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

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Rutgers University
On behalf of the GODDESS Collaboration

Stewardship Science Graduate Fellowship
Program Review

June 22, 2022

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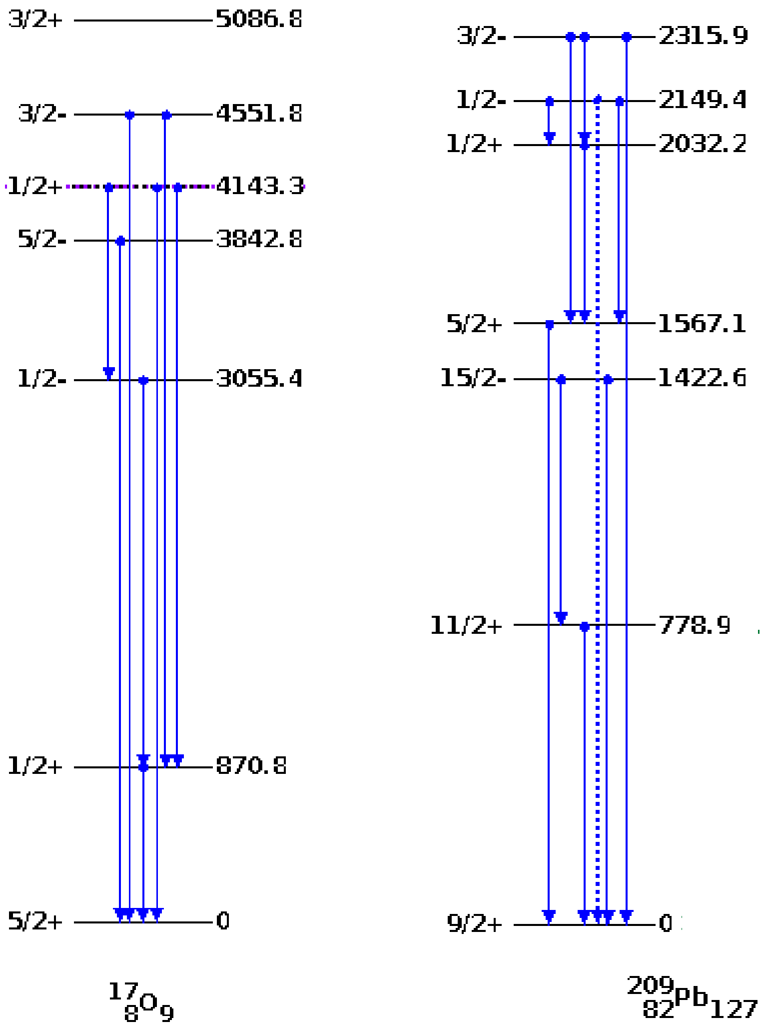
Nuclear Structure



NNDC

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

Can we theoretically describe this structure?

Ab-Initio Approach to Nuclear Structure

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

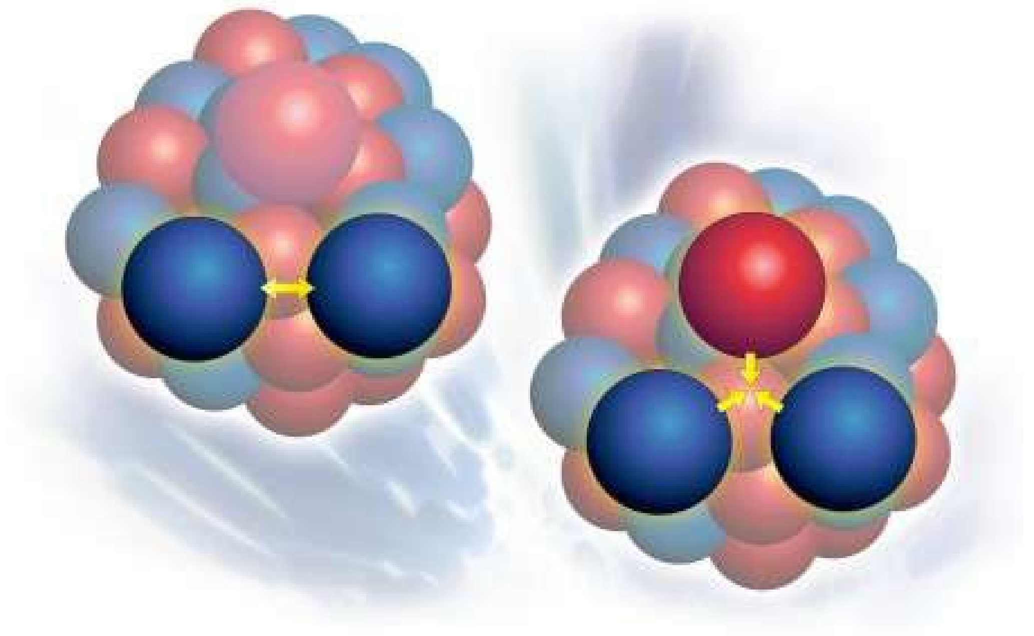
We can solve the Schrödinger equation:

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

For all A nucleons

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

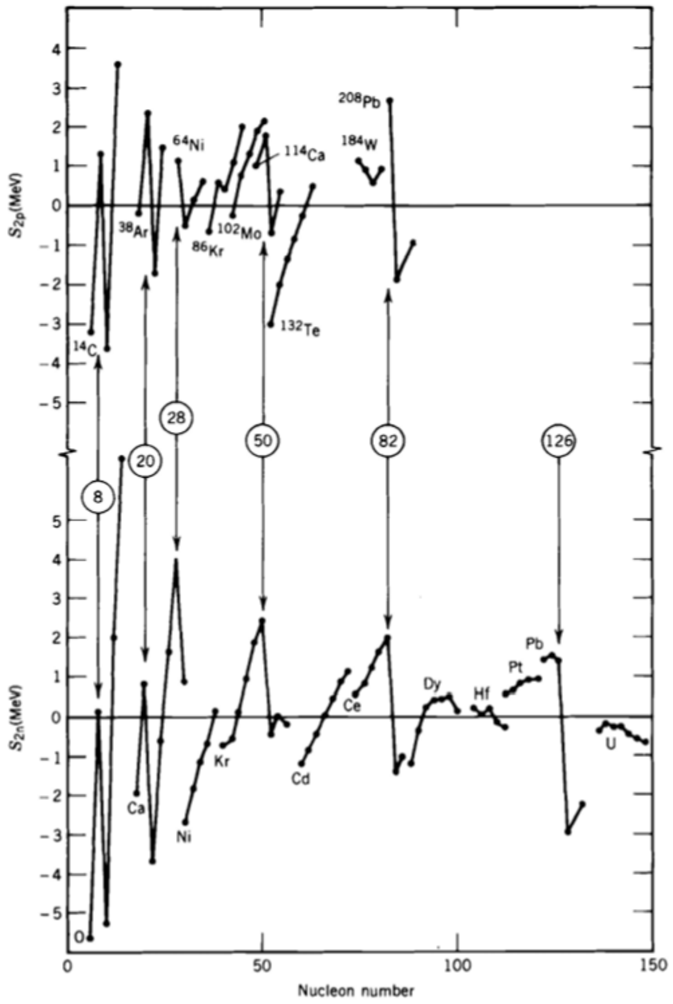
So for now, we must rely on **models** to describe the structure of heavy nuclei



phys.org

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).

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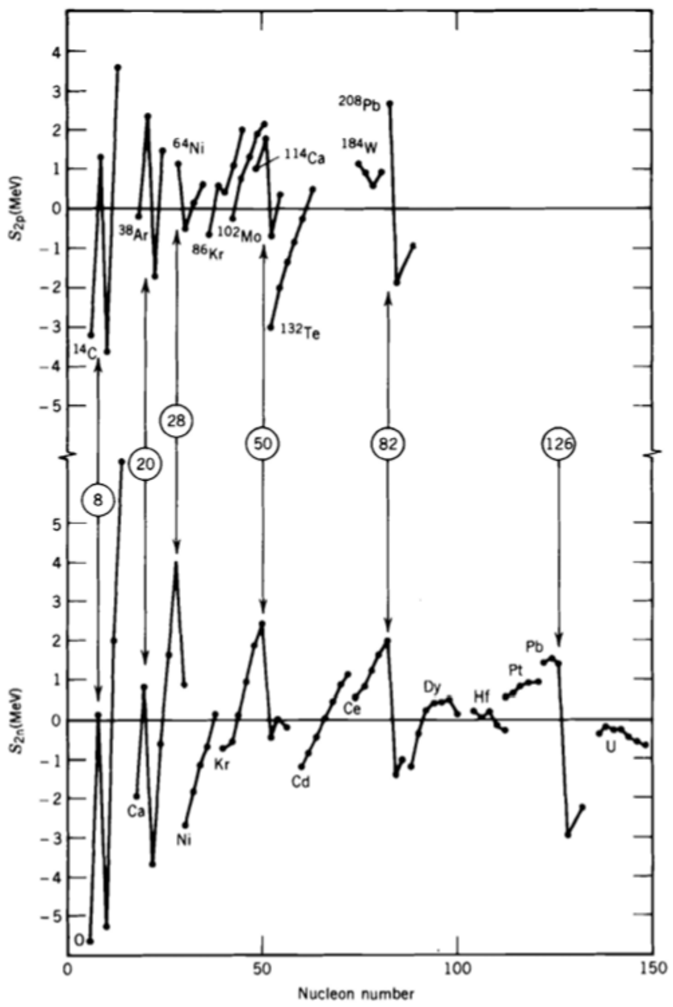
Very similar to electron shells in atomic physics!



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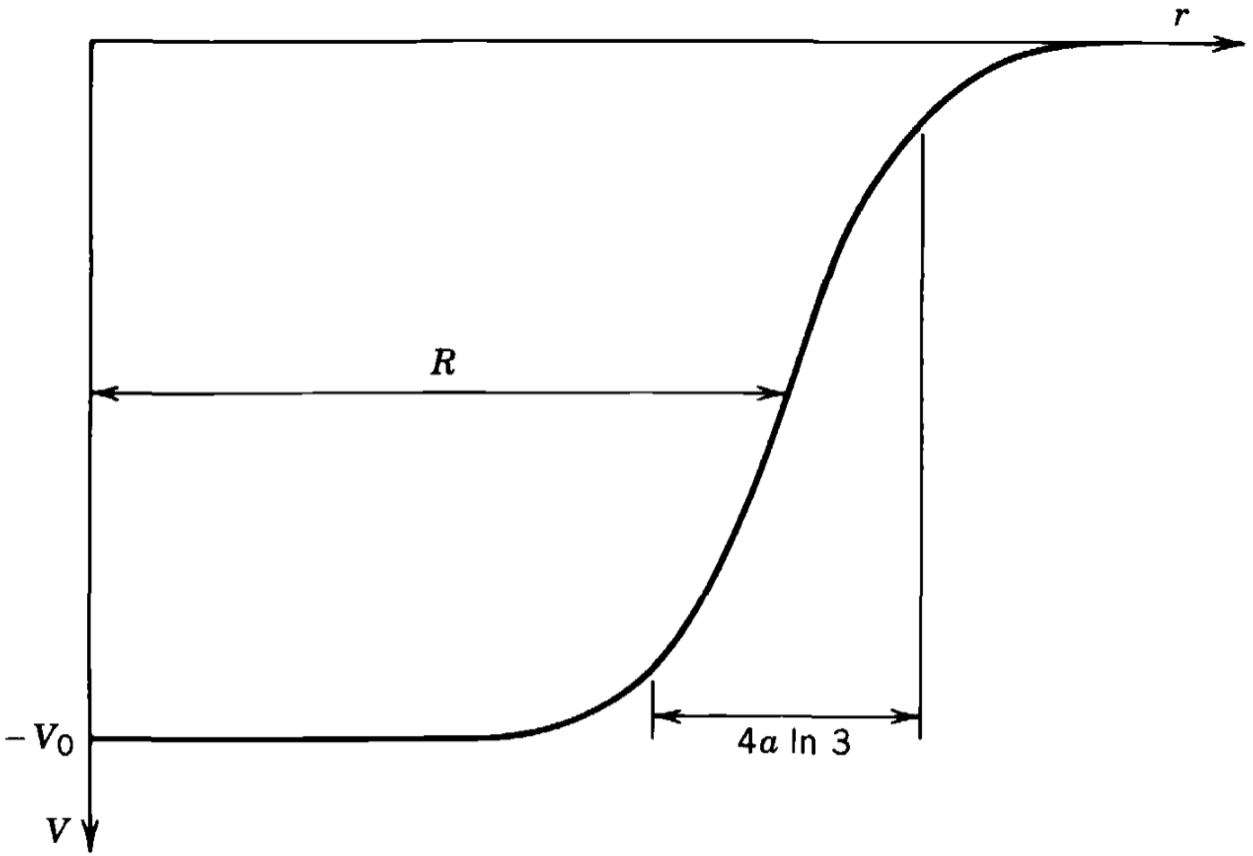
Building Shell Structure—Woods-Saxon Potential

$$V_{WS}(r) = -\frac{V_0}{1 + \exp\left(\frac{r - R}{a}\right)}$$

- $V_0 \sim 50$ MeV
- $R = r_0 A^{1/3}$, $r_0 \approx 1.25$ fm
- $a \approx 0.65$ fm, "diffuseness"

This is the *mean-field* potential experienced by all nucleons



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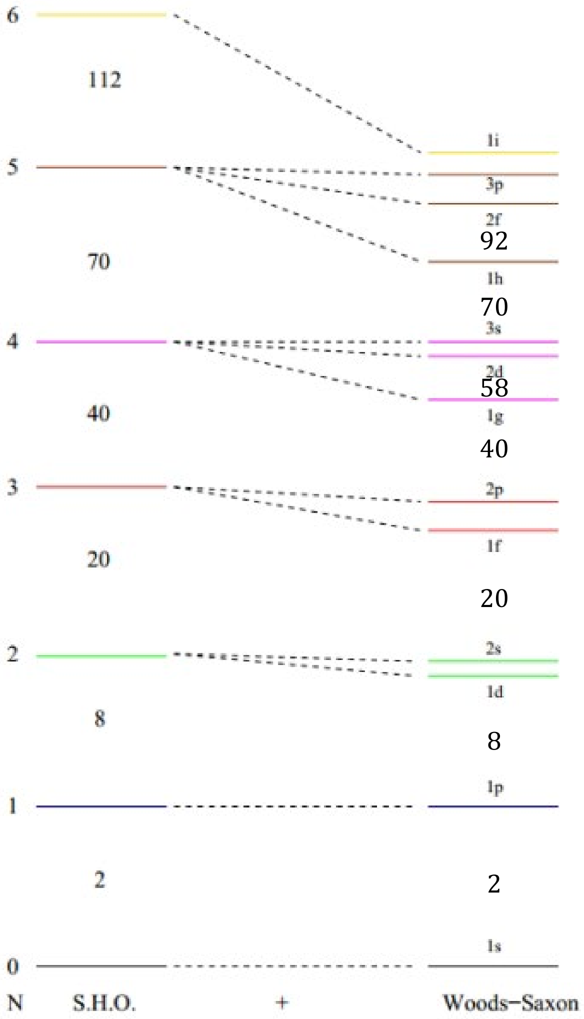
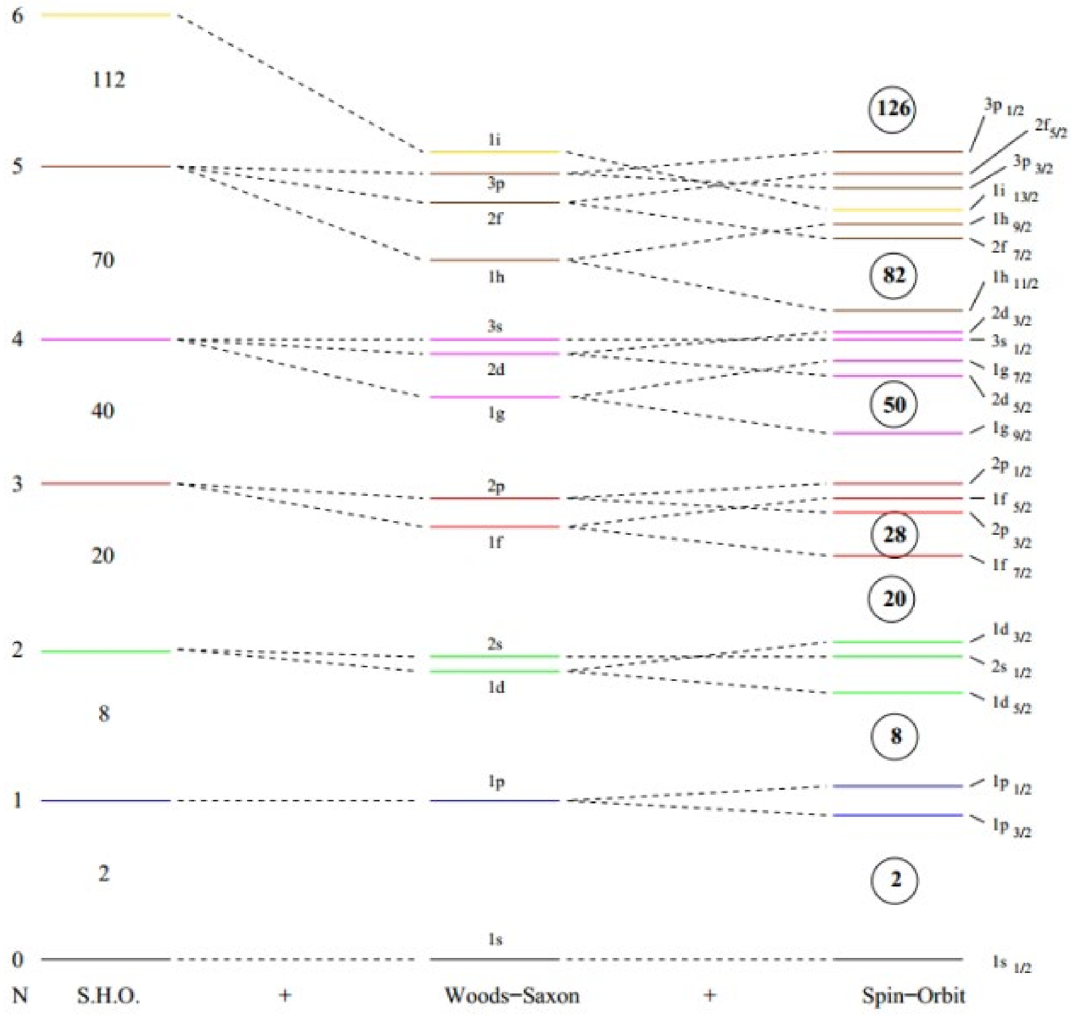
The Woods-Saxon Potential



S.M. Brown, PhD Thesis (2010)

Spin-Orbit Coupling



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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

$$j=\boldsymbol{l}+\boldsymbol{s}=l\pm\frac{1}{2}$$

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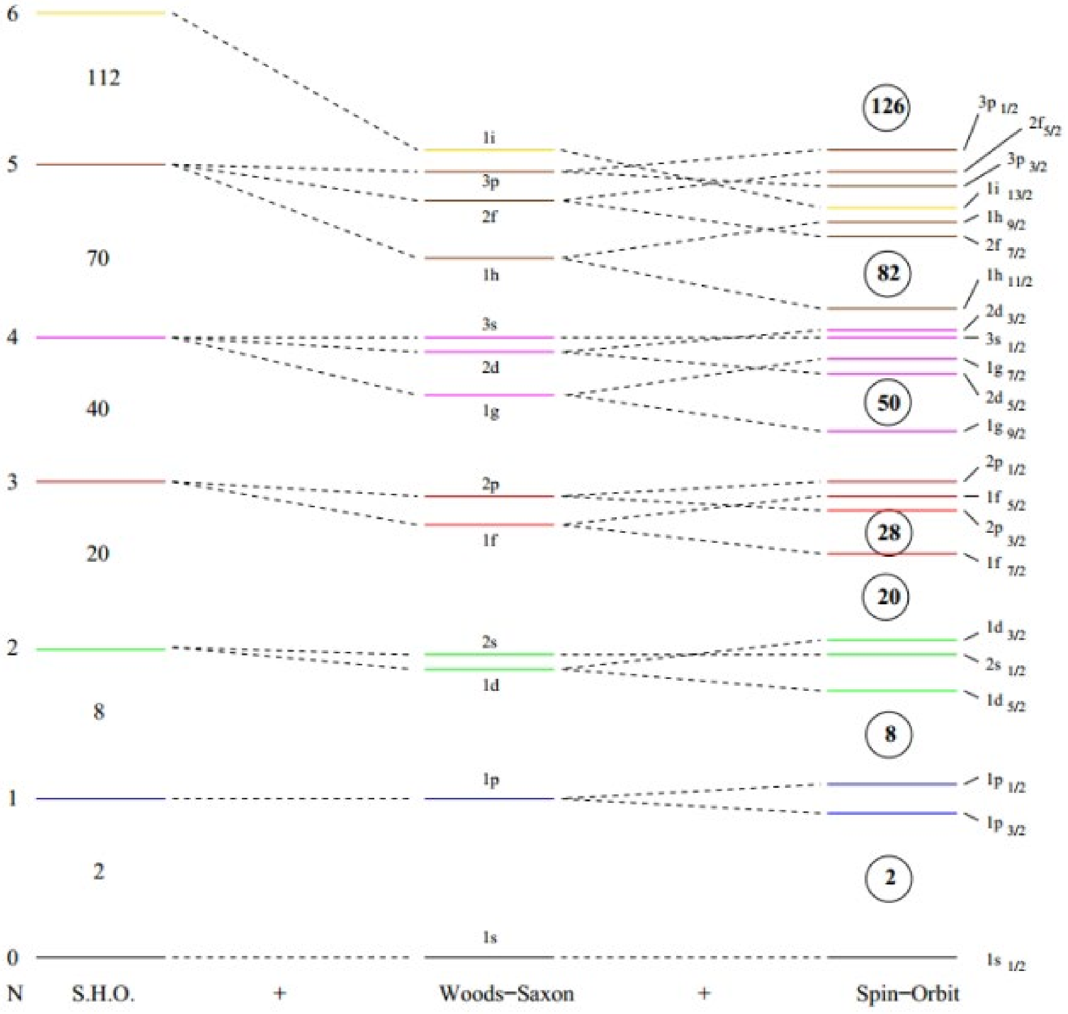

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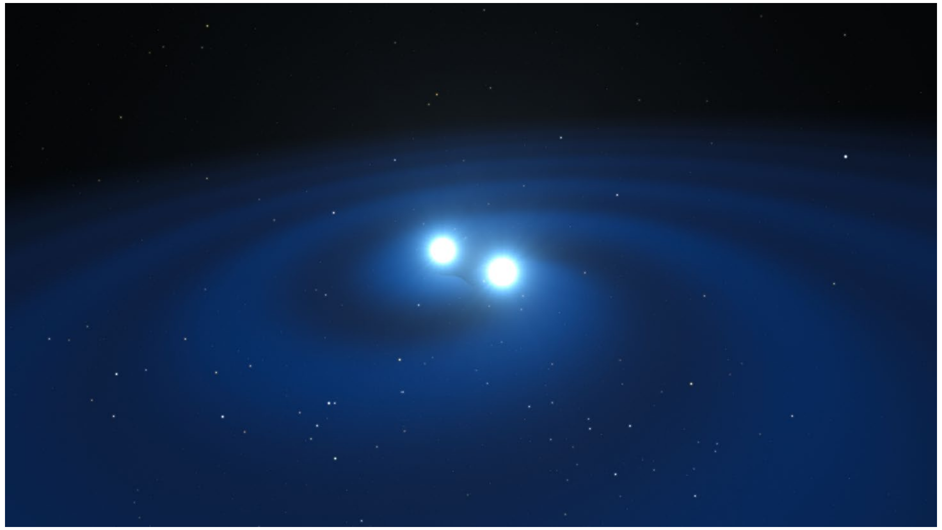
The magic numbers are reproduced exactly!

Shell Model Applications

Okay, but what is the Shell Model good for?

Shell Model Applications—Nuclear Astrophysics



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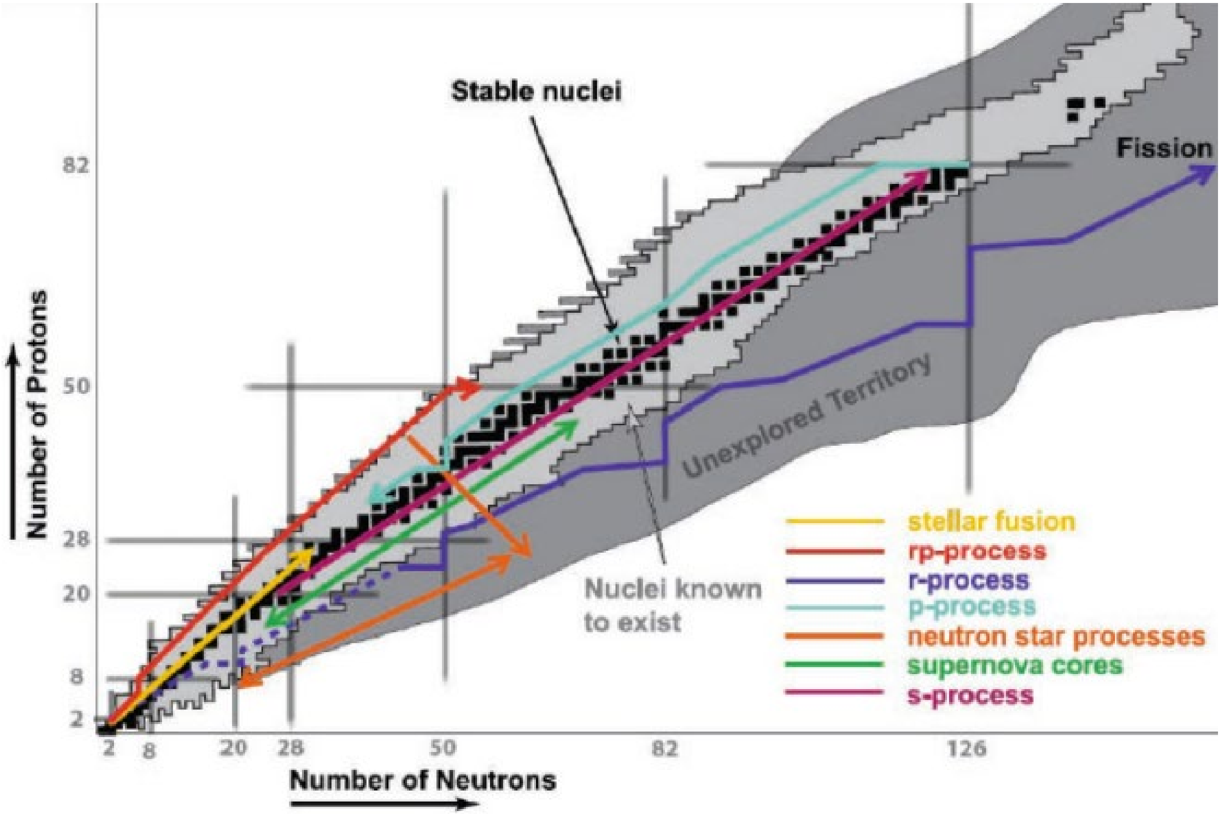
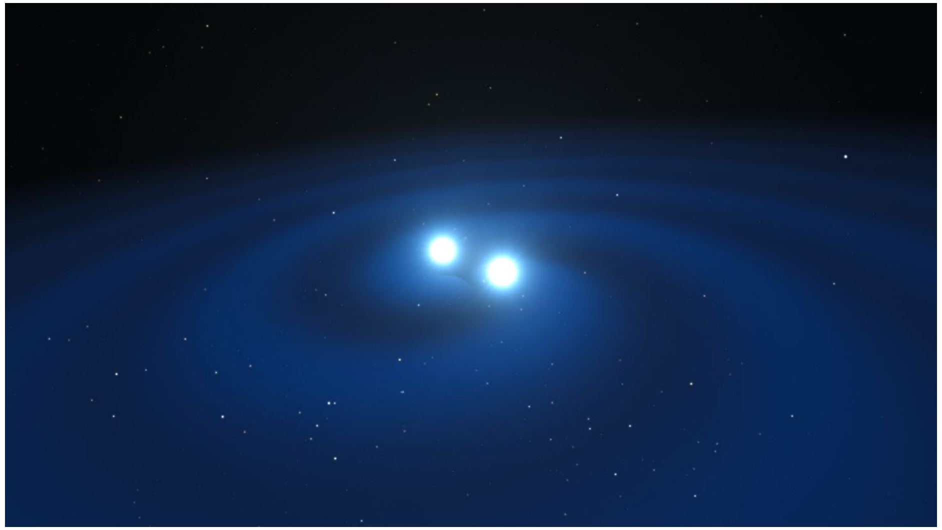
The rapid neutron-capture process (r-process) is responsible for the synthesis of approximately half of all elements heavier than iron

How are the chemical elements made?



From F. Timmes

Shell Model Applications—Nuclear Astrophysics



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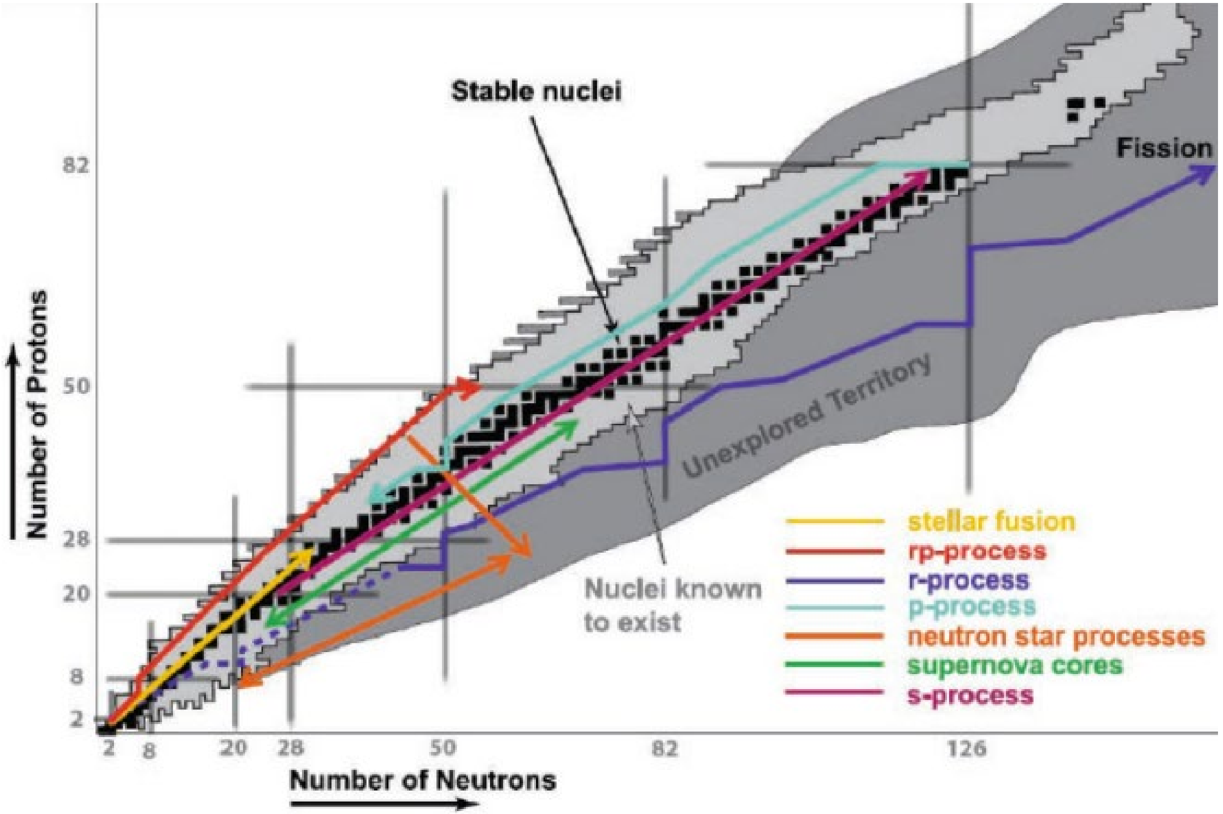

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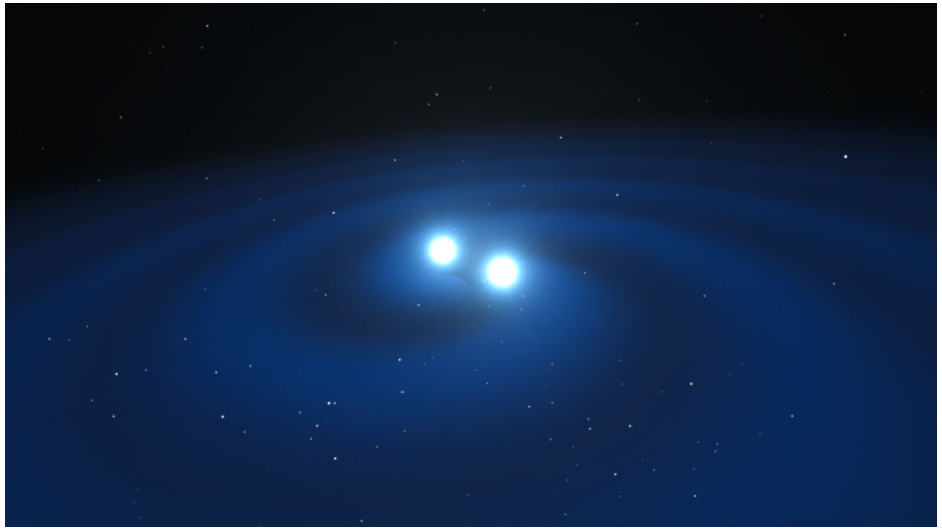

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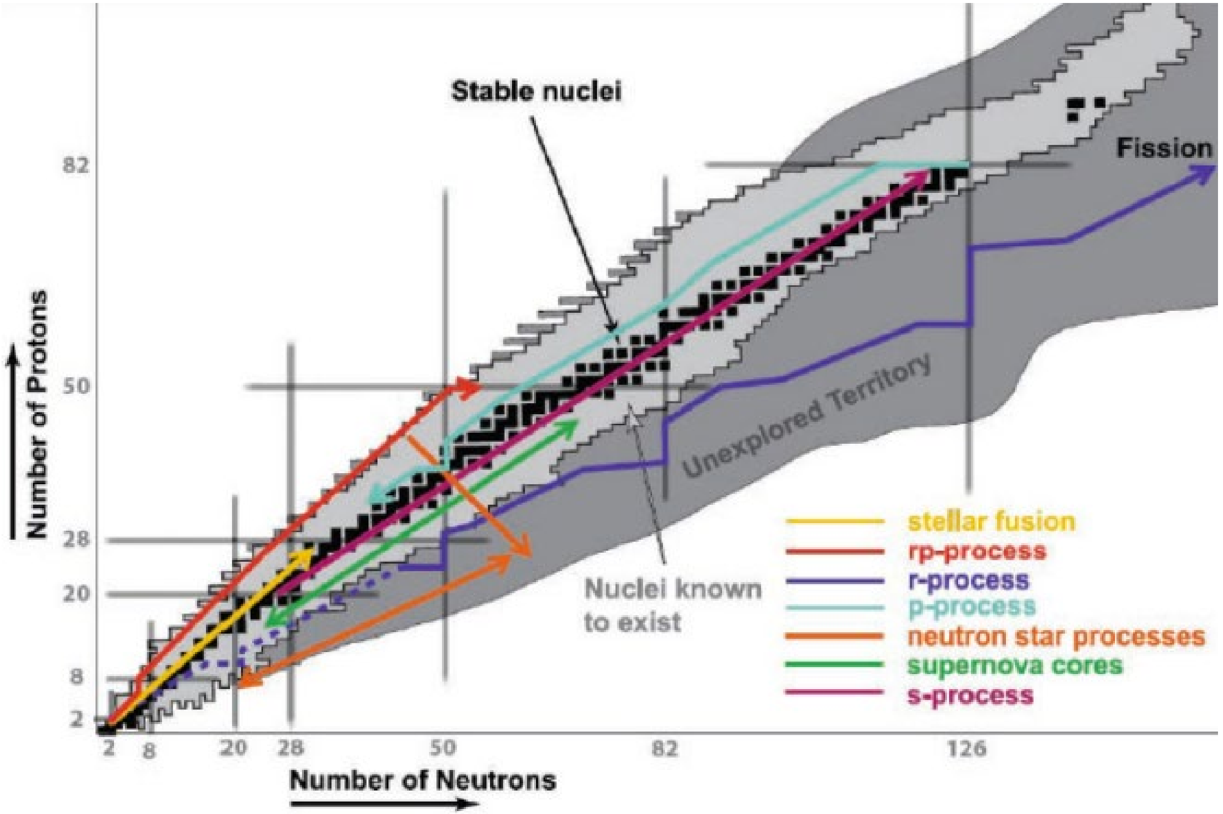

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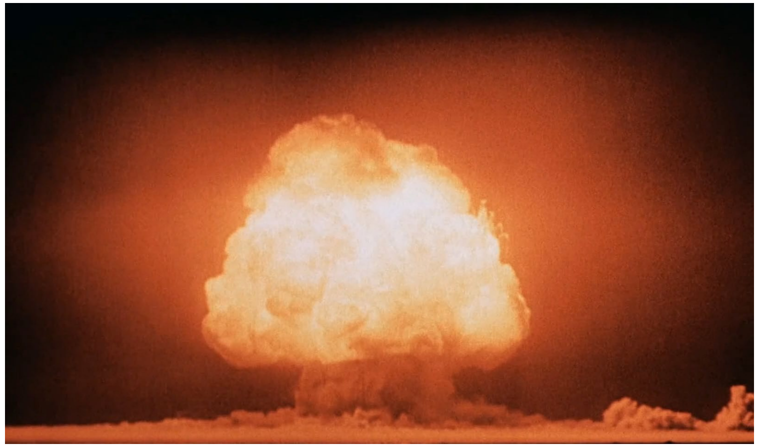
We cannot measure neutron-capture reactions on all the isotopes of importance

Can we predict them instead?

