

Measuring the ¹³⁴Xe(d,pγ)¹³⁵Xe Reaction with GODDESS to Probe the Single-Particle Structure of ¹³⁵Xe

Chad Ummel Rutgers University On behalf of the GODDESS Collaboration

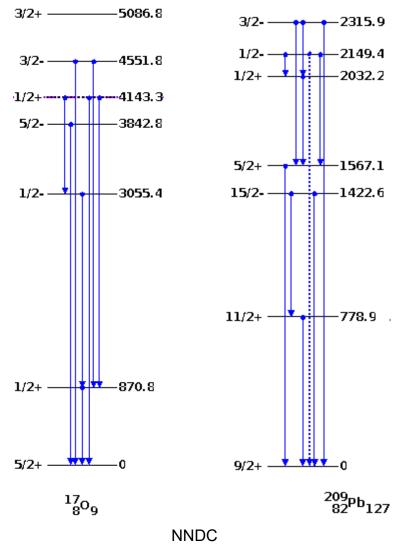
Stewardship Science Graduate Fellowship Program Review June 22, 2022

This material is based upon work supported by the United States Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship under Grant Award Numbers DE-NA0003864 and DE-NA0003960. Additional support was provided by the NNSA under Grant Award Numbers DE-NA0002132 and DE-NA0003897, by the Office of Science Office of Nuclear Physics under Grant Award Numbers DE-AC05-00OR22725, DE-AC02-06CH11357, DE-FG02-96ER40983, DE-SC0001174, and DE-FG02-96ER40955, and by the National Science Foundation under Grant Award Number PHY-1419765. This research used resources at Argonne National Laboratory's ATLAS facility, which is a DOE Office of Science User Facility.





Nuclear Structure



All atomic nuclei have a binding energy as well as a characteristic energy level structure, with many levels, each with different spin-parities J^{π}

Can we theoretically describe this structure?



Ab-Initio Approach to Nuclear Structure

Provided strong understandings of the nuclear forces, \widehat{H} , experienced by each nucleon

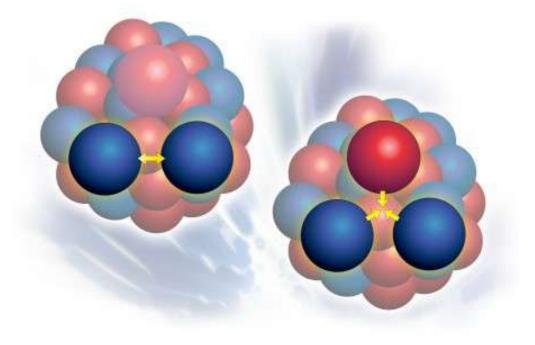
We can solve the Schrödinger equation:

 $\widehat{H}\Psi = E\Psi$

For all A nucleons

Tremendous advancements in recent years, but extending to heavier nuclei remains difficult

So for now, we must rely on **models** to describe the structure of heavy nuclei



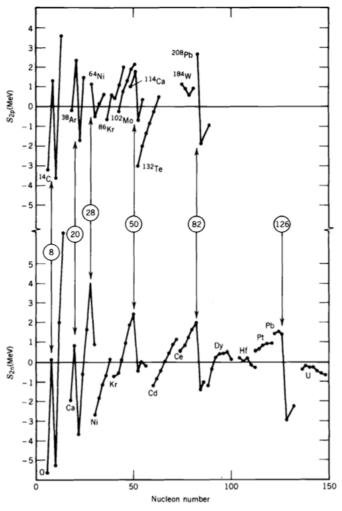
phys.org

C.C. Ummel



The Shell Model

Many observables in atomic nuclei imply a shell structure, with particularly stable numbers of protons and neutrons at the *magic numbers*: 8, 20, 28, 50, 82, and 126



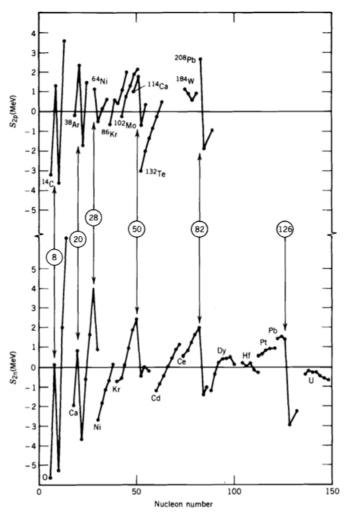
K.S. Krane, *Introductory Nuclear Physics*, 2nd ed. (John Wiley & Sons, 1988).



The Shell Model

Many observables in atomic nuclei imply a shell structure, with particularly stable numbers of protons and neutrons at the *magic numbers*: 8, 20, 28, 50, 82, and 126

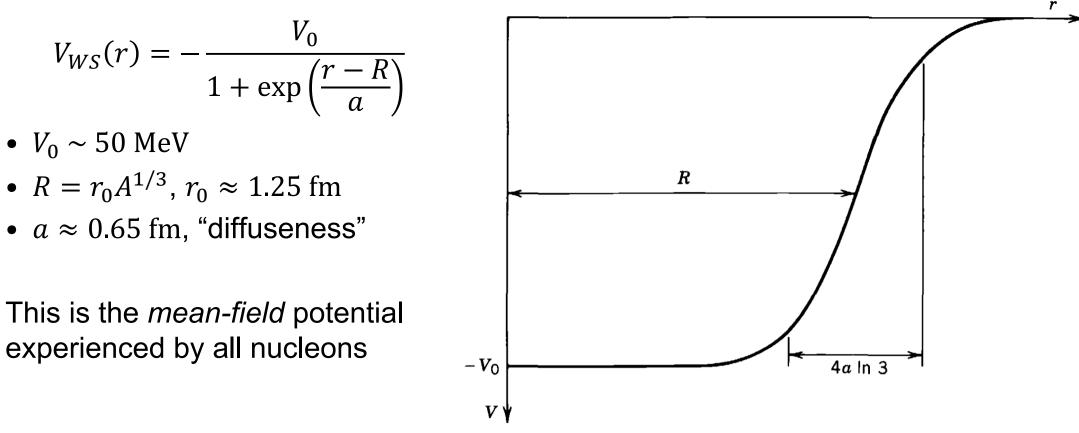
Very similar to electron shells in atomic physics!



K.S. Krane, *Introductory Nuclear Physics*, 2nd ed. (John Wiley & Sons, 1988).



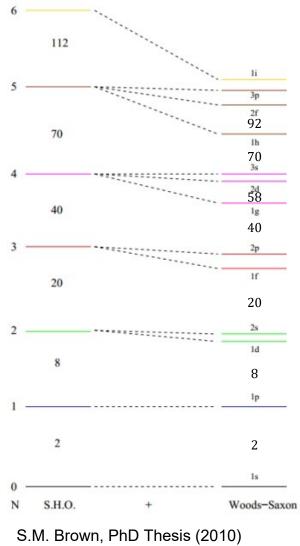
Building Shell Structure—Woods-Saxon Potential



K.S. Krane, Introductory Nuclear Physics, 2nd ed. (John Wiley & Sons, 1988).

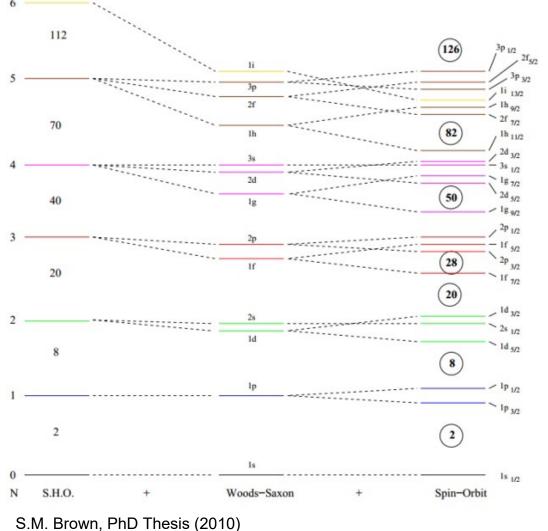


The Woods-Saxon Potential





Spin-Orbit Coupling



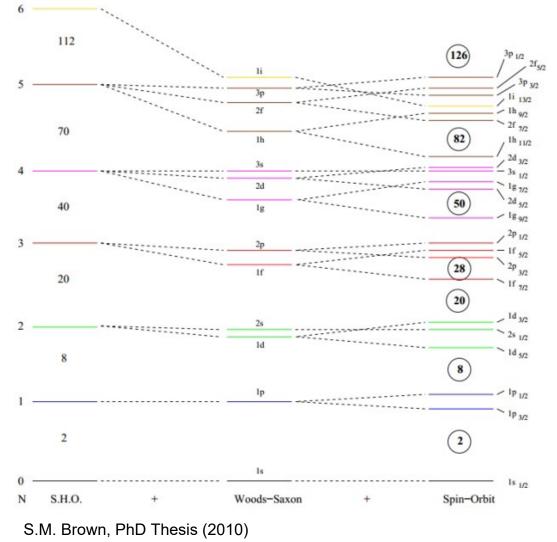
However, adding in a spin-orbit potential of the form

 $V_{SO} \boldsymbol{l} \cdot \boldsymbol{s}$

splits orbitals according to their total angular momentum $j = l + s = l \pm \frac{1}{2}$



Spin-Orbit Coupling



However, adding in a spin-orbit potential of the form

 $V_{SO} \boldsymbol{l} \cdot \boldsymbol{s}$

splits orbitals according to their total angular momentum $j = l + s = l \pm \frac{1}{2}$

The magic numbers are reproduced exactly!

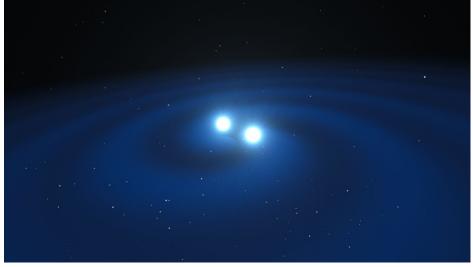


Shell Model Applications

Okay, but what is the Shell Model good for?

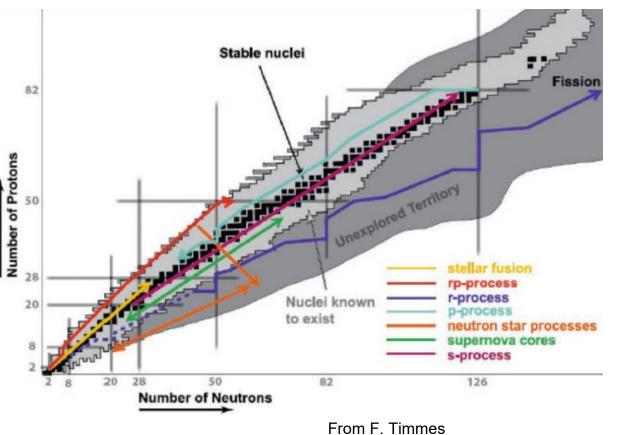


Shell Model Applications—Nuclear Astrophysics



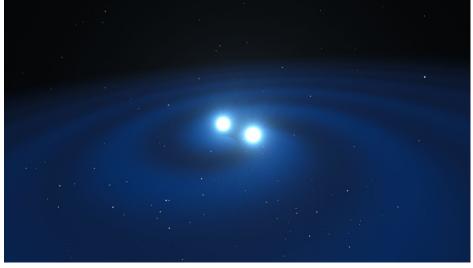
commons.wikimedia.org

The rapid neutron-capture process (r-process) is responsible for the synthesis of approximately half of all elements heavier than iron How are the chemical elements made?





Shell Model Applications—Nuclear Astrophysics

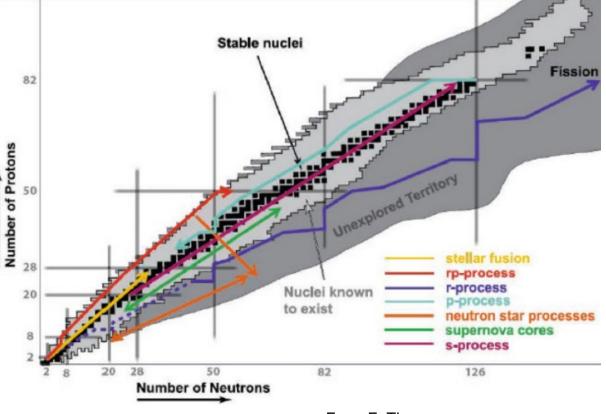


commons.wikimedia.org

The rapid neutron-capture process (r-process) is responsible for the synthesis of approximately half of all elements heavier than iron

We cannot measure neutron-capture reactions on all the isotopes of importance

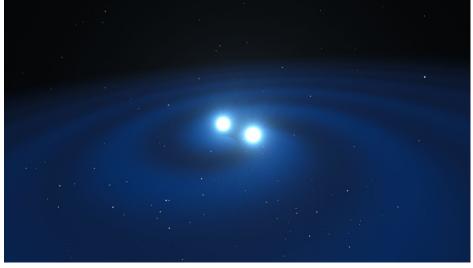
How are the chemical elements made?







Shell Model Applications—Nuclear Astrophysics



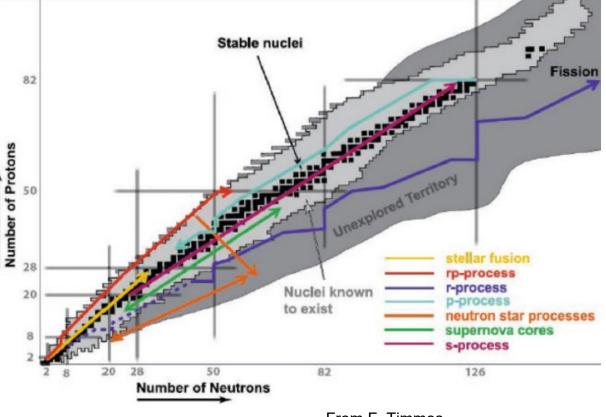
commons.wikimedia.org

The rapid neutron-capture process (r-process) is responsible for the synthesis of approximately half of all elements heavier than iron

We cannot measure neutron-capture reactions on all the isotopes of importance

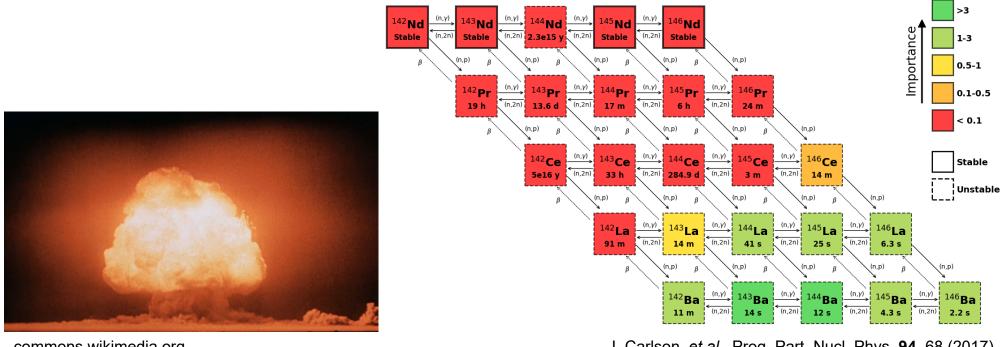
Can we predict them instead?

How are the chemical elements made?





Shell Model Applications—Stockpile Stewardship



commons.wikimedia.org

J. Carlson, et al., Prog. Part. Nucl. Phys. 94, 68 (2017).

All the most important neutron-induced reactions affecting the production of stockpile stewardship diagnostic ¹⁴⁴Ce involve highly unstable isotopes

Can we predict these reactions?

