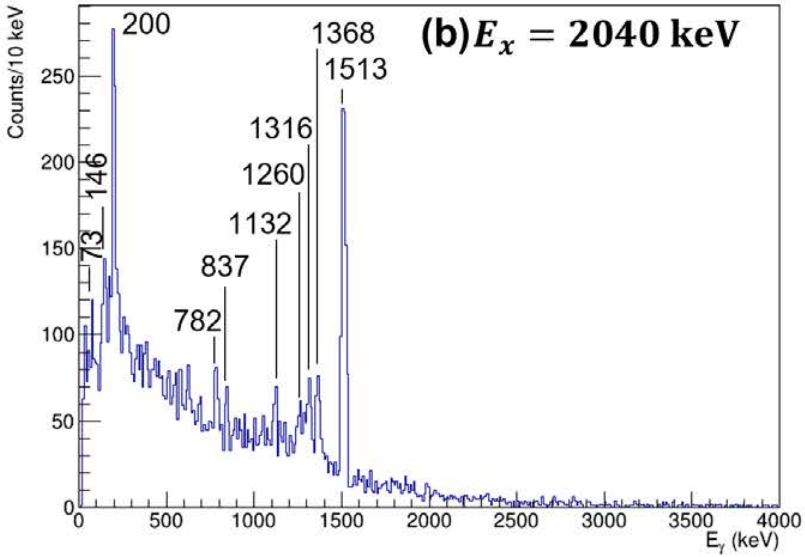


Figure 4.13: (a) Coincidence excitation energy spectra observed when gating on a gamma ray at 1513 keV. (b) Coincidence gamma-ray energy spectra observed when gating on an excitation energy of 2040 keV.

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Gate on 2129 keV g=>2417 keV level; gate on 2417 keV level = 288 keV g.s. transition

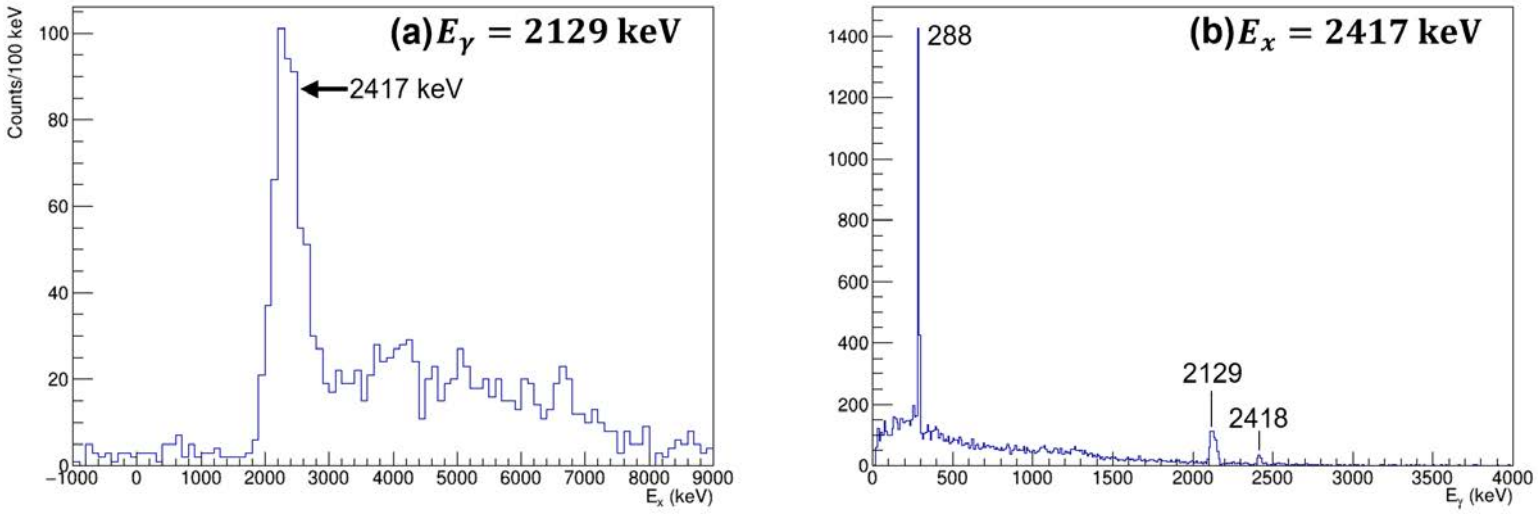

Figure 4.15: (a) Coincidence excitation energy spectra observed when gating on a gamma ray at 2129 keV. (b) Coincidence gamma-ray energy spectra observed when gating on an excitation energy of 2417 keV.