Shell Model Applications—Stockpile Stewardship



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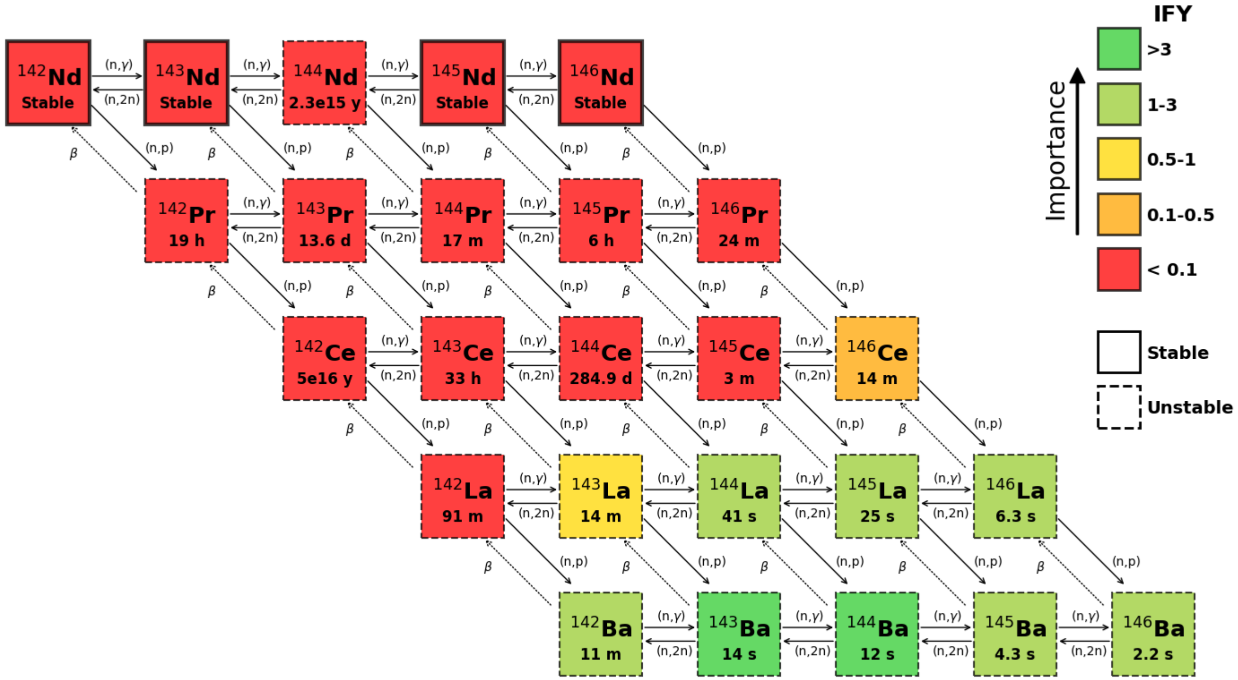


J. Carlson, *et al.*, Prog. Part. Nucl. Phys. **94**, 68 (2017).

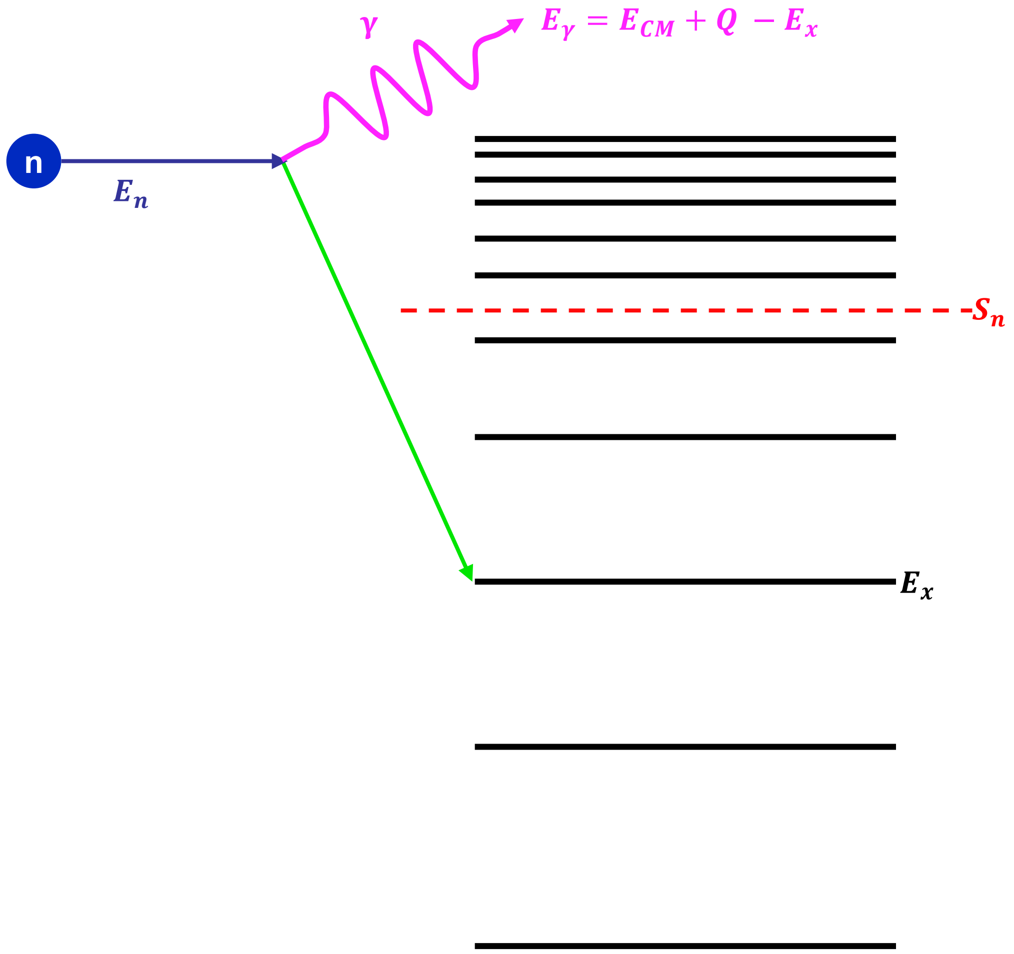
All the most important neutron-induced reactions affecting the production of stockpile stewardship diagnostic ^{144}Ce involve highly unstable isotopes

Can we predict these reactions?

Direct/Semi-Direct (DSD) Neutron Capture

- Neutron is captured directly into a low-lying, 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

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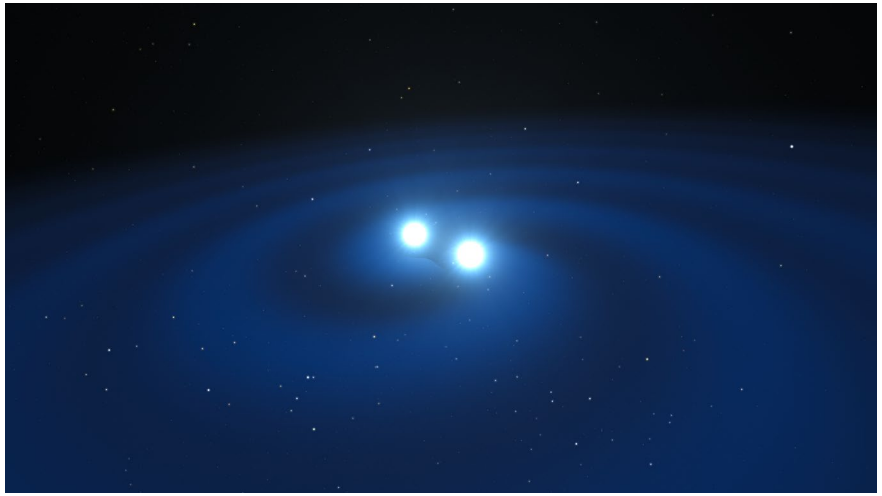
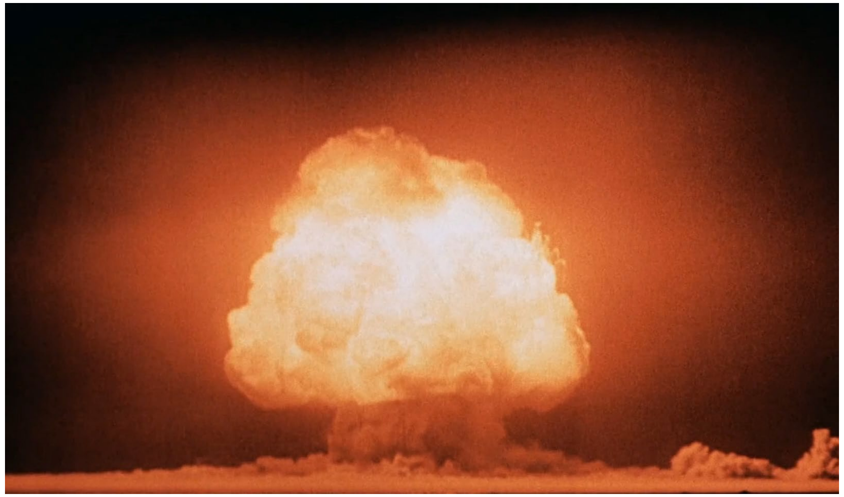
An accurate Shell Model enhances predictions of nuclear properties that cannot be measured in the laboratory





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How do we know when the Shell Model is correct?

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We test it!

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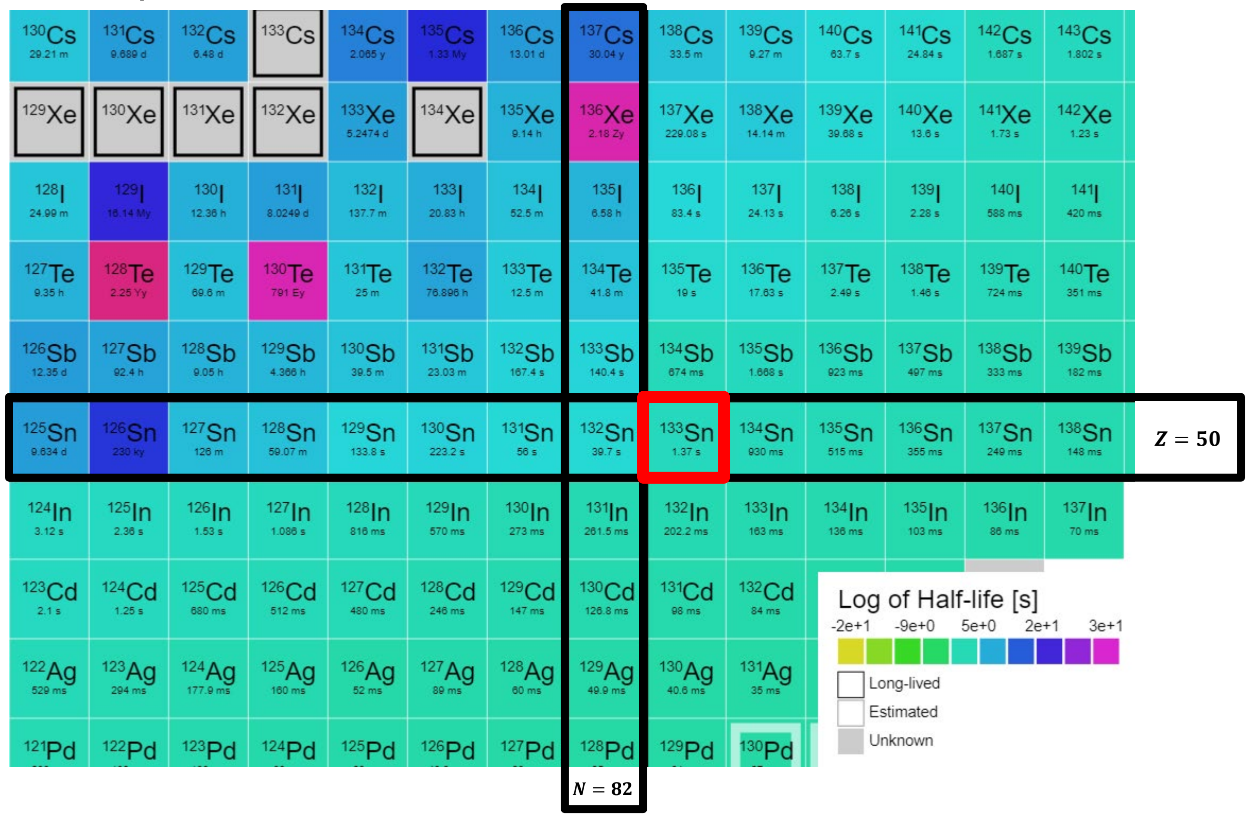
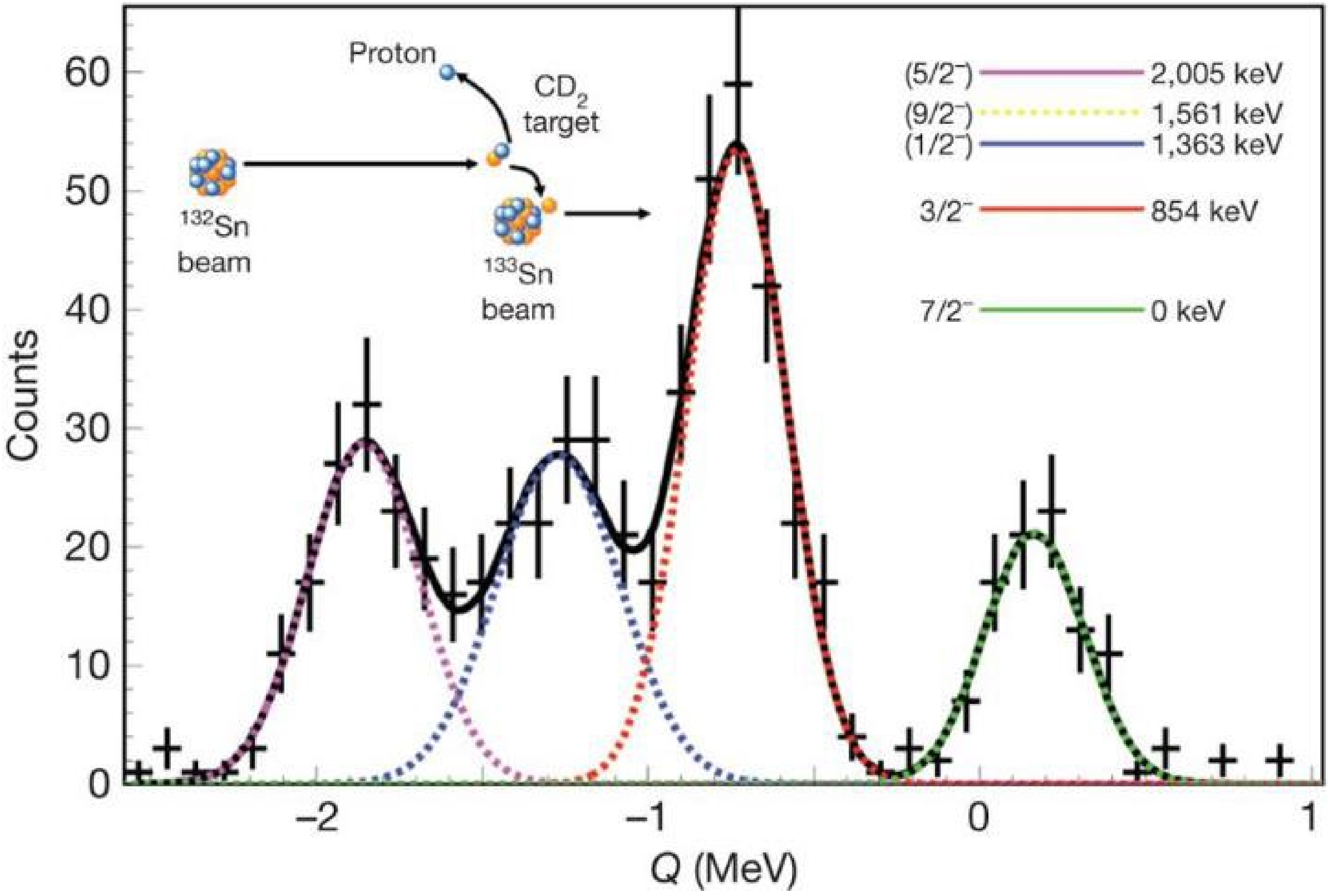
Example: ^{133}Sn



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

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

$^{132}Sn(d,p)^{133}Sn$



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

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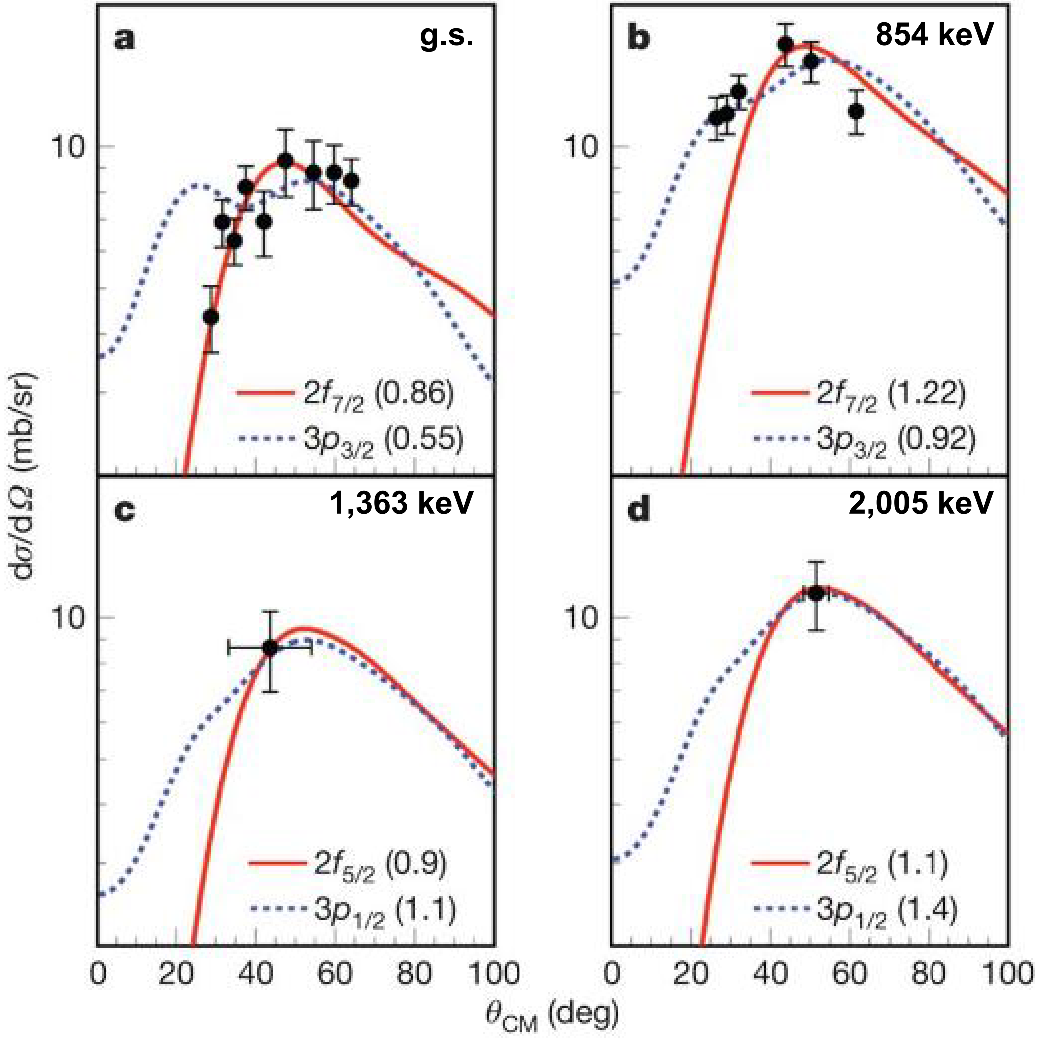

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Define a *spectroscopic factor*, S:

$$S_i = \left(\frac{d\sigma_i}{d\Omega}\right)_{exp} / \left(\frac{d\sigma_i}{d\Omega}\right)_{theory}$$

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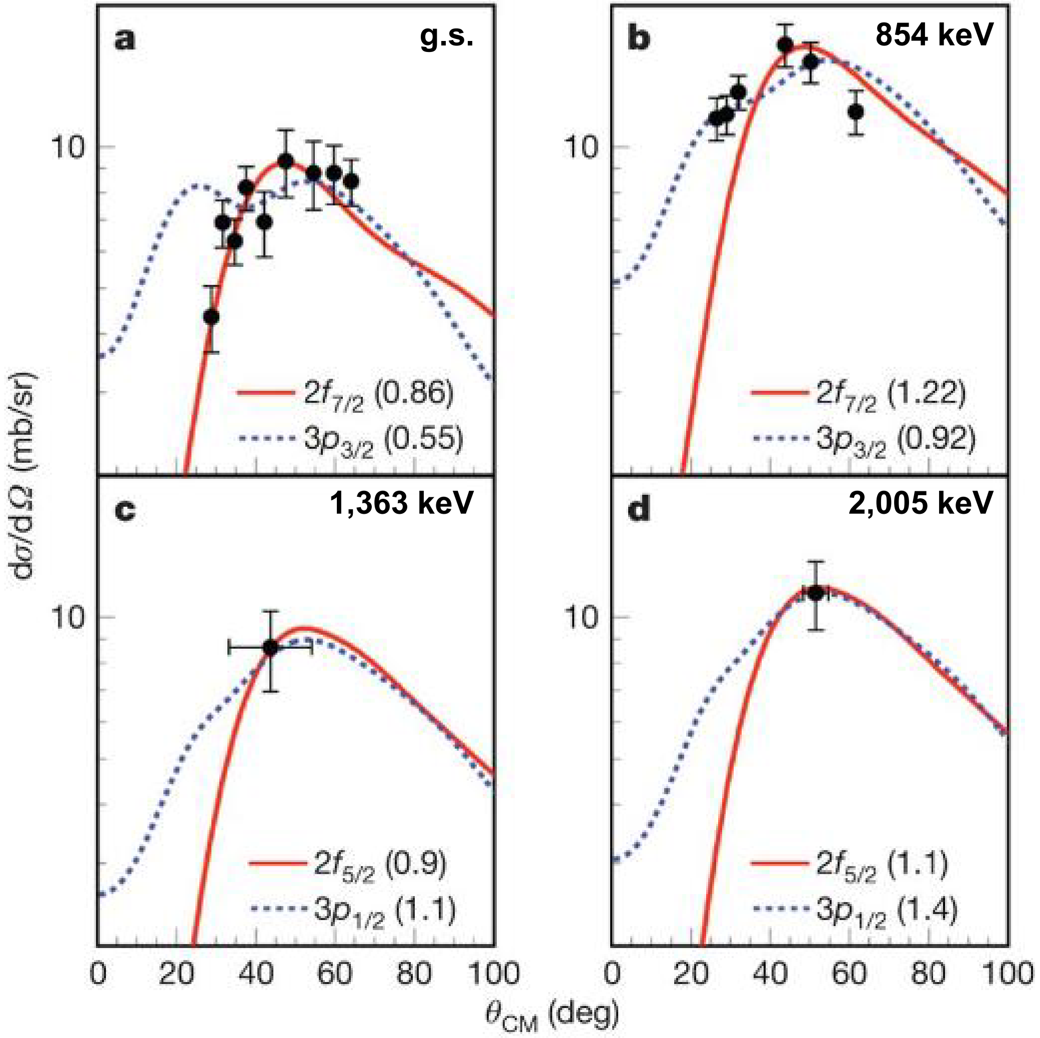

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$S \approx 1$ for all states indicates purely single-neutron structure!

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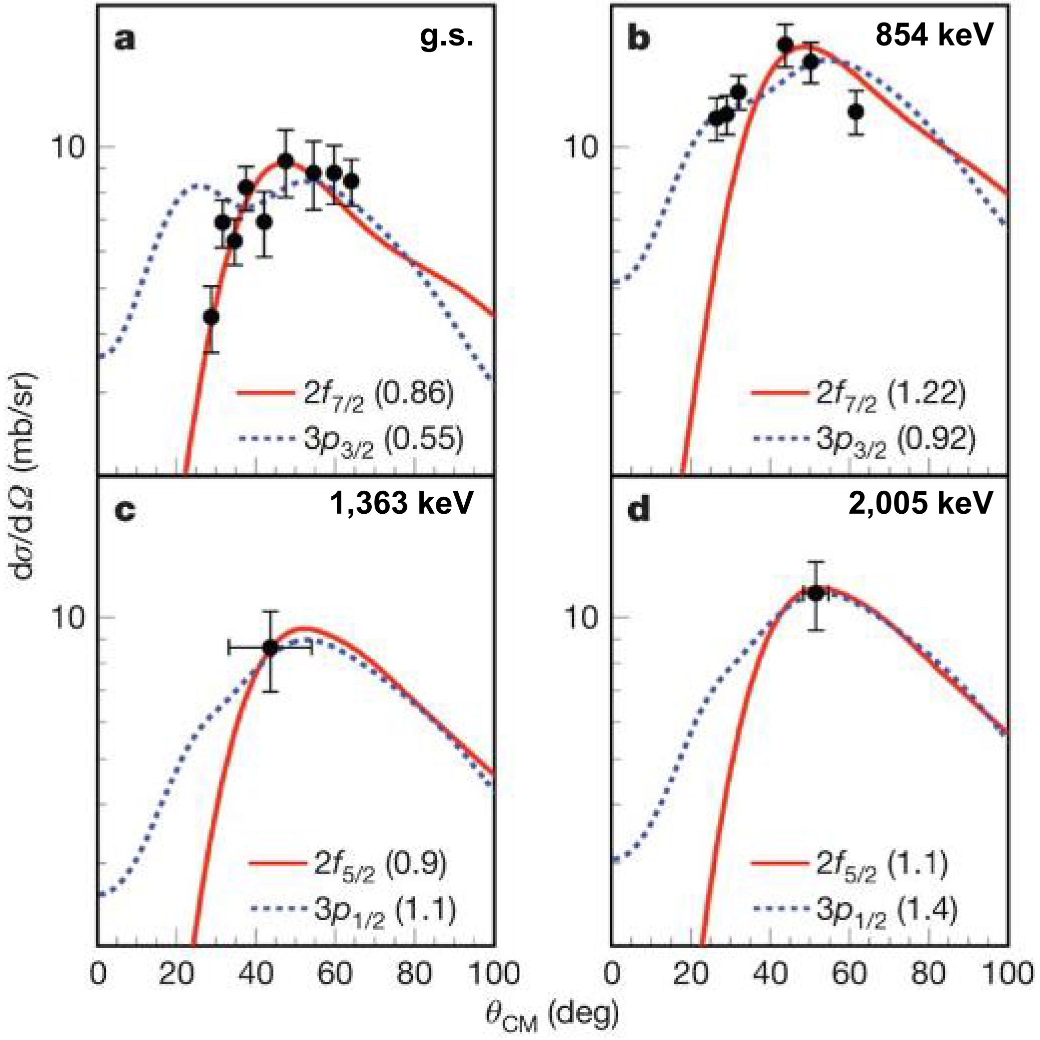

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E_x (keV)	J^π	S
0	$7/2^-$	0.86 ± 0.16
854	$3/2^-$	0.92 ± 0.18
1363 ± 31	$(1/2^-)$	1.1 ± 0.3
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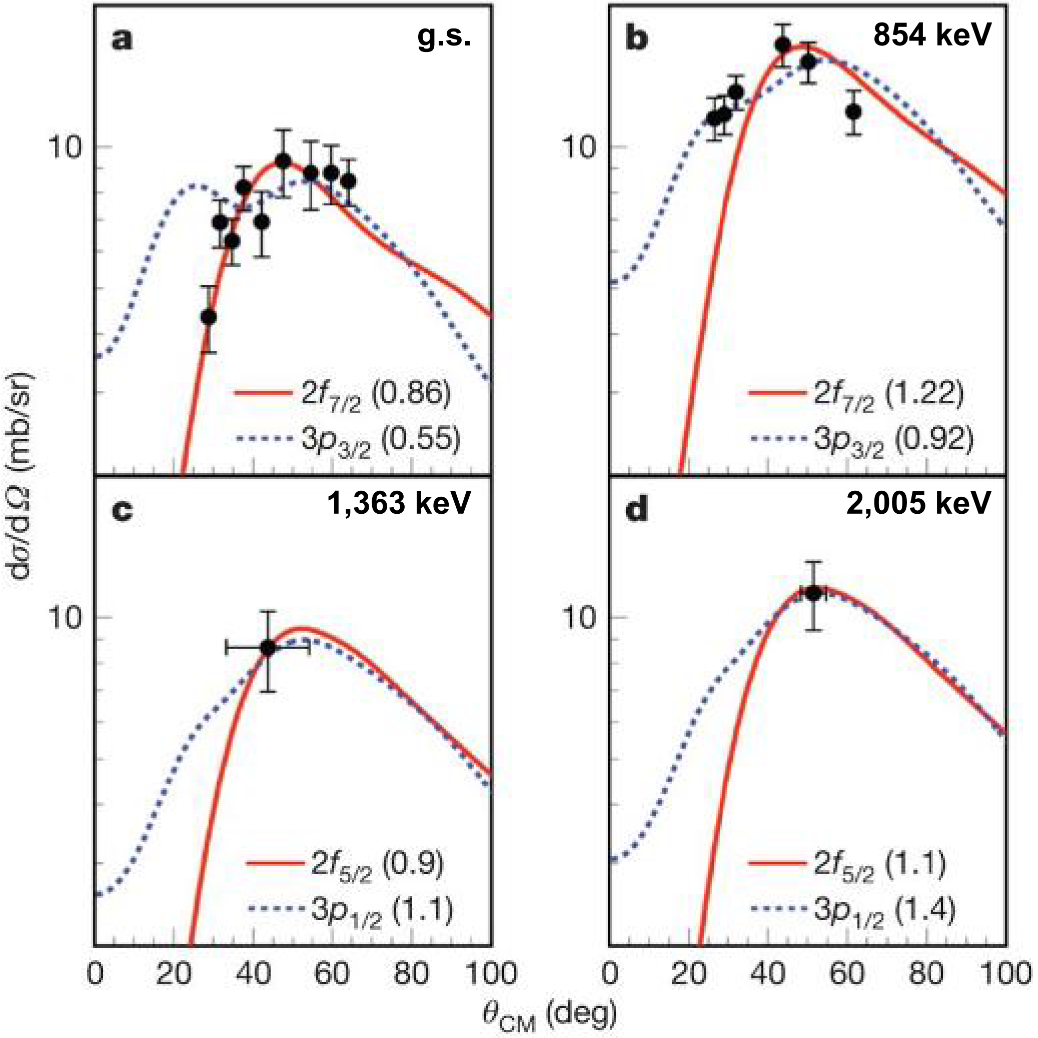

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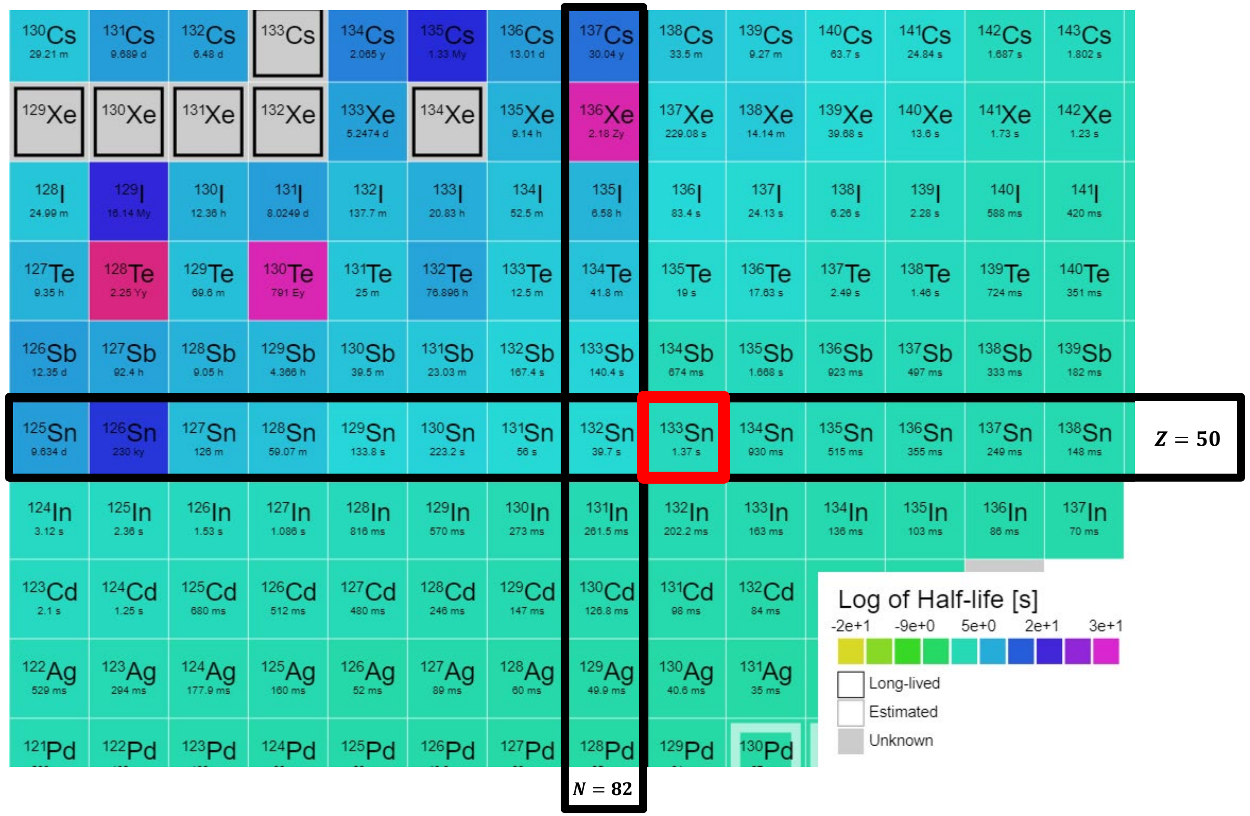
^{133}Sn perfectly exhibits the pure single-neutron structure predicted by the shell model