SSGF Program Review

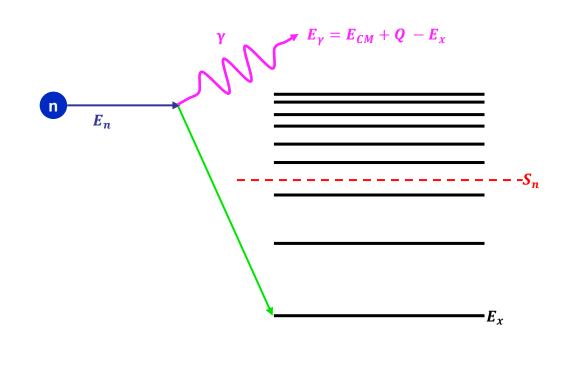
IFY

RUTGERS

Direct/Semi-Direct (DSD) Neutron Capture

- Neutron is captured directly into a lowlying, bound, single-particle state
 - Gamma ray emitted to conserve energy
- Requires low level density and highly single particle-like structure
 - Thus, DSD capture is the dominant mechanism of neutron capture on nuclei near shell closures
 - DSD capture can be constrained using measurements or accurate predictions of single-neutron structure properties

$$\sigma_{DC,total} = \sum_{nlj} \frac{2J_f + 1}{2J_i + 1} \frac{S_{nlj}}{2j + 1} \sigma_{DC,th}^{nlj}$$





Shell Model Applications

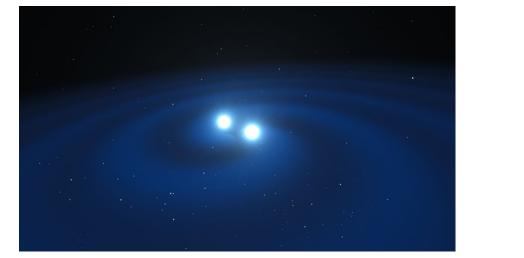
Okay, but what is the Shell Model good for?



Shell Model Applications

Okay, but what is the Shell Model good for?

An accurate Shell Model enhances predictions of nuclear properties that cannot be measured in the laboratory





commons.wikimedia.org



How do we know when the Shell Model is correct?



How do we know when the Shell Model is correct, and how do we improve it?



How do we know when the Shell Model is correct, and how do we improve it?

We test it!



How do we know when the Shell Model is correct, and how do we improve it?

We test it!

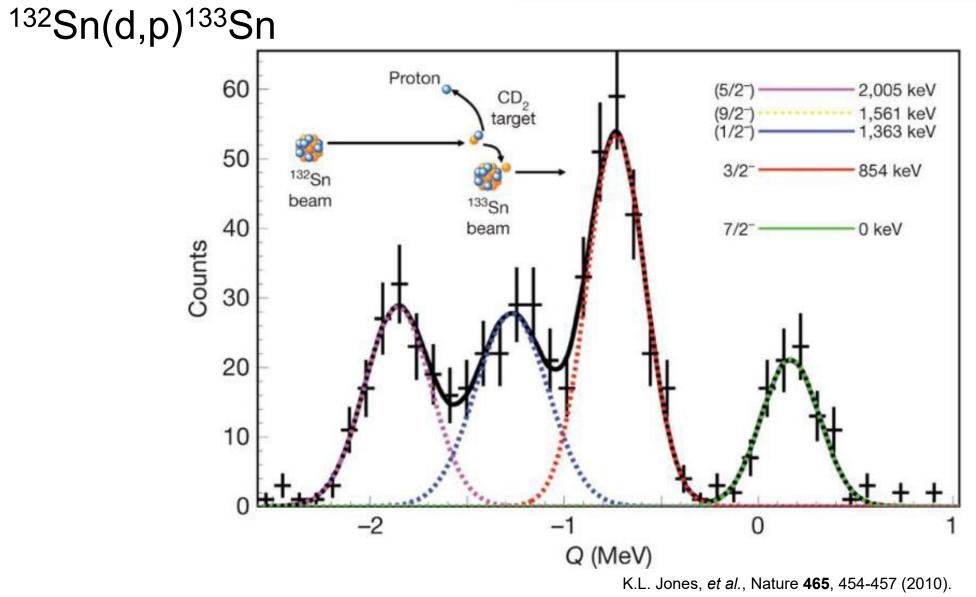
Example: ¹³³Sn

| ¹³⁰ Cs 29.21 m | ¹³¹ CS 9.689 d | ¹³² Cs | ¹³³ Cs | ¹³⁴ Cs 2.085 y | ¹³⁵ Cs _{1.33 My} | 136 CS 13.01 d | ¹³⁷ Cs _{30.04 y} | ¹³⁸ Cs _{33.5 m} | ¹³⁹ CS _{9.27 m} | ¹⁴⁰ Cs _{63.7 s} | ¹⁴¹ CS _{24.84 s} | ¹⁴² CS 1.687 s | ¹⁴³ CS 1.802 s | |
|---------------------------------------|--|-------------------------------|---|---|---|---|--|--|--|---|---|--|--|---------------|
| ¹²⁹ Xe | ¹³⁰ Xe | ¹³¹ Xe | ¹³² Xe | ¹³³ Xe 5.2474 d | ¹³⁴ Xe | ¹³⁵ Xe _{9.14 h} | ¹³⁶ Xe ^{2.18 Zy} | ¹³⁷ Xe 229.08 s | ¹³⁸ Xe | ¹³⁹ Xe ^{39.68 s} | ¹⁴⁰ Xe | ¹⁴¹ Xe | ¹⁴² Xe | |
| 128 24.99 m | 129 18.14 My | 130 12.38 h | 131 8.0249 d | 132 137.7 m | 133 20.83 h | 134 52.5 m | 135 6.58 h | 136 83.4 s | 137 24.13 s | 138 6.26 s | 139 2.28 s | 140 588 ms | 141 420 ms | |
| 127 Te 9.35 h | ¹²⁸ Te 2.25 Yy | ¹²⁹ Te | ¹³⁰ Te 701 Ey | ¹³¹ Te | ¹³² Te 76.896 h | ¹³³ Te | ¹³⁴ Te | ¹³⁵ Te | ¹³⁶ Te | ¹³⁷ Te 2.49 s | ¹³⁸ Te | ¹³⁹ Te _{724 ms} | ¹⁴⁰ Te _{351 ms} | |
| ¹²⁶ Sb 12.35 d | ¹²⁷ Sb _{92.4 h} | ¹²⁸ Sb 9.05 h | ¹²⁹ Sb 4.366 h | ¹³⁰ Sb ^{39.5 m} | ¹³¹ Sb _{23.03 m} | ¹³² Sb _{167.4 s} | ¹³³ Sb _{140.4 s} | ¹³⁴ Sb 874 ms | ¹³⁵ Sb 1.888 s | ¹³⁶ Sb _{923 ms} | ¹³⁷ Sb 497 ms | ¹³⁸ Sb ^{333 ms} | ¹³⁹ Sb 182 ms | |
| ¹²⁵ Sn 9.634 d | ¹²⁶ Sn ^{230 ky} | ¹²⁷ Sn | ¹²⁸ Sn ^{59.07 m} | ¹²⁹ Sn ^{133.8 s} | ¹³⁰ Sn 223.2 s | ¹³¹ Sn 56 s | ¹³² Sn ^{39.7 ₅} | ¹³³ Sn _{1.37 s} | ¹³⁴ Sn ^{930 ms} | ¹³⁵ Sn ^{515 ms} | ¹³⁶ Sn 355 ms | ¹³⁷ Sn ^{249 ms} | ¹³⁸ Sn 148 ms | <i>Z</i> = 50 |
| ¹²⁴ In 3.12 s | ¹²⁵ In 2.36 s | ¹²⁶ In 1.53 s | 127 n 1.086 s | 128 1n 818 ms | 129 n 570 ms | 130 1n 273 ms | 131 N 261.5 ms | ¹³² In ^{202.2 ms} | ¹³³ In ^{163 ms} | ¹³⁴ In ^{136 ms} | ¹³⁵ In ^{103 ms} | ¹³⁶ In ^{86 ms} | ¹³⁷ In ^{70 ms} | |
| ¹²³ Cd _{2.1 s} | ¹²⁴ Cd | 125 Cd 880 ms | 126Cd 512 ms | 127 Cd 480 ms | ¹²⁸ Cd ^{246 ms} | ¹²⁹ Cd _{147 ms} | ¹³⁰ Cd _{128.8 ms} | ¹³¹ Cd 98 ms | ¹³² Cd ^{84 ms} | Log -2e+1 | of Half -9e+0 | -life [s] 5e+0 2e | +1 3e+1 | |
| 122Ag 529 ms | ¹²³ Ag 294 ms | ¹²⁴ Ag 177.9 ms | ¹²⁵ Ag | ¹²⁶ Ag _{52 ms} | ¹²⁷ Ag ^{89 ms} | ¹²⁸ Ag | ¹²⁹ Ag | ¹³⁰ Ag 40.6 ms | ¹³¹ Ag _{35 ms} | | ong-lived | | | |
| ¹²¹ Pd | ¹²² Pd | ¹²³ Pd | ¹²⁴ Pd | ¹²⁵ Pd | ¹²⁶ Pd | ¹²⁷ Pd | ¹²⁸ Pd | ¹²⁹ Pd | ¹³⁰ Pd | | nknown | | | |
| | | | | | | | N = 82 | | | | | | | |

If the shell model is valid in this region, then ¹³³Sn should have a purely single-neutron structure

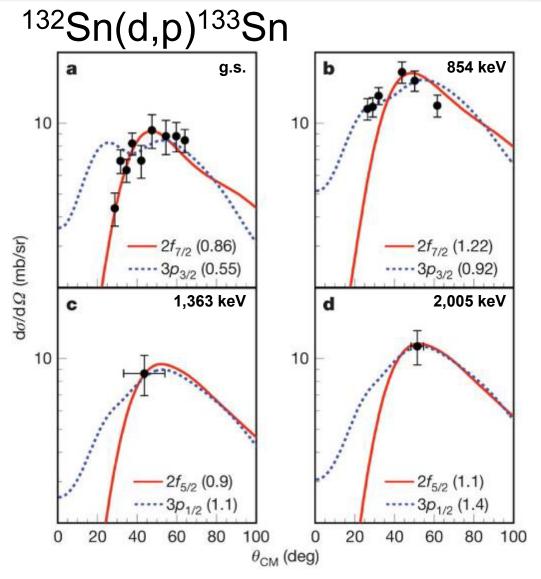
Modified from people.physics.anu.edu/~ecs103/chart-beta/





C.C. Ummel





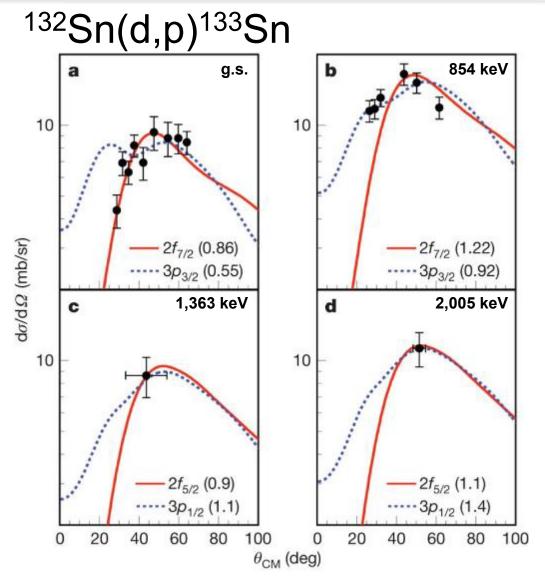
Define a spectroscopic factor, S:

$$S_{i} = \left(\frac{d\sigma_{i}}{d\Omega}\right)_{exp} / \left(\frac{d\sigma_{i}}{d\Omega}\right)_{theory}$$

Modified from K.L. Jones, *et al.*, Nature **465**, 454-457 (2010).

C.C. Ummel





Define a spectroscopic factor, S:

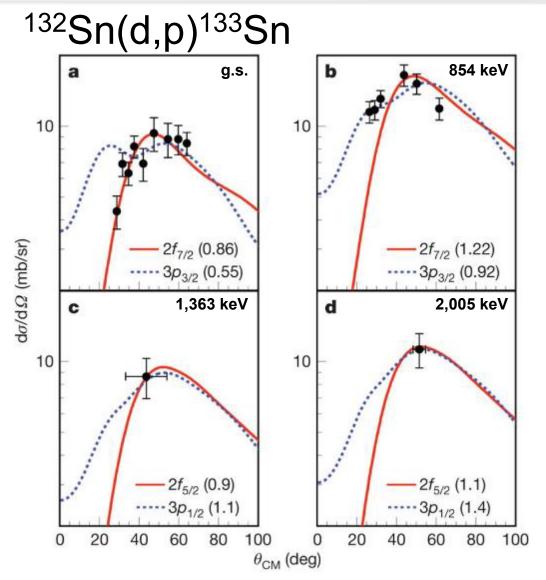
$$S_{i} = \left(\frac{d\sigma_{i}}{d\Omega}\right)_{exp} / \left(\frac{d\sigma_{i}}{d\Omega}\right)_{theory}$$

 $S \approx 1$ for all states indicates purely single-neutron structure!

Modified from K.L. Jones, *et al.*, Nature **465**, 454-457 (2010).

C.C. Ummel





Define a spectroscopic factor, S:

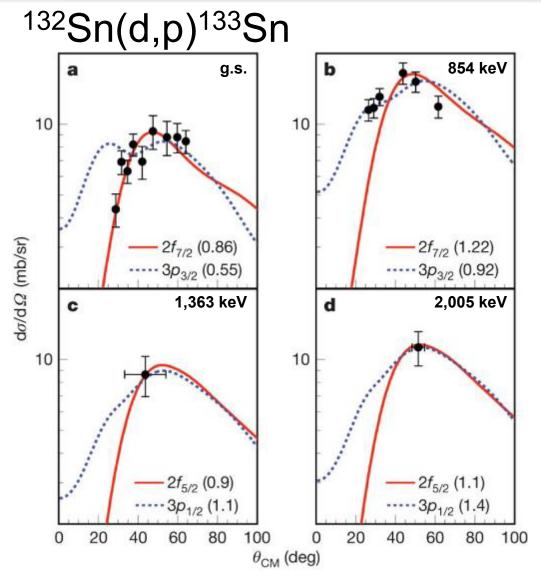
$$S_{i} = \left(\frac{d\sigma_{i}}{d\Omega}\right)_{exp} / \left(\frac{d\sigma_{i}}{d\Omega}\right)_{theory}$$

 $S \approx 1$ for all states indicates purely single-neutron structure!

| E_{χ} (keV) | Jπ | S |
|------------------|-------------|-----------------|
| 0 | 7/2- | 0.86 ± 0.16 |
| 854 | 3/2- | 0.92 ± 0.18 |
| 1363 ± 31 | $(1/2^{-})$ | 1.1 ± 0.3 |
| 2005 | $(5/2^{-})$ | 1.1 ± 0.2 |

Modified from K.L. Jones, et al., Nature 465, 454-457 (2010).