Differences in ang dist of protons vs 135Xe Ex

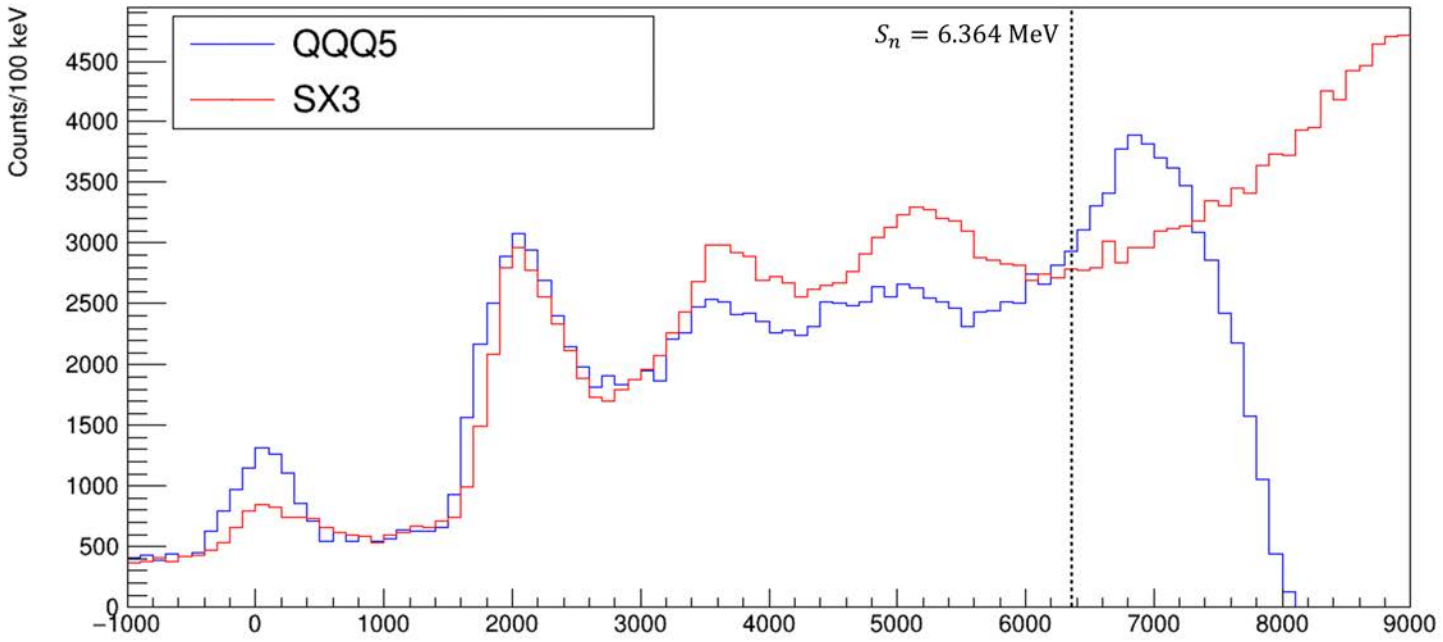

Figure 4.7: ^{135}Xe excitation energy spectrum calculated for all hits in the upstream QQQ5 and Super X3 detectors. Note that the 1 MeV noise gate removes all QQQ5 hits with $E_x \gtrsim 8$ MeV.

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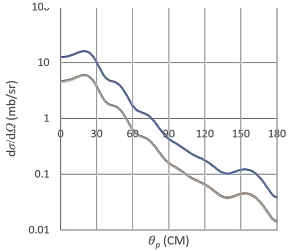
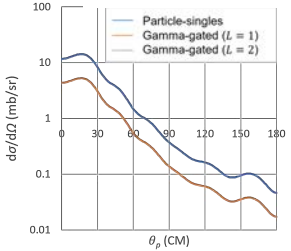
ADWA: Gating on gamma does not change shape of ang dist

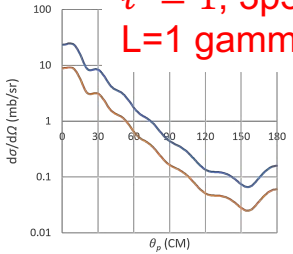
$\ell = 3$; 2f7/2
L=2 gamma



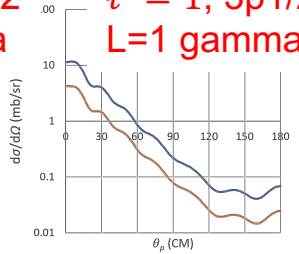
$\ell = 3$; 2f5/2
L=1 gamma



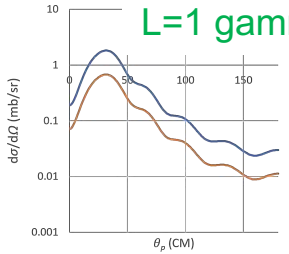
$\ell = 1$; 3p3/2
L=1 gamma



$\ell = 1$; 3p1/2
L=1 gamma



$\ell = 5$; 1h9/2
L=1 gamma



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