Exploring the Onset of Shape Coexistence using (d,p) with Exotic Sr Isotopes

Monday 25th July 2016.

Peter C Bender

NSCL

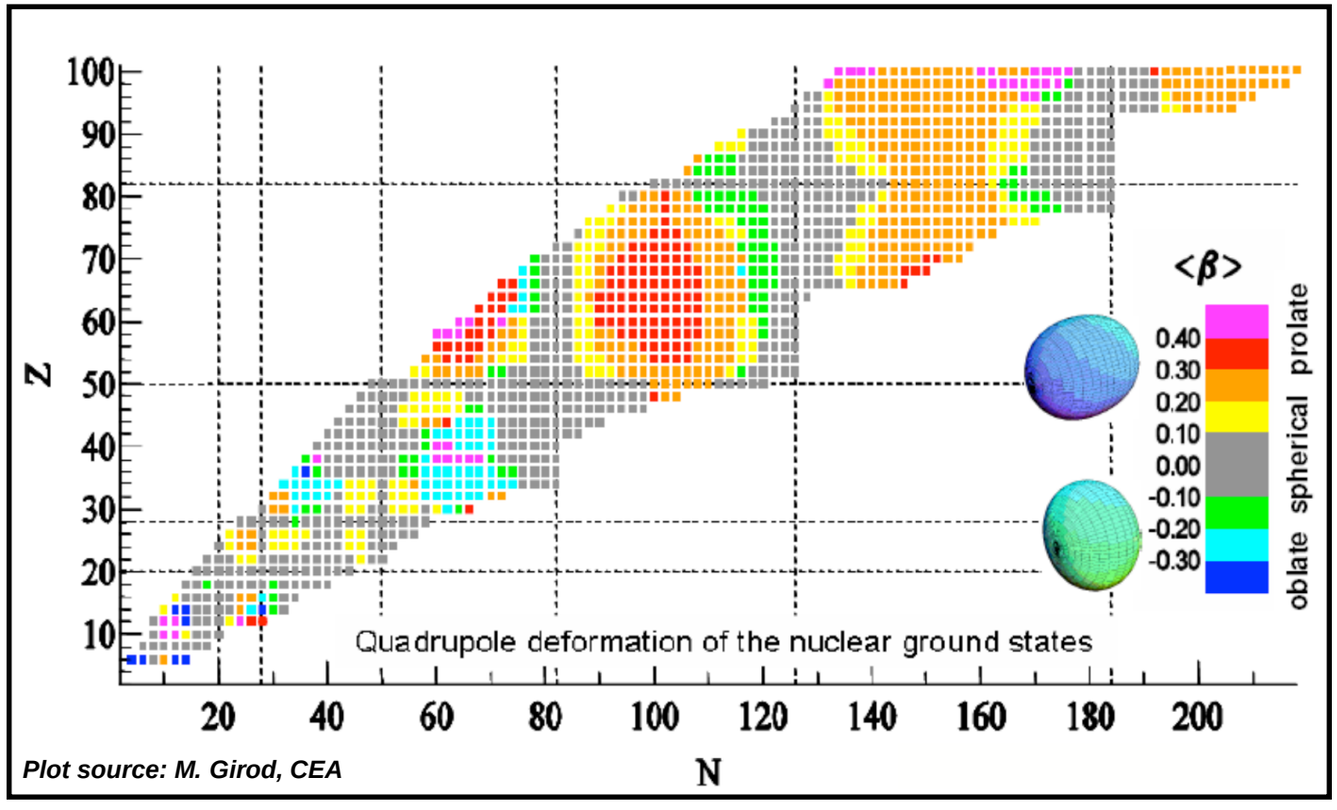
On behalf of the TRIUMF S1389 experimental team

Quadrupole Deformation

- Shape deformation enables the nucleus to minimize its energy.