Modified from K.L. Jones, *et al.*, Nature **465**, 454-457 (2010). SSGF Program Review

Define a spectroscopic factor, S:

$$S_{i} = \left(\frac{d\sigma_{i}}{d\Omega}\right)_{exp} / \left(\frac{d\sigma_{i}}{d\Omega}\right)_{theory}$$

 $S \approx 1$ for all states indicates purely single-neutron structure!

| E_{χ} (keV) | Jπ | S |
|------------------|-------------|-----------------|
| 0 | 7/2- | 0.86 ± 0.16 |
| 854 | 3/2- | 0.92 ± 0.18 |
| 1363 ±31 | $(1/2^{-})$ | 1.1 ± 0.3 |
| 2005 | $(5/2^{-})$ | 1.1 ± 0.2 |

¹³³Sn perfectly exhibits the pure single-neutron structure predicted by the shell model



Shell Model Tests

Example: ¹³³Sn

| ¹³⁰ Cs _{29.21 m} | 131 CS 9.689 d | ¹³² Cs _{6.48 d} | ¹³³ Cs | ¹³⁴ СS 2.065 у | ¹³⁵ Cs 1.33 My | ¹³⁶ Cs | 137 CS 30.04 y | ¹³⁸ CS _{33.5 m} | ¹³⁹ CS _{9.27 m} | ¹⁴⁰ CS _{63.7 s} | ¹⁴¹ CS _{24.84 s} | 142 CS 1.687 s | ¹⁴³ CS 1.802 s | |
|---|-----------------------------|--|---|---|---|--|--|--|--|---|---|--|--|---------------|
| ¹²⁹ Xe | ¹³⁰ Xe | ¹³¹ Xe | ¹³² Xe | ¹³³ Xe 5.2474 d | ¹³⁴ Xe | ¹³⁵ Xe 9.14 h | ¹³⁶ Xe 2.18 Zy | ¹³⁷ Xe 229.08 s | ¹³⁸ Xe | ¹³⁹ Xe ^{39.68 s} | ¹⁴⁰ Xe | ¹⁴¹ Xe | ¹⁴² Xe | |
| 128 24.99 m | 129 18.14 My | 130 12.36 h | 131 8.0249 d | 132 137.7 m | 133 20.83 h | 134 52.5 m | 135 6.58 h | 136 83.4 s | 137 24.13 s | 138 6.26 s | 139 2.28 s | 140 588 ms | 141 420 ms | |
| ¹²⁷ Te _{9.35 h} | ¹²⁸ Te | ¹²⁹ Te | ¹³⁰ Te _{791 Ey} | ¹³¹ Te | ¹³² Te | ¹³³ Te 12.5 m | ¹³⁴ Te | ¹³⁵ Te | ¹³⁶ Te 17.63 s | ¹³⁷ Te 2.49 s | ¹³⁸ Te | ¹³⁹ Te 724 ms | ¹⁴⁰ Te _{351 ms} | |
| 126 Sb 12.35 d | 127 Sb 92.4 h | ¹²⁸ Sb 9.05 h | ¹²⁹ Sb 4.366 h | ¹³⁰ Sb _{39.5 m} | ¹³¹ Sb _{23.03 m} | ¹³² Sb 167.4 s | ¹³³ Sb _{140.4 s} | ¹³⁴ Sb _{674 ms} | ¹³⁵ Sb 1.668 s | ¹³⁶ Sb _{923 ms} | ¹³⁷ Sb 497 ms | ¹³⁸ Sb ^{333 ms} | ¹³⁹ Sb 182 ms | |
| ¹²⁵ Sn 9.634 d | 126 Sn 230 ky | ¹²⁷ Sn 126 m | ¹²⁸ Sn ^{59.07 m} | ¹²⁹ Sn ^{133.8 s} | ¹³⁰ Sn 223.2 s | ¹³¹ Sn | ¹³² Sn ^{39.7 s} | ¹³³ Sn _{1.37 s} | ¹³⁴ Sn ^{930 ms} | ¹³⁵ Sn 515 ms | ¹³⁶ Sn 355 ms | ¹³⁷ Sn 249 ms | ¹³⁸ Sn 148 ms | <i>Z</i> = 50 |
| | | | | | | | | | and the second second | | | | | |
| ¹²⁴ In ^{3.12 s} | ¹²⁵ In 2.36 s | ¹²⁶ In 1.53 s | 127 n 1.086 s | 128 1n 810 ms | ¹²⁹ In ^{570 ms} | 130 n 273 ms | ¹³¹ In ^{261.5 ms} | ¹³² In ^{202.2 ms} | ¹³³ In ^{163 ms} | ¹³⁴ In ^{136 ms} | ¹³⁵ In ^{103 ms} | ¹³⁶ In ^{86 ms} | ¹³⁷ In ^{70 ms} | |
| | | ¹²⁶ In 1.53 s ¹²⁵ Cd 880 ms | | | | ¹³⁰ In ^{273 ms} ¹²⁹ Cd ^{147 ms} | | | | 136 ms | of Half | 86 ms | 70 ms | |
| ^{3.12 s} | ^{2.36 s} | ^{1.53 s} | ^{1.086 s} | 810 ms | ^{570 ms} | ^{273 ms} | ^{261.5 ms} | ^{202.2} ms | ^{163 ms} | 138 ms Log -2e+1 | 0f Half -9e+0 | ^{88 ms} -life [s] | 70 ms | |
| 3.12 s 123Cd 2.1 s | 2.38 s 124Cd 1.25 s | 1.53 s 125 Cd 880 ms | 1.086 s 126Cd 512 ms | 816 ms 127 Cd 480 ms 126 Ag | 570 ms 128Cd 246 ms 127Ag | ^{273 ms} ¹²⁹ Cd ^{147 ms} | 201.5 ms 130 Cd 128.8 ms 129 Ag | 202.2 ms ¹³¹ Cd ^{98 ms} ¹³⁰ Ag | ^{163 ms} ¹³² Cd ^{84 ms} | 138 ms | of Half | ^{88 ms} -life [s] | 70 ms | |

Modified from people.physics.anu.edu/~ecs103/chart-beta/



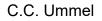
Shell Model Tests

Example: ¹³⁵Xe

| ¹³⁰ Cs ^{29,21 m} | ¹³¹ Cs | ¹³² Cs _{0.48 d} | ¹³³ Cs | ¹³⁴ Cs 2.085 y | ¹³⁵ CS 1.33 My | ¹³⁶ Cs ^{13.01 d} | ¹³⁷ Cs _{30.04 y} | ¹³⁸ Cs _{33.5 m} | ¹³⁹ Cs _{9.27 m} | ¹⁴⁰ CS _{63.7 s} | ¹⁴¹ CS _{24.84 s} | ¹⁴² CS 1.687 s | ¹⁴³ CS 1.802 s | |
|--|--|--|--|--|--|--|--|--|---|--|---|--|--|---------------|
| ¹²⁹ Xe | ¹³⁰ Xe | ¹³¹ Xe | ¹³² Xe | ¹³³ Xe 5.2474 d | ¹³⁴ Xe | ¹³⁵ Xe | ¹³⁶ Xe ^{2.18 Zy} | ¹³⁷ Xe 229.08 s | ¹³⁸ Xe | ¹³⁹ Xe ^{39.68 s} | ¹⁴⁰ Xe | ¹⁴¹ Xe 1.73 s | ¹⁴² Xe | |
| 128 24.99 m | 129 18.14 My | 130 12.36 h | 131 8.0249 d | 132 137.7 m | 133 20.83 h | 134 52.5 m | 135 6.58 h | 136 83.4 s | 137 24.13 s | 138 6.26 s | 139 2.28 s | 140 588 ms | 141 420 ms | |
| ¹²⁷ Те _{9.35 h} | ¹²⁸ Te | ¹²⁹ Te | ¹³⁰ Te _{791 Ey} | ¹³¹ Te | ¹³² Te 76.896 h | ¹³³ Te | ¹³⁴ Te | ¹³⁵ Te | ¹³⁶ Te 17.83 s | ¹³⁷ Te 2.49 s | ¹³⁸ Te | ¹³⁹ Te 724 ms | ¹⁴⁰ Te _{351 ms} | |
| ¹²⁶ Sb 12.35 d | ¹²⁷ Sb _{92.4 h} | ¹²⁸ Sb 9.05 h | ¹²⁹ Sb 4.366 h | ¹³⁰ Sb 39.5 m | ¹³¹ Sb ^{23.03 m} | ¹³² Sb _{167.4 s} | ¹³³ Sb _{140.4 s} | ¹³⁴ Sb 874 ms | ¹³⁵ Sb 1.068 s | ¹³⁶ Sb 923 ms | ¹³⁷ Sb 497 ms | ¹³⁸ Sb ^{333 ms} | ¹³⁹ Sb 182 ms | |
| | | | | | | | | | | | | | | |
| ¹²⁵ Sn 9.634 d | ¹²⁶ Sn ^{230 ky} | 127 Sn 128 m | ¹²⁸ Sn ^{59.07 m} | ¹²⁹ Sn ^{133.8 s} | ¹³⁰ Sn 223.2 s | ¹³¹ Sn 56 s | ¹³² Sn ^{39.7 s} | ¹³³ Sn _{1.37 s} | ¹³⁴ Sn 930 ms | ¹³⁵ Sn ^{515 ms} | ¹³⁶ Sn 355 ms | 137 Sn 249 ms | ¹³⁸ Sn 148 ms | <i>Z</i> = 50 |
| | | | | | | | | | | | | | | <i>Z</i> = 50 |
| 9.634 d | ^{230 ky} | ^{126 m} | ^{59.07 m} | ^{133.8 s} | ^{223.2 s} | ^{58 s} | ^{39.7 s} | ^{1.37 s} | 930 ms | 515 ms 134 n 136 ms | 355 ms 135 In 103 ms of Half | 249 ms | 148 ms | <i>Z</i> = 50 |
| e.634 d 124 n 3.12 s 123 Cd | ^{230 ky} ¹²⁵ In ^{2.36 s} ¹²⁴ Cd | ¹²⁶ In ^{1.53 s} | ^{59.07 m} ¹²⁷ In ^{1.086 s} ¹²⁶ Cd | 128 In 818 ms | 223.2 s ¹²⁹ In ⁵⁷⁰ ms ¹²⁸ Cd | 56 s 130 n 273 ms 129 Cd | 39.7 s 131 n 261.5 ms 130 Cd | 1.37 s 132 n 202.2 ms 131Cd 98 ms | 930 ms | 515 ms 134 n 136 ms Log -2e+1 Lo | 355 ms 135 In 103 ms of Half -9e+0 ong-lived | 249 ms 136 n 88 ms | 148 ms | <i>Z</i> = 50 |
| e.834 d 124 [n 3.12 s 123 Cd 2.1 s 122 Ag | 230 ky 125 In 2.36 s 124 Cd 1.25 s 123 Ag | 126 m 126 n 1.53 s 125 Cd 880 ms | 59.07 m 127 n 1.088 s 126 Cd 512 ms 125 Ag | 133.8 s 128 n 816 ms 127 Cd 480 ms 126 Ag | 223.2 s 129 In 570 ms 128 Cd 246 ms 127 Ag | 50 s 130 n 273 ms 129 Cd 147 ms 128 Ag | ^{39.7 s} ¹³¹ n ^{201.5 ms} ¹³⁰ Cd ^{126.8 ms} ¹²⁹ Ag | 1.37 s 132 n 202.2 ms 131Cd 98 ms 130Ag | 930 ms 133 In 153 ms 132 Cd 84 ms 131 Ag | 515 ms 134 n 136 ms Log -2e+1 Lo Es | 355 ms 135 In 103 ms of Half -9e+0 | 249 ms 136 n 88 ms | 148 ms | <i>Z</i> = 50 |

What happens when we move further from the shell closures?

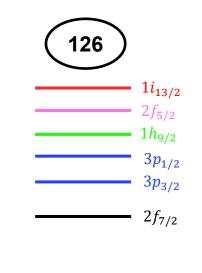
Modified from people.physics.anu.edu/~ecs103/chart-beta/



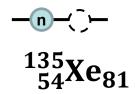


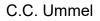
¹³⁵Xe

 $^{135}_{54}$ Xe₈₁ has a single, unpaired neutron lying just below the N = 82 shell gap







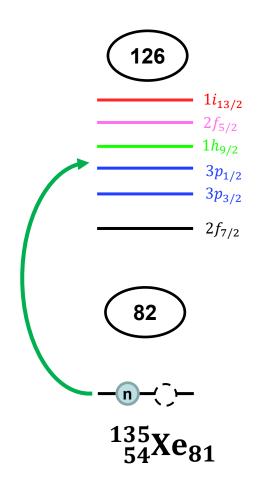




¹³⁵Xe

 $^{135}_{54}$ Xe₈₁ has a single, unpaired neutron lying just below the N = 82 shell gap

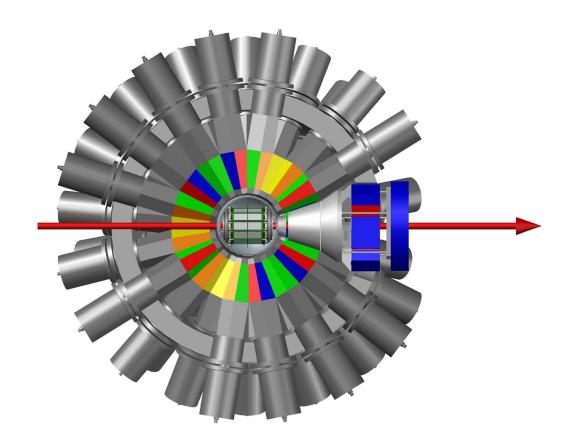
Single-neutron excitations will require crossing the shell gap





Gammasphere-ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS)

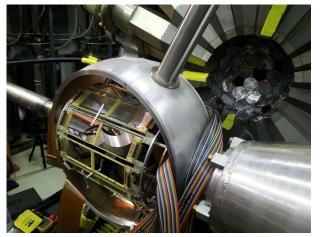


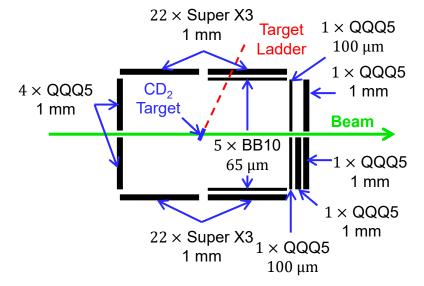


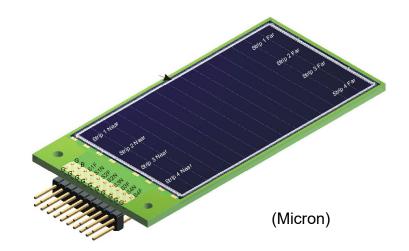
From S.D. Pain, et al., Physics Procedia 90, 455 (2017).