Shell Model Tests

Example: ^{133}Sn



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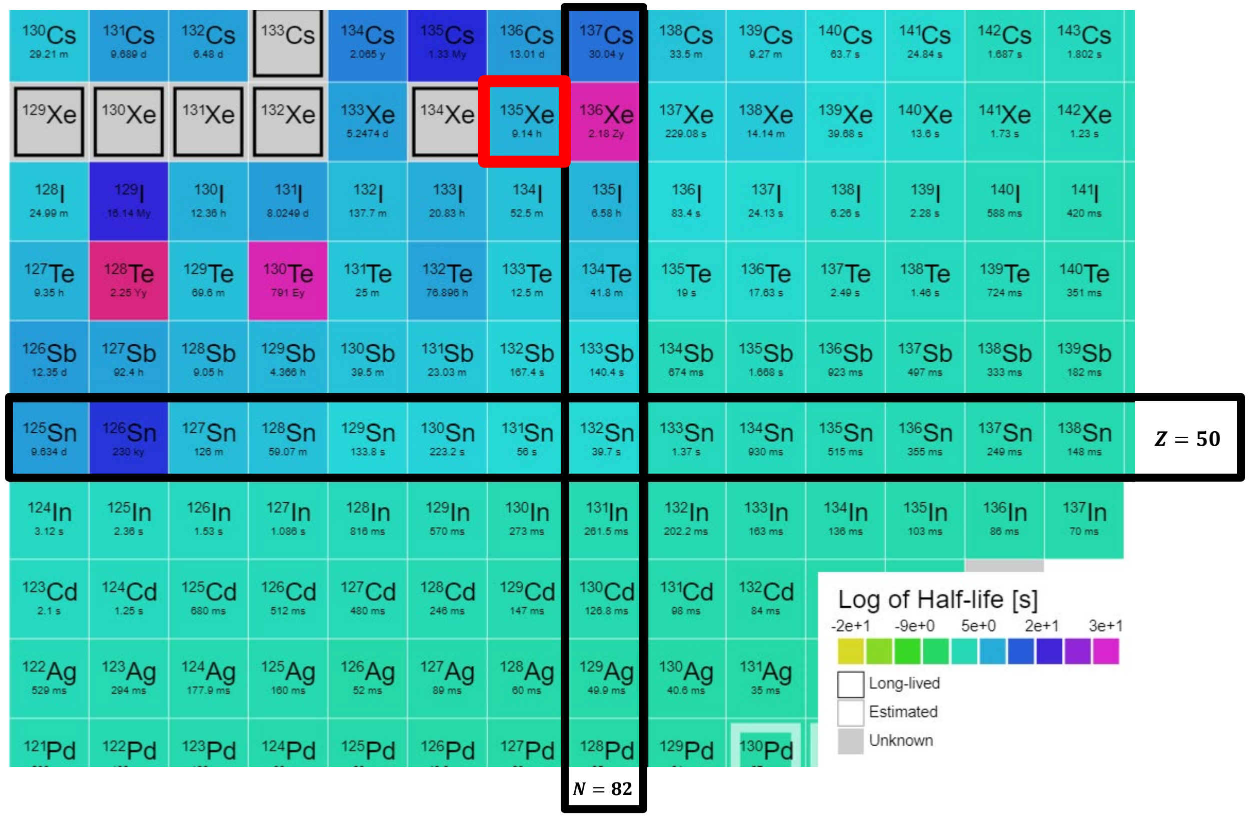
Shell Model Tests

Example: ^{135}Xe

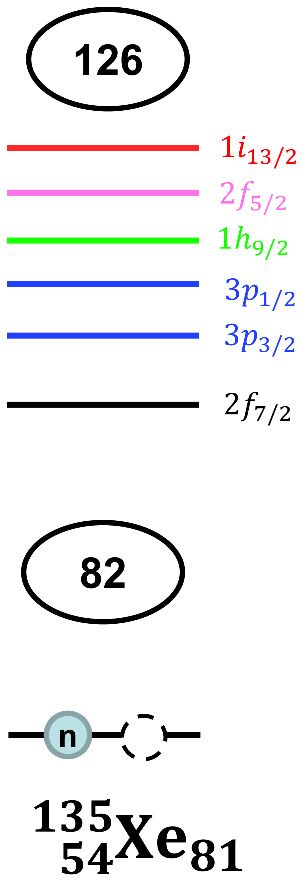


Modified from people.physics.anu.edu/~ecs103/chart-beta/

What happens when we move further from the shell closures?

^{135}Xe

$^{135}_{54}\mathrm{Xe}_{81}$ has a single, unpaired neutron lying just below the $N = 82$ shell gap



^{135}Xe

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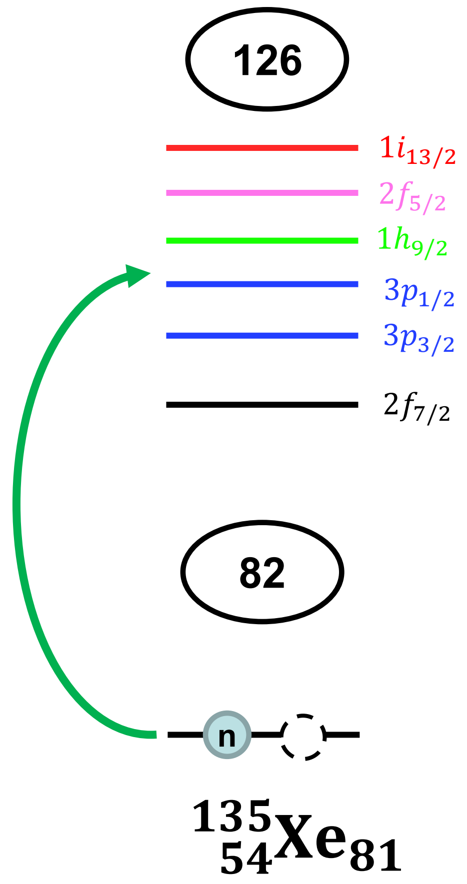
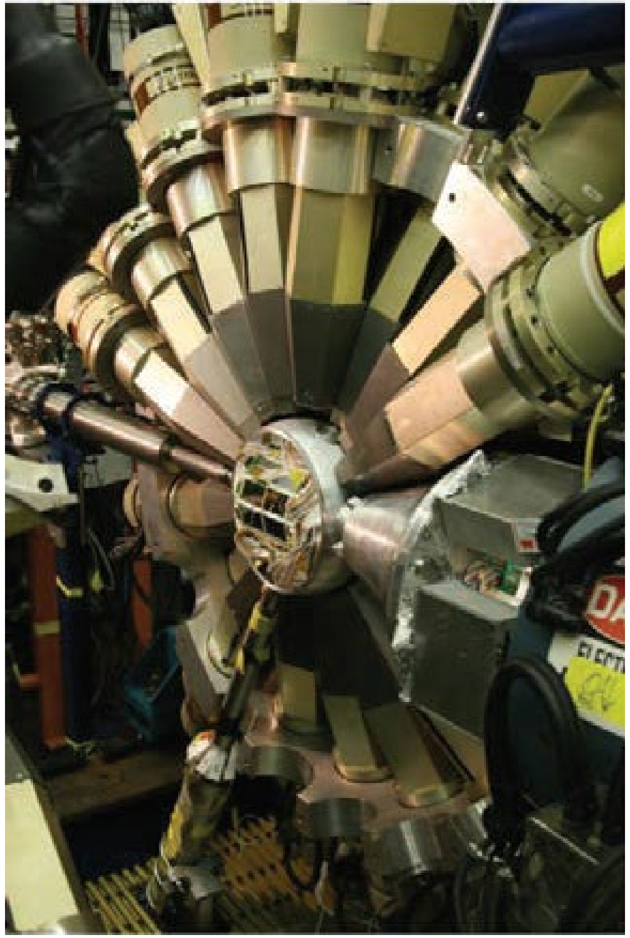
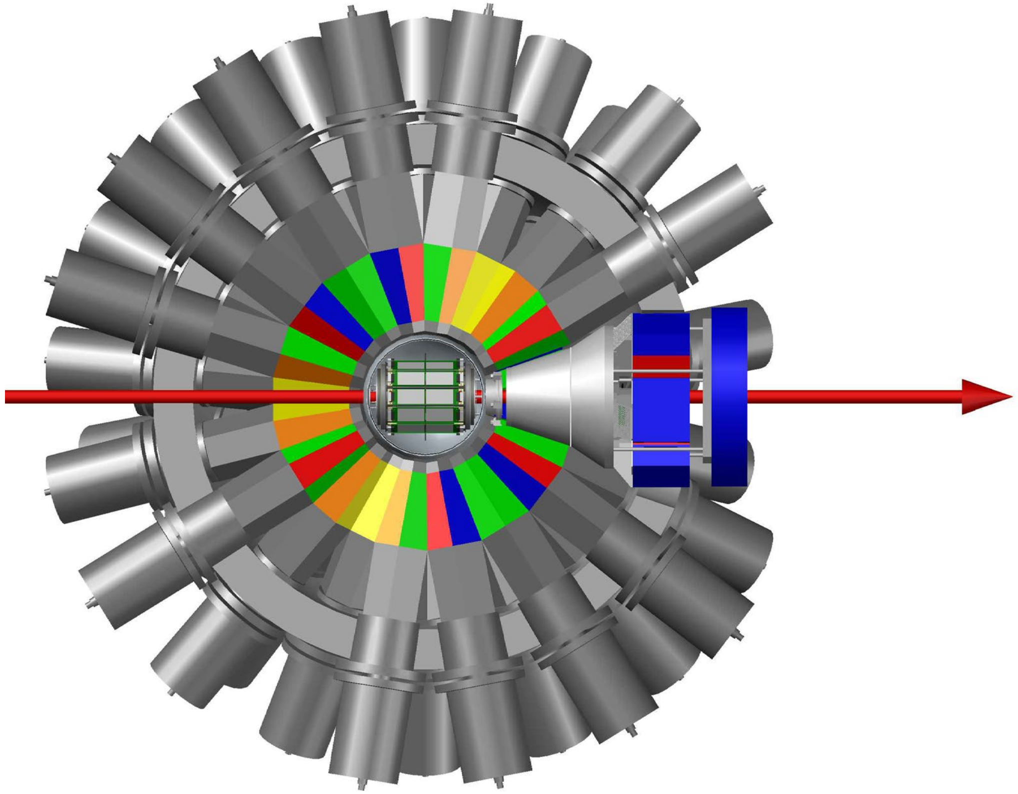
Single-neutron excitations will require crossing the shell gap



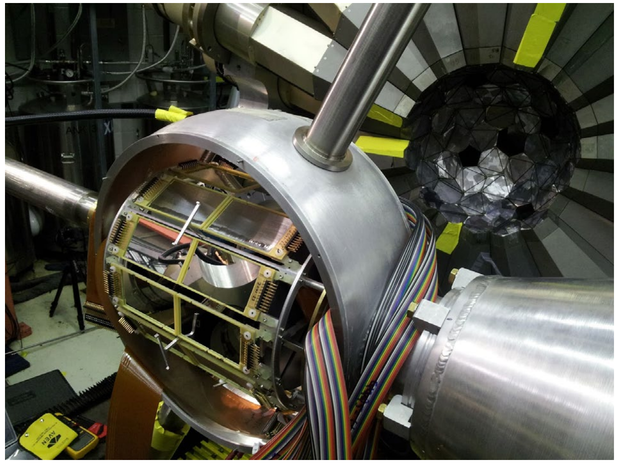
Gammasphere-ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS)

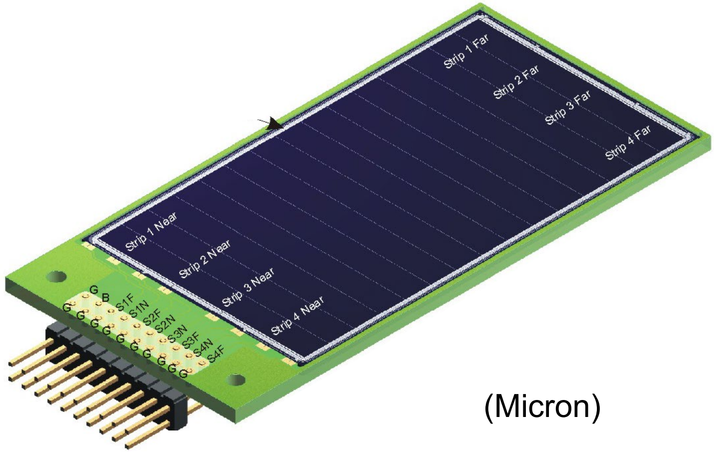




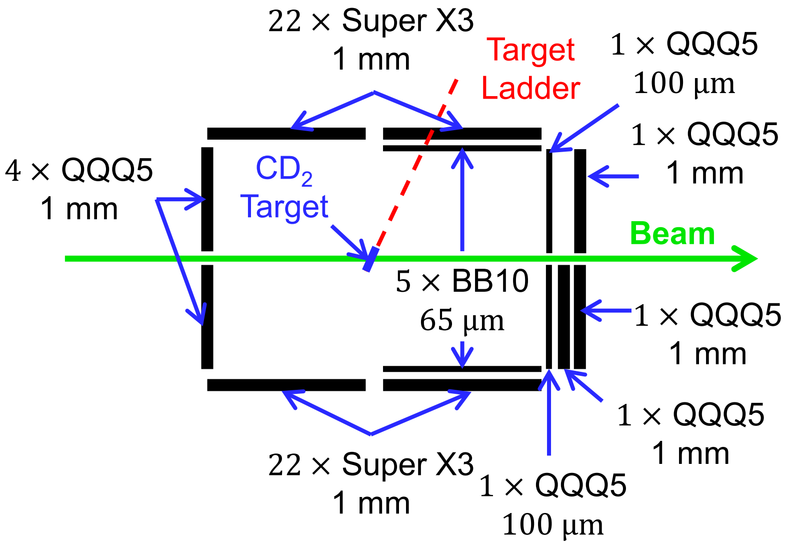
From S.D. Pain, *et al.*, Physics Procedia **90**, 455 (2017).

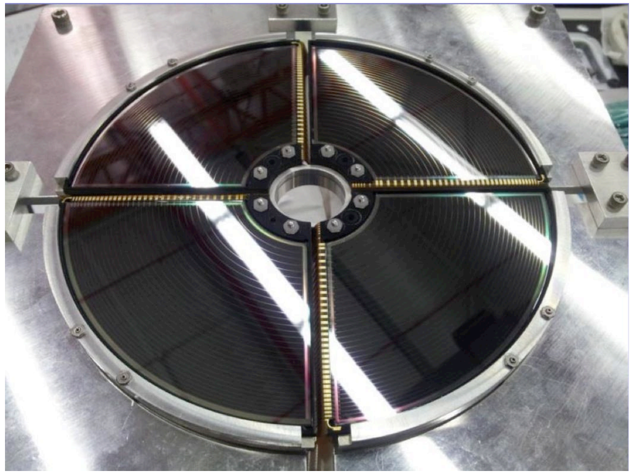
Oak Ridge Rutgers University Barrel Array (ORRUBA)





(Micron)





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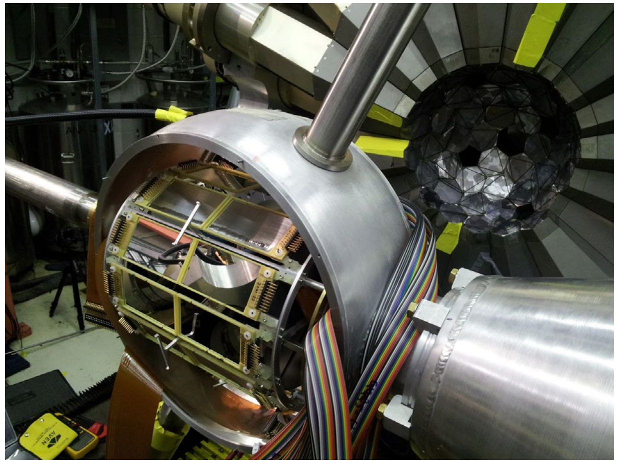
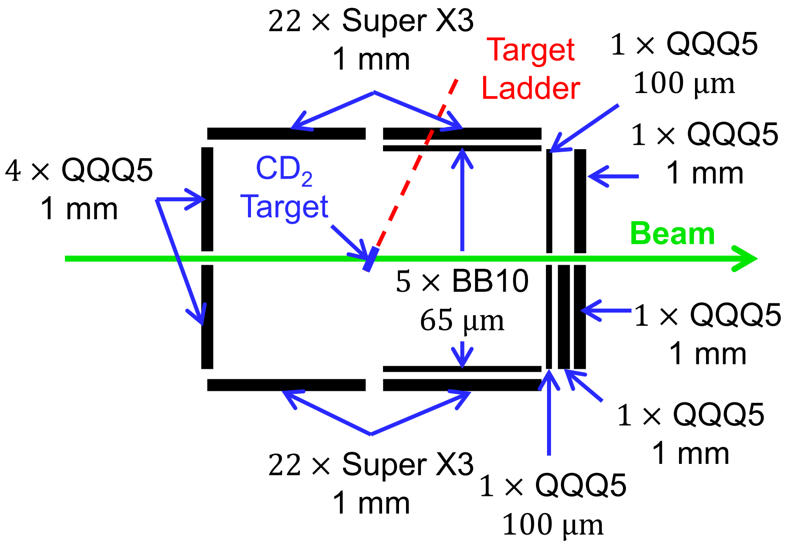
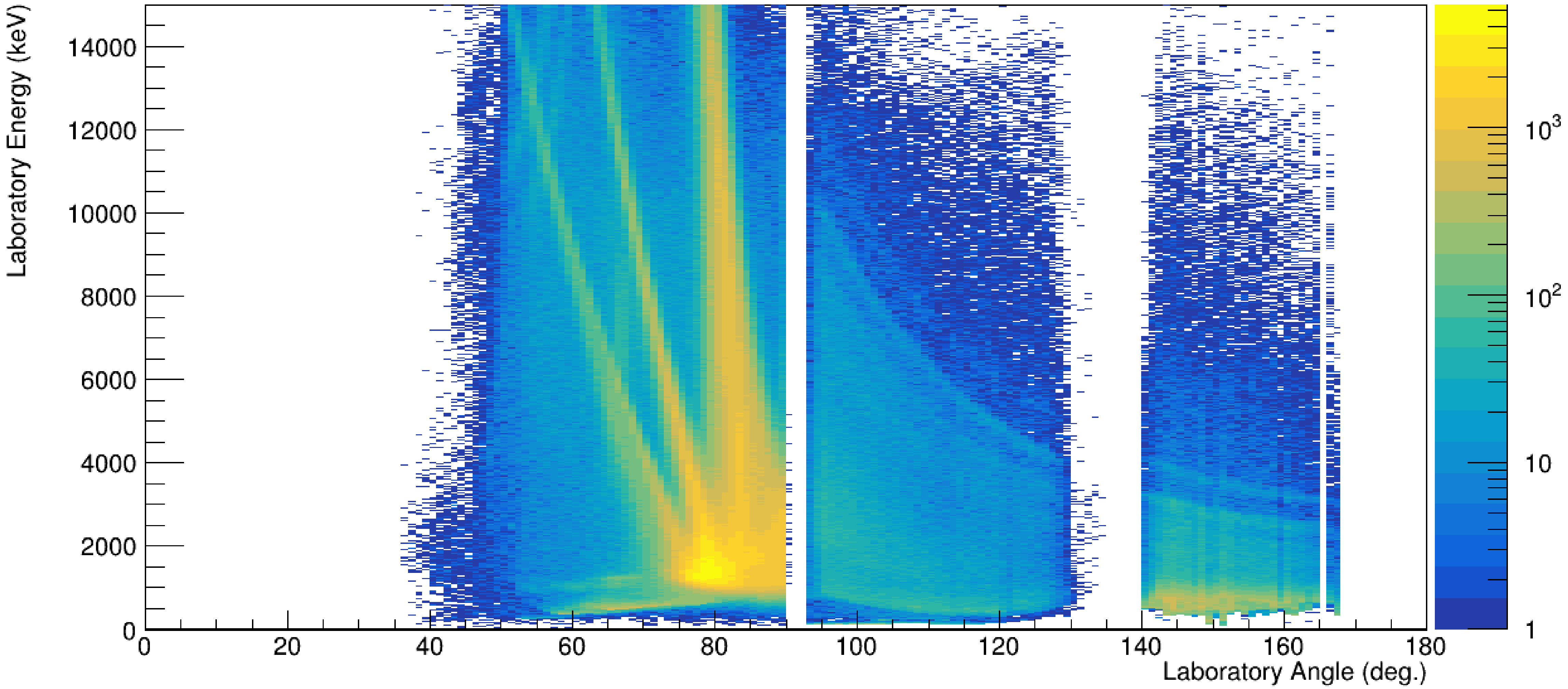




Gammasphere

Preliminary Results

Preliminary Results—Si E_{tot} vs. θ



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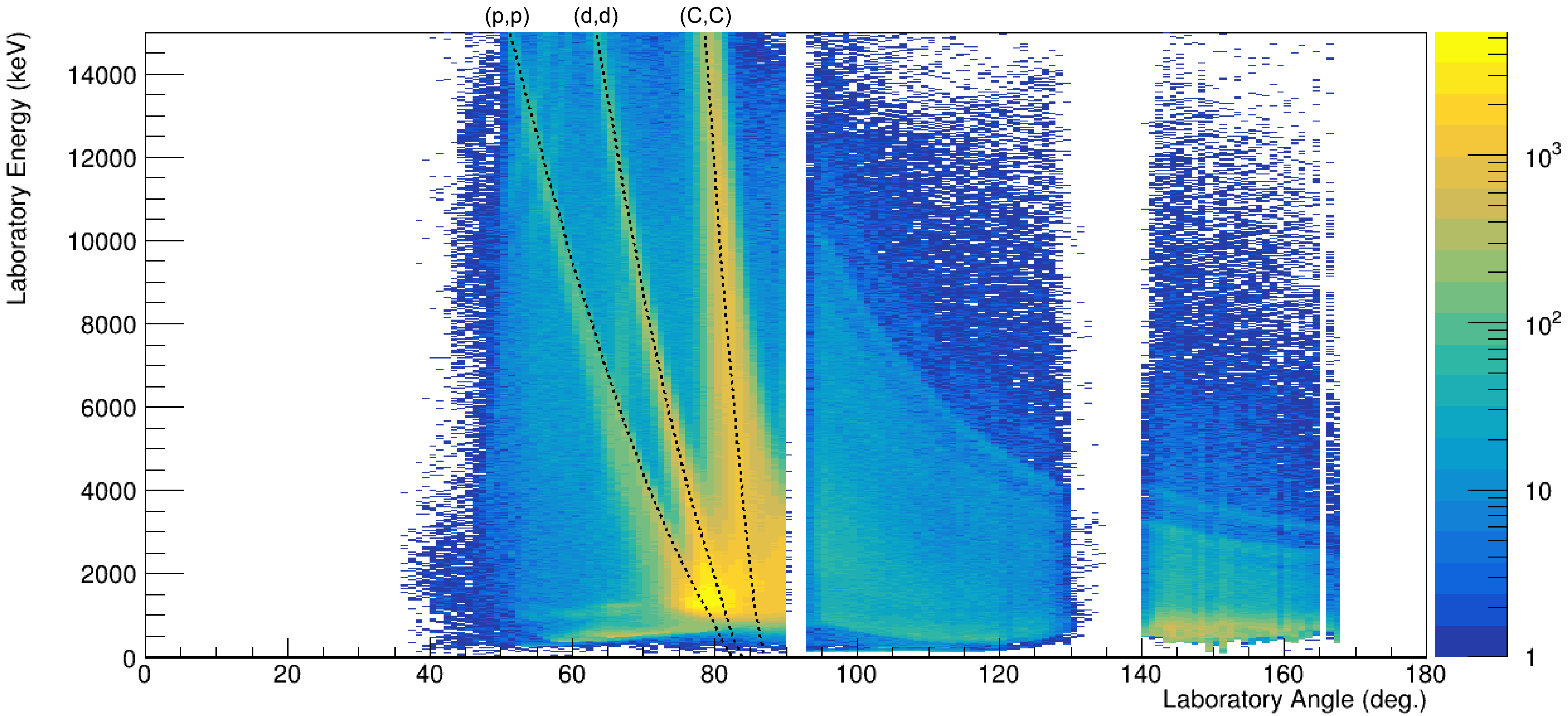

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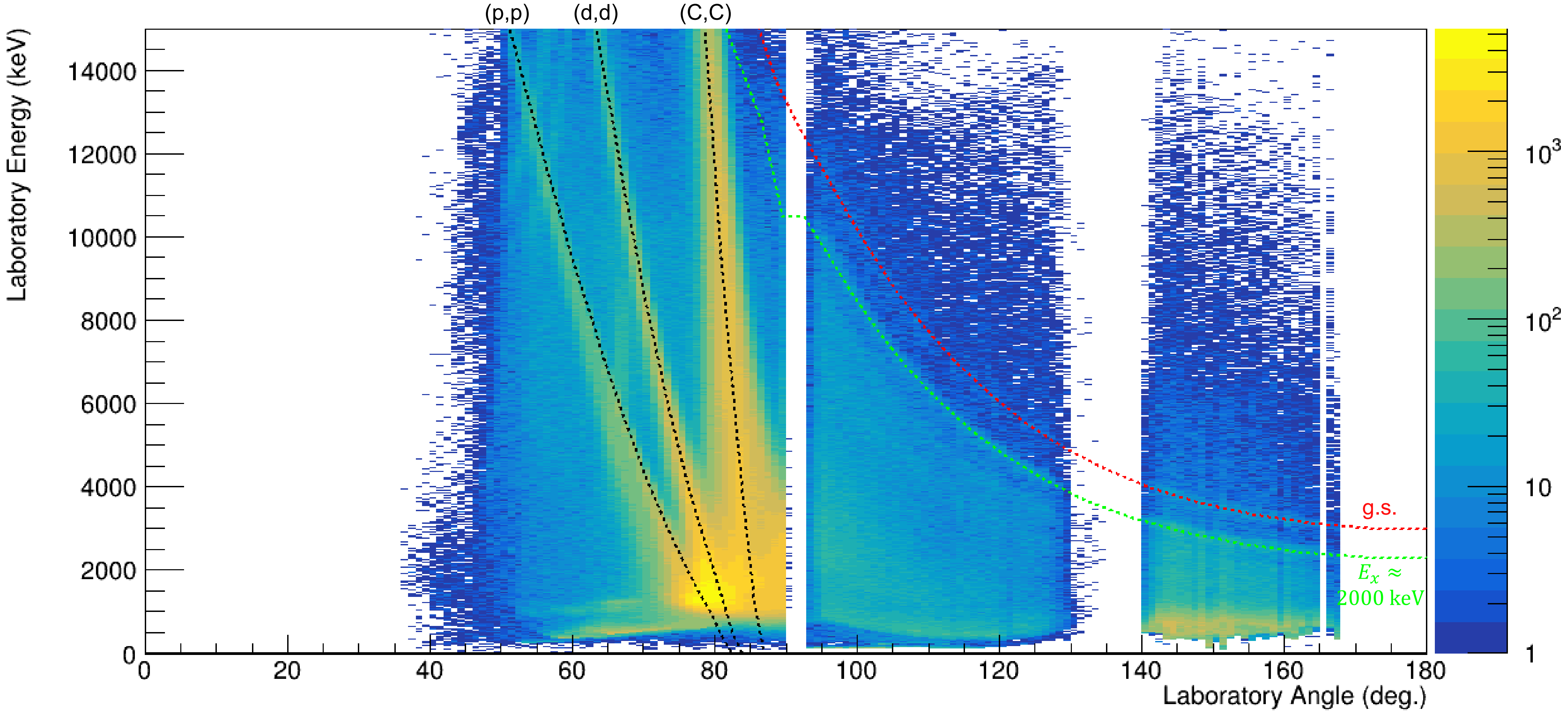
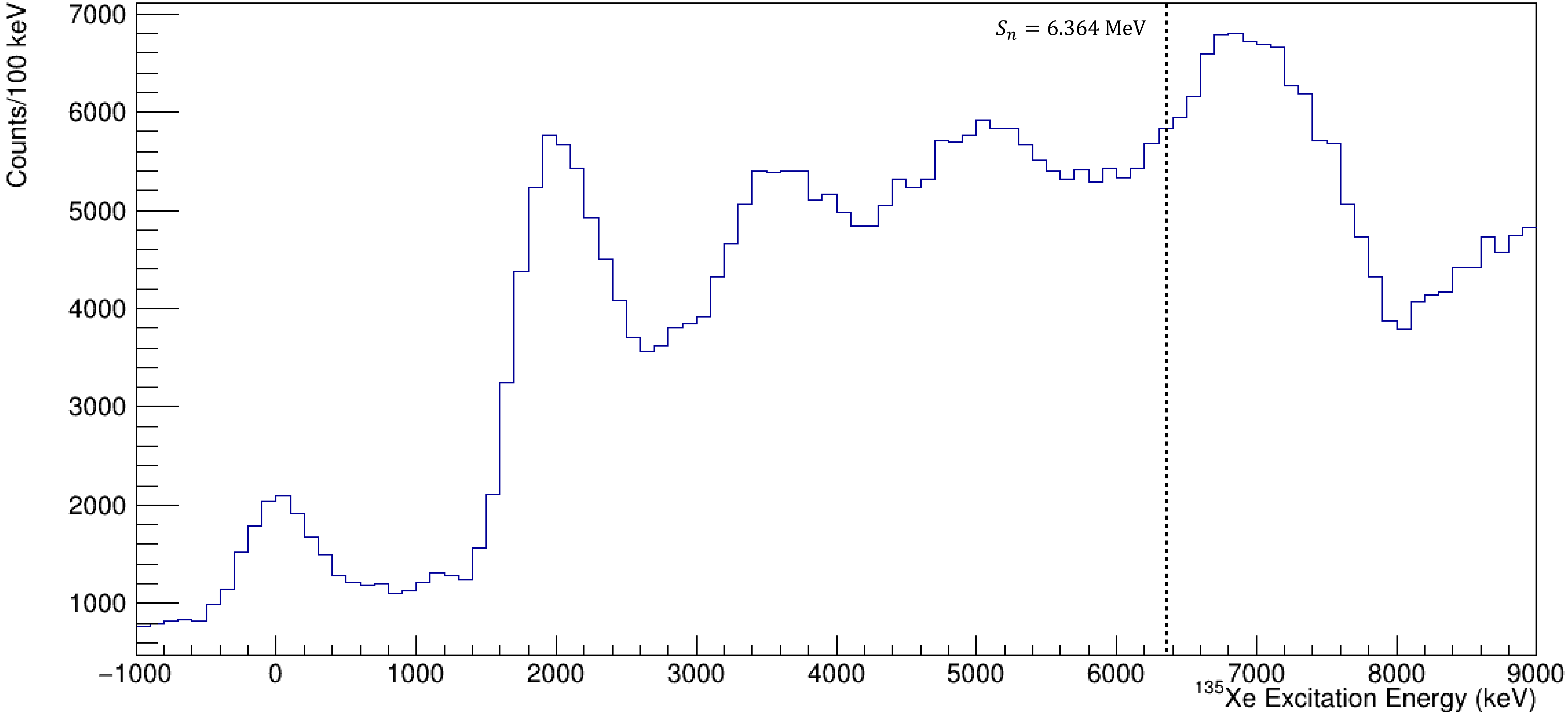
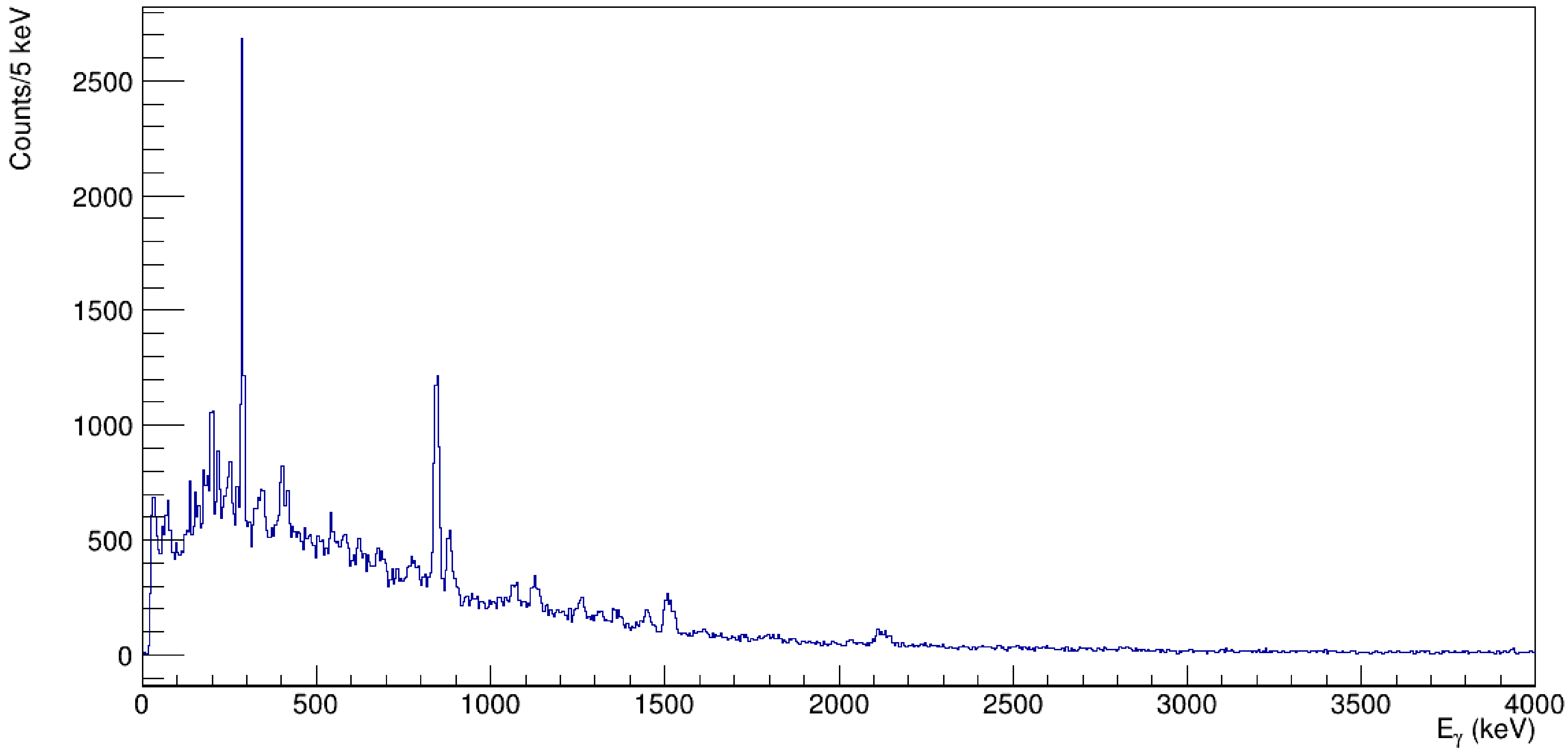