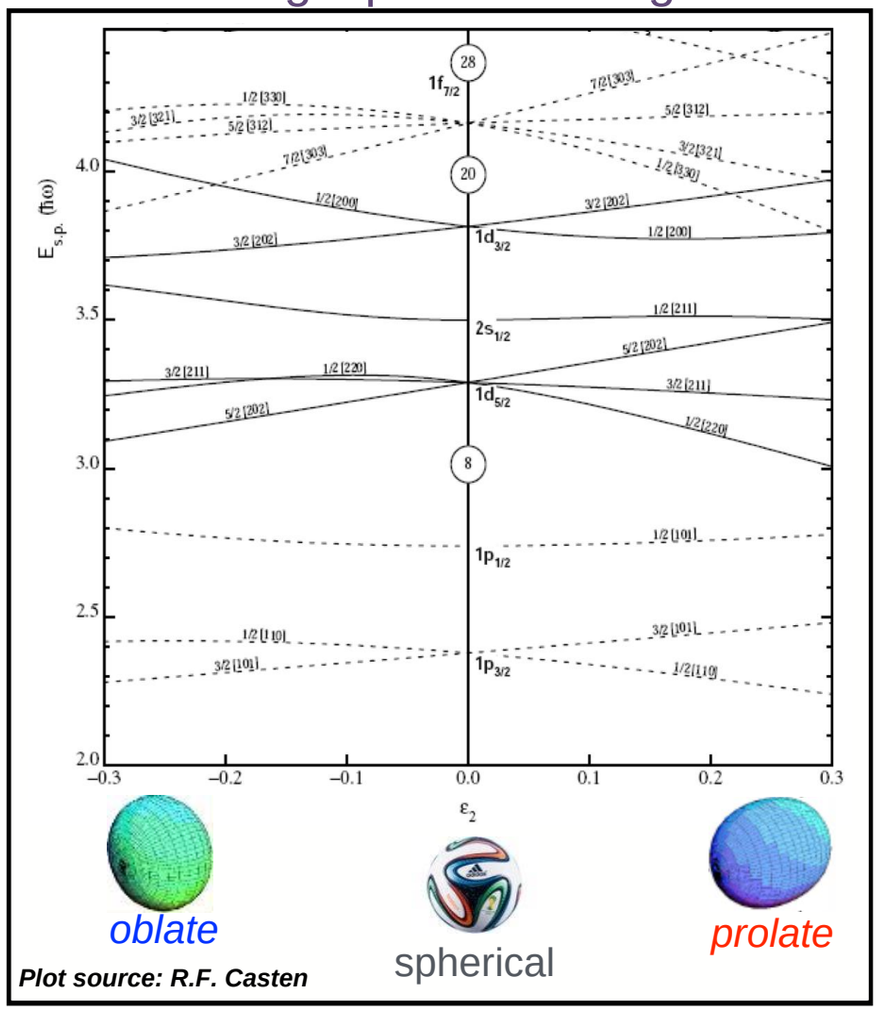
- HFB calculation (left) shows expected quadrupole deformation across nuclear chart.

Quadrupole deformation is a measure of nuclear shape.