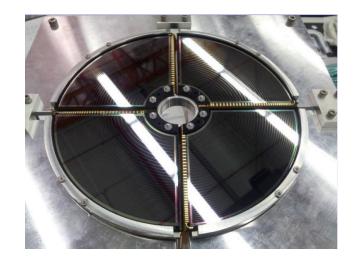


Oak Ridge Rutgers University Barrel Array (ORRUBA)





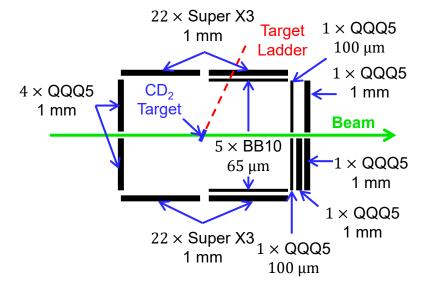






Oak Ridge Rutgers University Barrel Array (ORRUBA)





Gammasphere

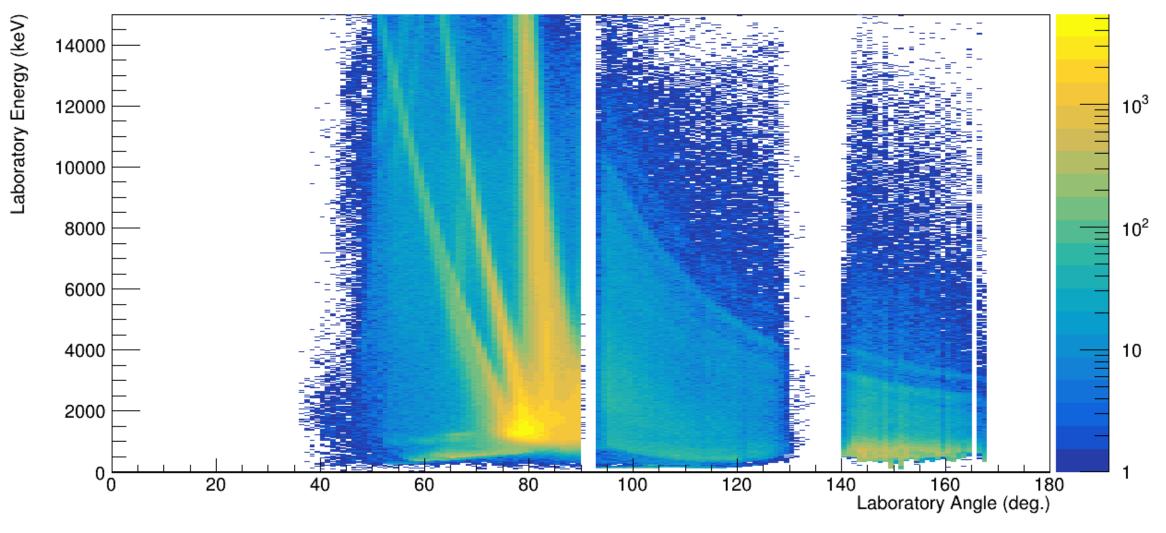




Preliminary Results



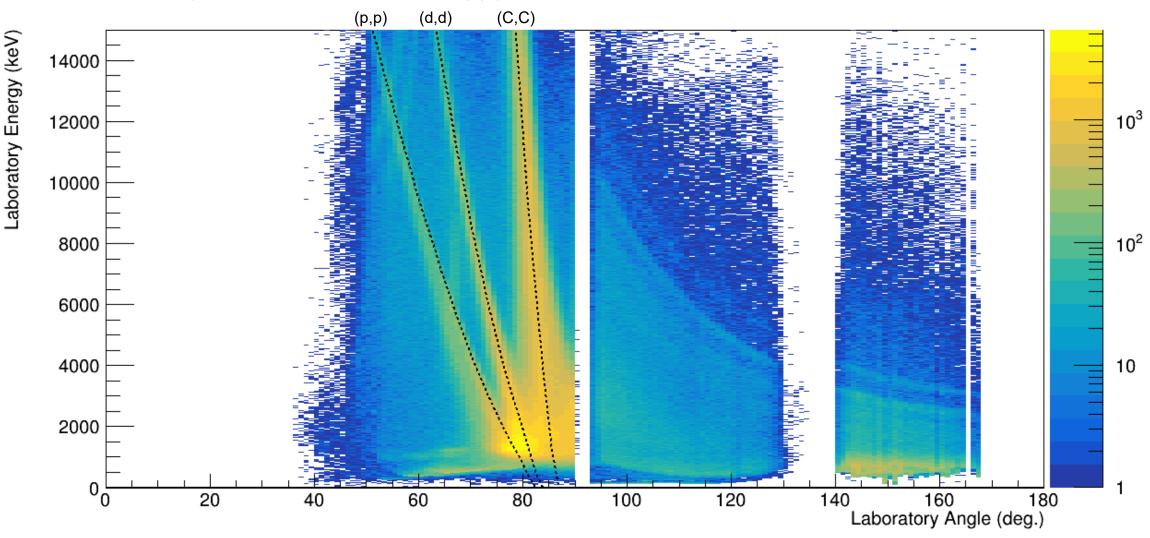
Preliminary Results—Si E_{tot} vs. θ



RUTGERS

C.C. Ummel

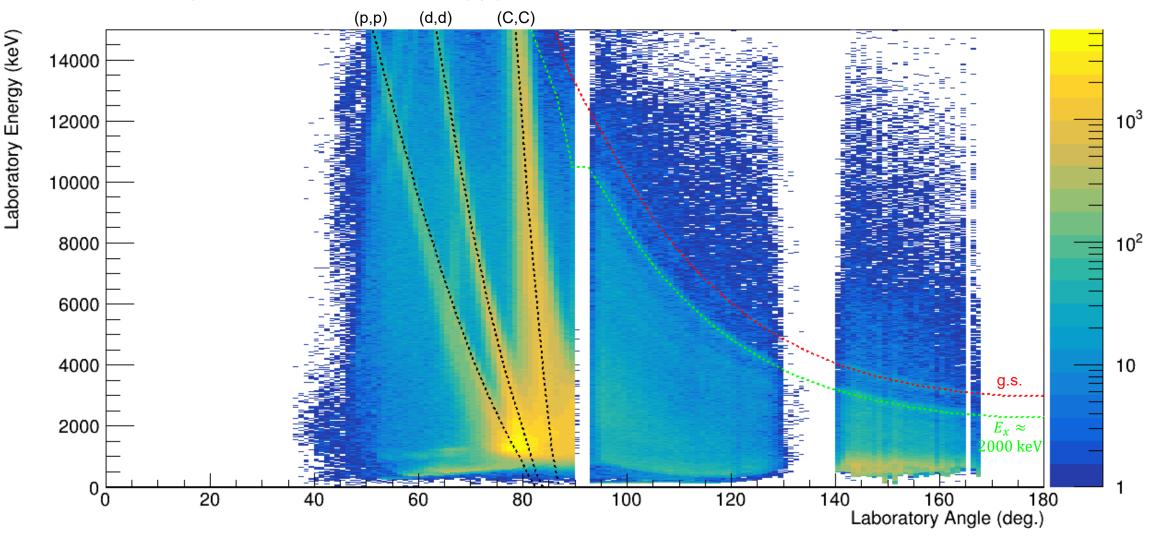
Preliminary Results—Si E_{tot} vs. θ



RUTGERS

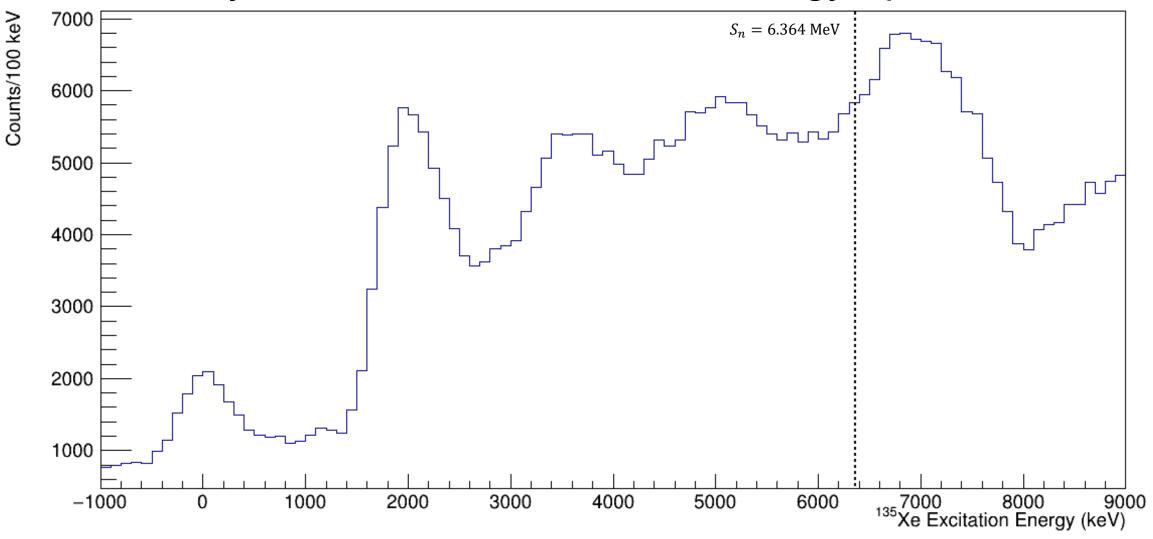
C.C. Ummel

Preliminary Results—Si E_{tot} vs. θ



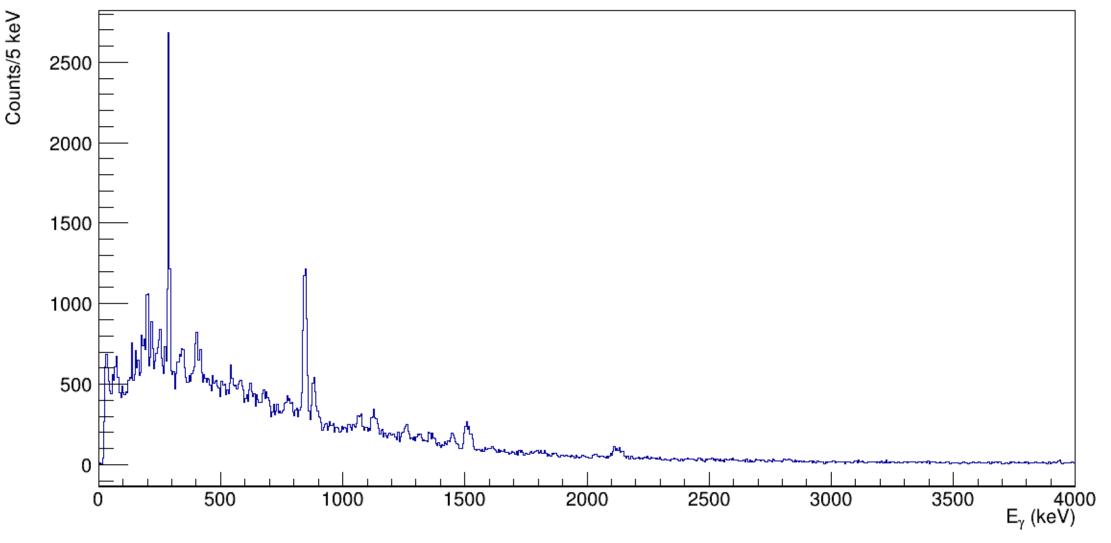


Preliminary Results—¹³⁵Xe Excitation Energy Spectrum



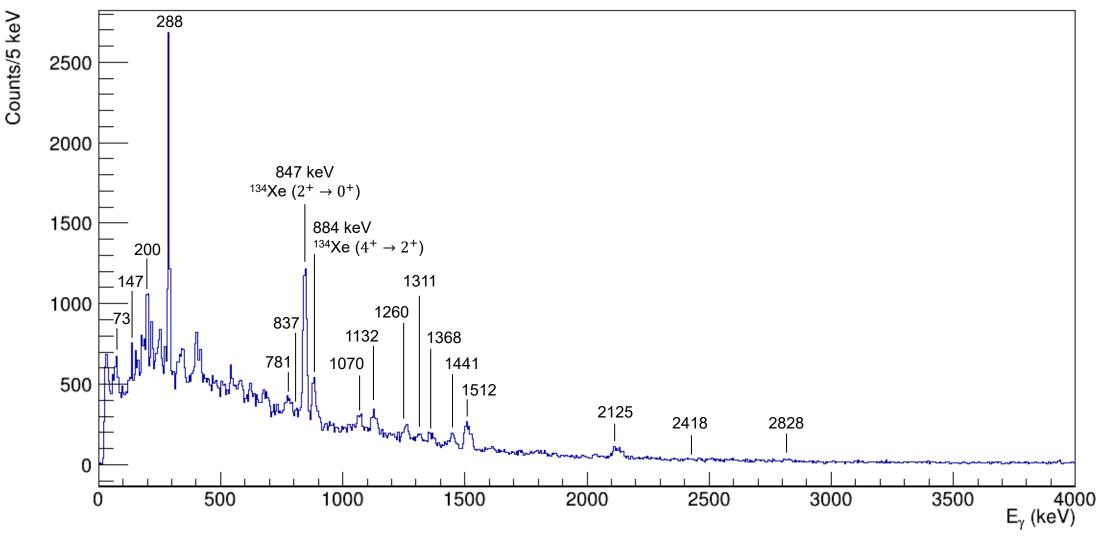


Preliminary Results—Gamma Rays





Preliminary Results—Gamma Rays

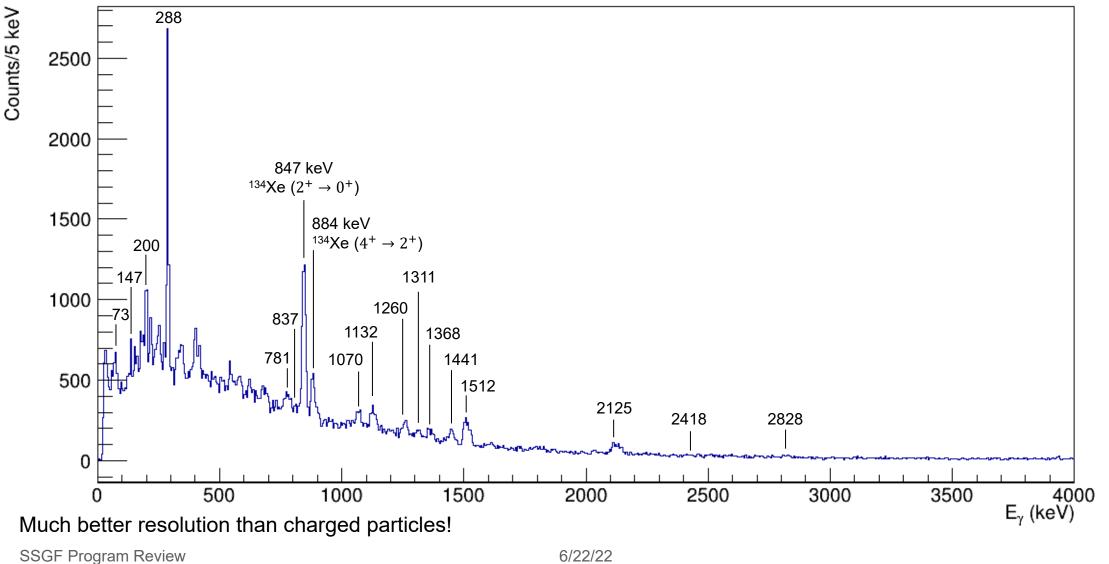


SSGF Program Review

6/22/22