Preliminary Results—^{135}Xe Excitation Energy Spectrum



Preliminary Results—Gamma Rays



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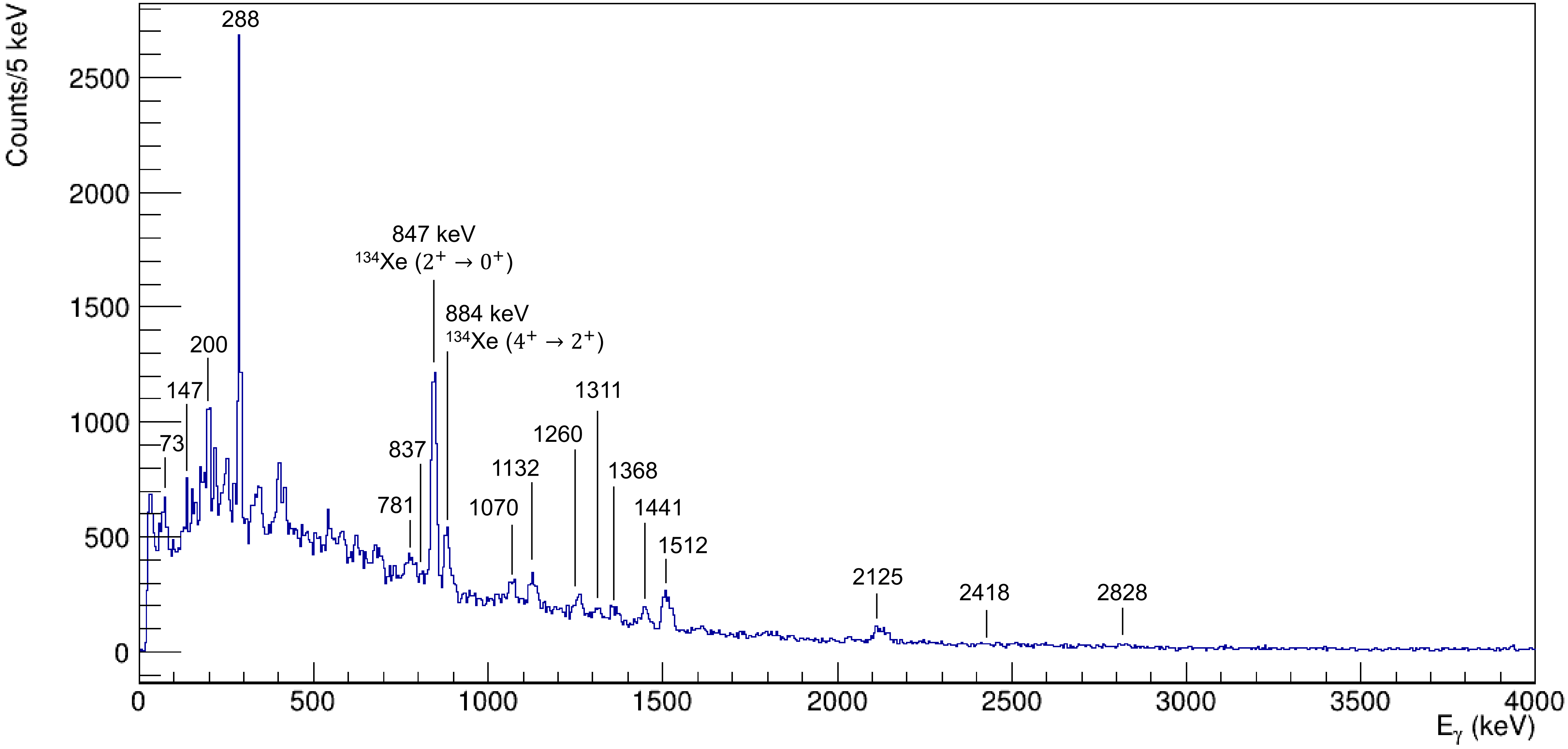

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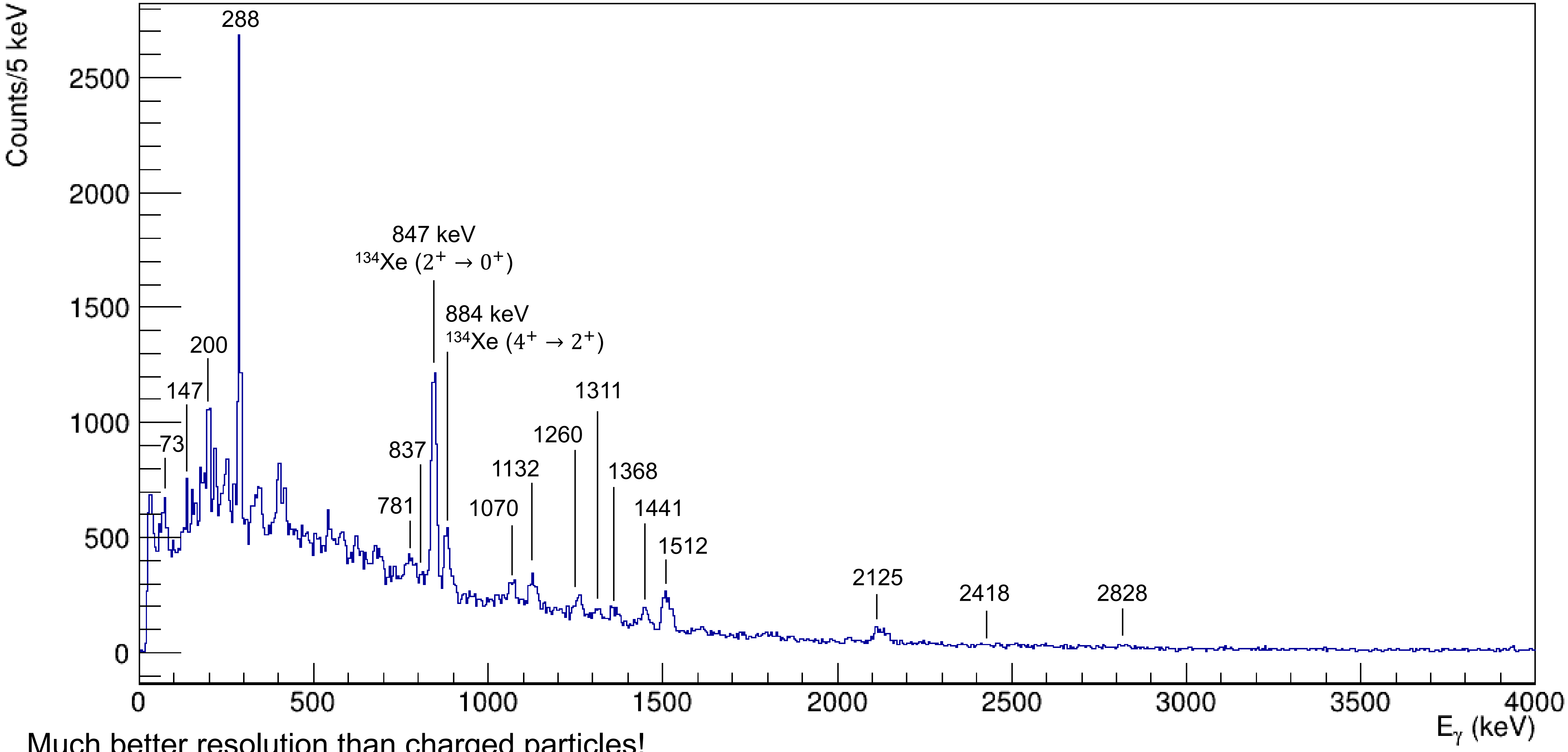
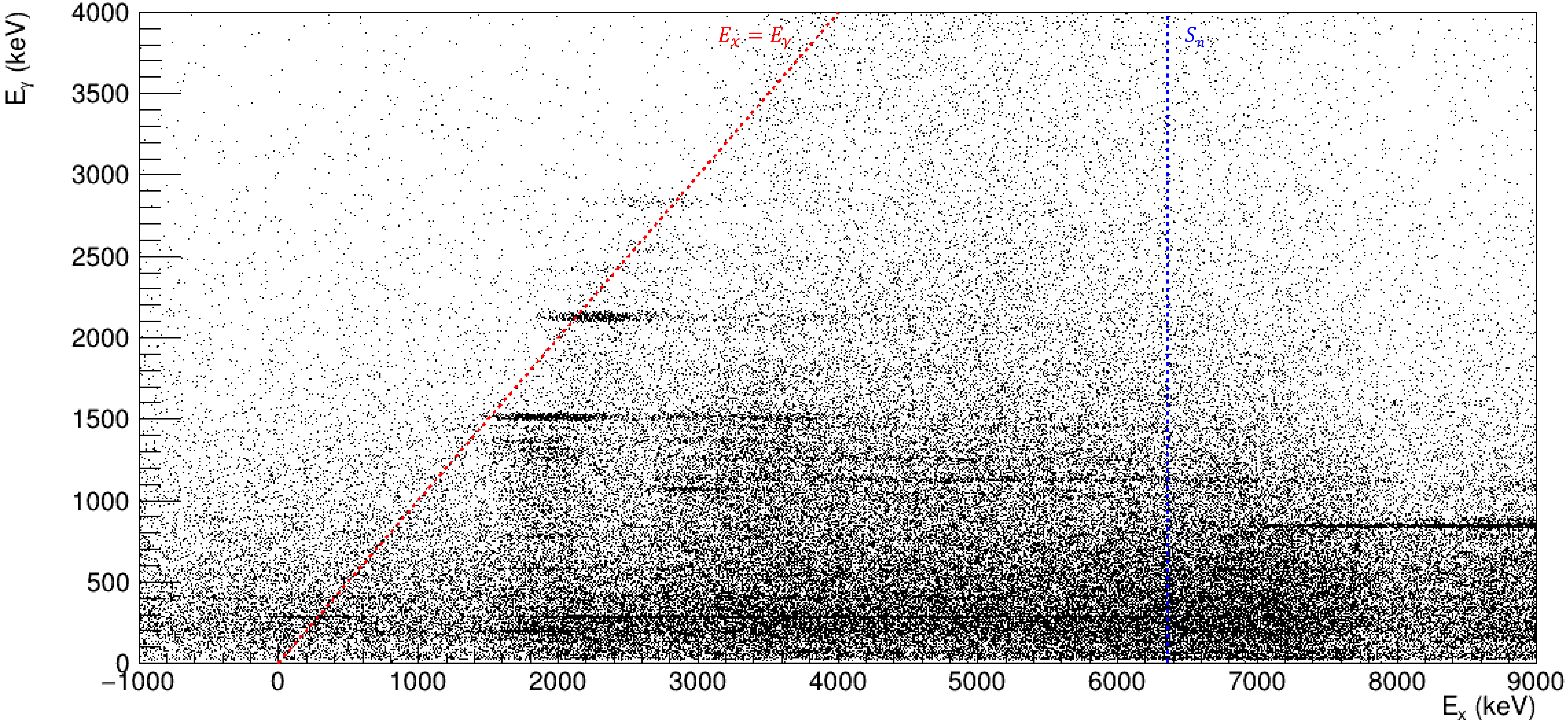


Much better resolution than charged particles!

Preliminary Results – Coincidences!



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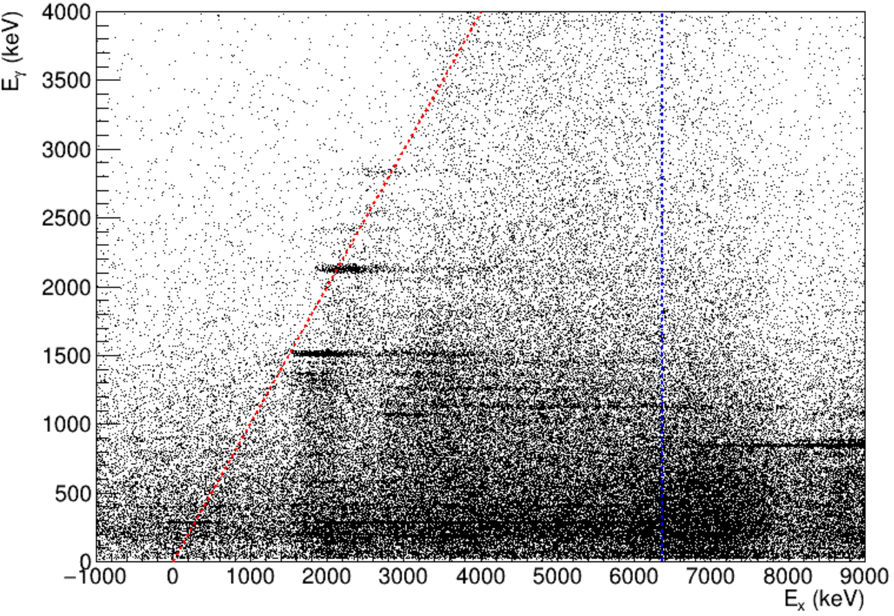

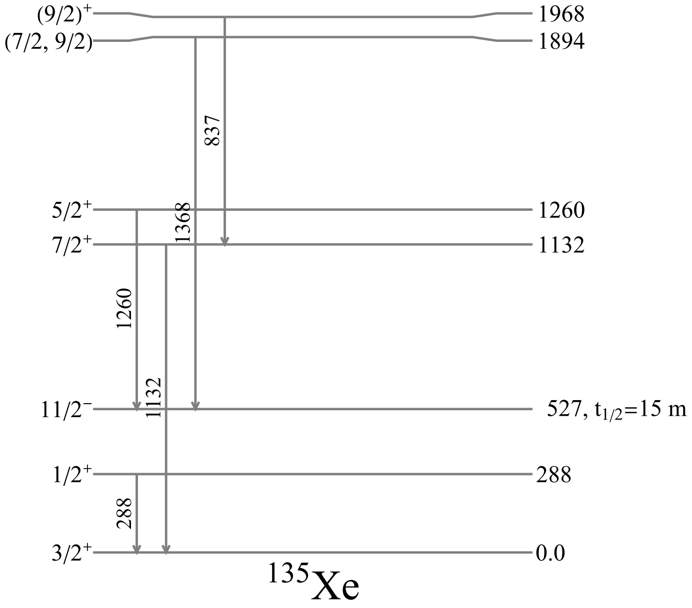

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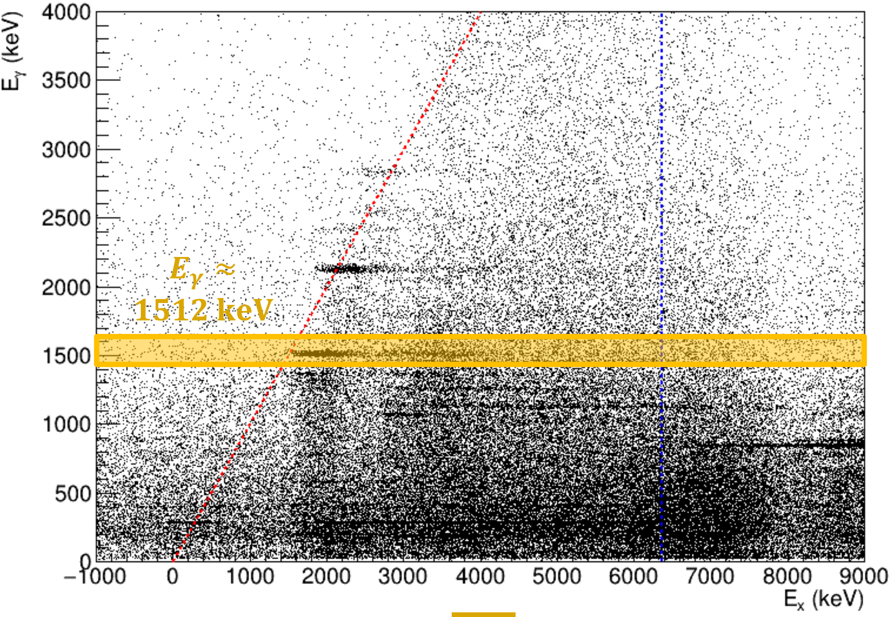

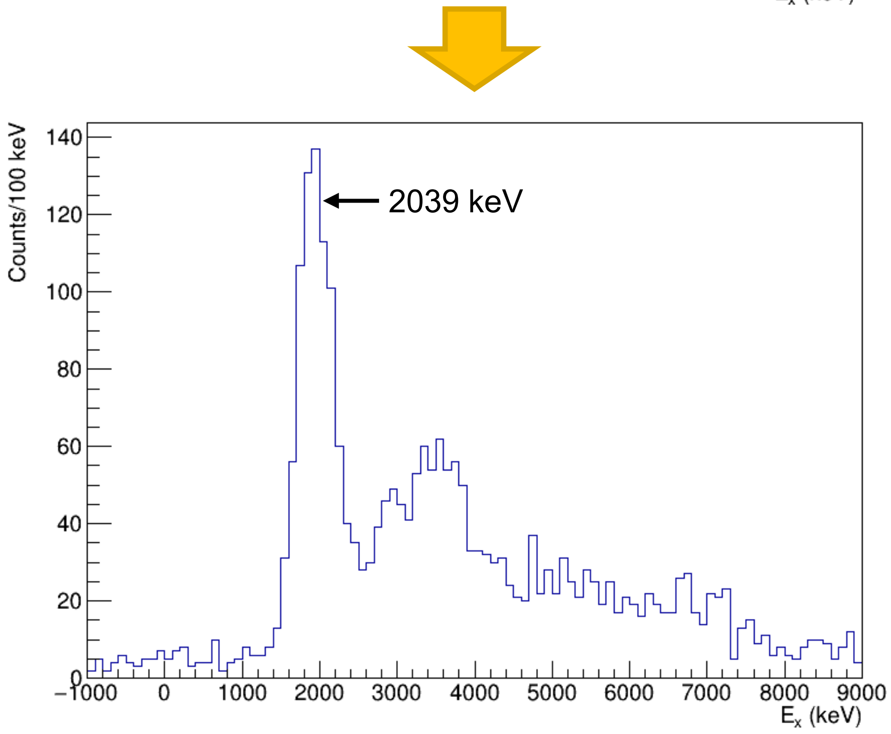

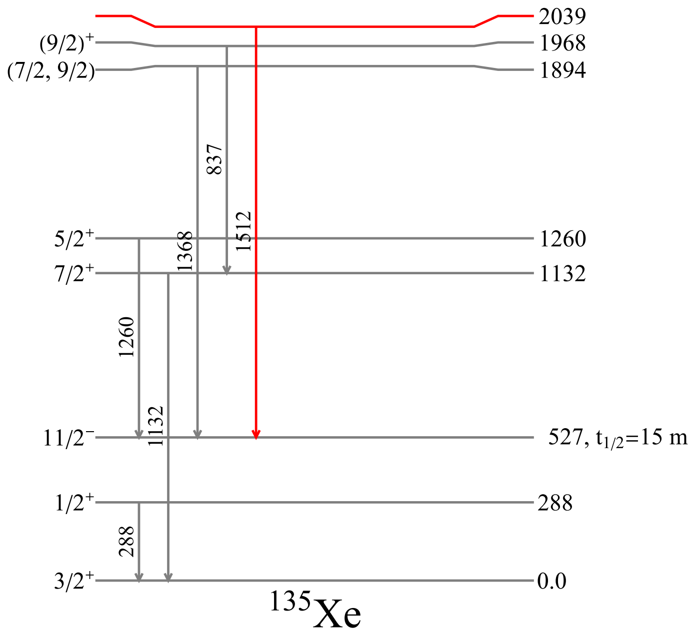

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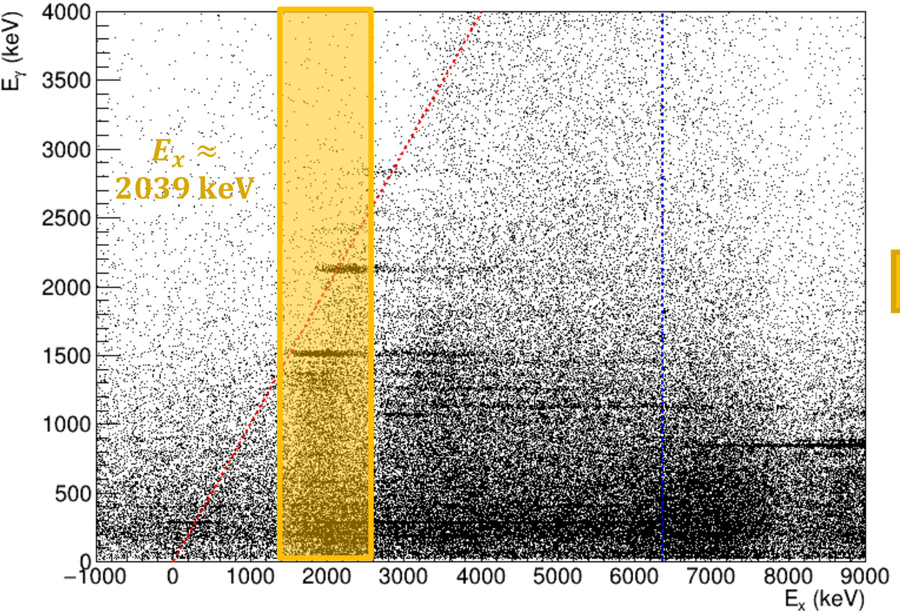
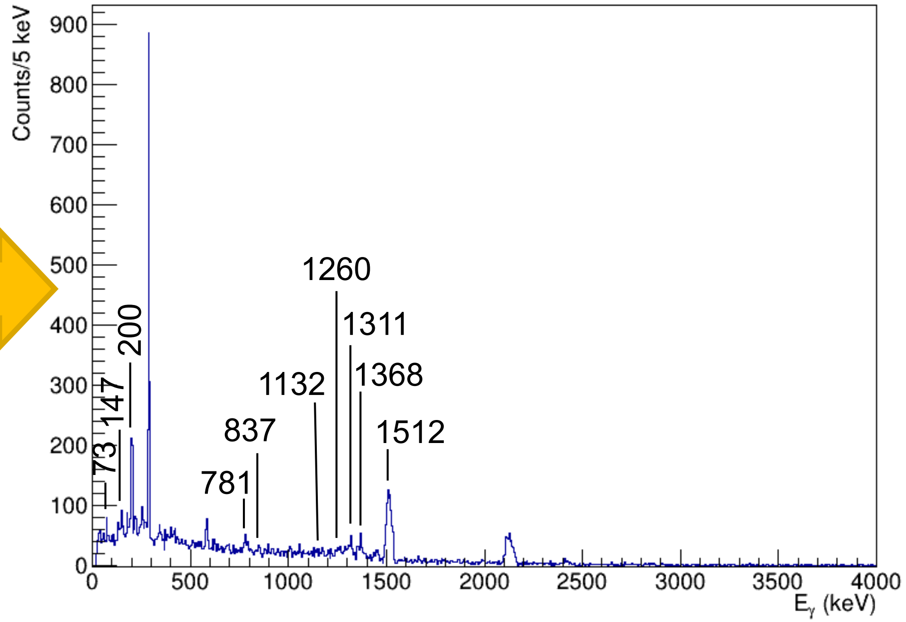
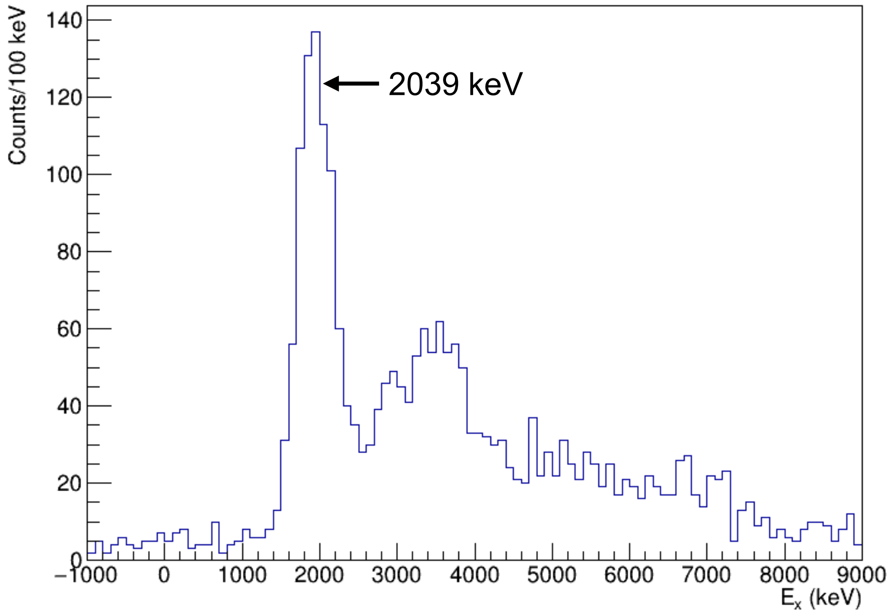
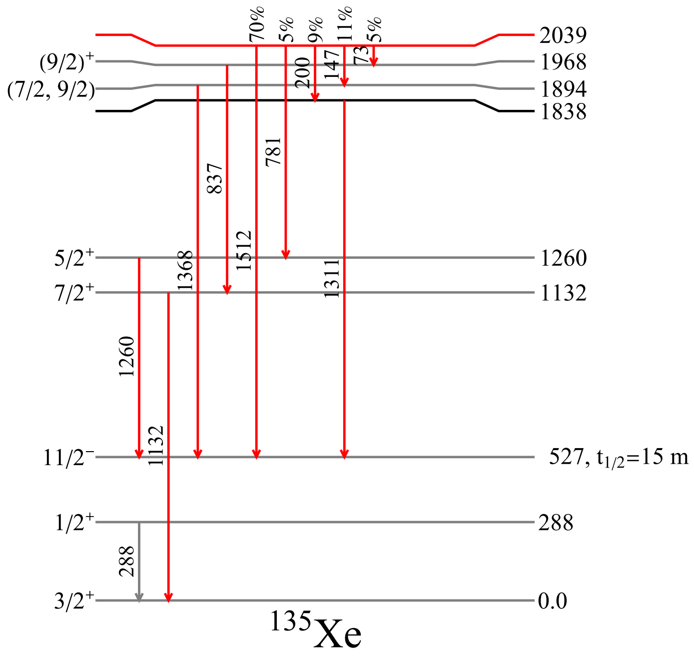
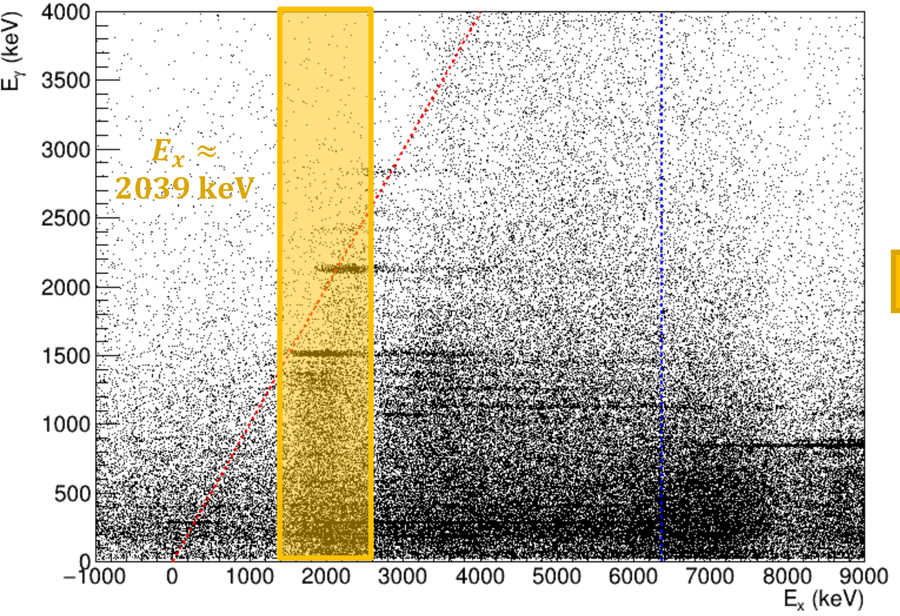


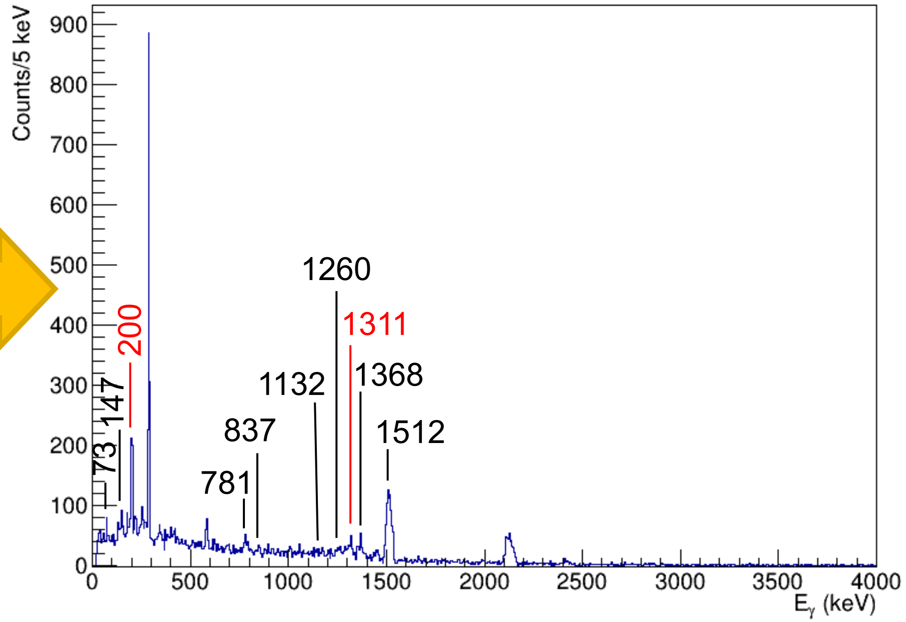


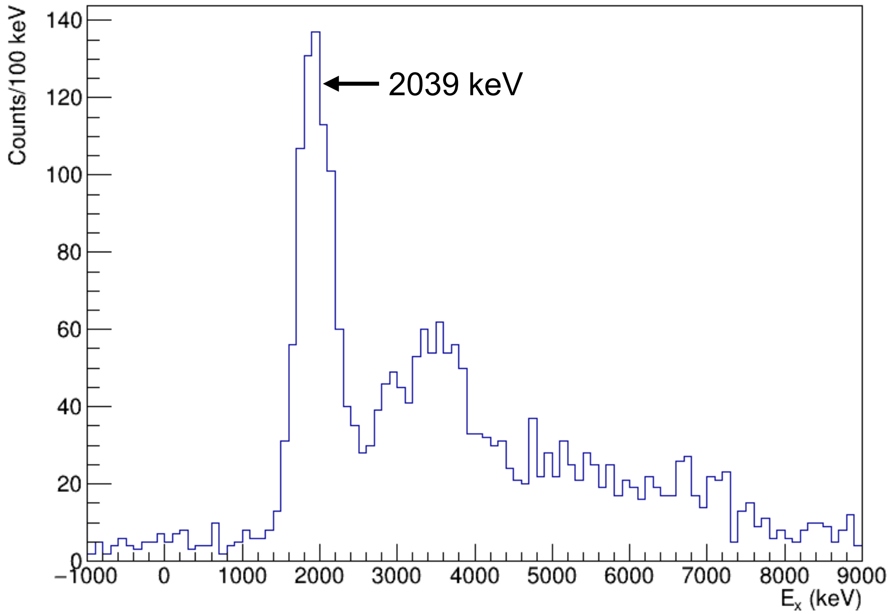


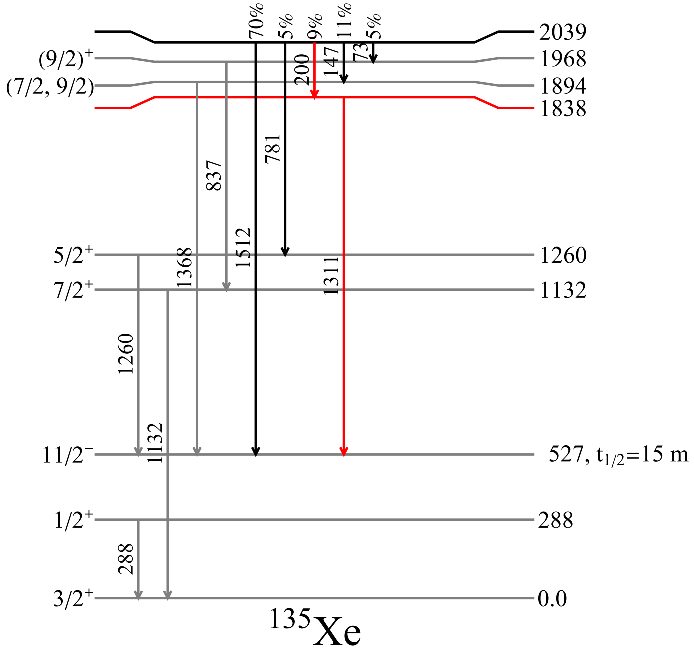


Preliminary Results – Coincidences!