Plot source: M. Girod, CEA

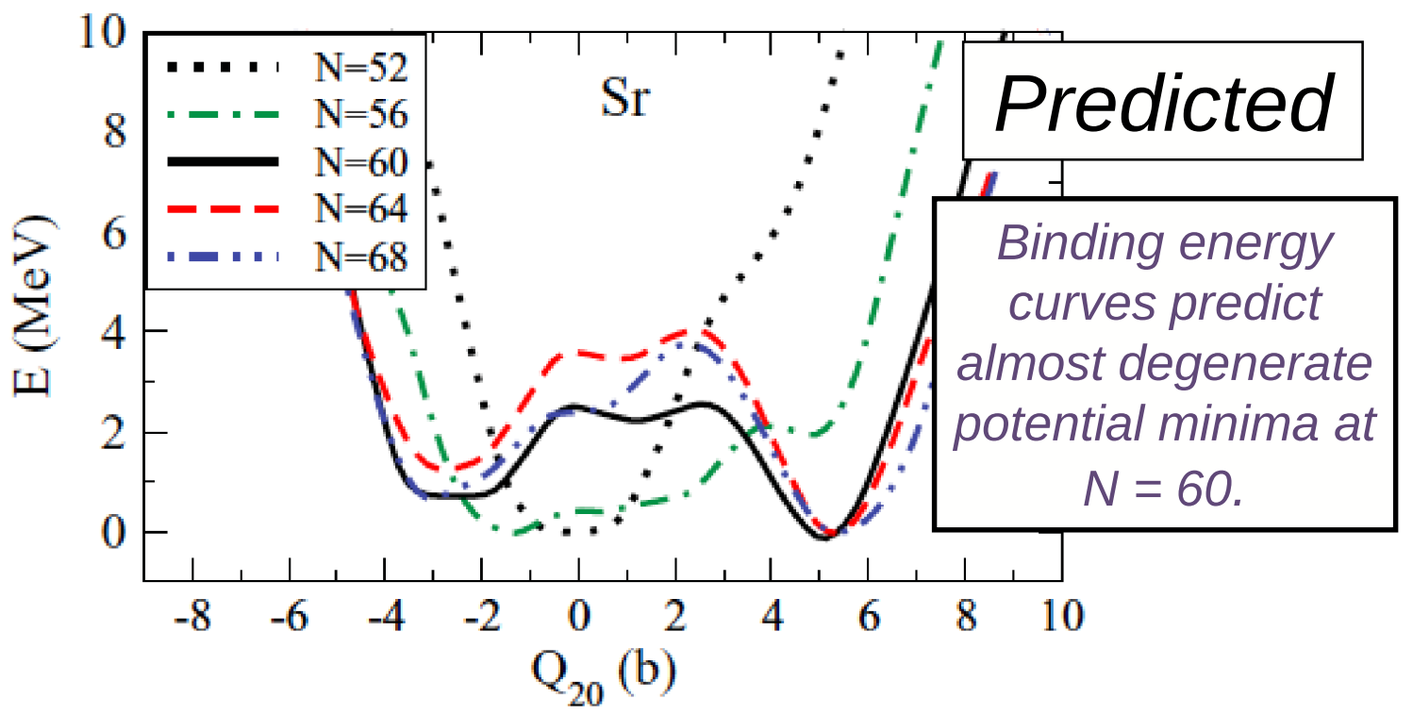
Nilsson model: Different deformations have different single particle configurations

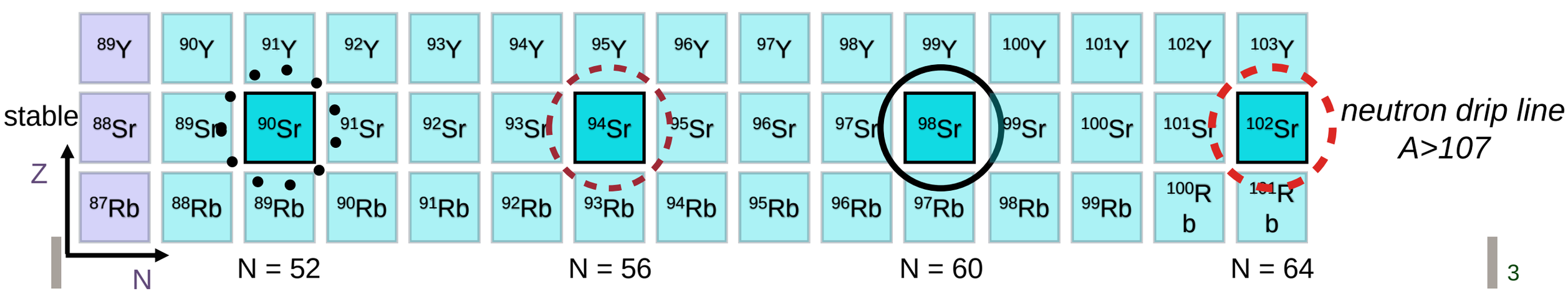


Plot source: R.F. Casten

Shape Coexistence at Z~40 N~60

- State of the art (beyond mean field) calculations predict binding energy as a function of deformation.
- Measurements of single particle levels in ^{95,96,97}Sr essential for a detailed description of this transitional region.