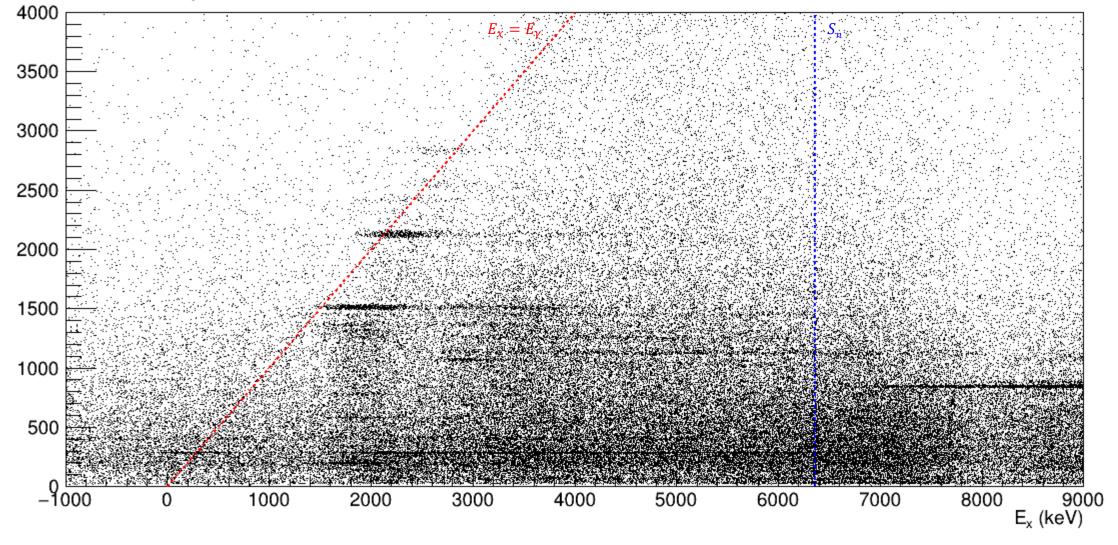


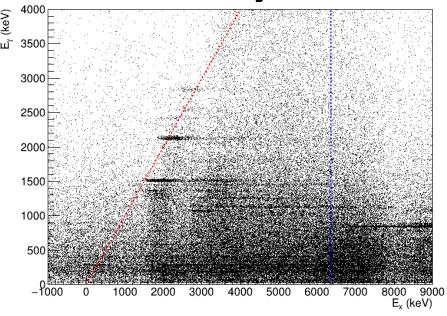
Preliminary Results—Gamma Rays

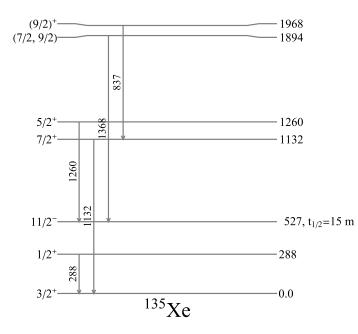


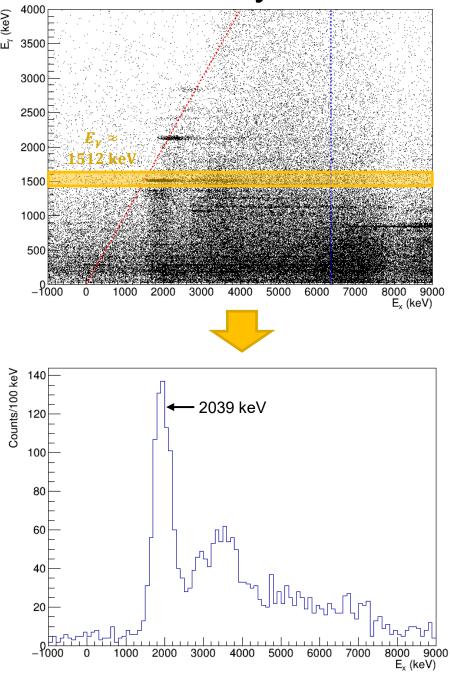


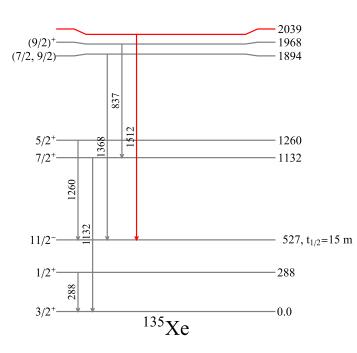
 E_{γ} (keV)



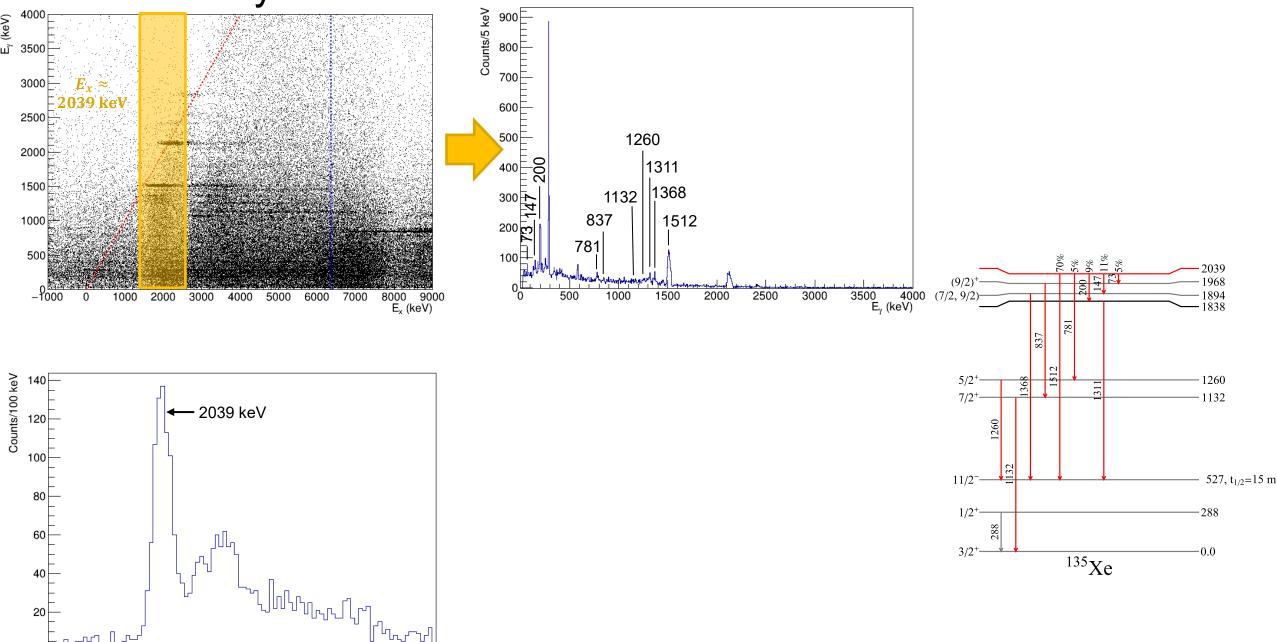








Preliminary Results – Coincidences!



4000 5000 6000 7000

0

-1000

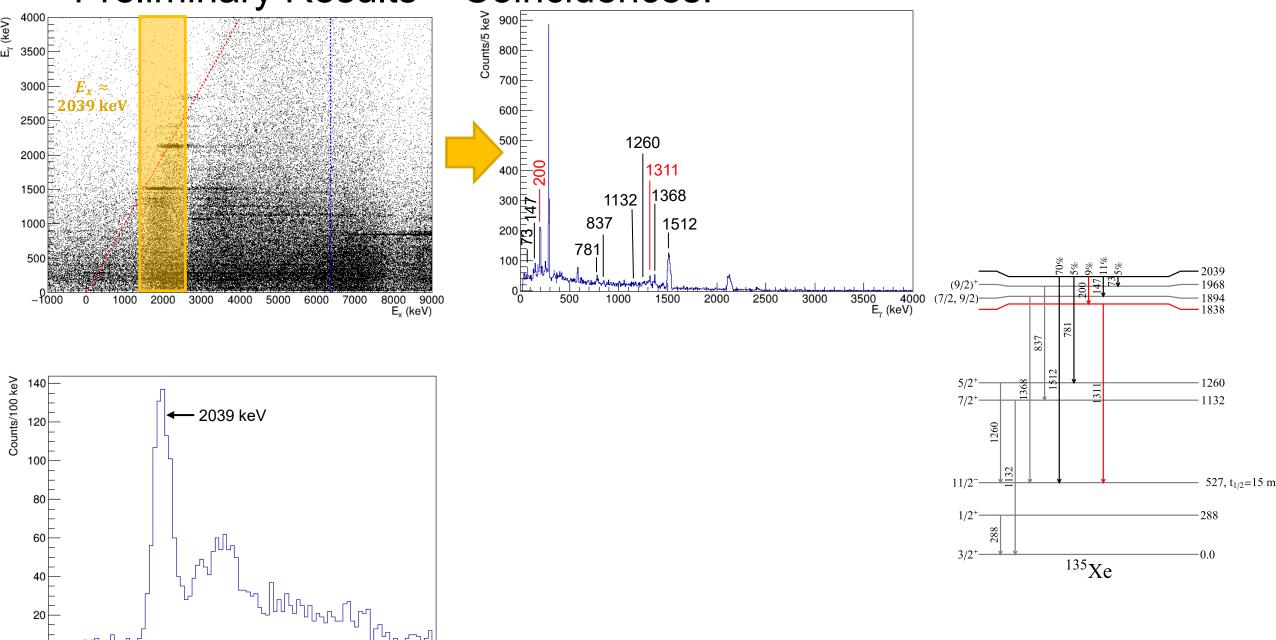
1000

2000

3000

8000 9000 E_x (keV)

Preliminary Results – Coincidences!



5000 6000 7000 8000 9000 E_x (keV)

0

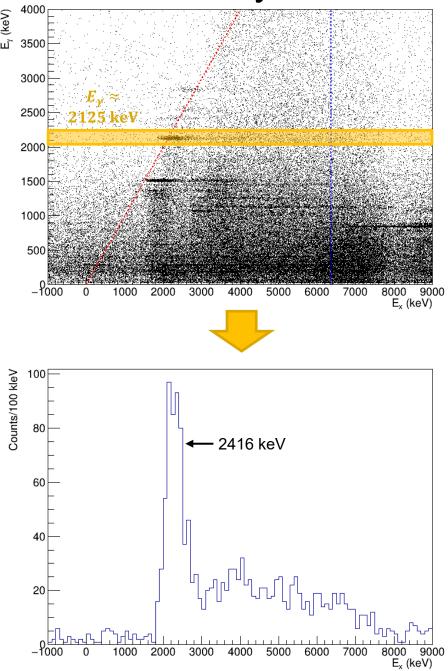
-1000

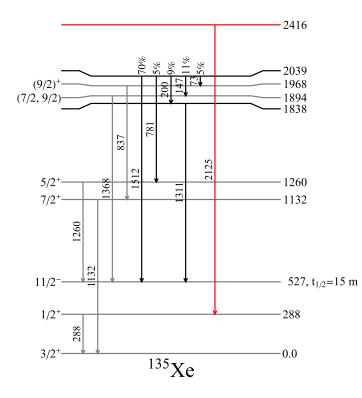
1000

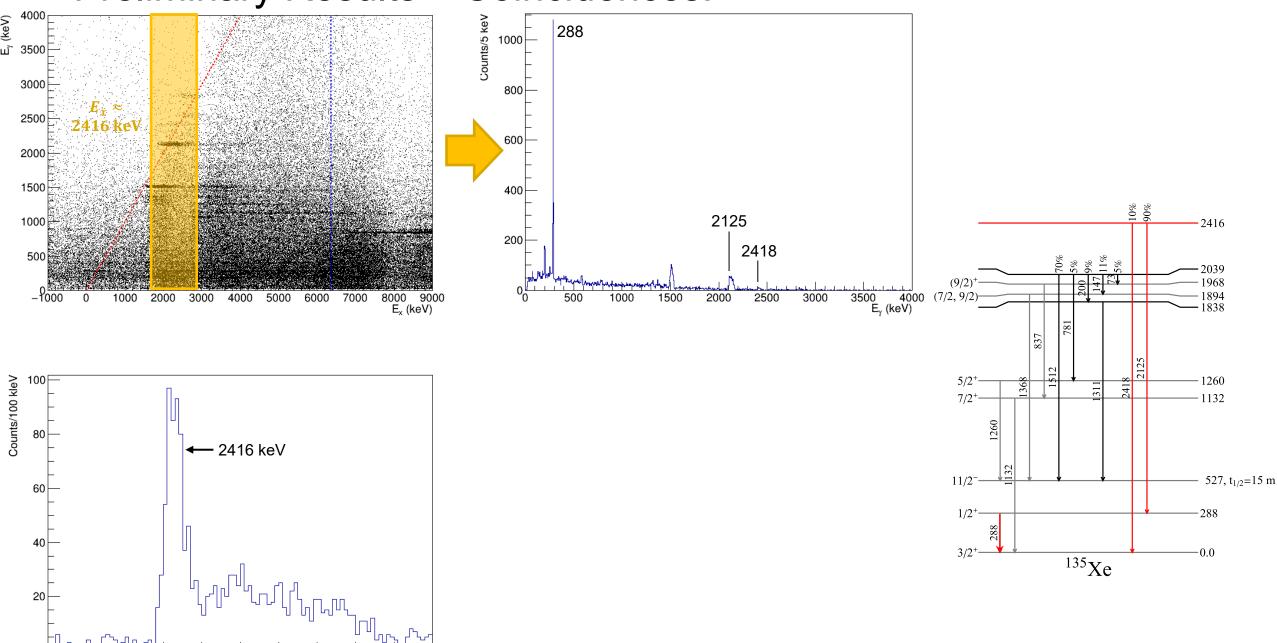
2000

3000

4000

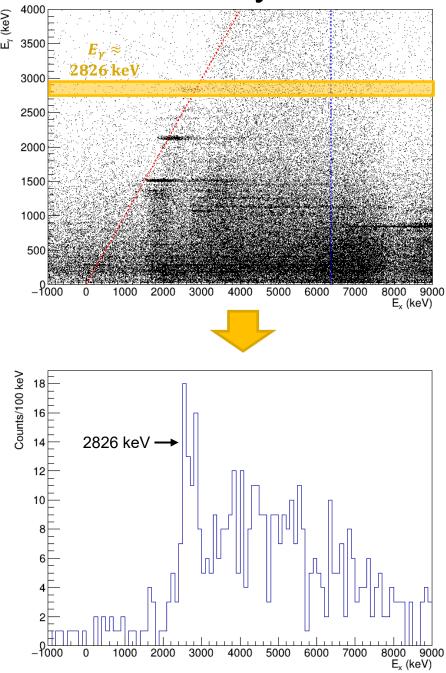


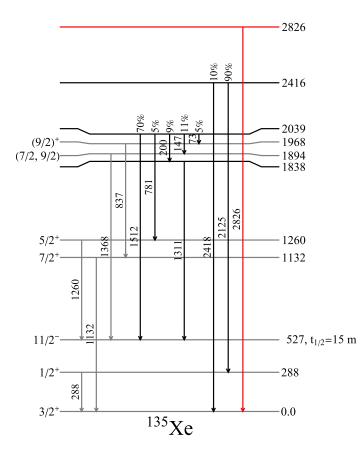


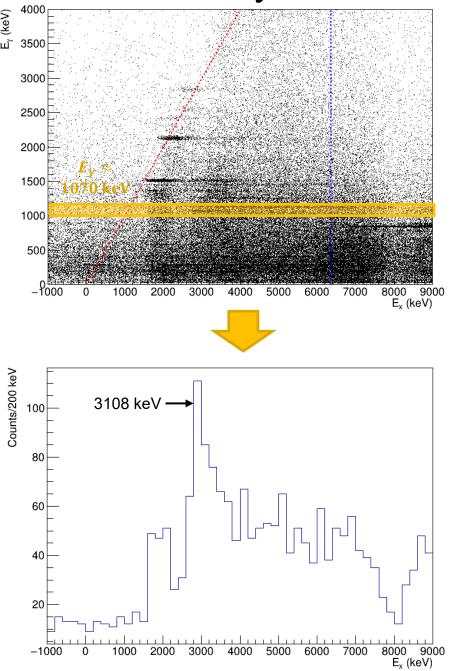


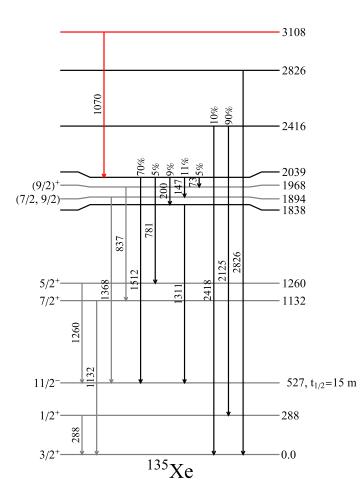
. 8000 9000 E_x (keV)