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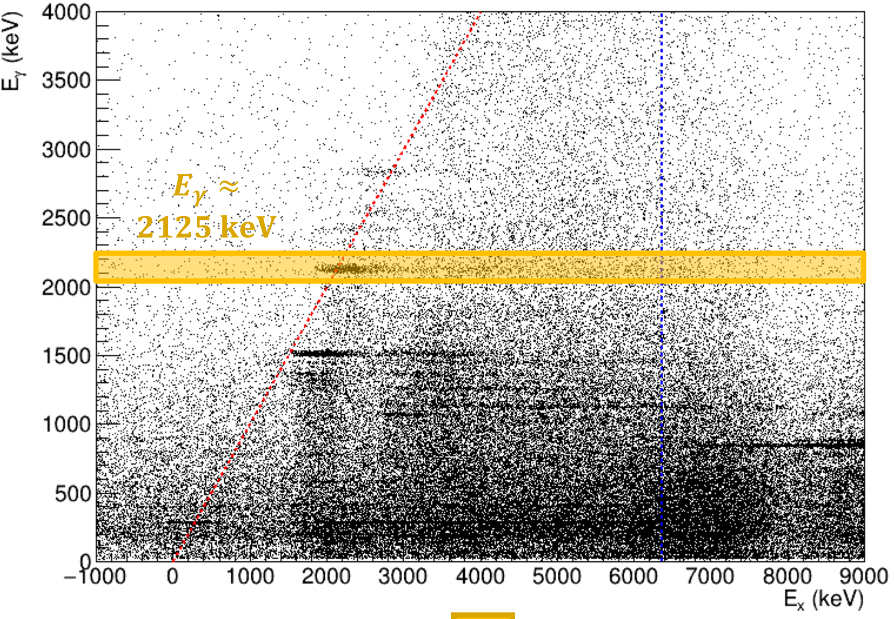

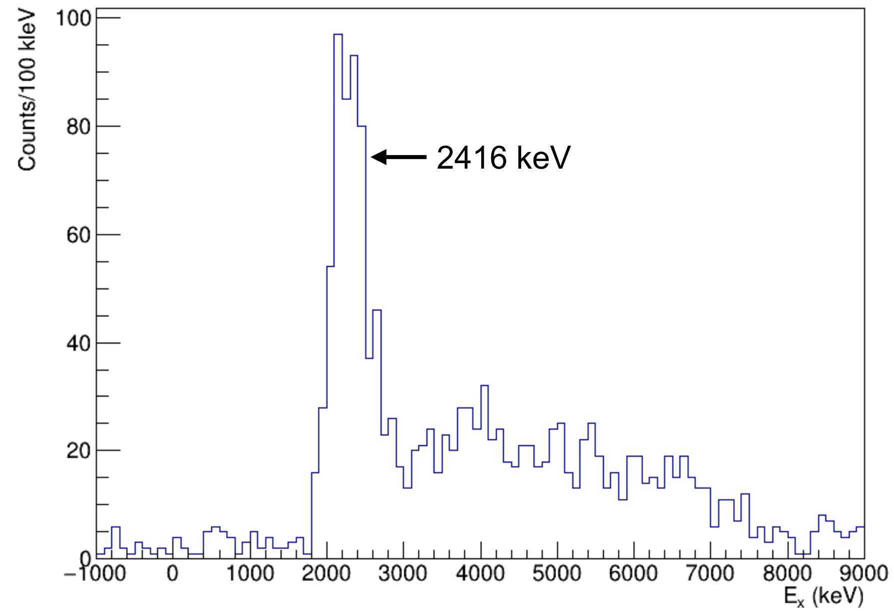

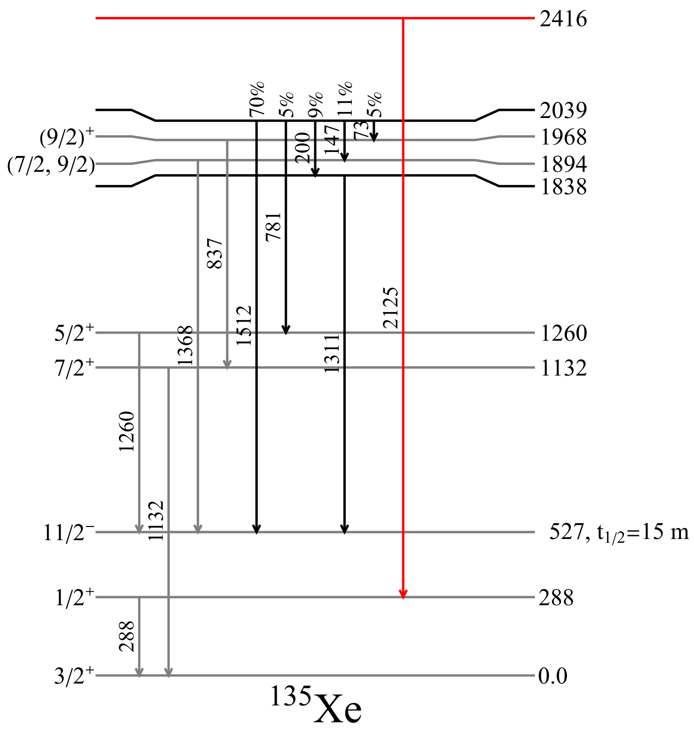

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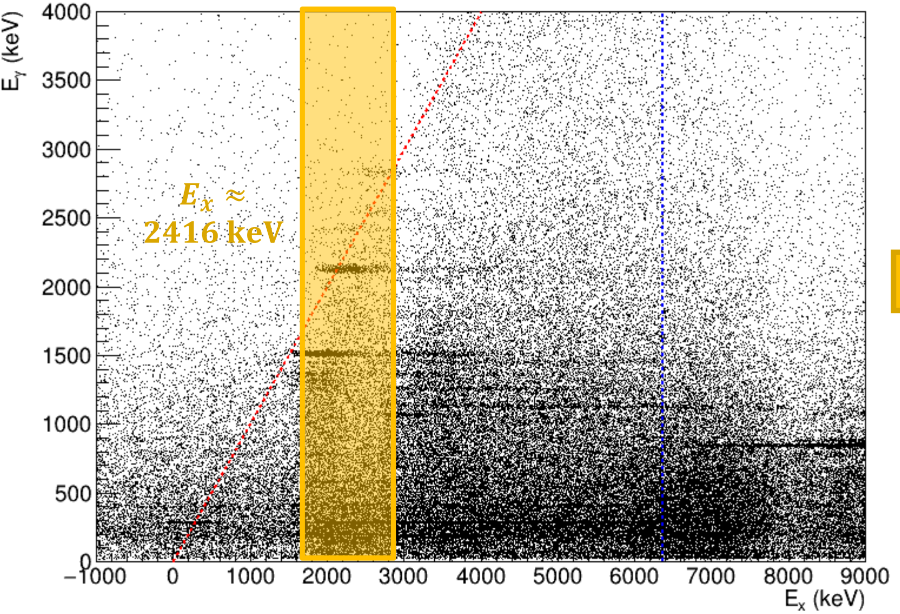

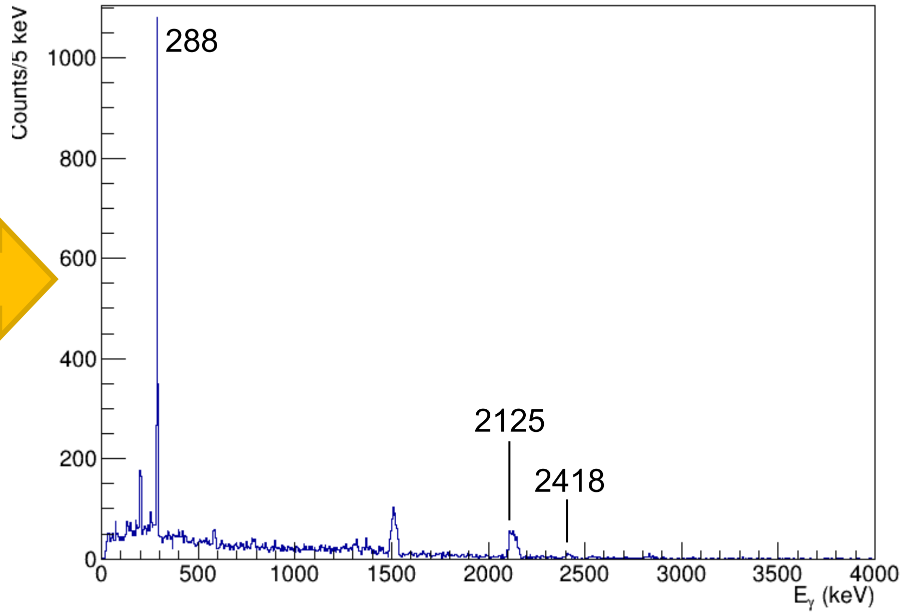

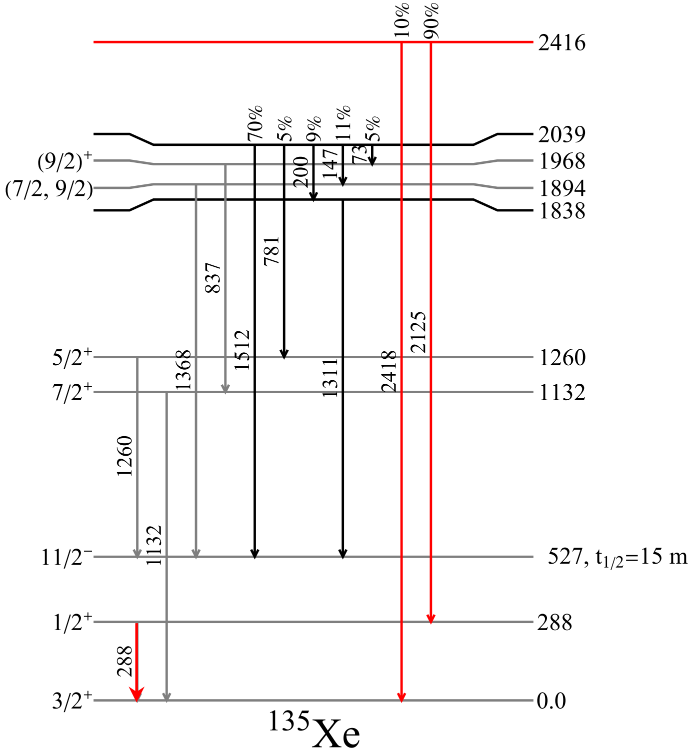

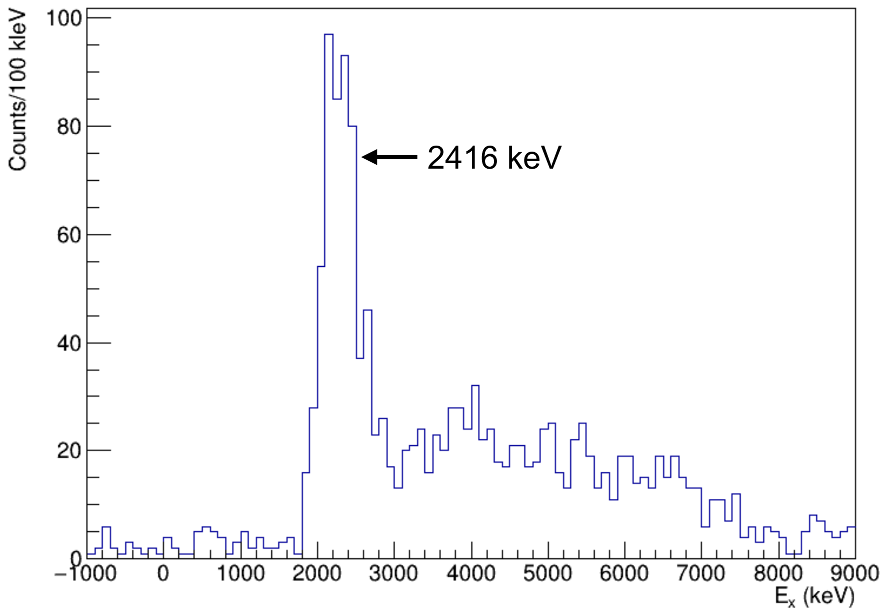

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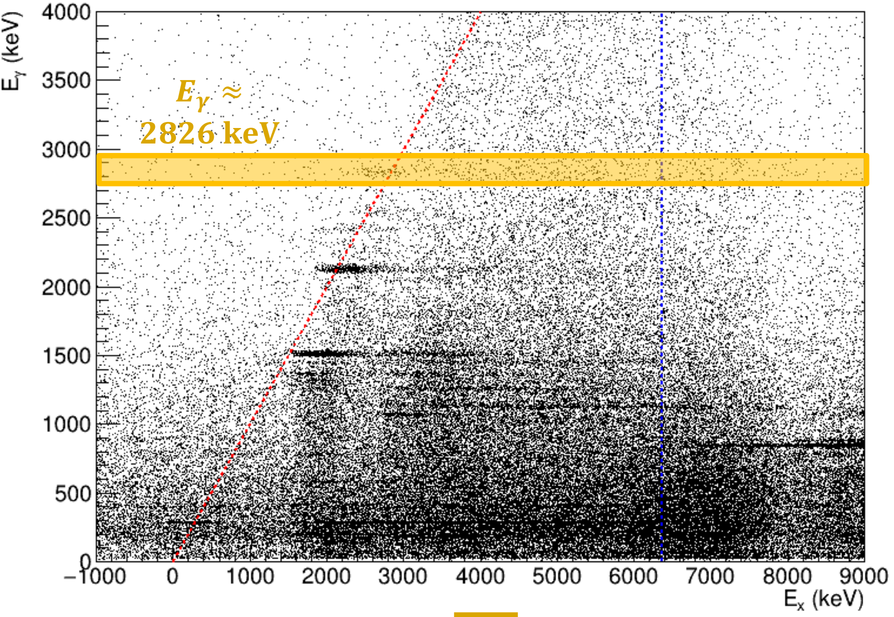

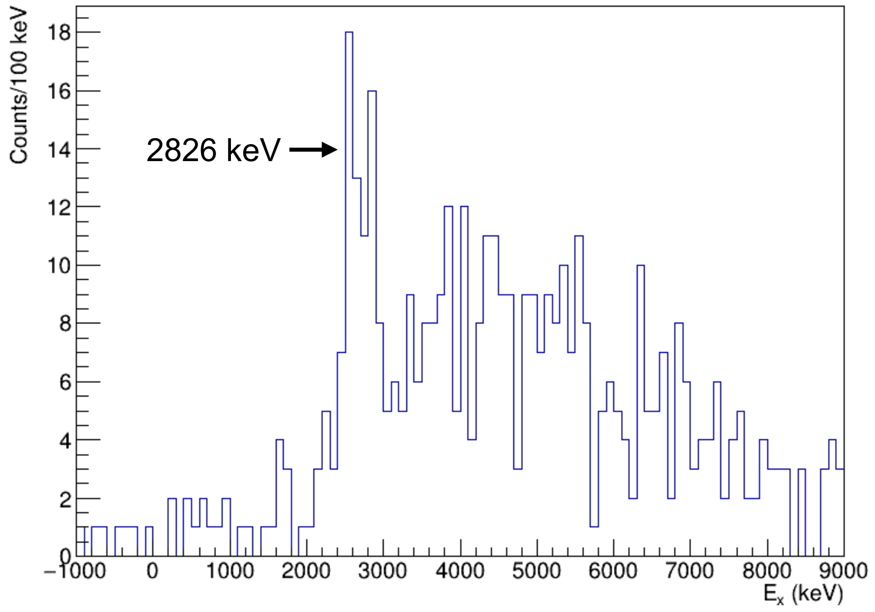

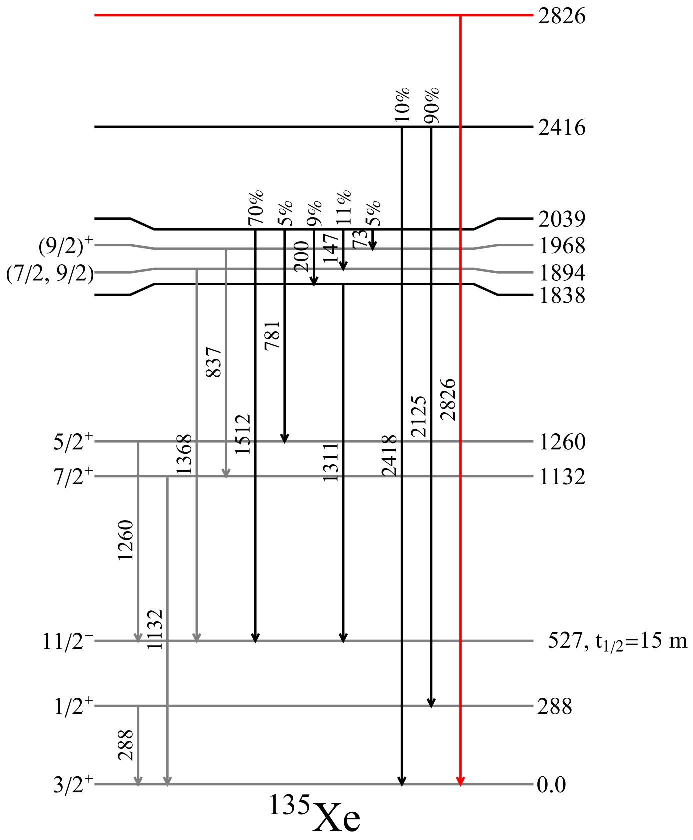

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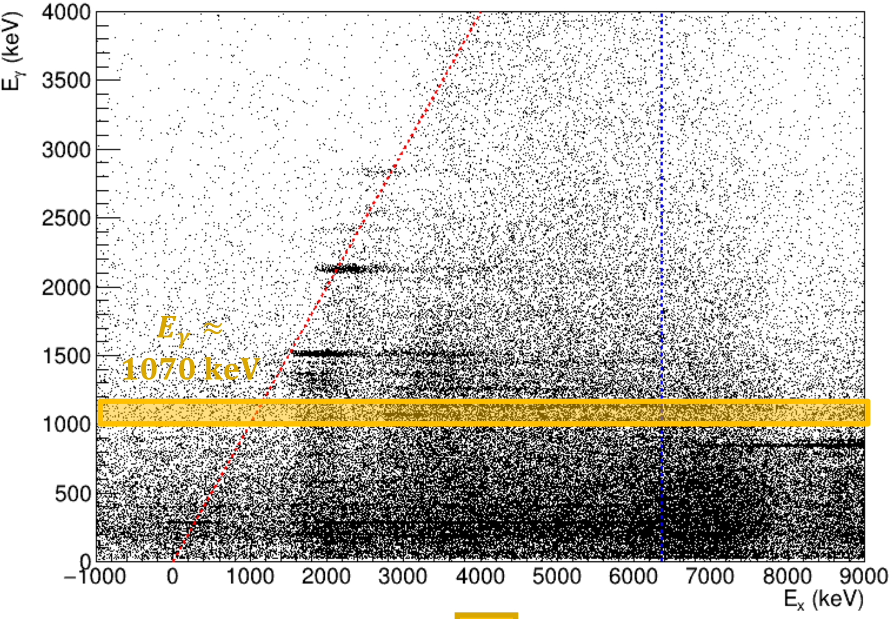

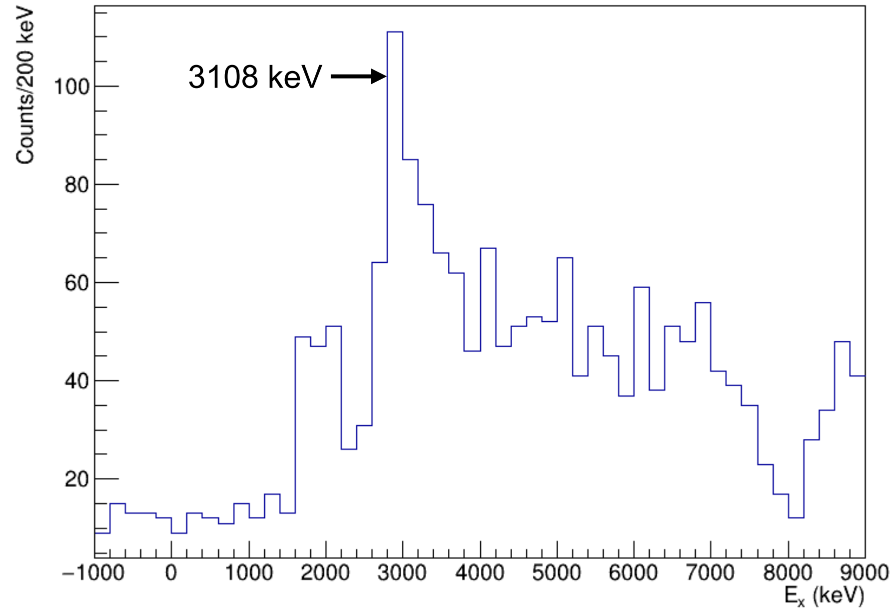

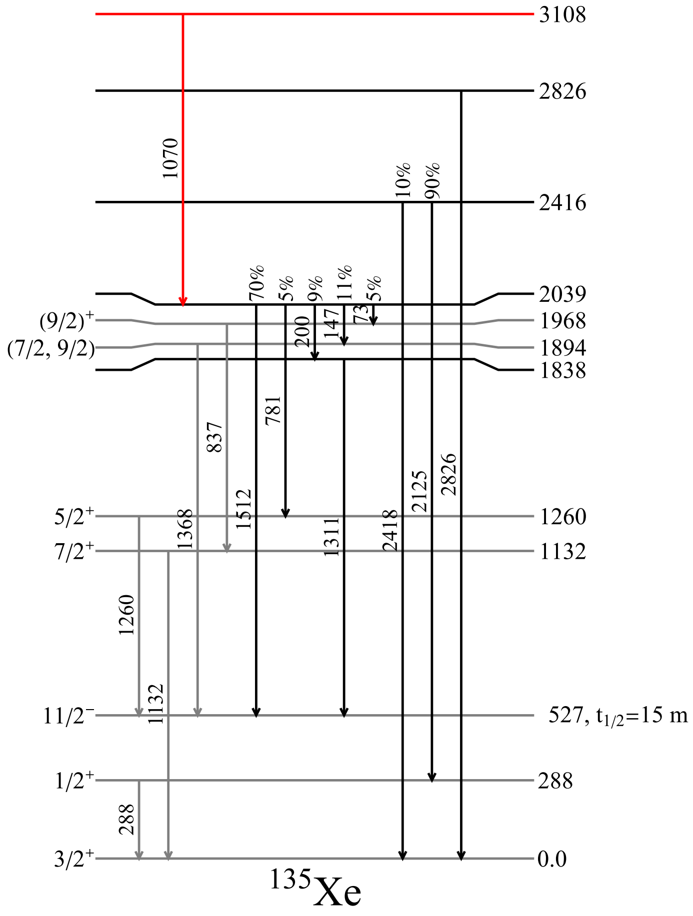

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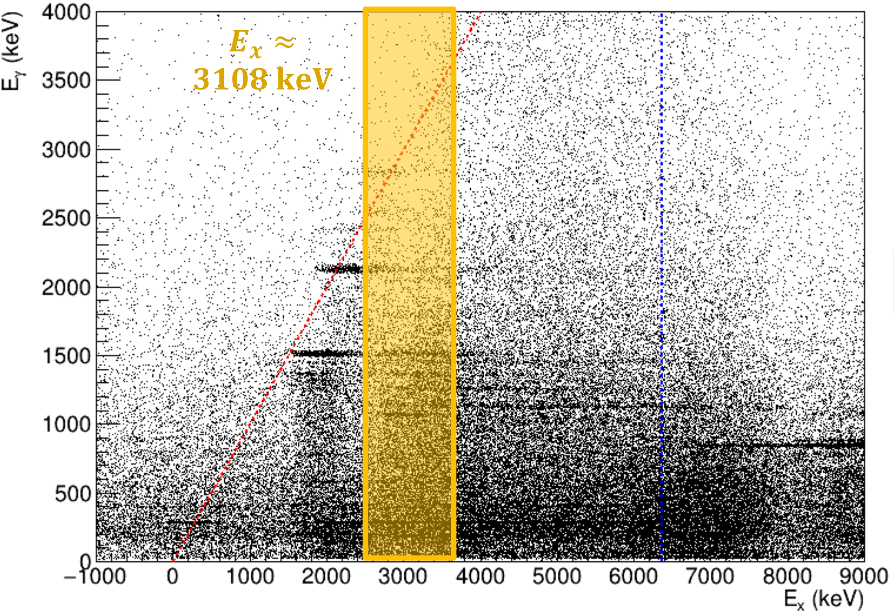

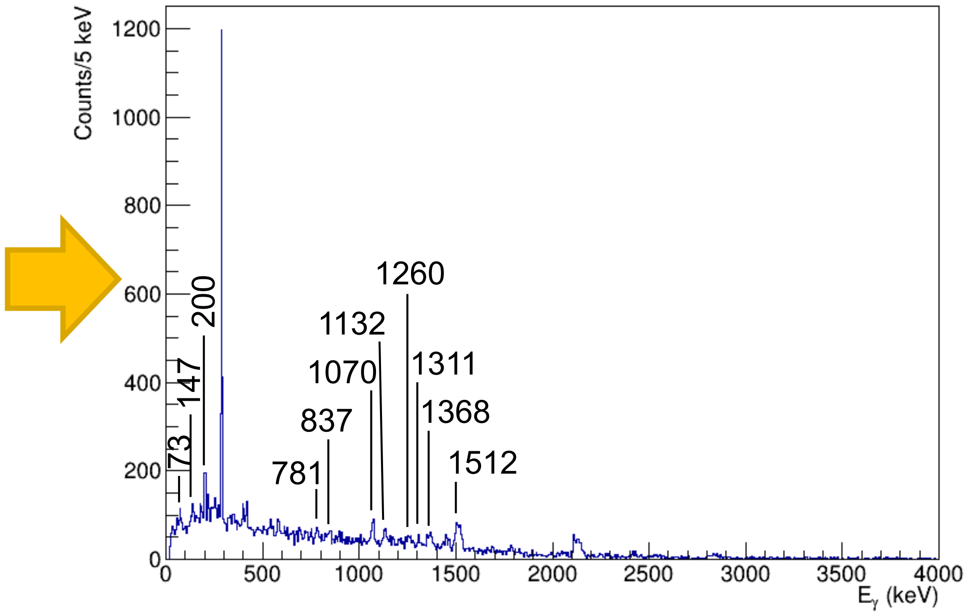

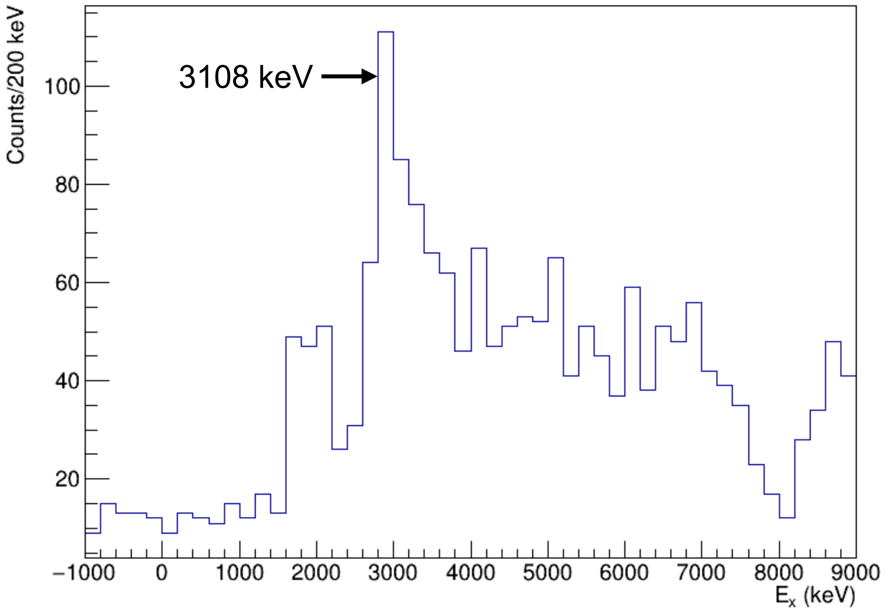

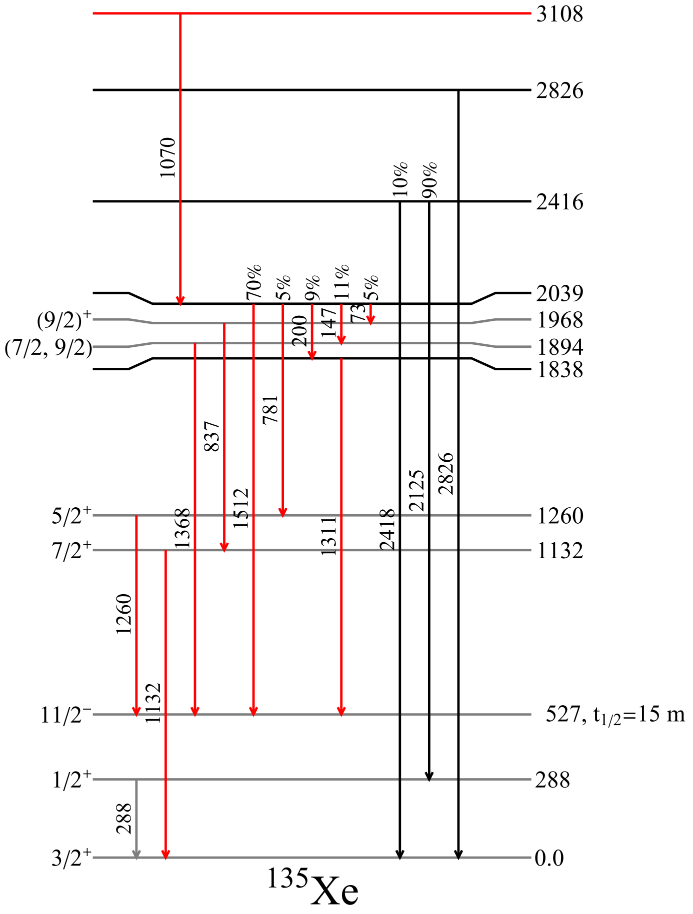

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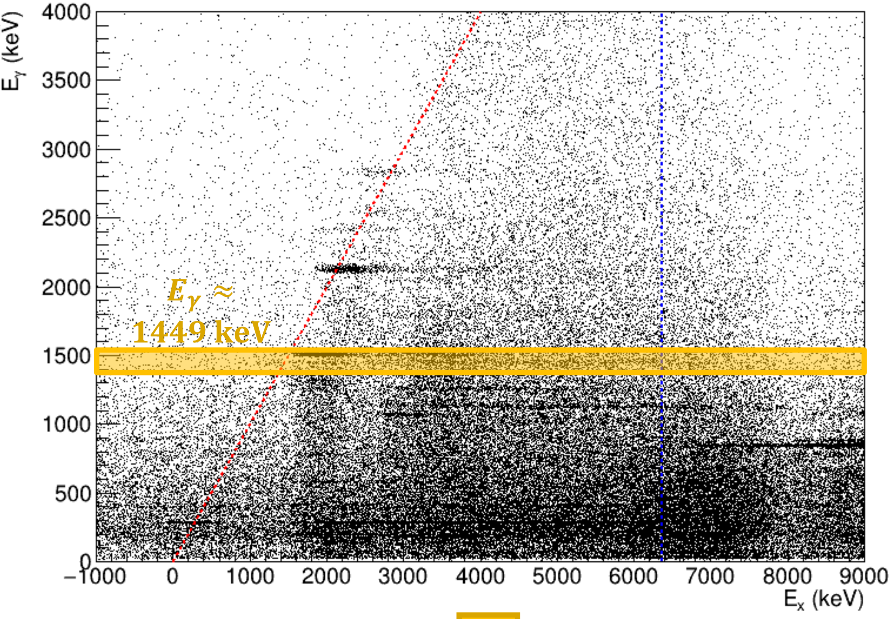