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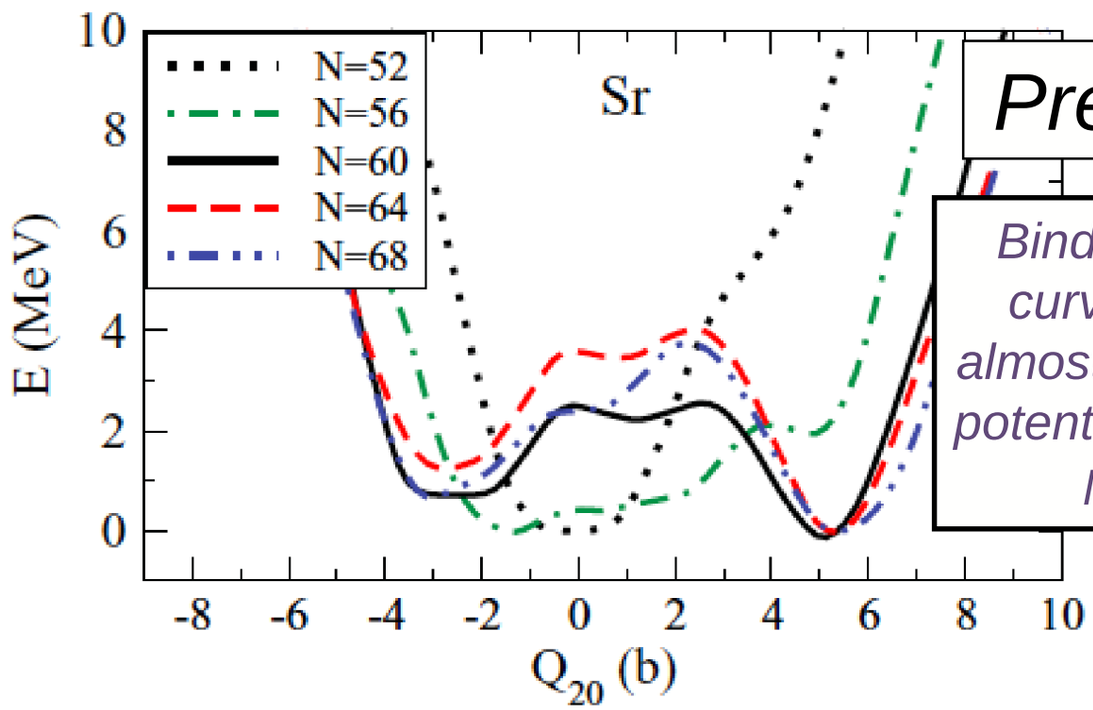