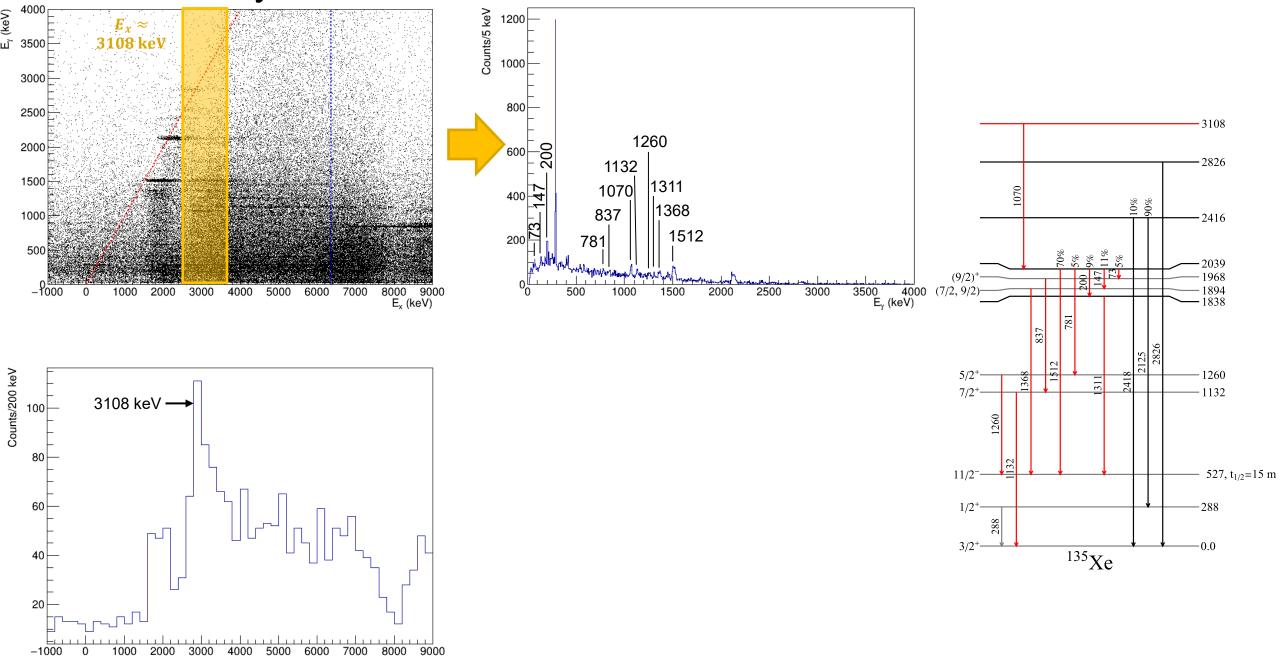
-1000





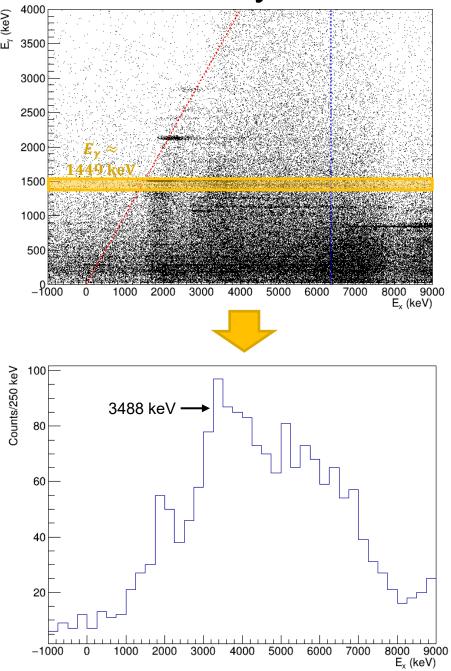


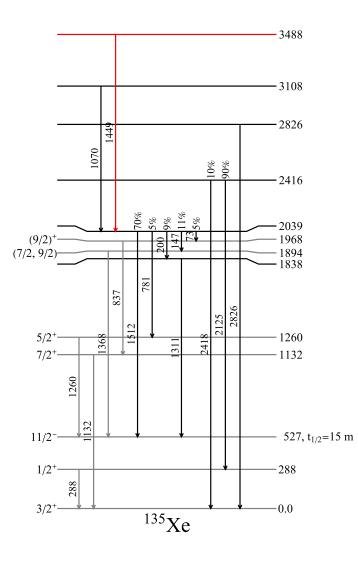




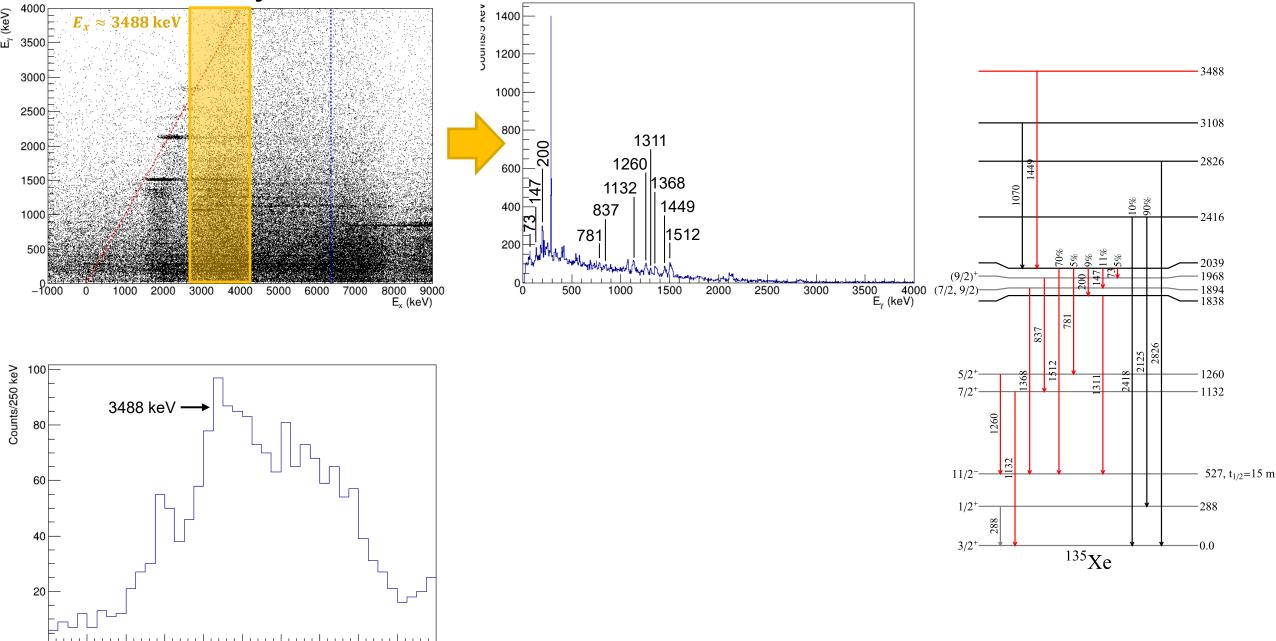
4000 5000 6000

E_x (keV)





Preliminary Results – Coincidences!



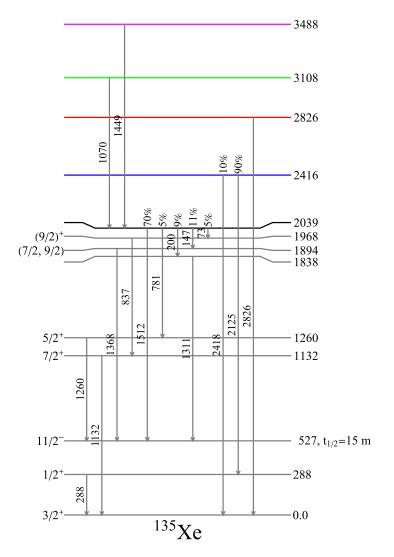
8000 9000

E_x (keV)

-1000



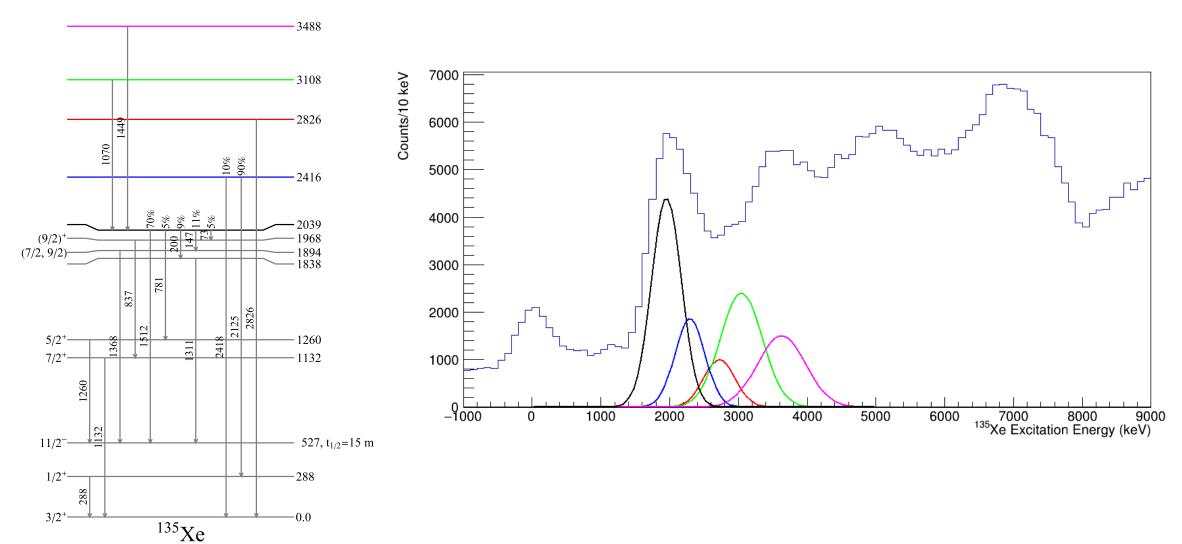
¹³⁵Xe Level Scheme



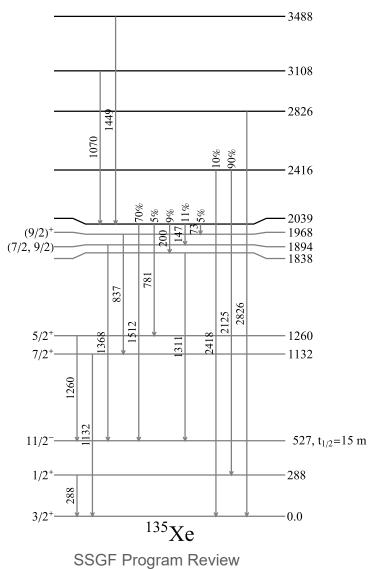
SSGF Program Review



¹³⁵Xe Level Scheme



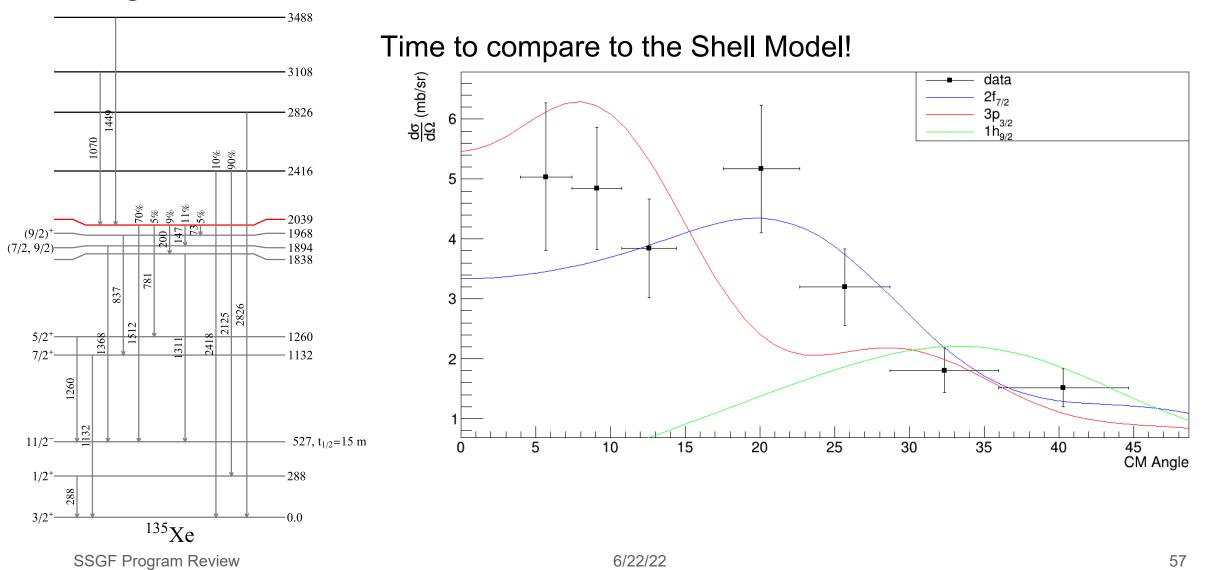




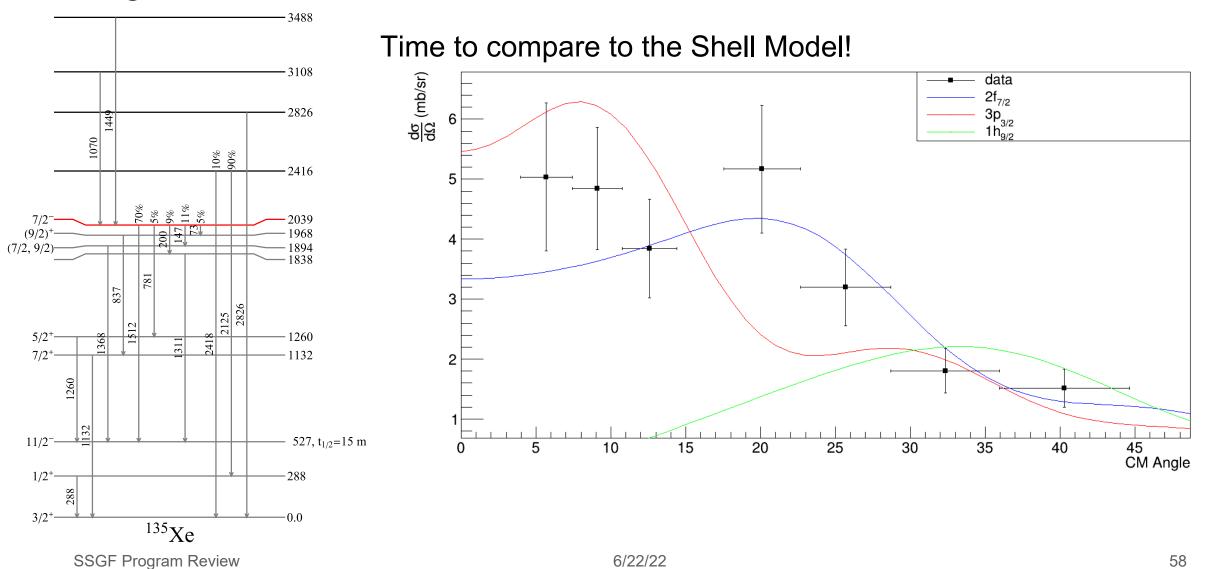
Time to compare to the Shell Model!