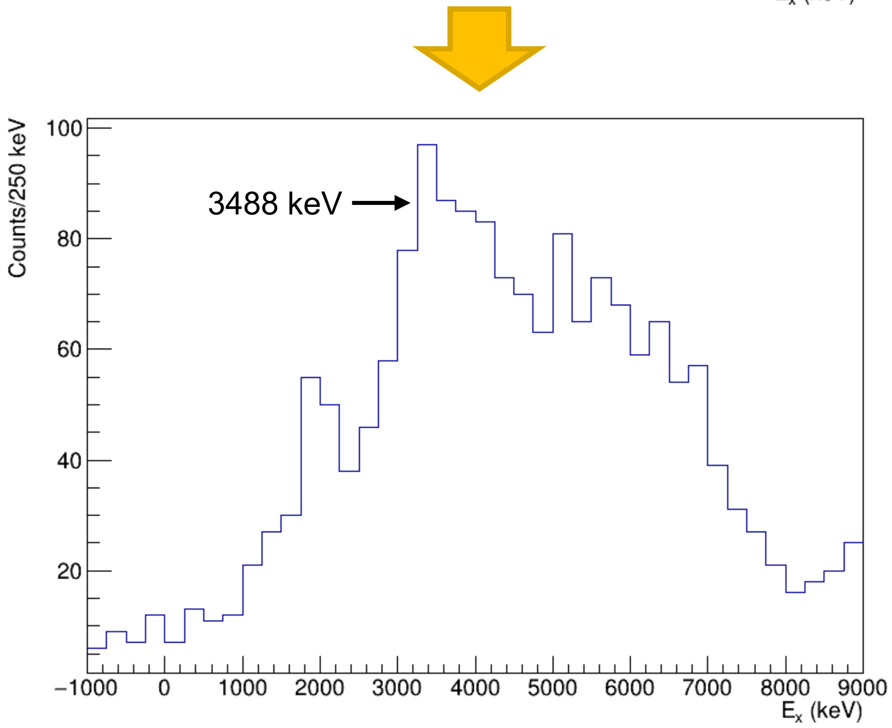

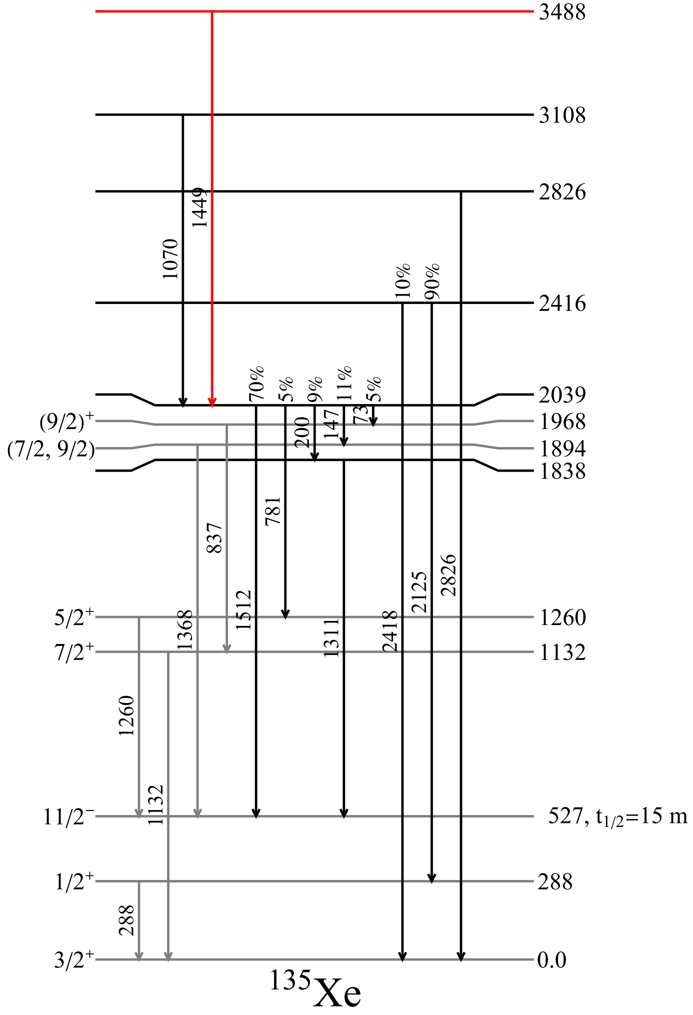

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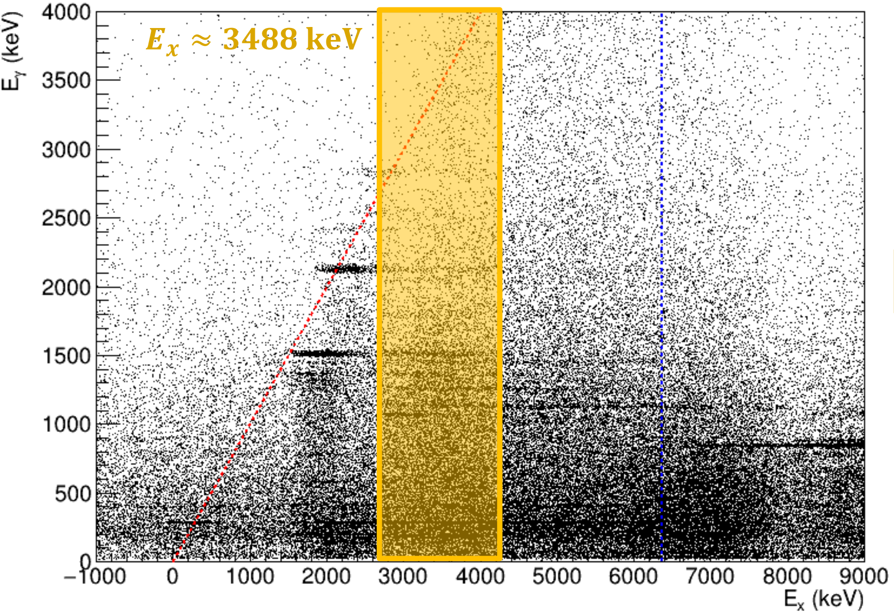
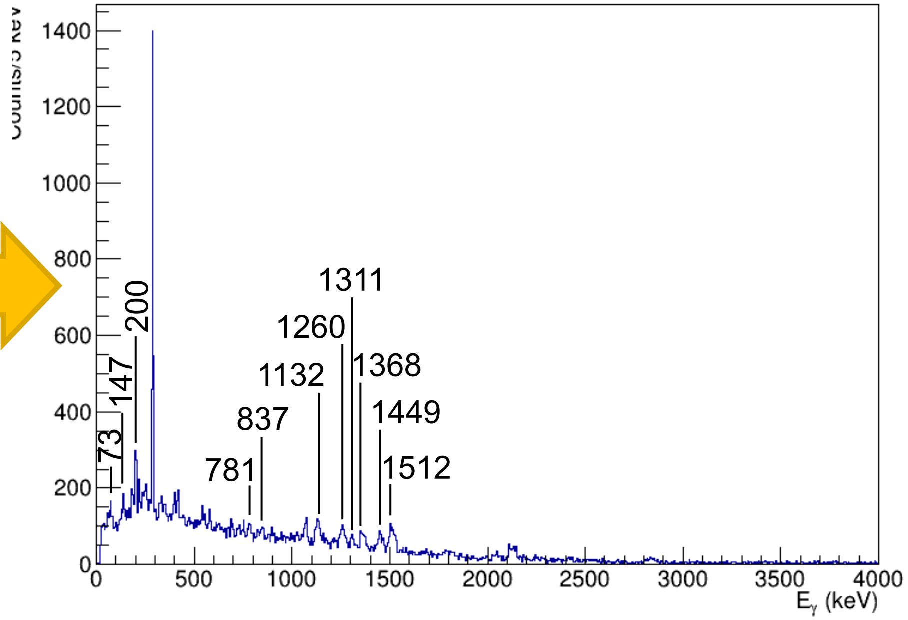
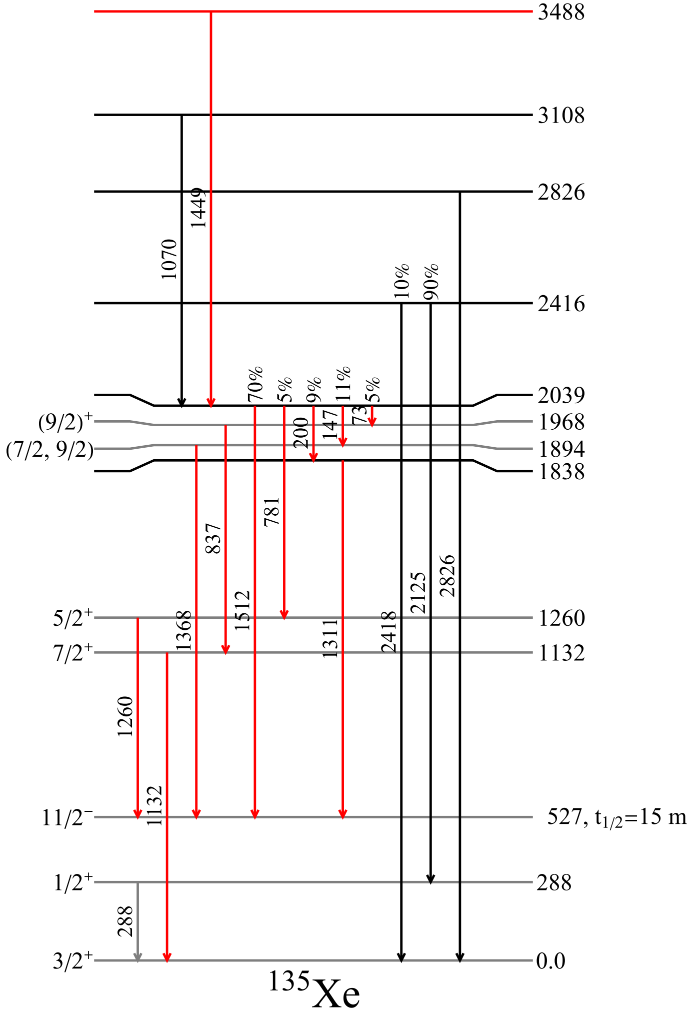
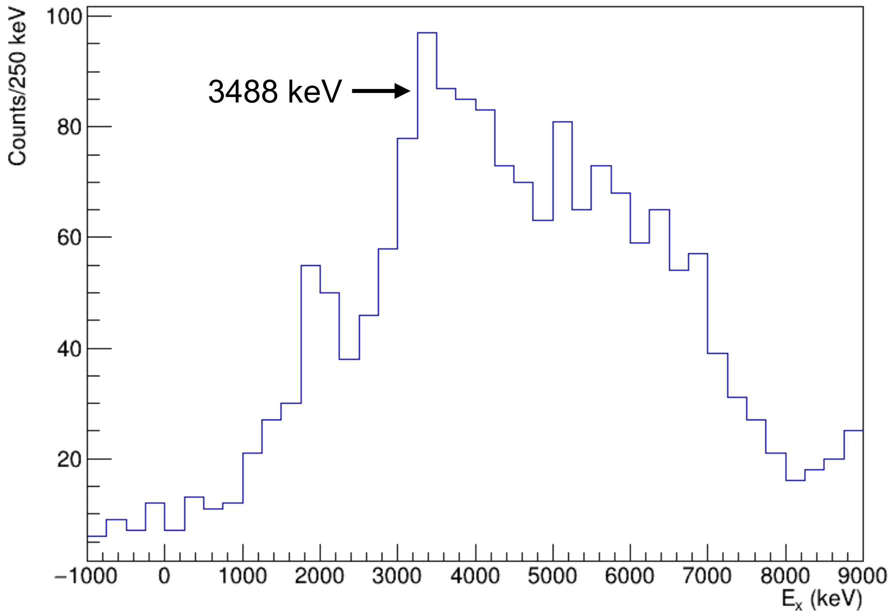
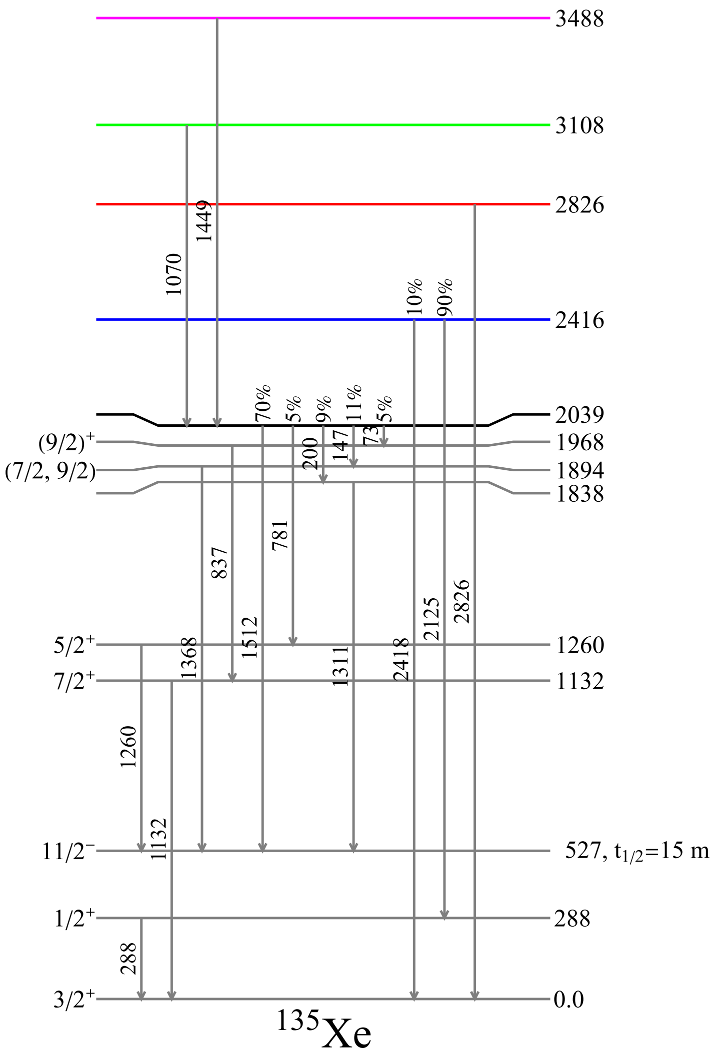








^{135}Xe Level Scheme



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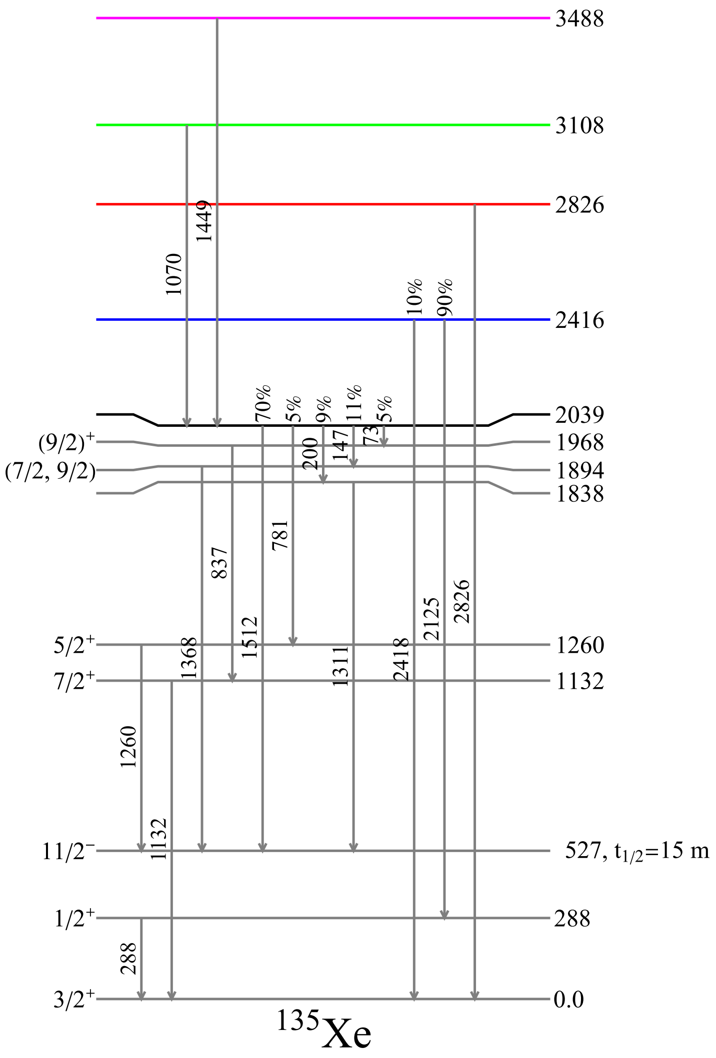
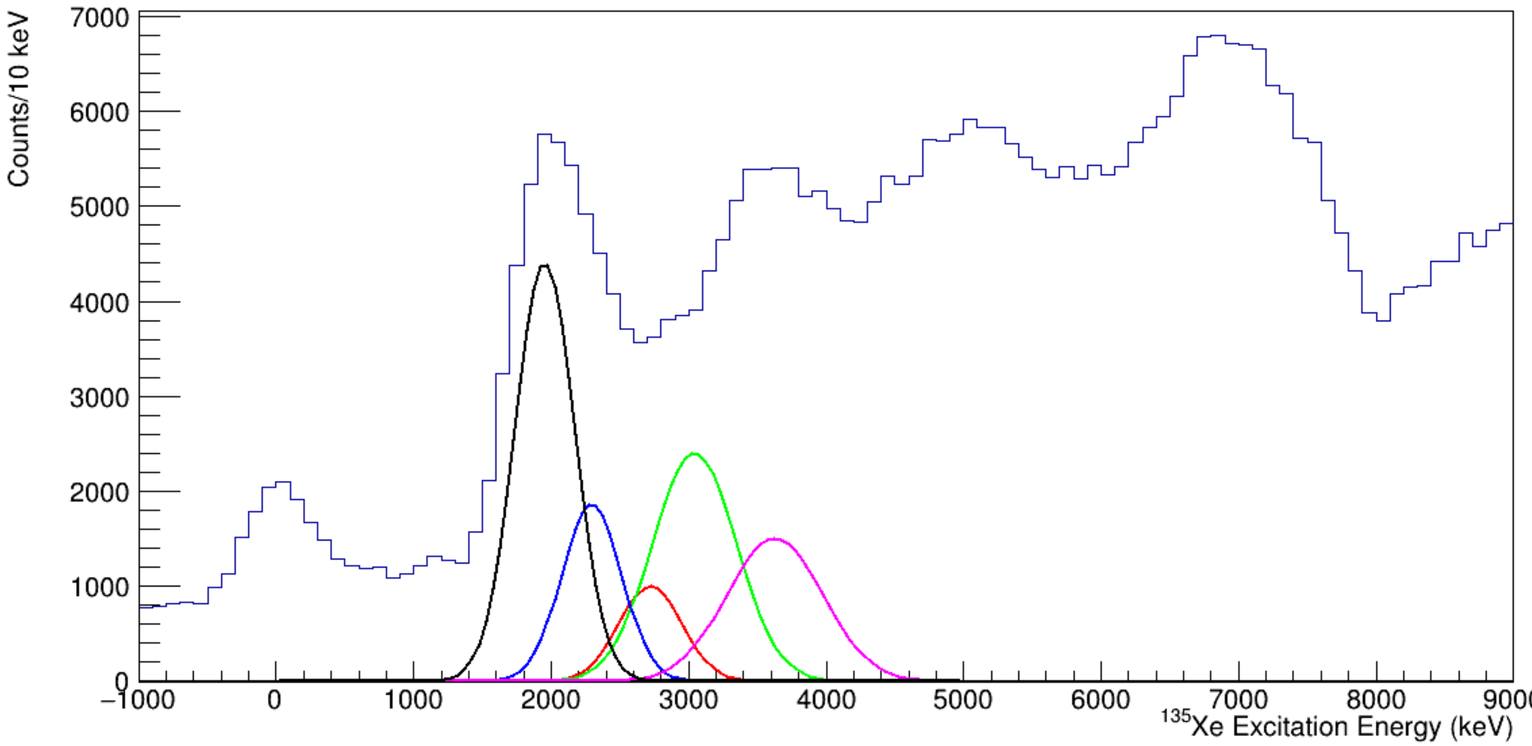
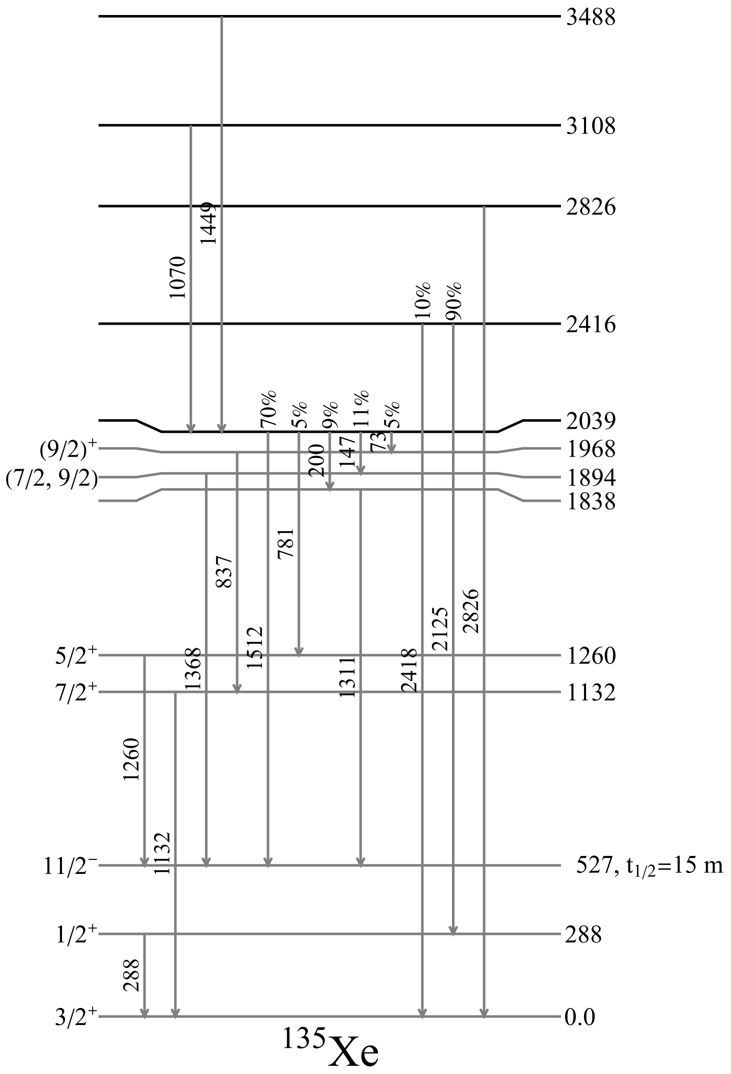




Angular Distributions



Time to compare to the Shell Model!

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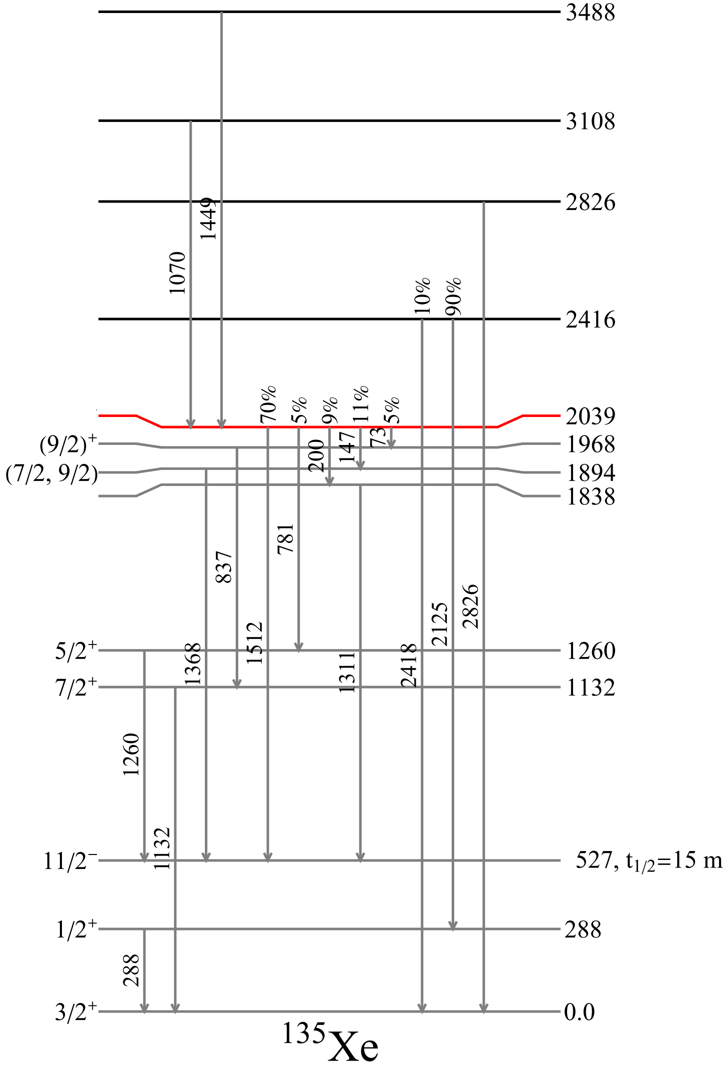

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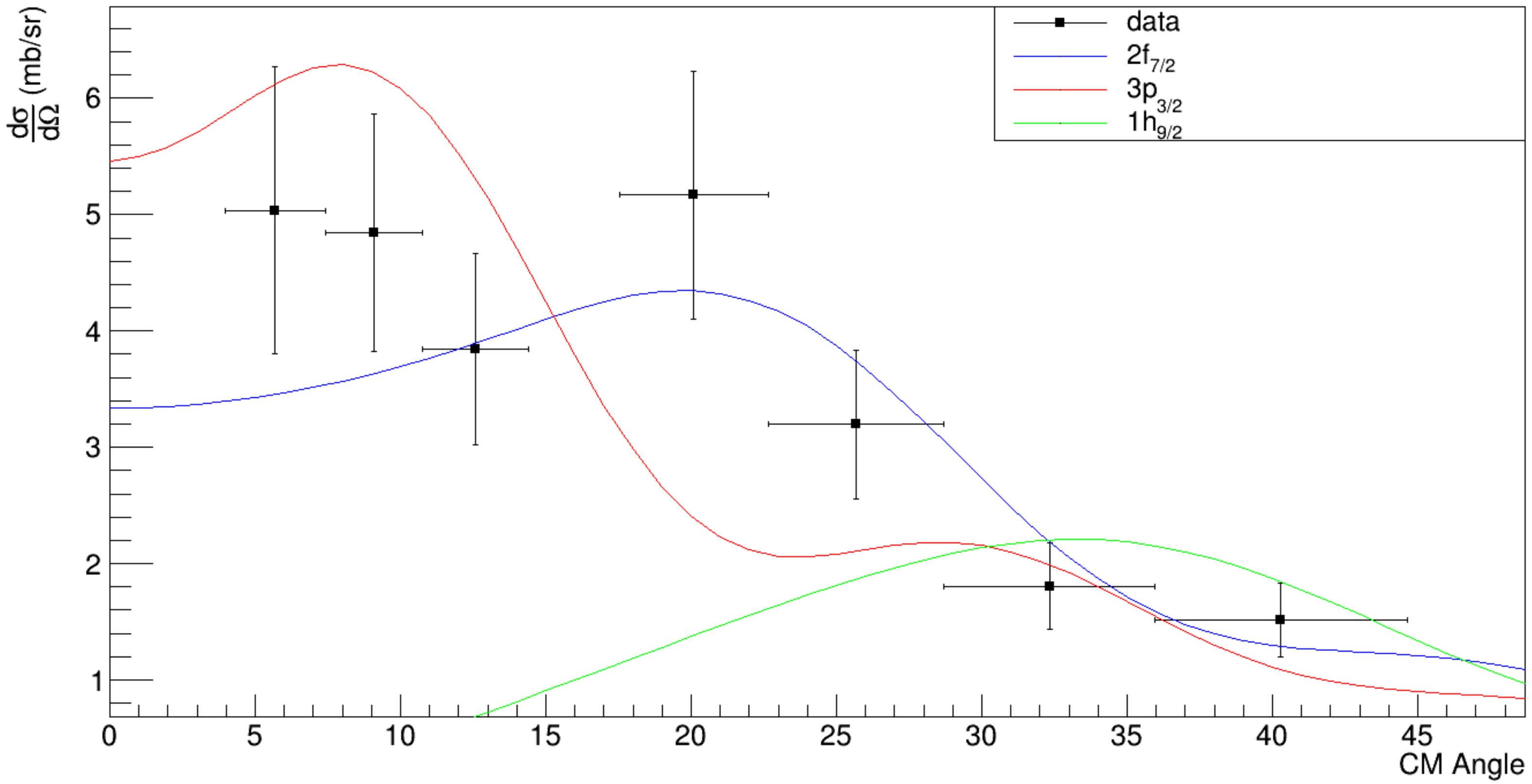

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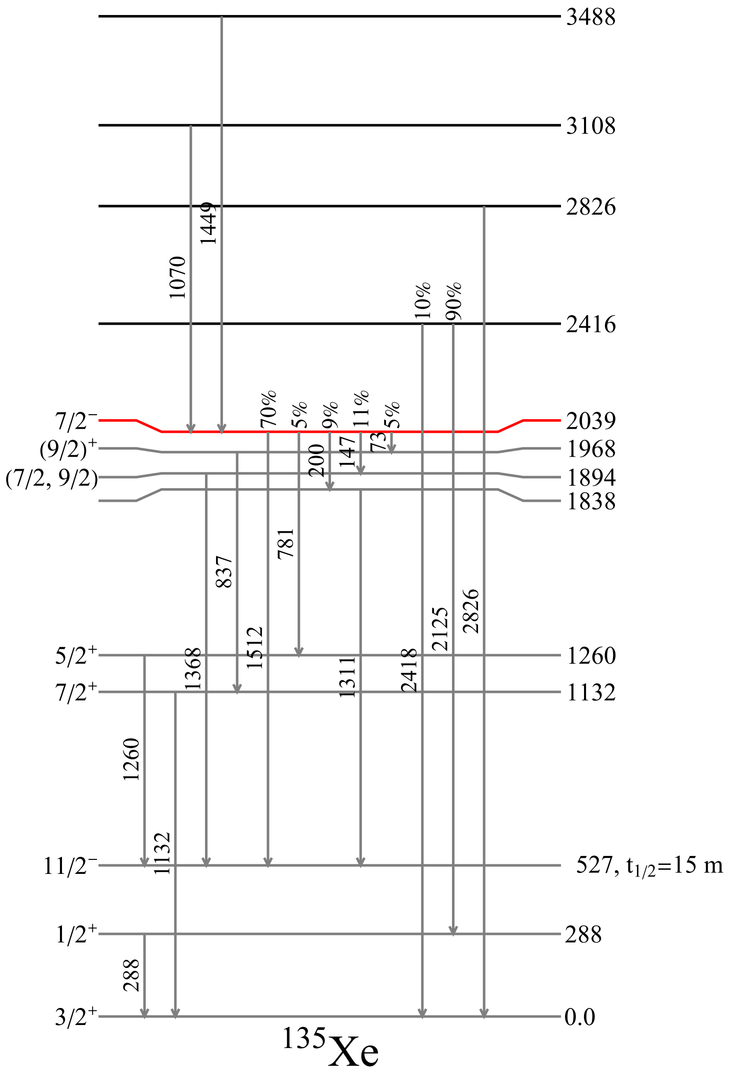

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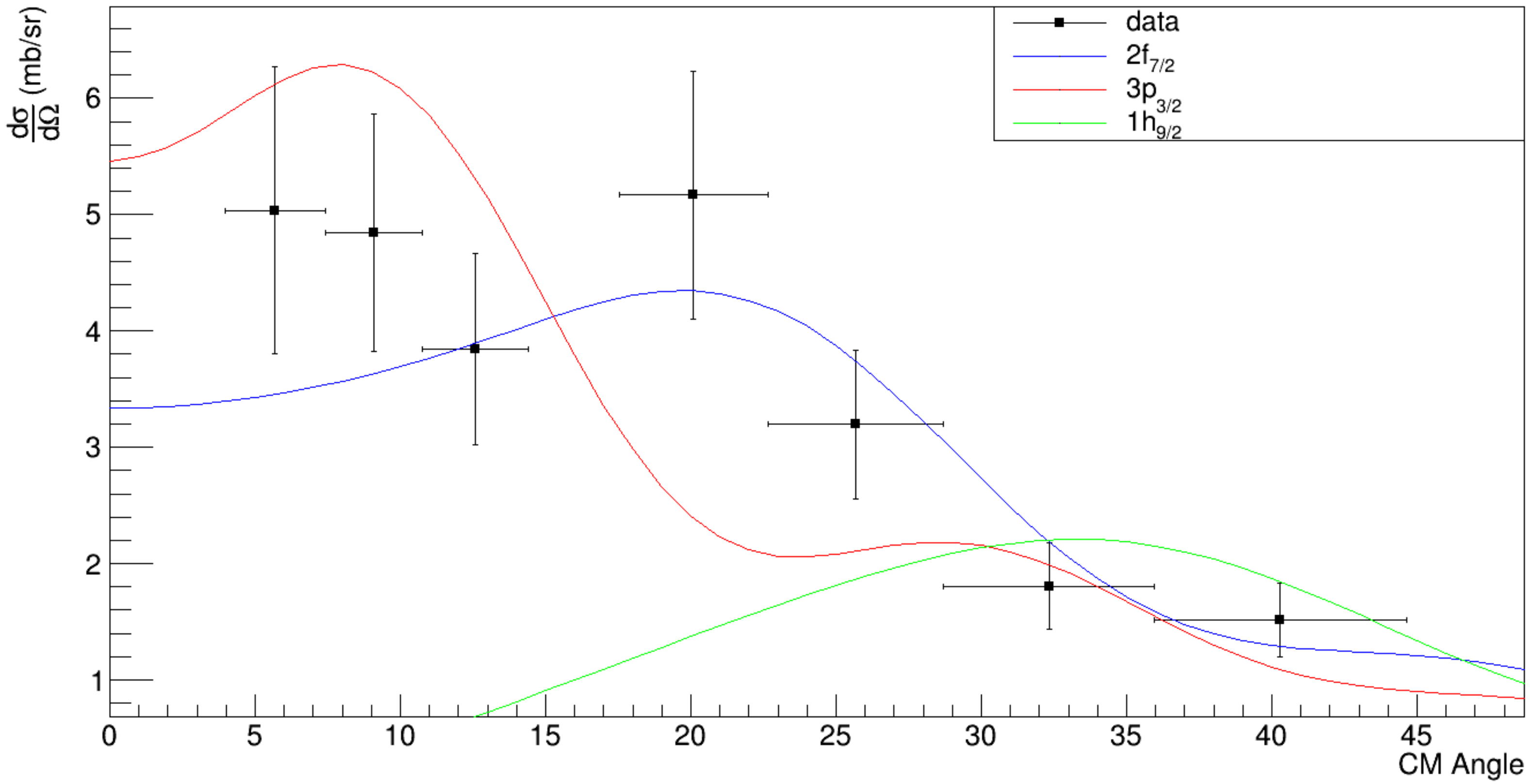

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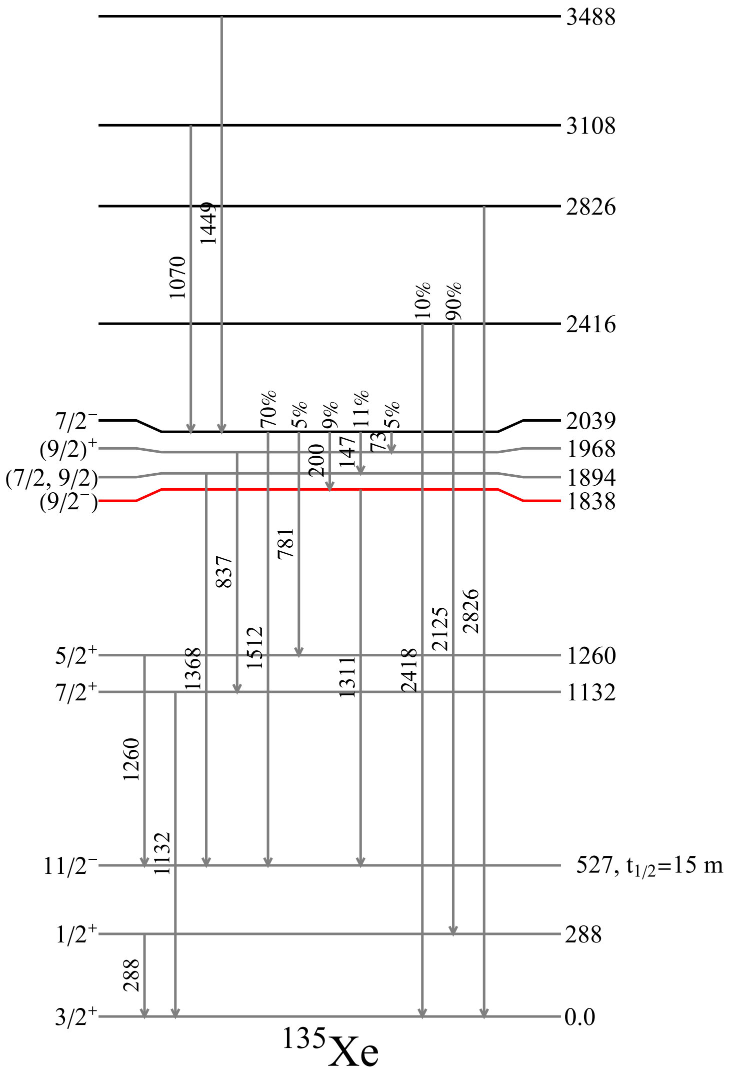

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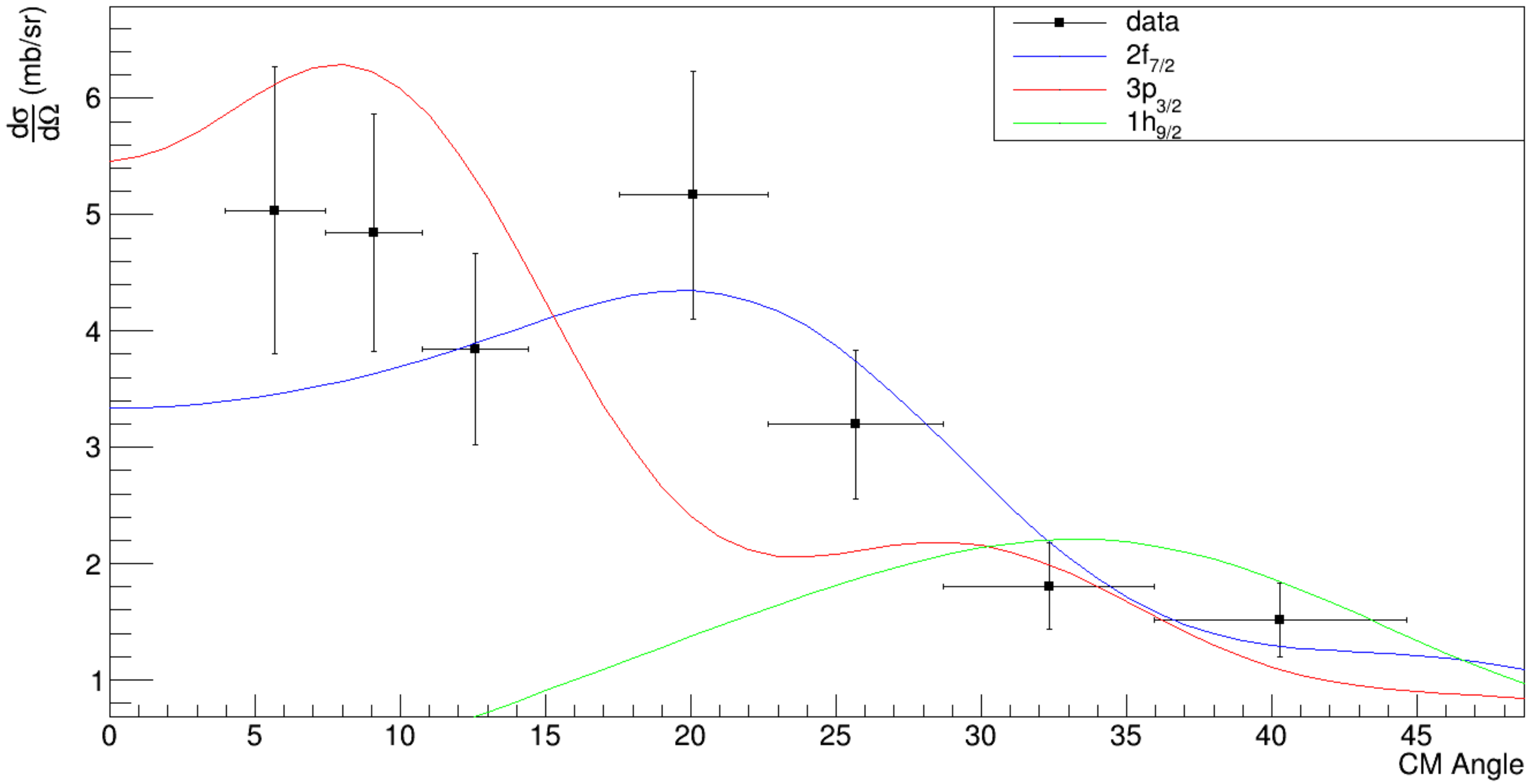