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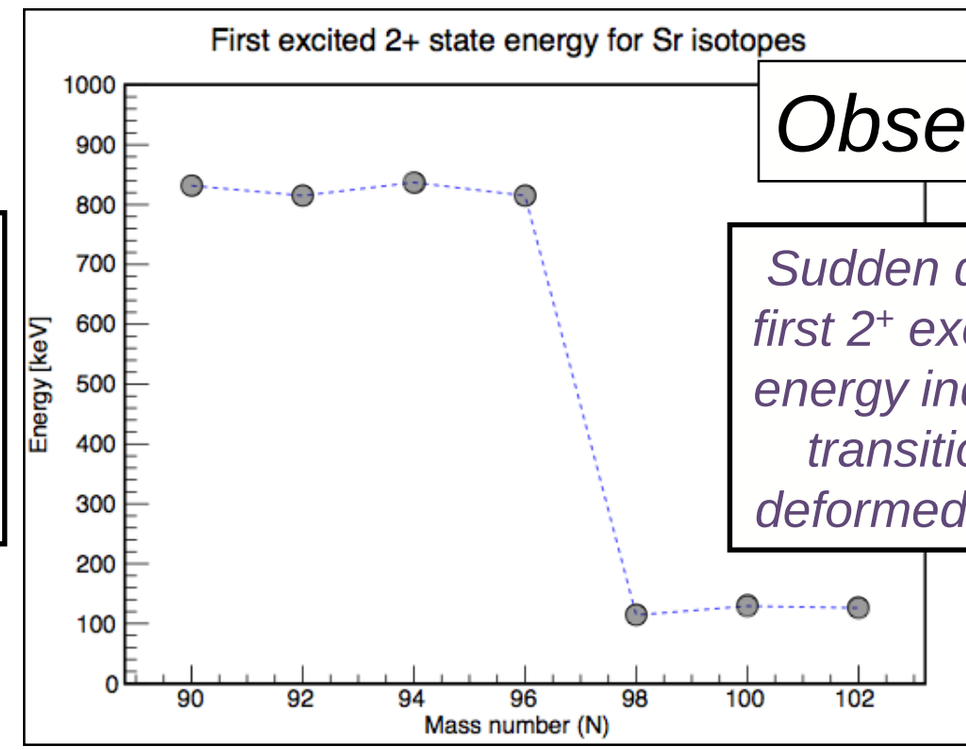
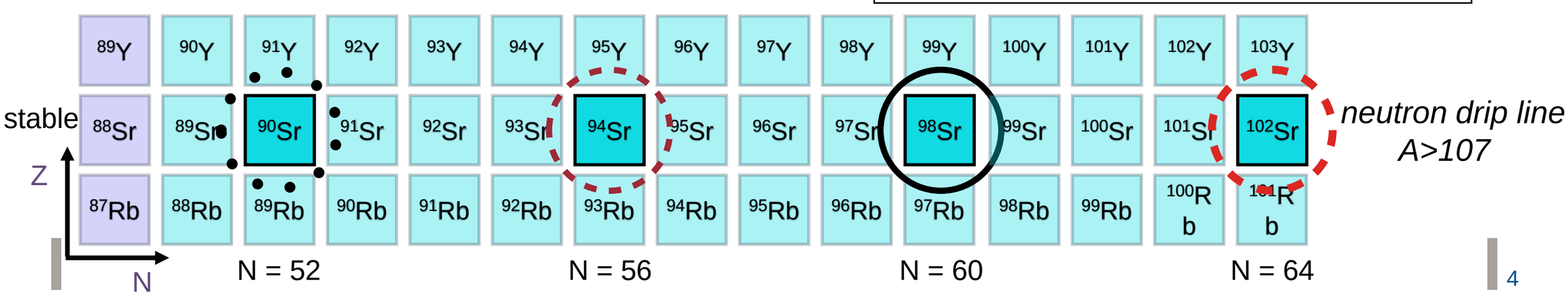


Observed

Sudden drop in first 2⁺ excitation energy indicates transition to deformed shape



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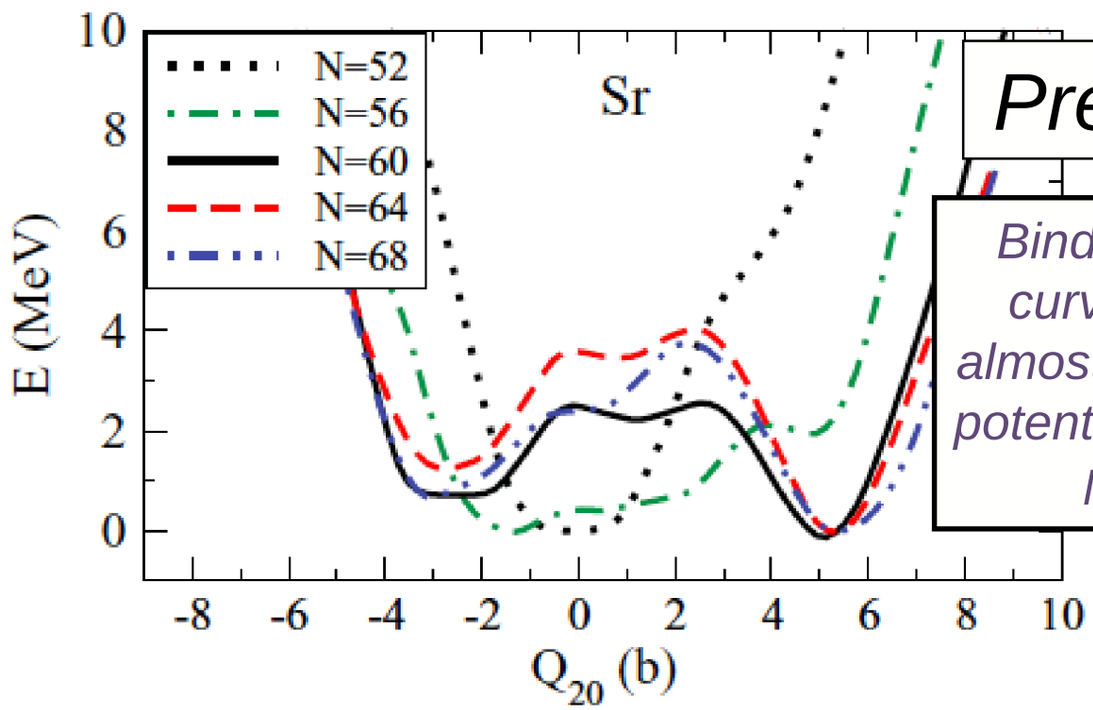