6/22/22

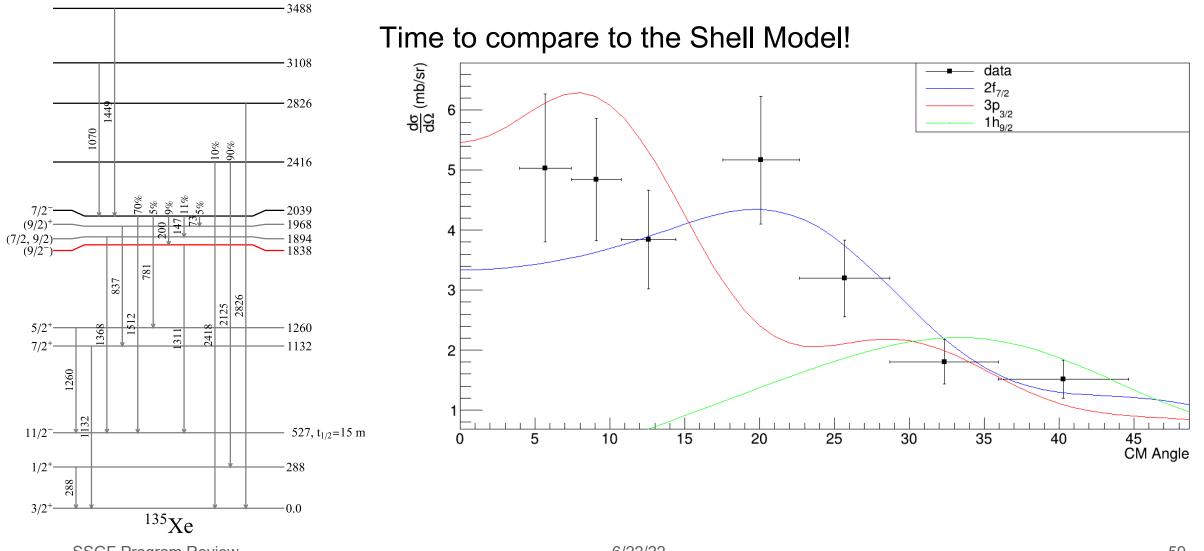






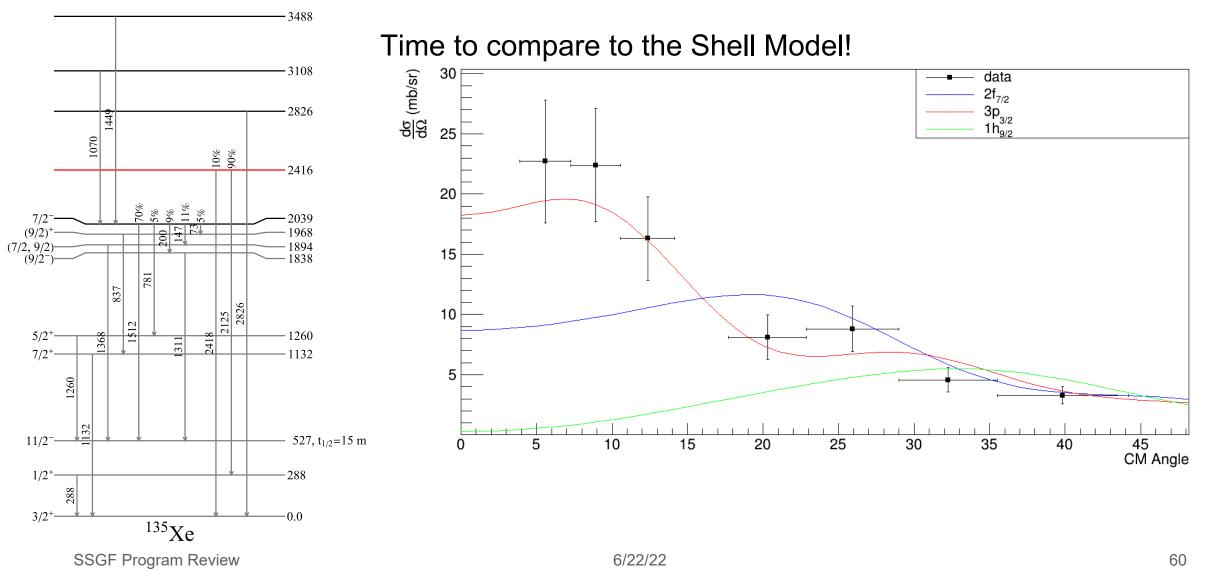




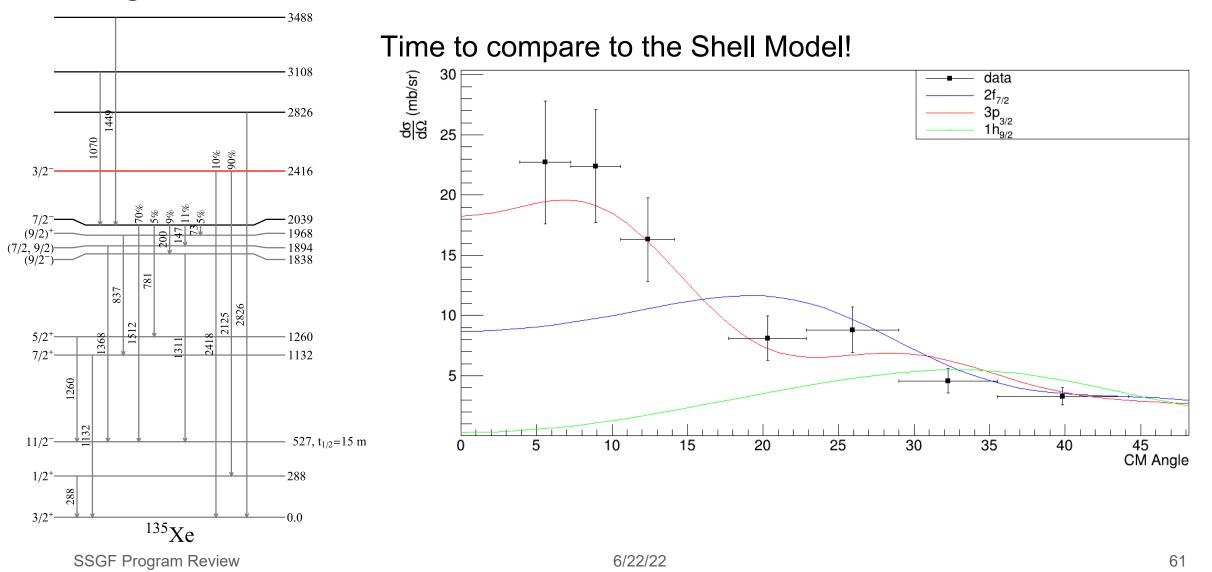


SSGF Program Review

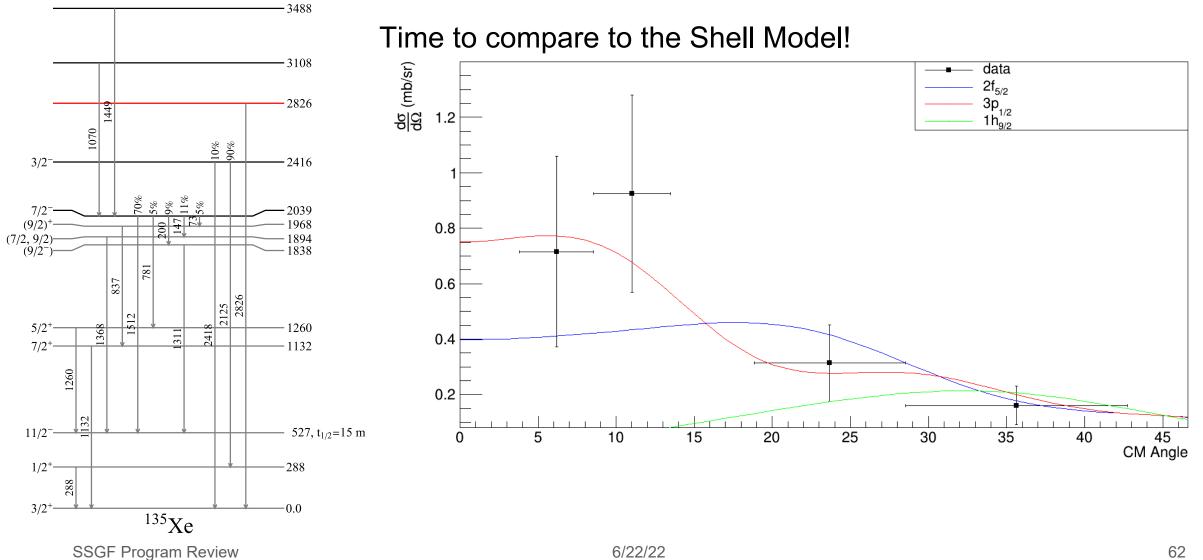




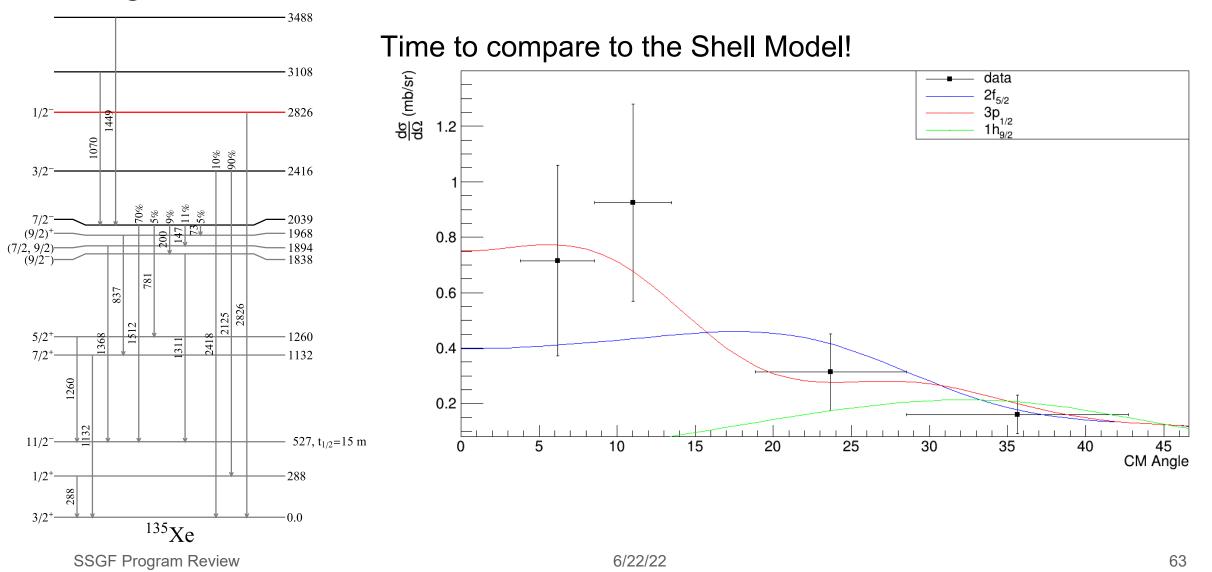




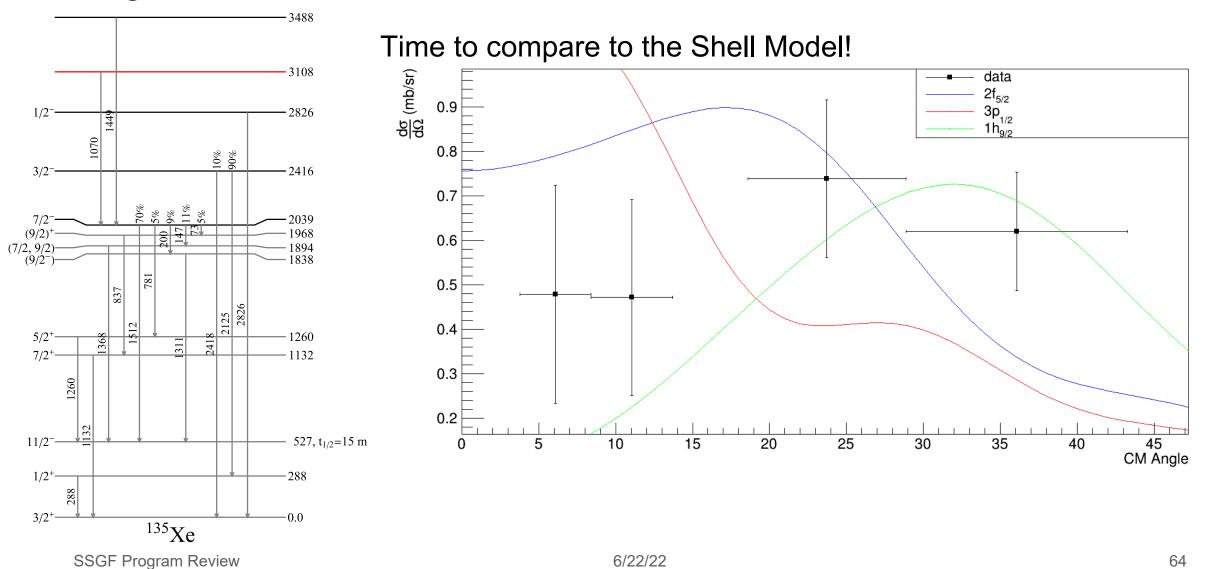




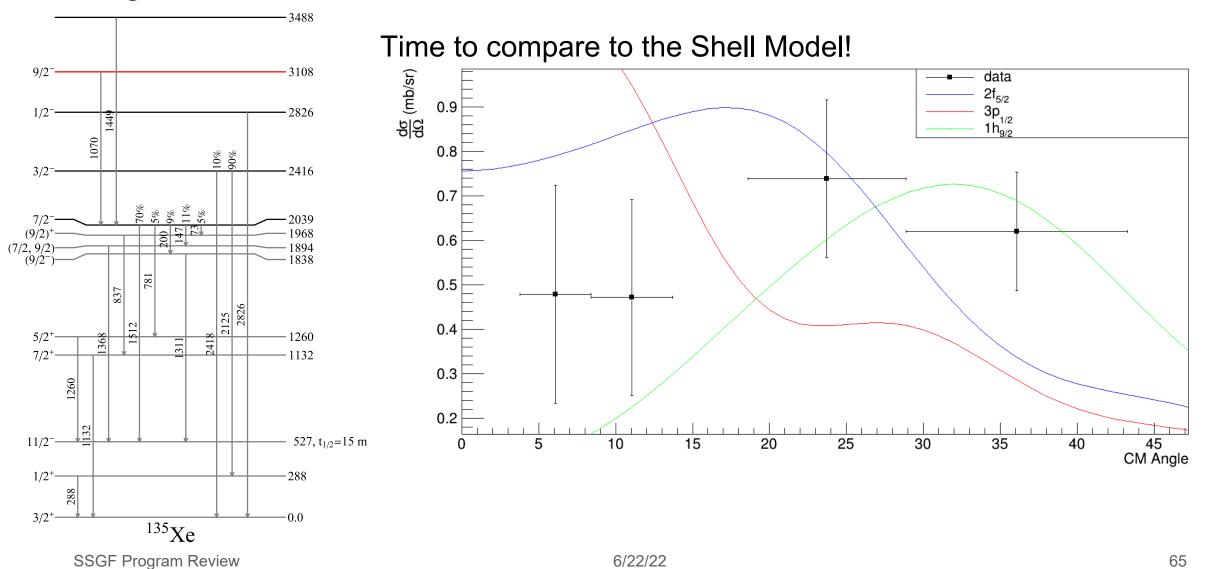




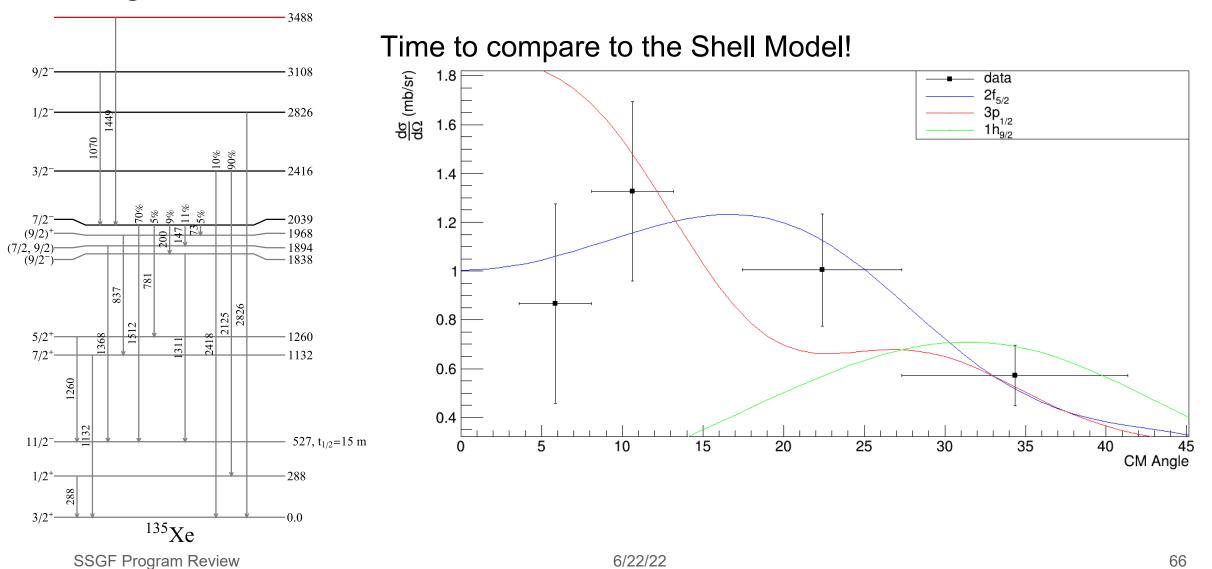




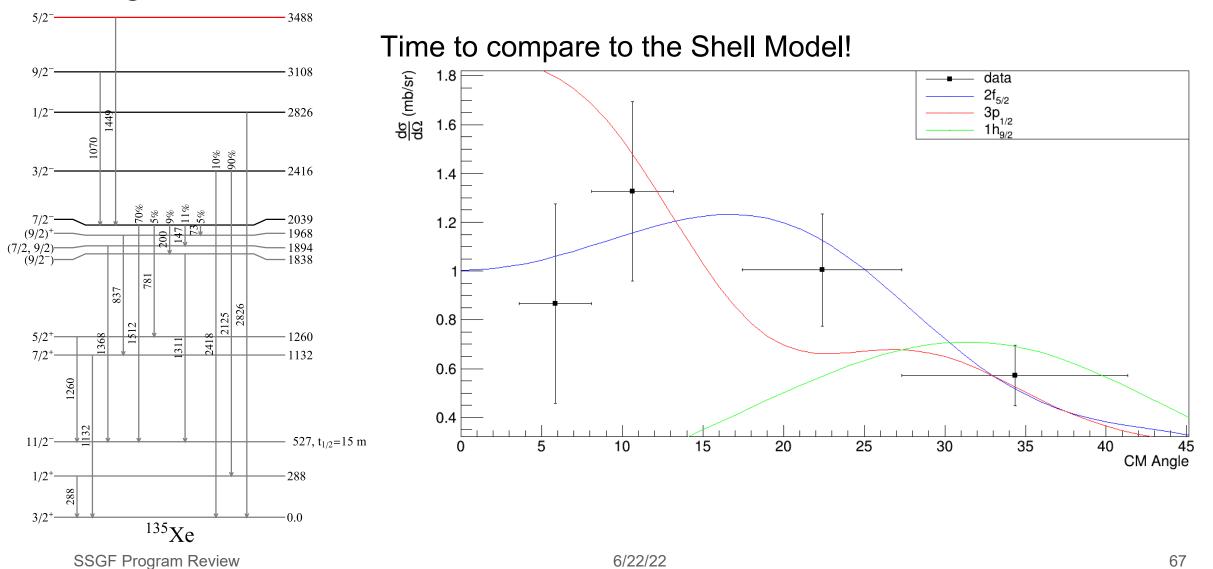




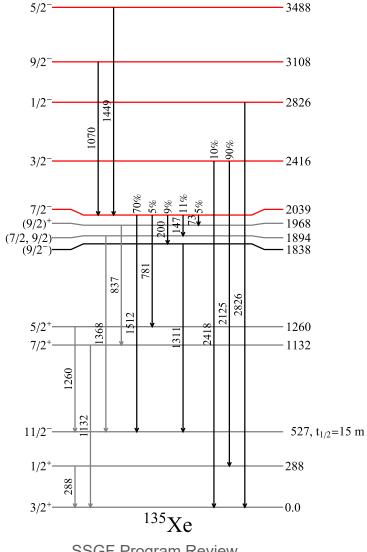


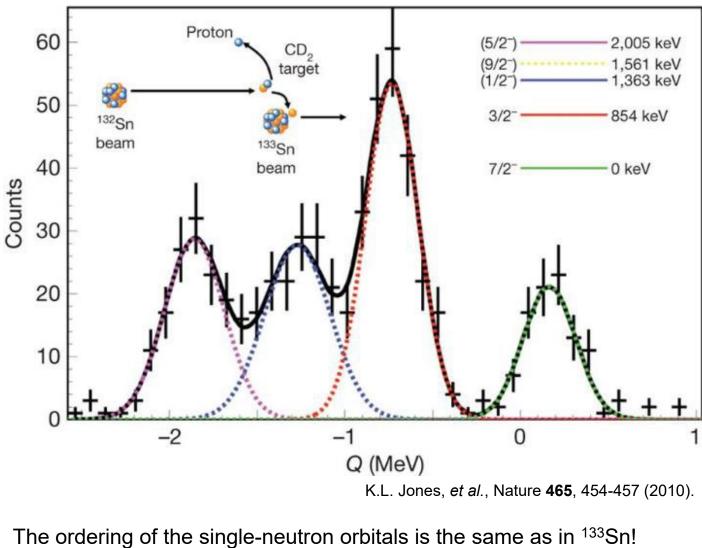












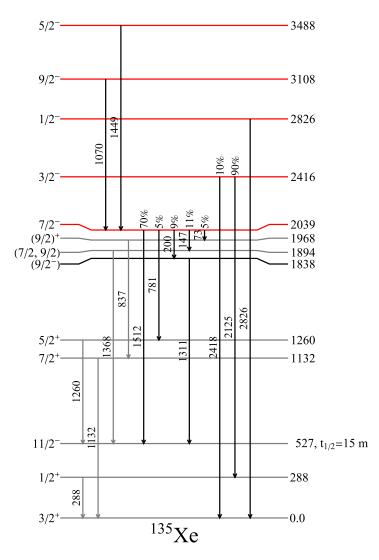
SSGF Program Review

6/22/22



Summary

- The Shell Model is a powerful tool for predicting nuclear structure observables
- Successfully measured the $^{134}\mbox{Xe}(d,p\gamma)^{135}\mbox{Xe}$ reaction with GODDESS
- Validated p- γ coincidences with GODDESS – Crucial for resolving the closely-spaced levels in ¹³⁵Xe
- Observed first five states above the N = 82 shell gap
 - Spin-parities confirm Shell Model predictions





Thank you to all "the GODDESSes"

A. Lepailleur¹, G. Seymour¹, J.A. Cizewski¹, **K.L. Jones²**, **S.D. Pain³**, **A. Ratkiewicz⁴**, H. Garland¹, H. Sims^{1,5}, D.W. Bardayan⁵, T. Baugher¹, K. Chipps³, M. Febbraro³, M. Hall⁵, K. Smith², D. Walter¹, G.L. Wilson^{6,7}, **and many more**!

¹Rutgers University, ²University of Tennessee-Knoxville, ³Oak Ridge National Laboratory, ⁴Lawrence Livermore National Laboratory, ⁵University of Surrey, ⁶University of Notre Dame, ⁷Louisiana State University, ⁸Argonne National Laboratory



















This material is based upon work supported by the United States Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship under Grant Award Numbers DE-NA0003864 and DE-NA0003960. Additional support was provided by the NNSA under Grant Award Numbers DE-NA0002132 and DE-NA0003897, by the Office of Science Office of Nuclear Physics under Grant Award Numbers DE-AC05-000R22725, DE-AC02-06CH11357, DE-FG02-96ER40983, DE-SC0001174, and DE-FG02-96ER40955, and by the National Science Foundation under Grant Award Number PHY-1419765. This research used resources at Argonne National Laboratory's ATLAS facility, which is a DOE Office of Science User Facility.





Thank you to all "the GODDESSes"

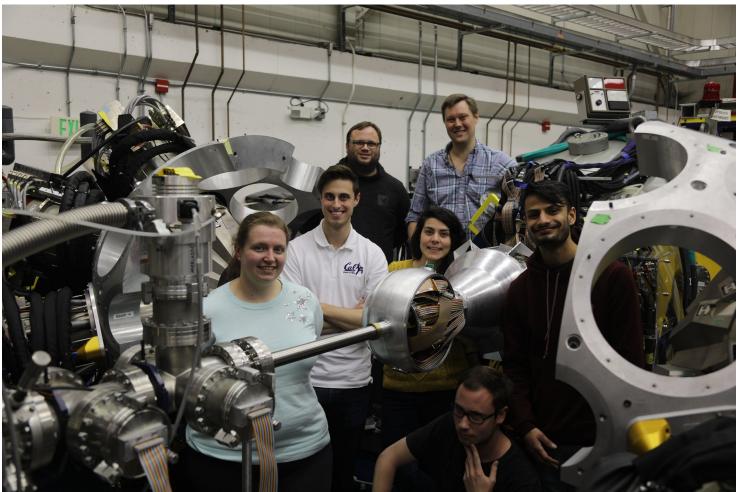


Photo by S.D. Pain and A. Ratkiewicz