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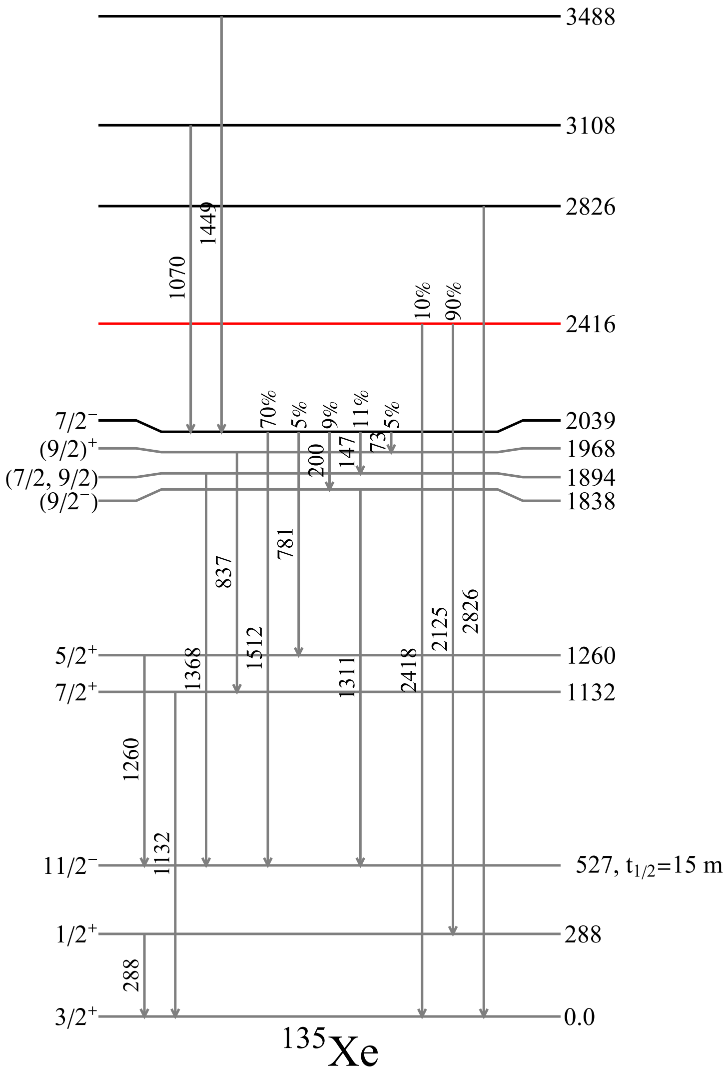

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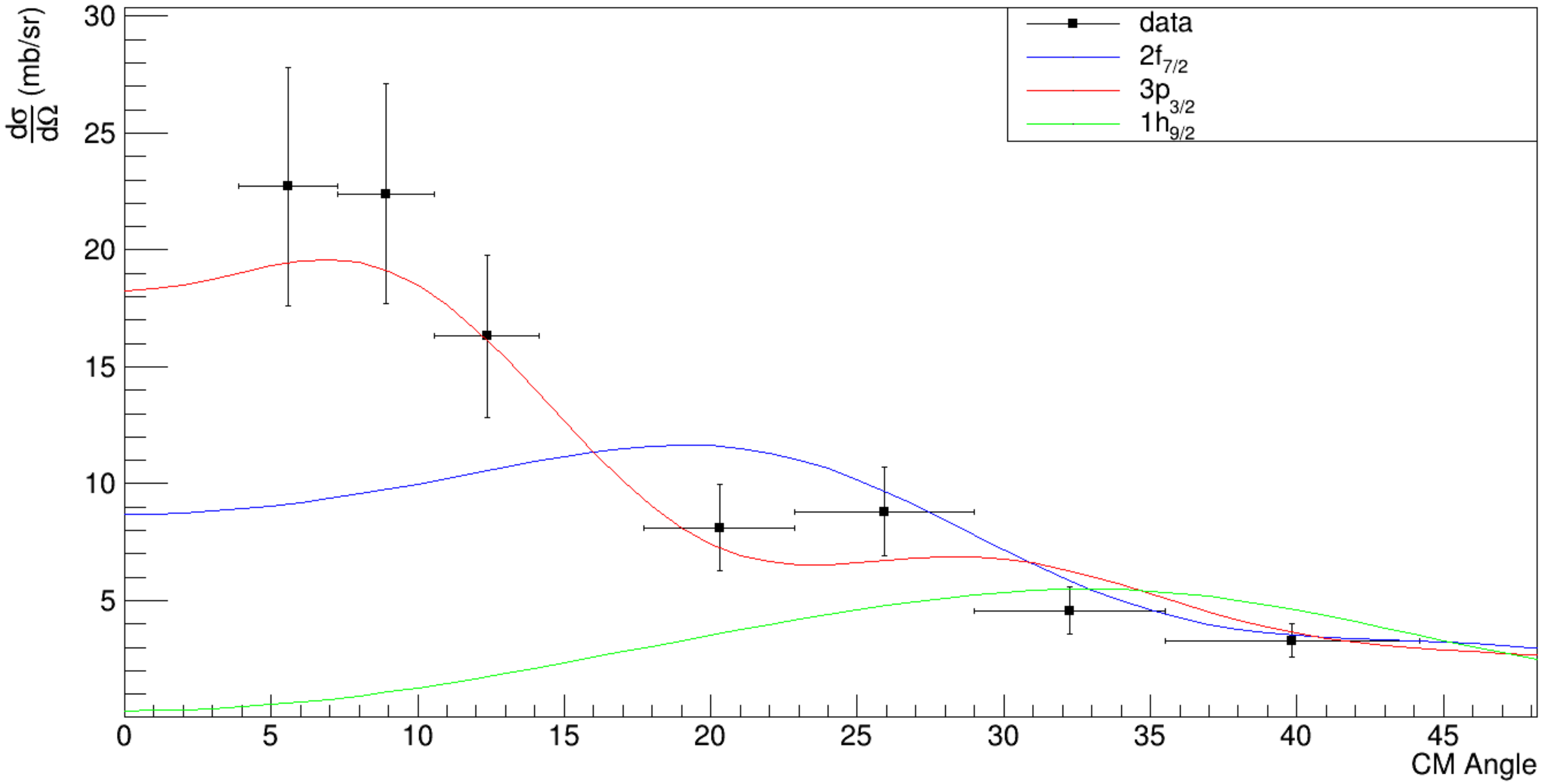

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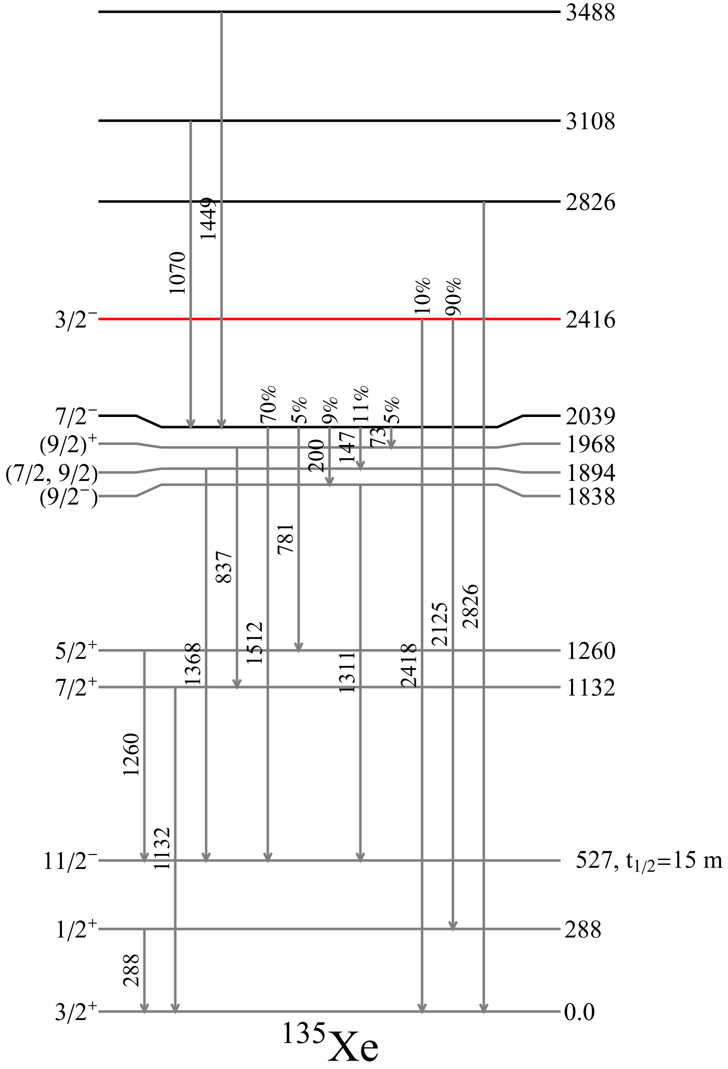

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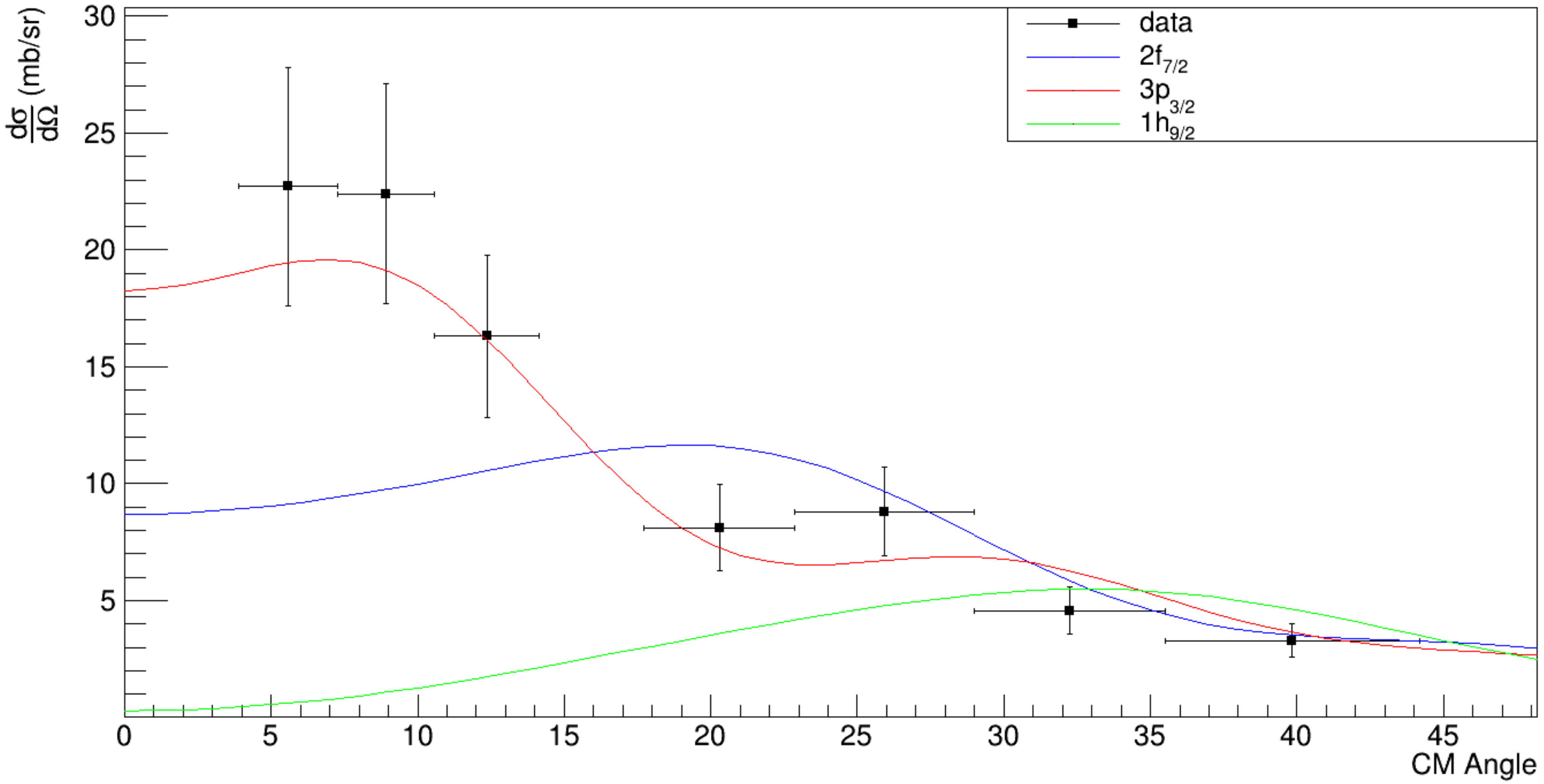

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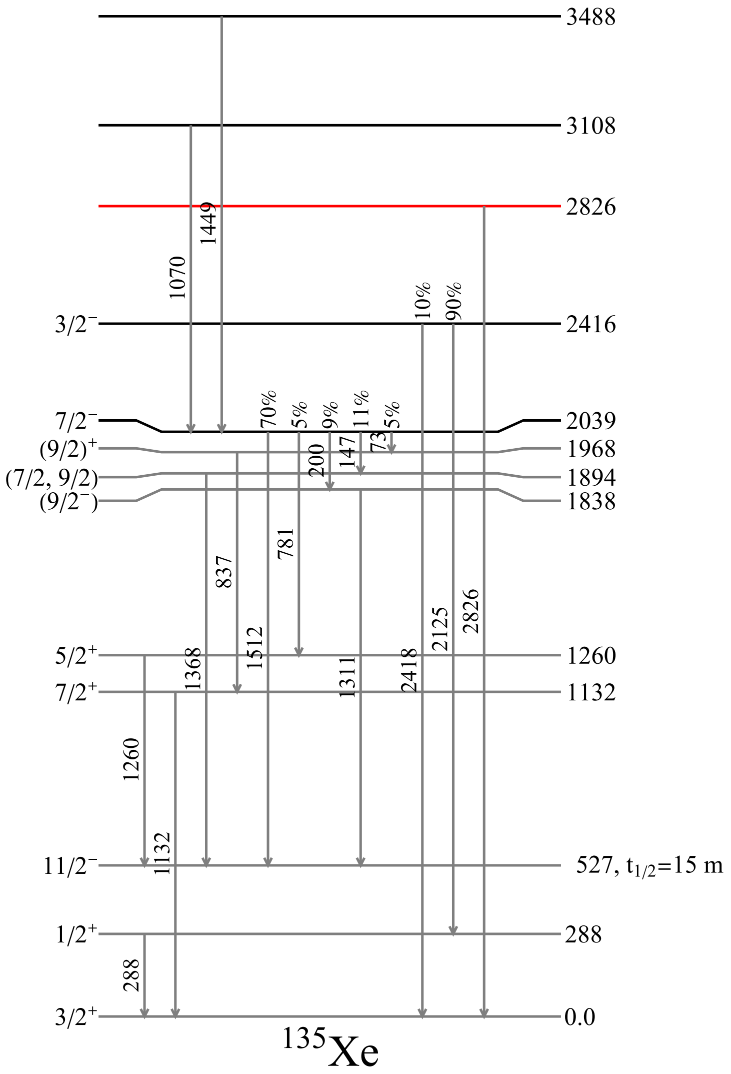

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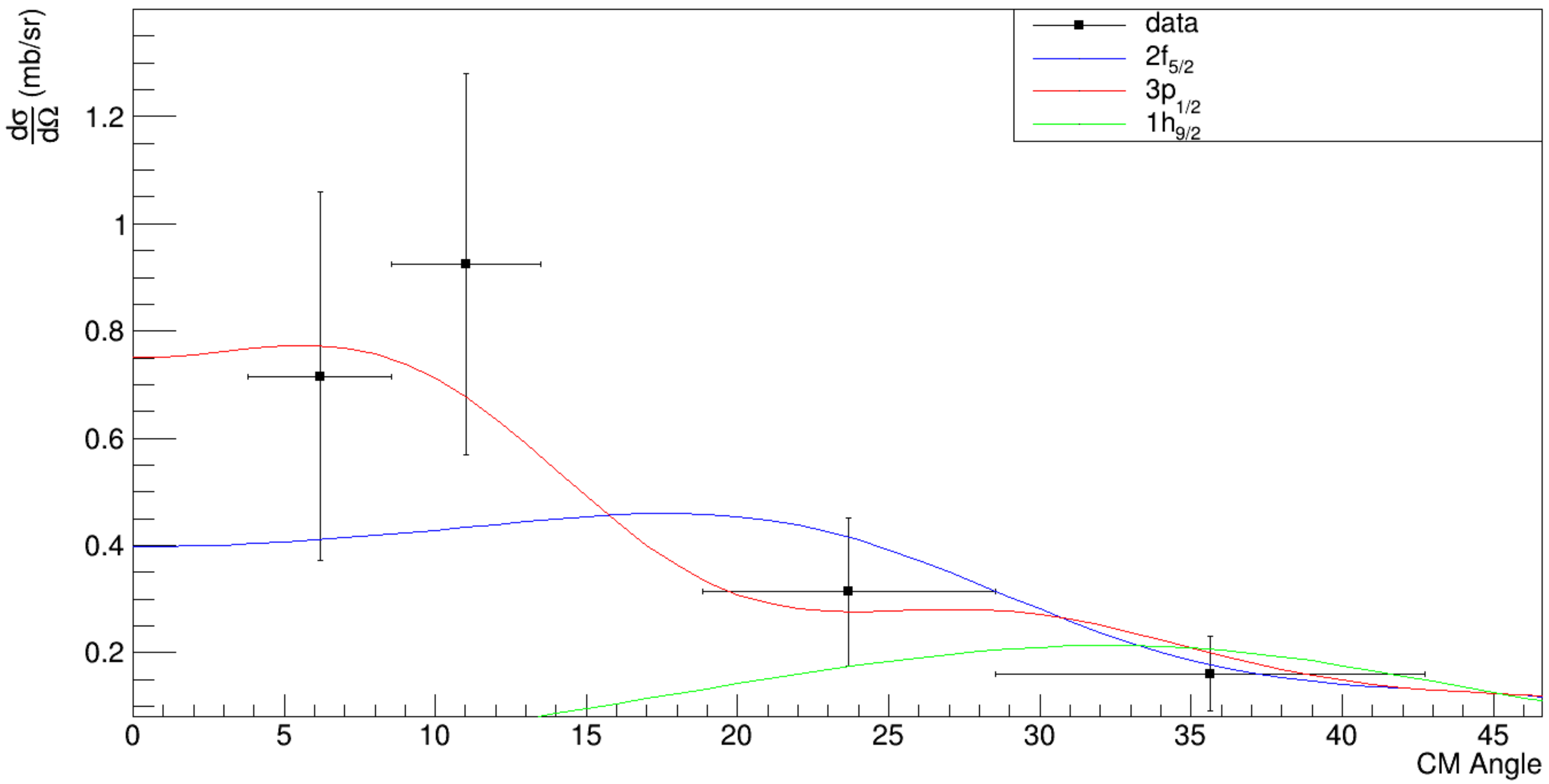

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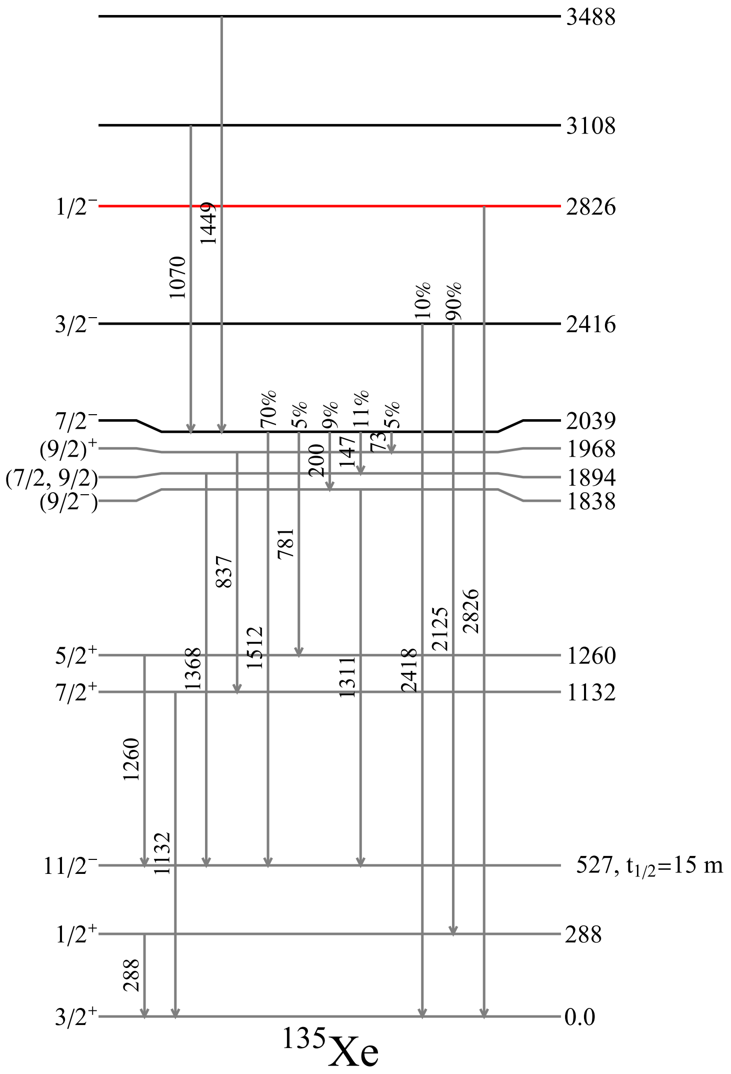

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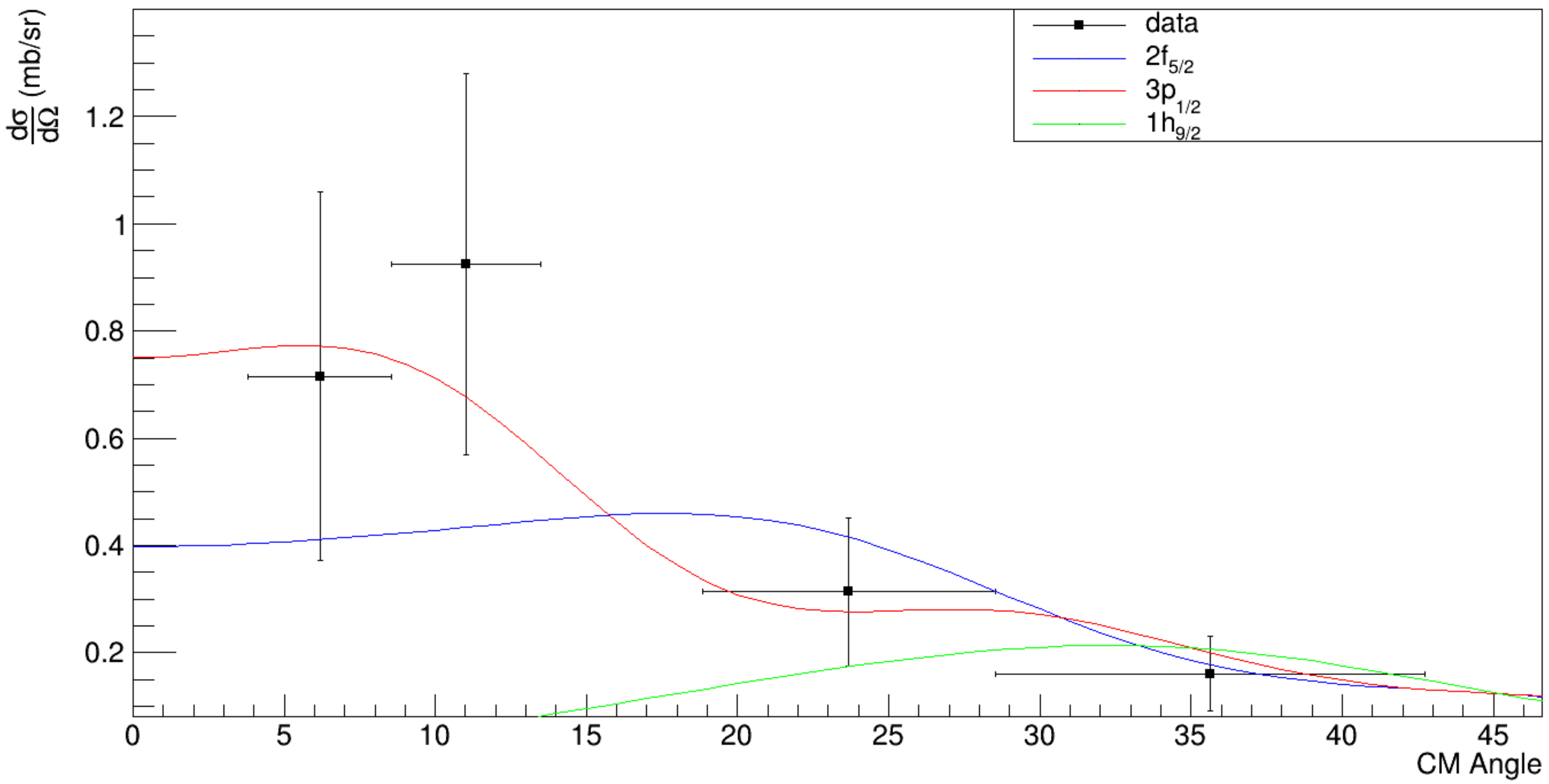

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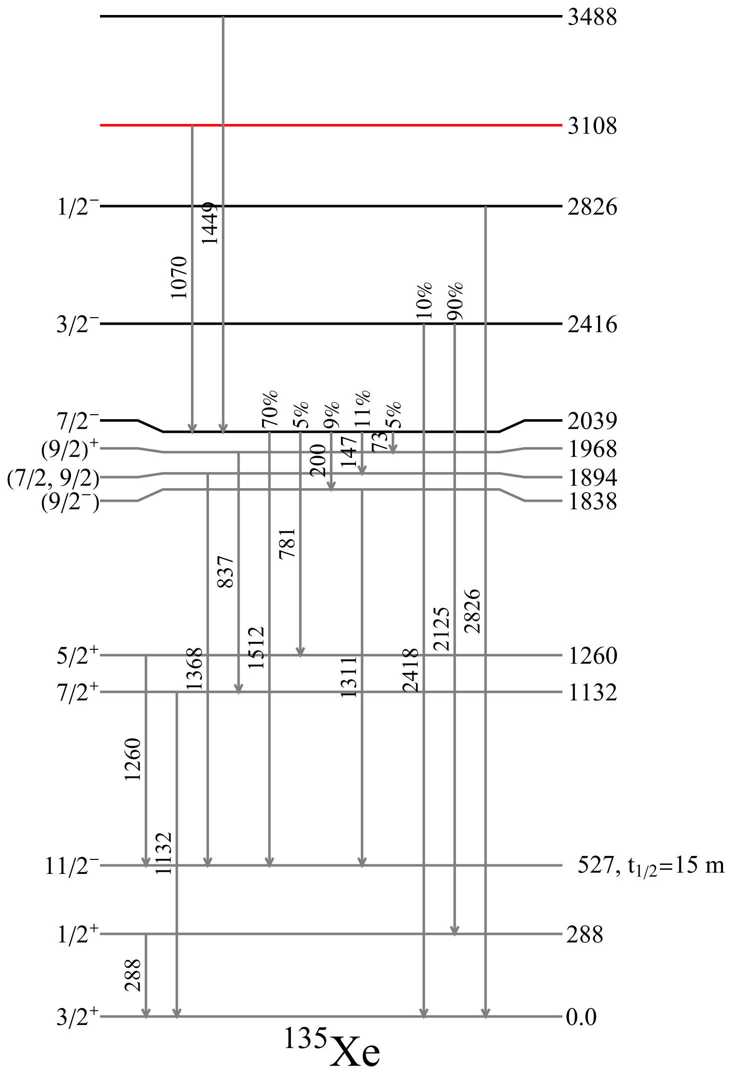

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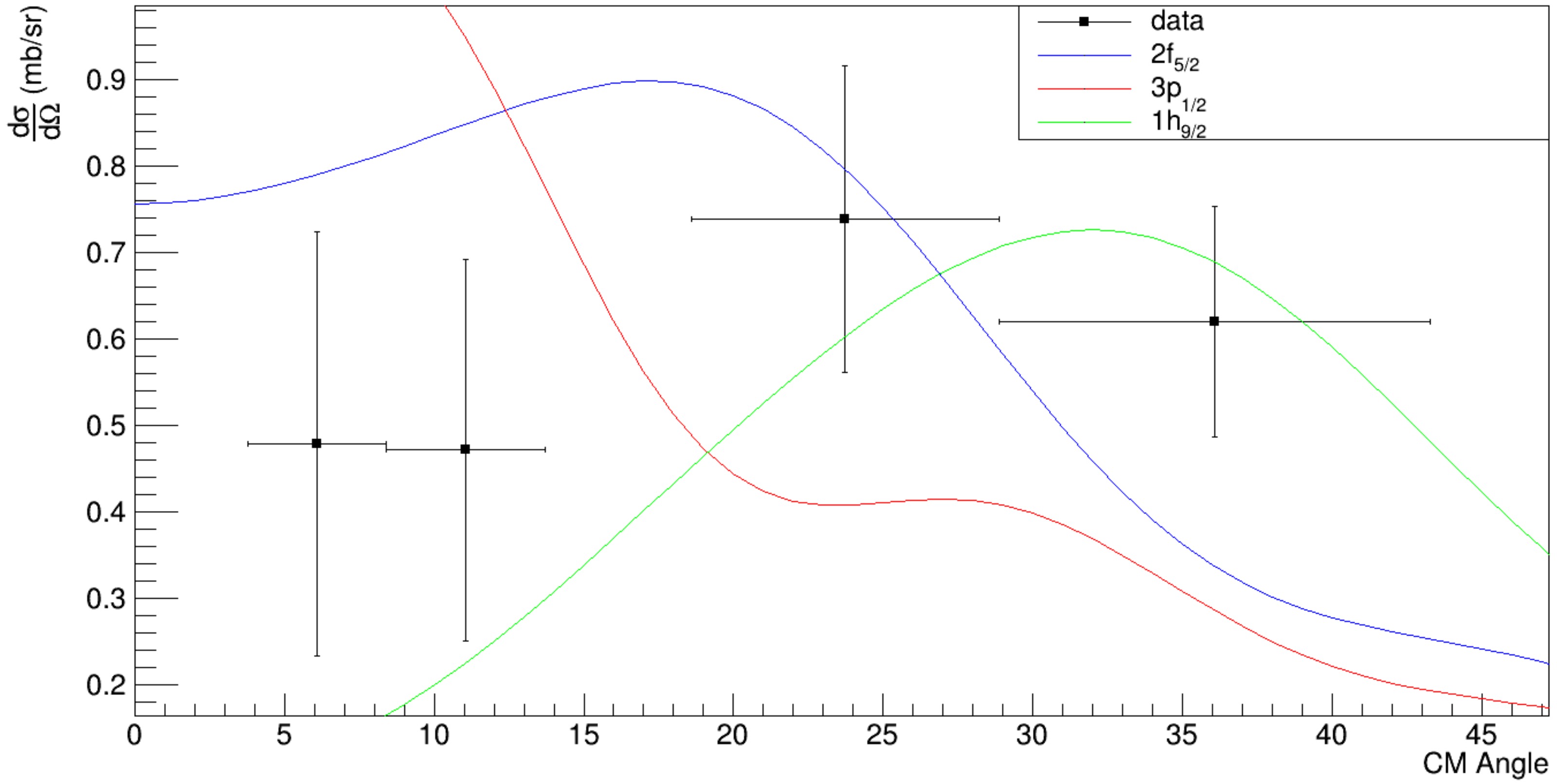

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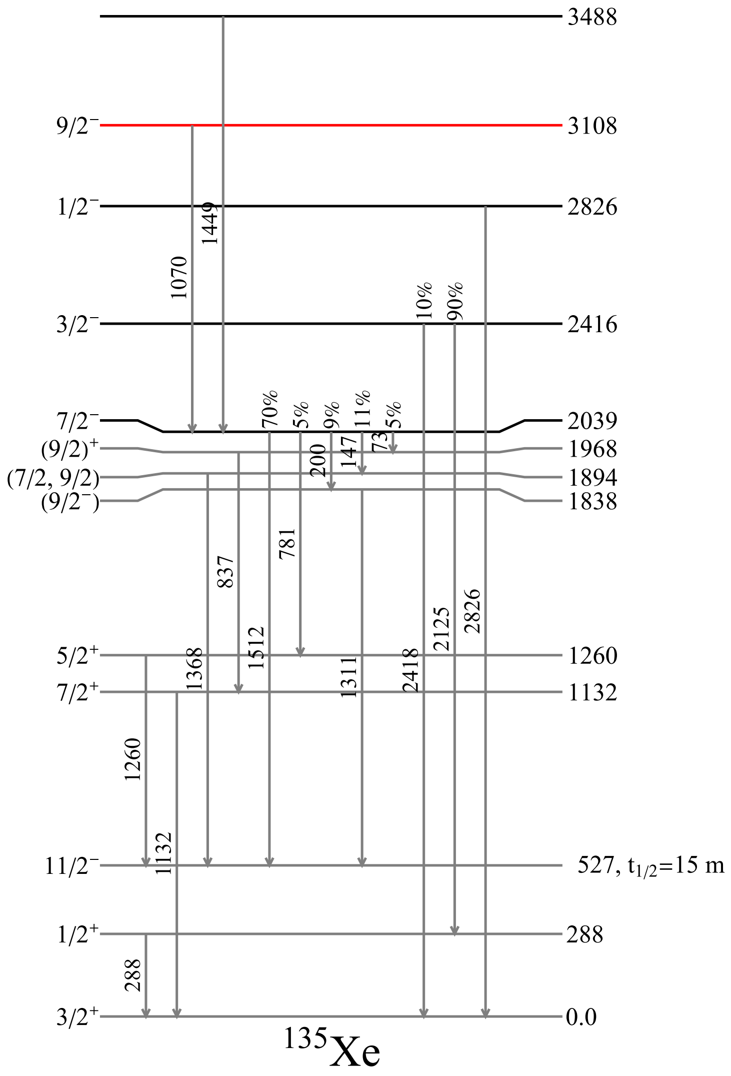