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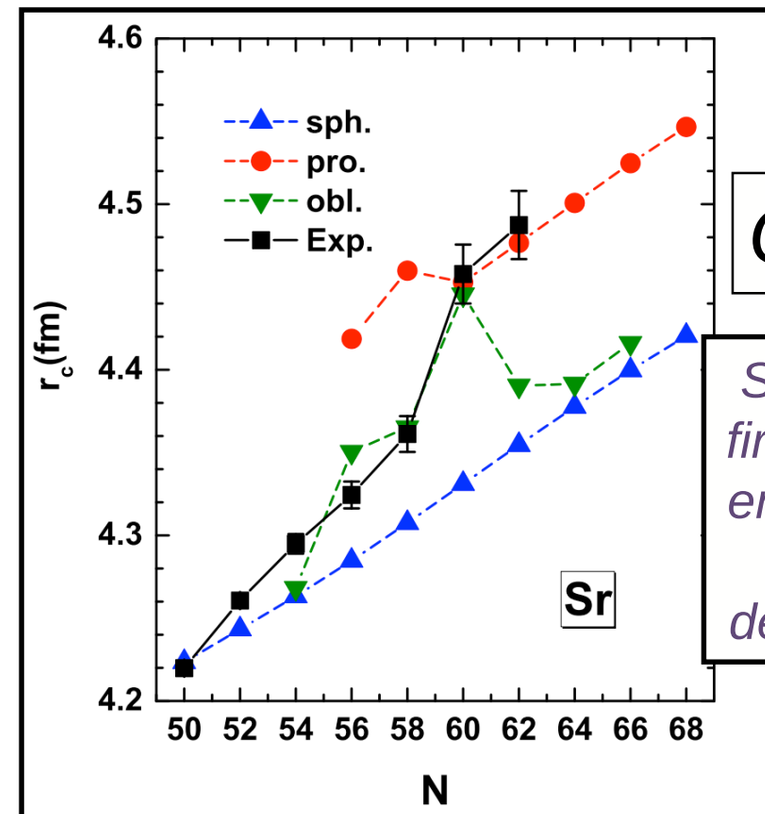