This material is based upon work supported by the United States Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship under Grant Award Numbers DE-NA0003864 and DE-NA0003960. Additional support was provided by the NNSA under Grant Award Numbers DE-NA0002132 and DE-NA0003897, by the Office of Science Office of Nuclear Physics under Grant Award Numbers DE-AC05-000R22725, DE-AC02-06CH11357, DE-FG02-96ER40983, DE-SC0001174, and DE-FG02-96ER40955, and by the National Science Foundation under Grant Award Number PHY-1419765. This research used resources at Argonne National Laboratory's ATLAS facility, which is a DOE Office of Science User Facility.





Thank you to SSGF, NNSA, and Krell for a fantastic four years!

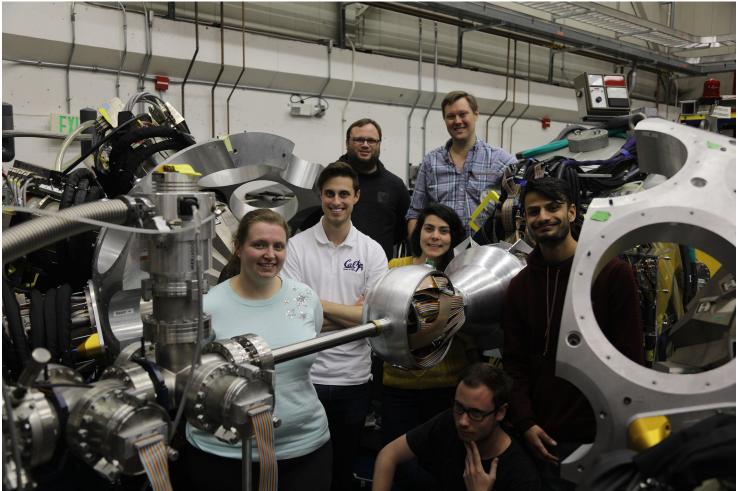


Photo by S.D. Pain and A. Ratkiewicz



This material is based upon work supported by the United States Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship under Grant Award Numbers DE-NA0003864 and DE-NA0003960. Additional support was provided by the NNSA under Grant Award Numbers DE-NA0002132 and DE-NA0003897, by the Office of Science Office of Nuclear Physics under Grant Award Numbers DE-AC05-00OR22725, DE-AC02-06CH11357, DE-FG02-96ER40983, DE-SC0001174, and DE-FG02-96ER40955, and by the National Science Foundation under Grant Award Number PHY-1419765. This research used resources at Argonne National Laboratory's ATLAS facility, which is a DOE Office of Science User Facility.

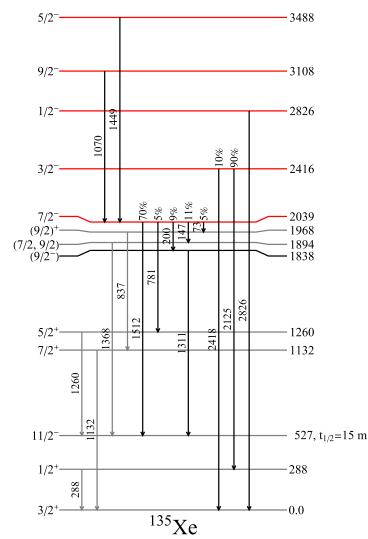


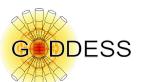


Summary

- The Shell Model is a powerful tool for predicting nuclear structure observables
- Successfully measured the $^{134}\mbox{Xe}(d,p\gamma)^{135}\mbox{Xe}$ reaction with GODDESS
- Validated p- γ coincidences with GODDESS – Crucial for resolving the closely-spaced levels in ¹³⁵Xe
- Observed first five states above the N = 82 shell gap
 - Spin-parities confirm Shell Model predictions

Thank you!





This material is based upon work supported by the United States Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship under Grant Award Numbers DE-NA0003864 and DE-NA0003960. Additional support was provided by the NNSA under Grant Award Numbers DE-NA0002132 and DE-NA0003897, by the Office of Science Office of Nuclear Physics under Grant Award Numbers DE-AC05-00OR22725, DE-AC02-06CH11357, DE-FG02-96ER40983, DE-SC0001174, and DE-FG02-96ER40955, and by the National Science Foundation under Grant Award Number PHY-1419765. This research used resources at Argonne National Laboratory's ATLAS facility, which is a DOE Office of Science User Facility.