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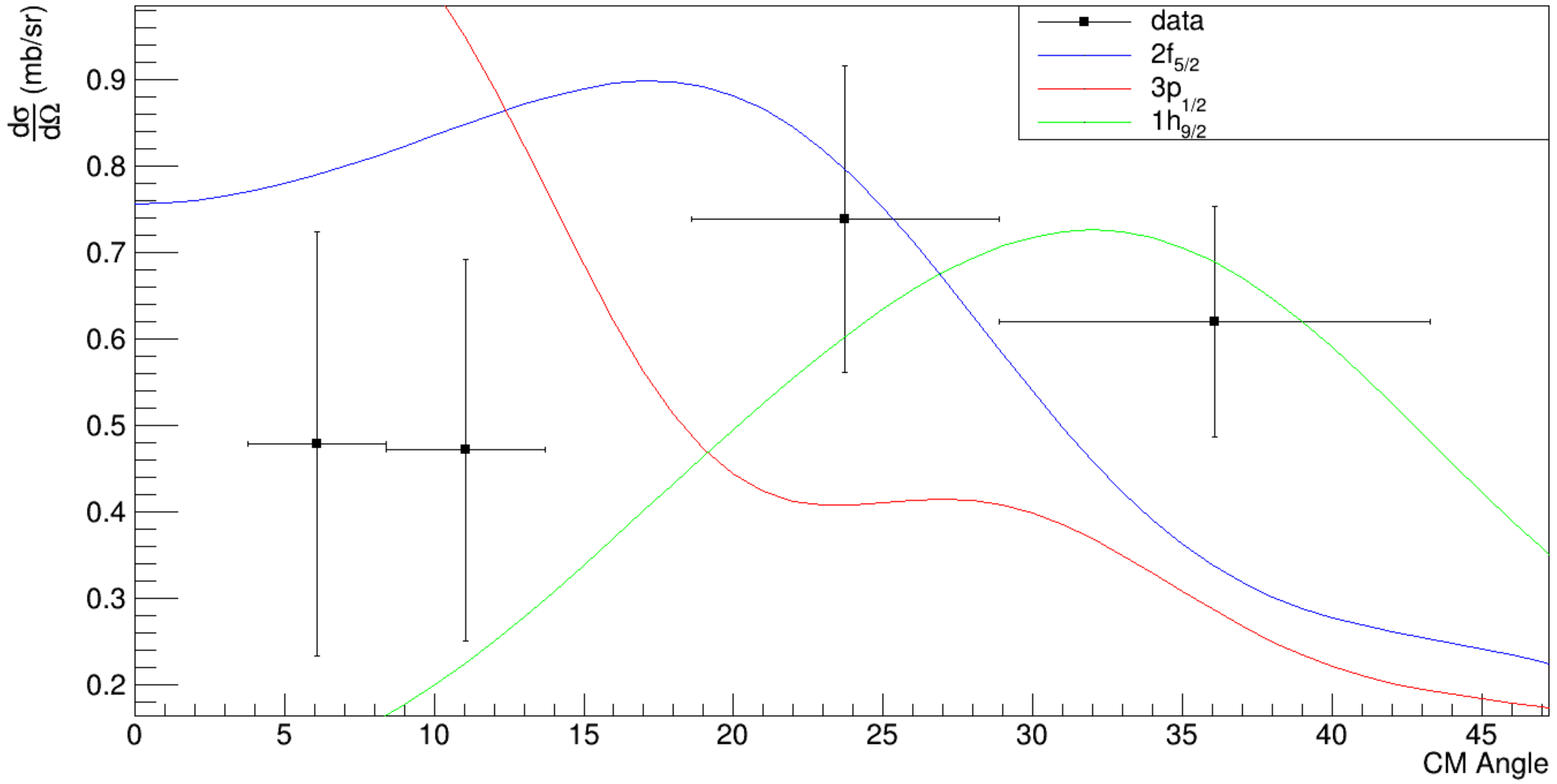

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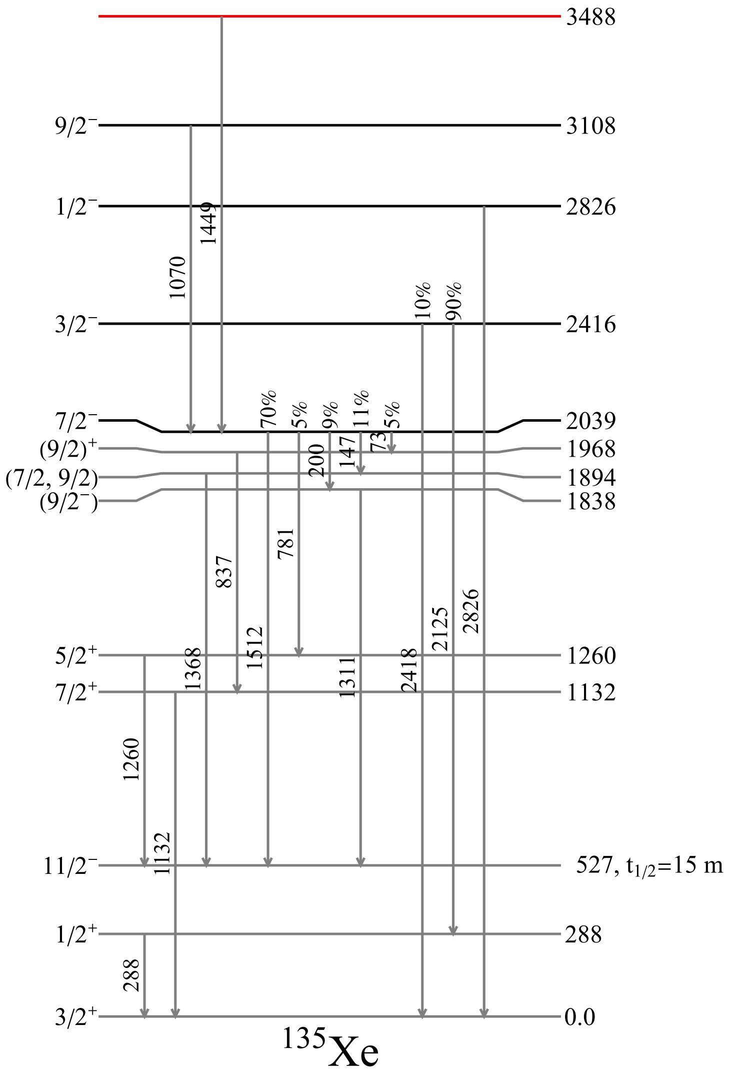

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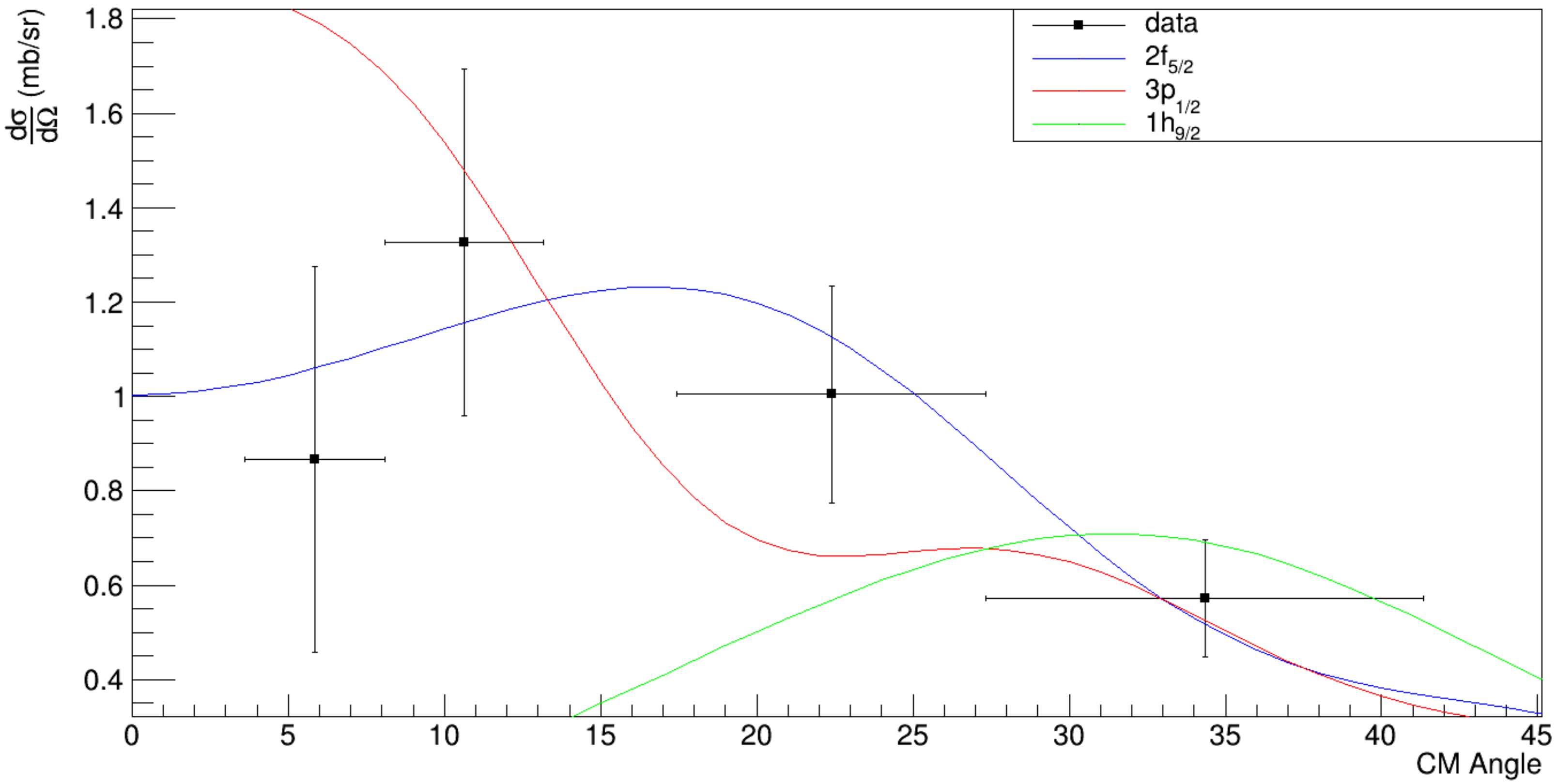

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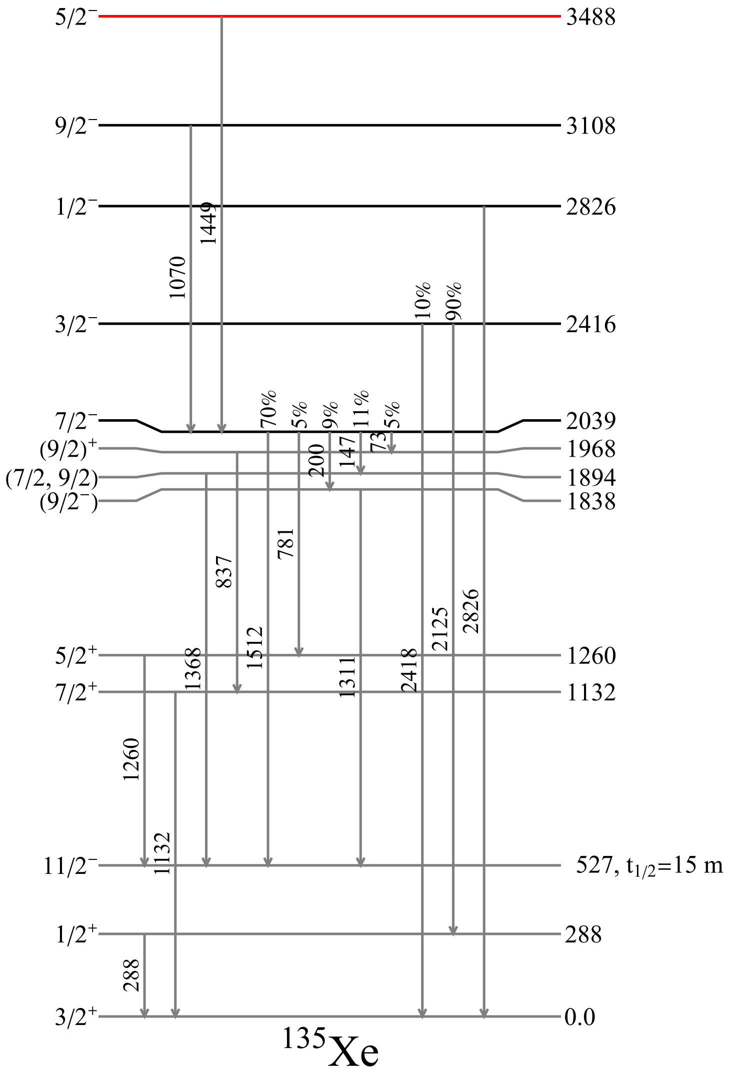

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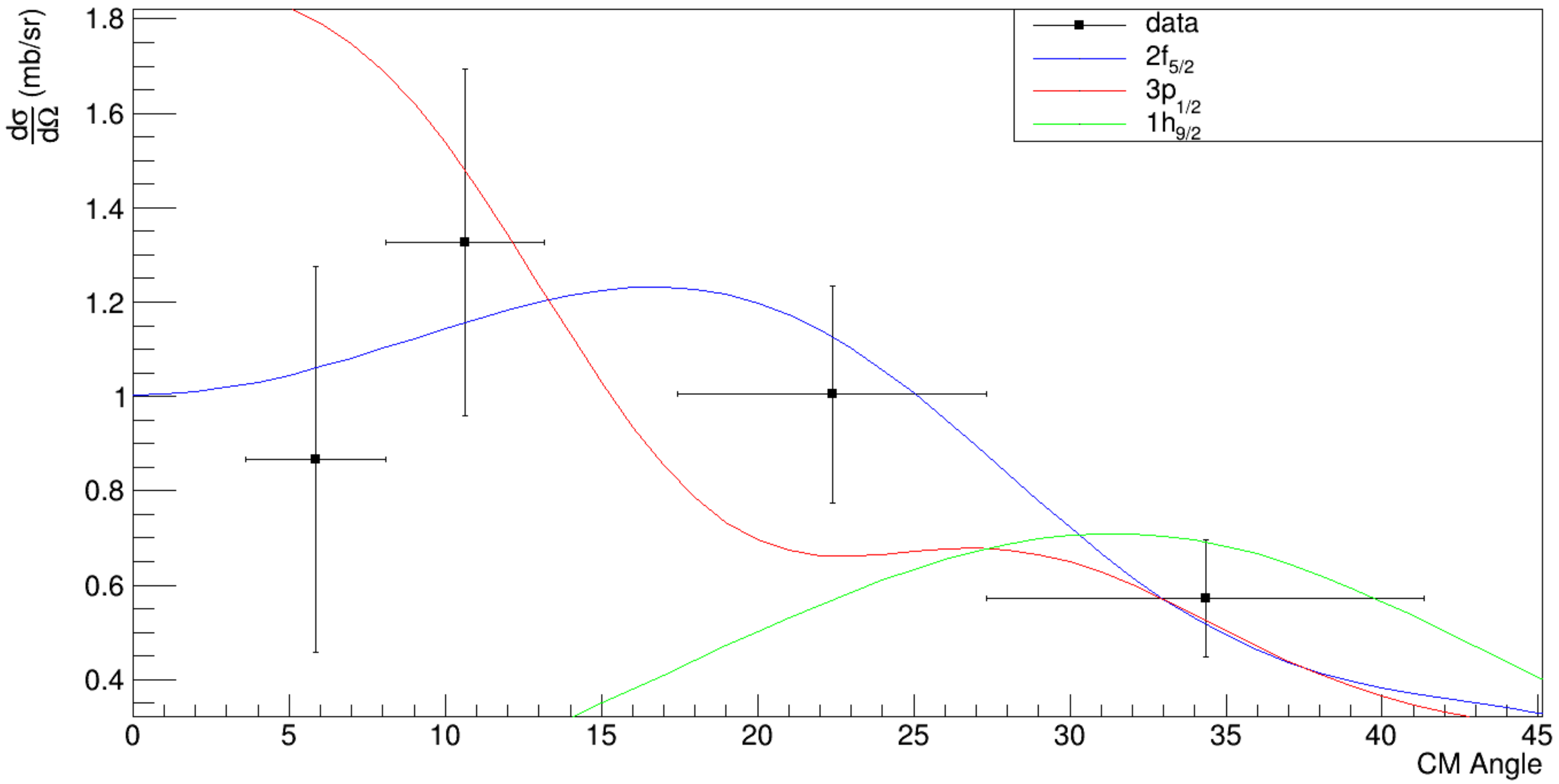

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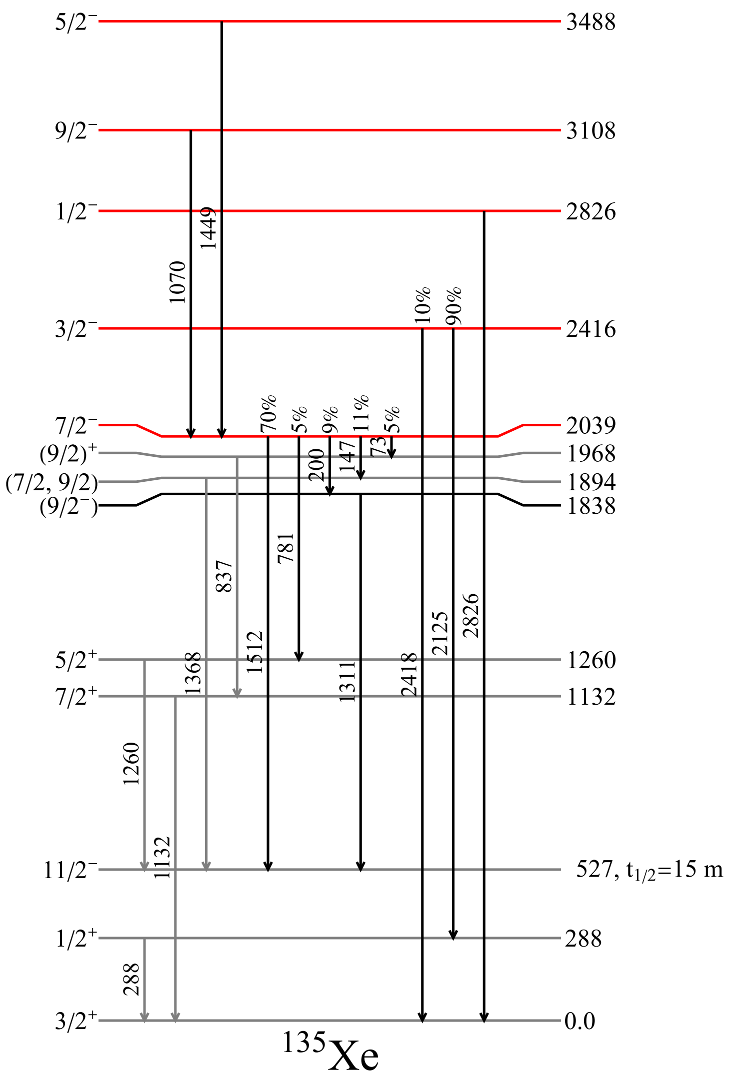

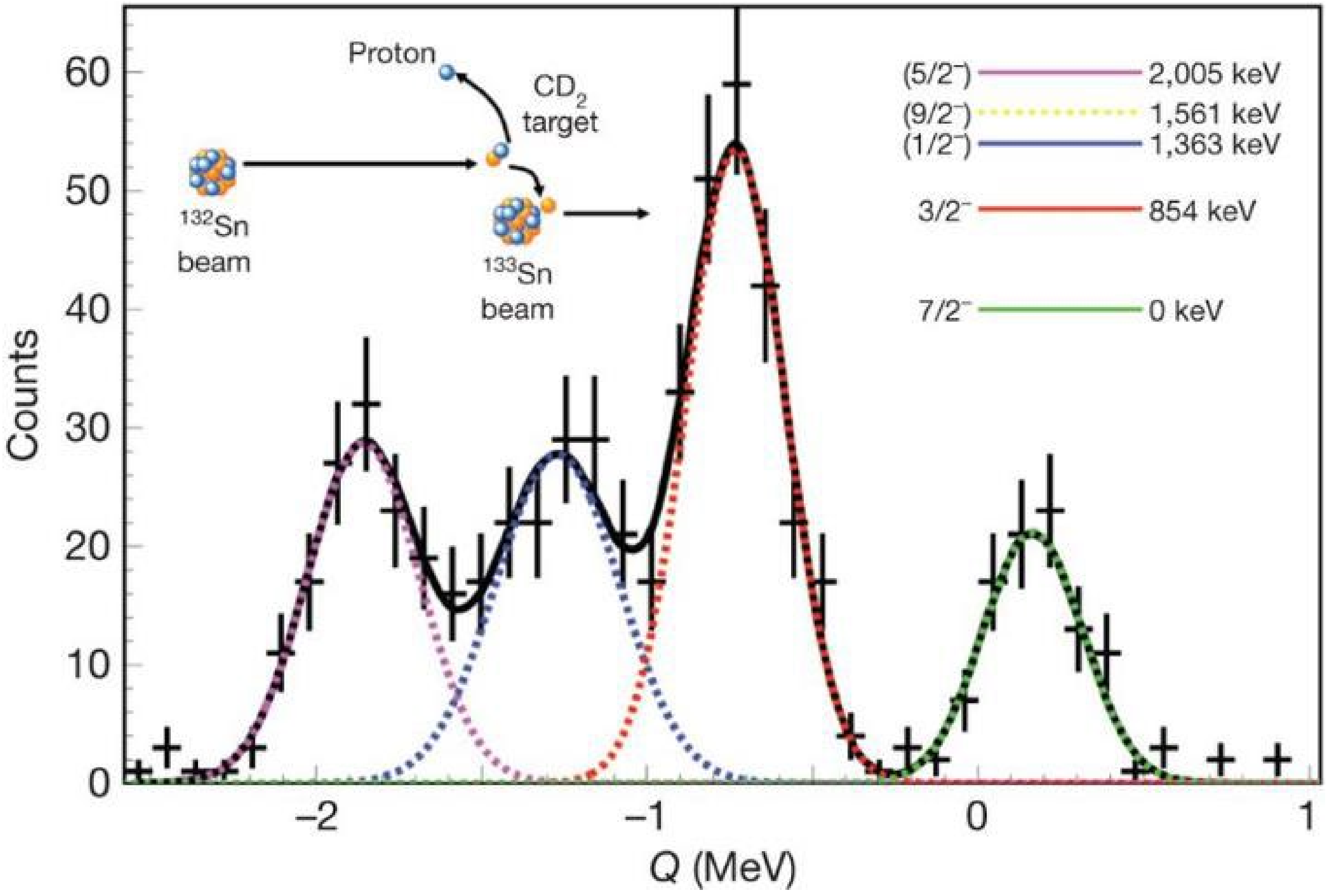

K.L. Jones, *et al.*, Nature **465**, 454-457 (2010).

The ordering of the single-neutron orbitals is the same as in ^{133}Sn!

Summary

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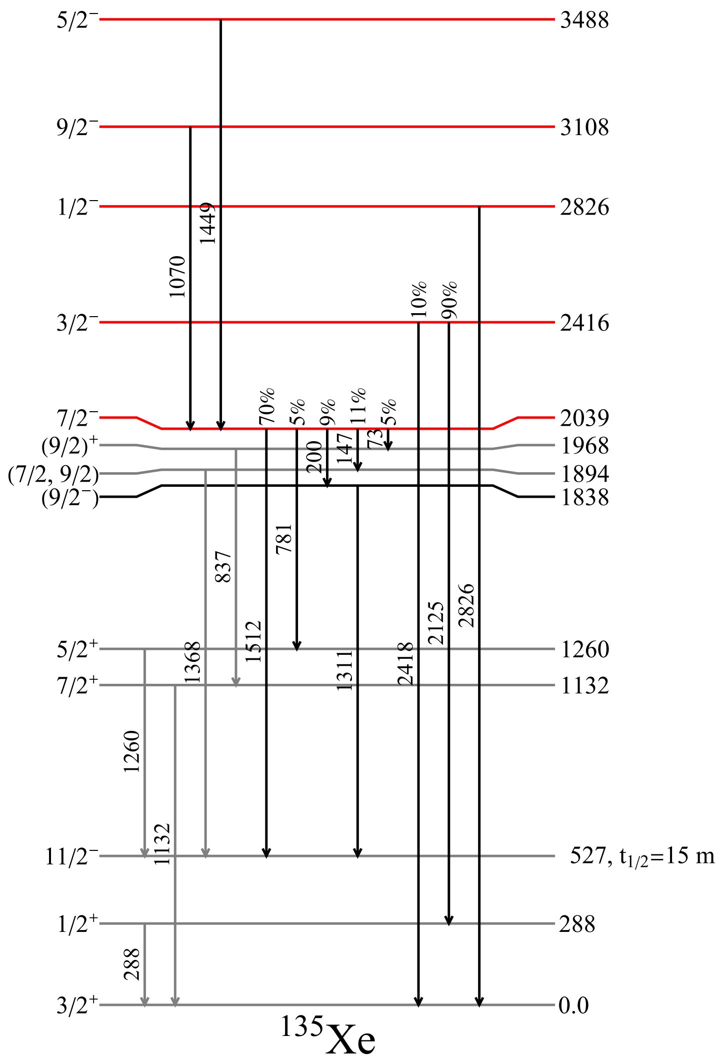

Thank you to all "the GODDESSes"

A. Lepailleur[1], **G. Seymour**[1], **J.A. Cizewski**[1], **K.L. Jones**[2], **S.D. Pain**[3], **A. Ratkiewicz**[4], H. Garland[1], H. Sims[1,5], D.W. Bardayan[5], T. Baugher[1], K. Chipps[3], M. Febbraro[3], M. Hall[5], K. Smith[2], D. Walter[1], G.L. Wilson[6,7], **and many more**!

[1]*Rutgers University*, [2]*University of Tennessee-Knoxville*, [3]*Oak Ridge National Laboratory*, [4]*Lawrence Livermore National Laboratory*, [5]*University of Surrey*, [6]*University of Notre Dame*, [7]*Louisiana State University*, [8]*Argonne 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-AC05-00OR22725, 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.

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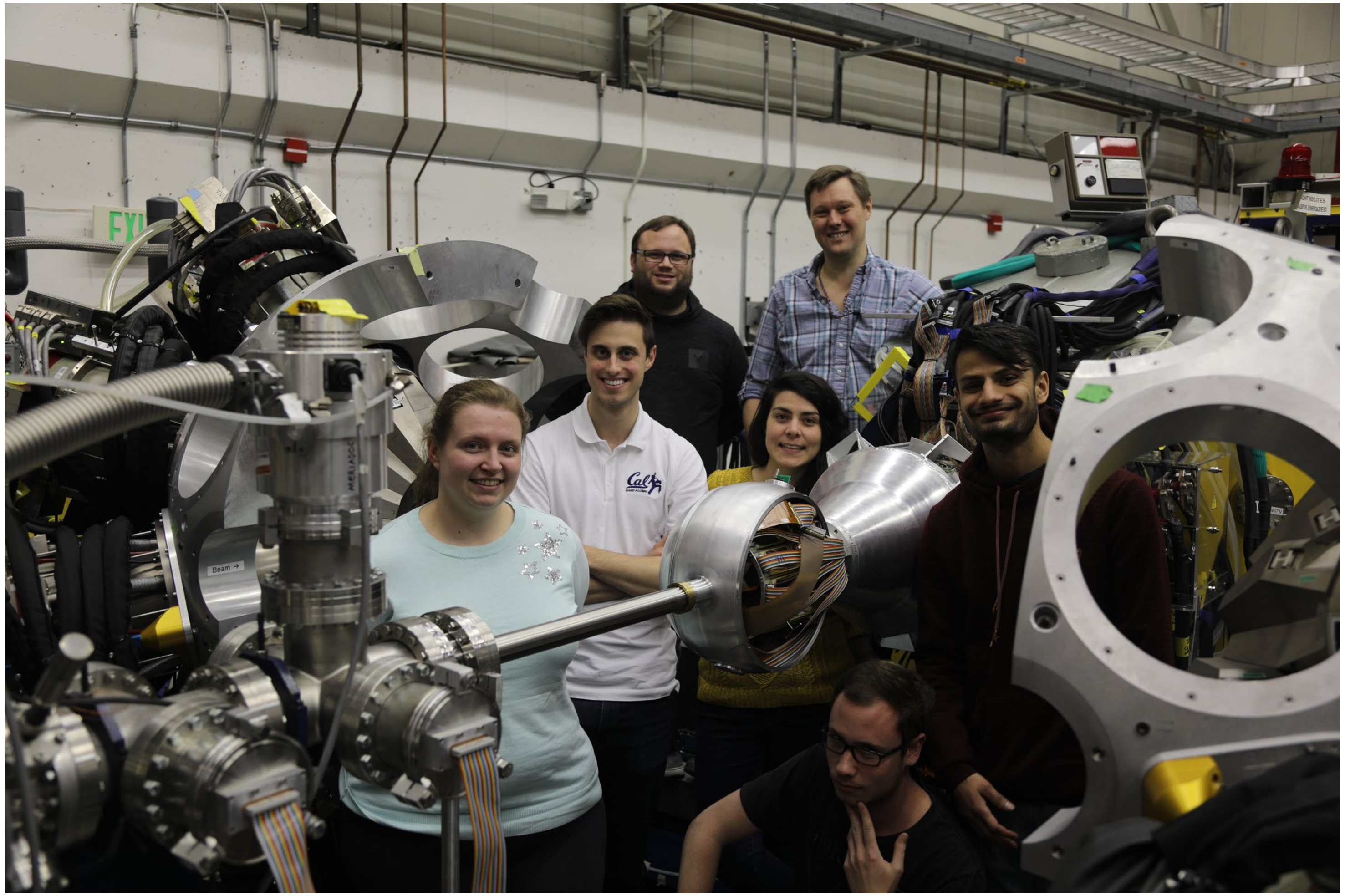

Photo by S.D. Pain and A. Ratkiewicz

GODDESS

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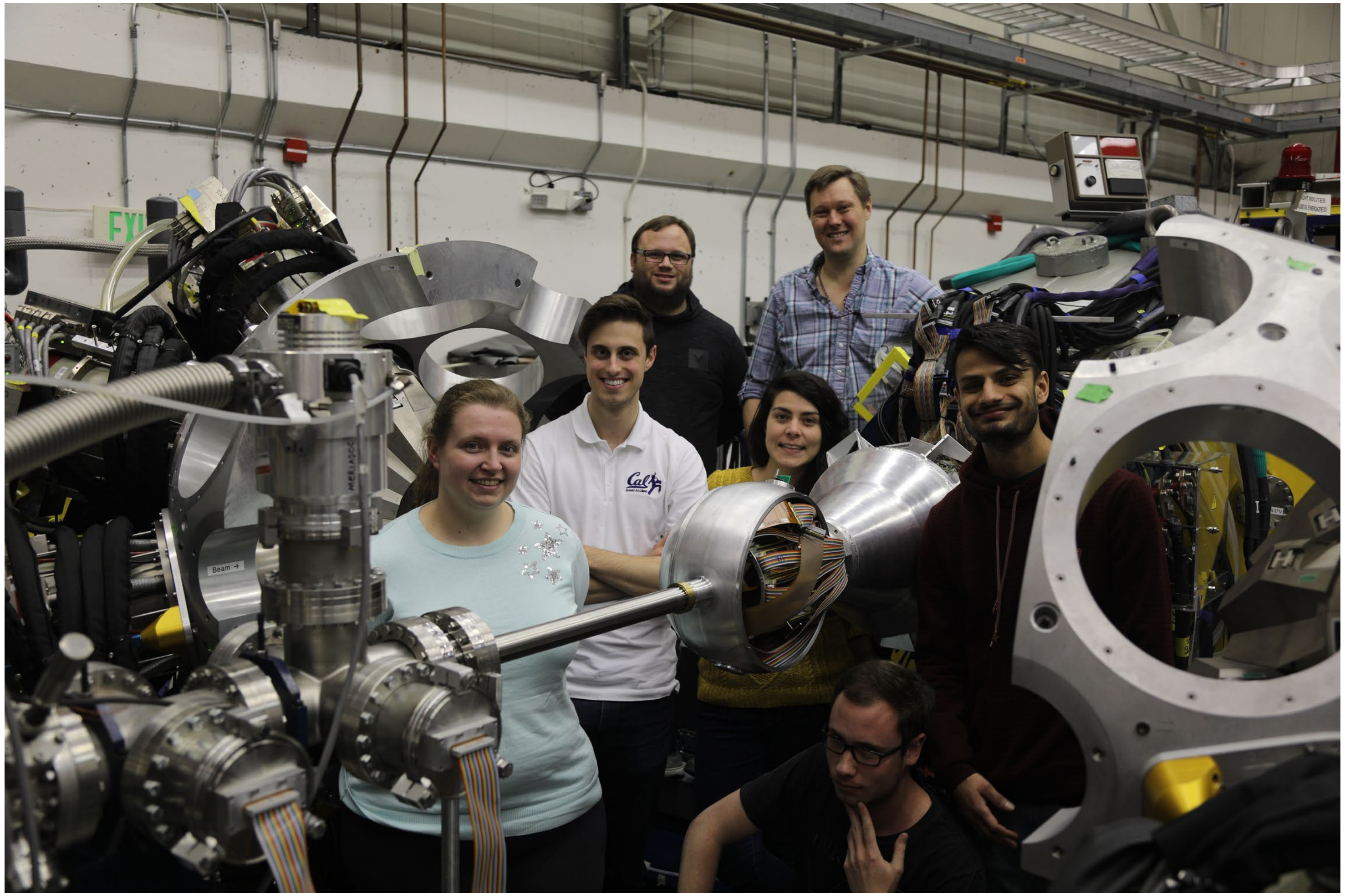
Thank you to SSGF, NNSA, and Krell for a fantastic four years!



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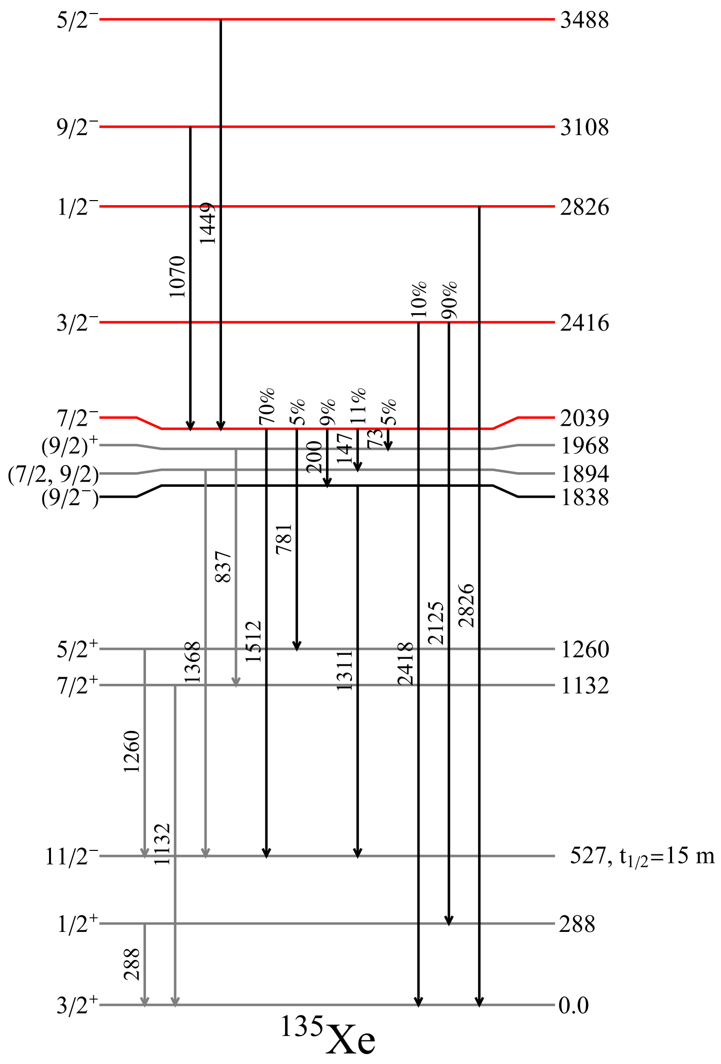

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