J. Xiang et al. / Nuclear Physics A 873 (2012) 1–16

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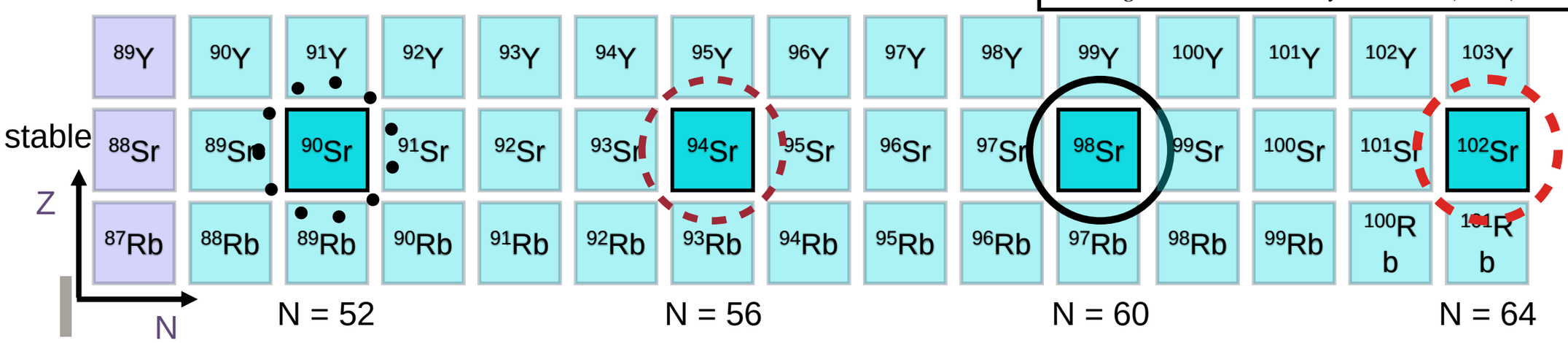
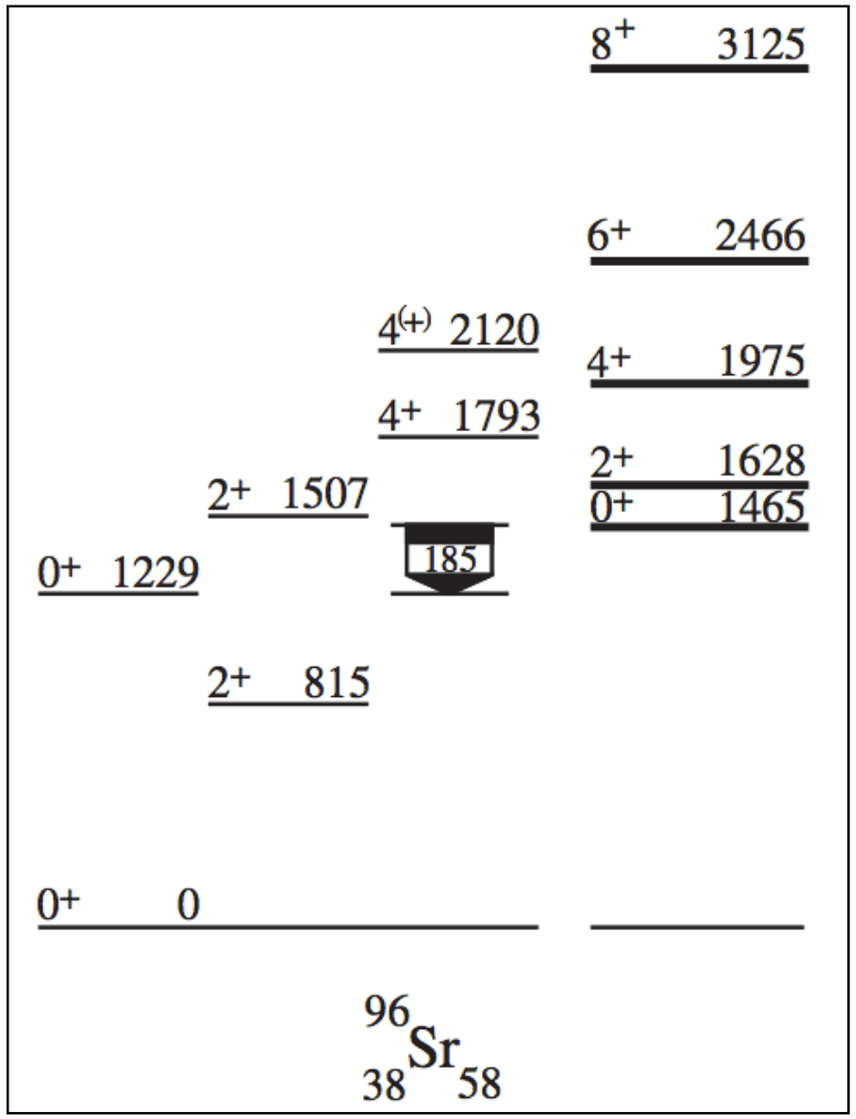


neutron drip line A>107

Shape Coexistence at Z~40 N~60

- The strong 0_3^+ (1465 keV) $\rightarrow 0_2^+$ (1229 keV) E0 transition is characteristic of coexisting shapes.
- The deformed 0_3^+ state at 1465 keV is expected to be the same structure as the ^{98}Sr ground state.



Shape coexistence in atomic nuclei [Rev. Mod. Phys. 83, 1467 (2011)]

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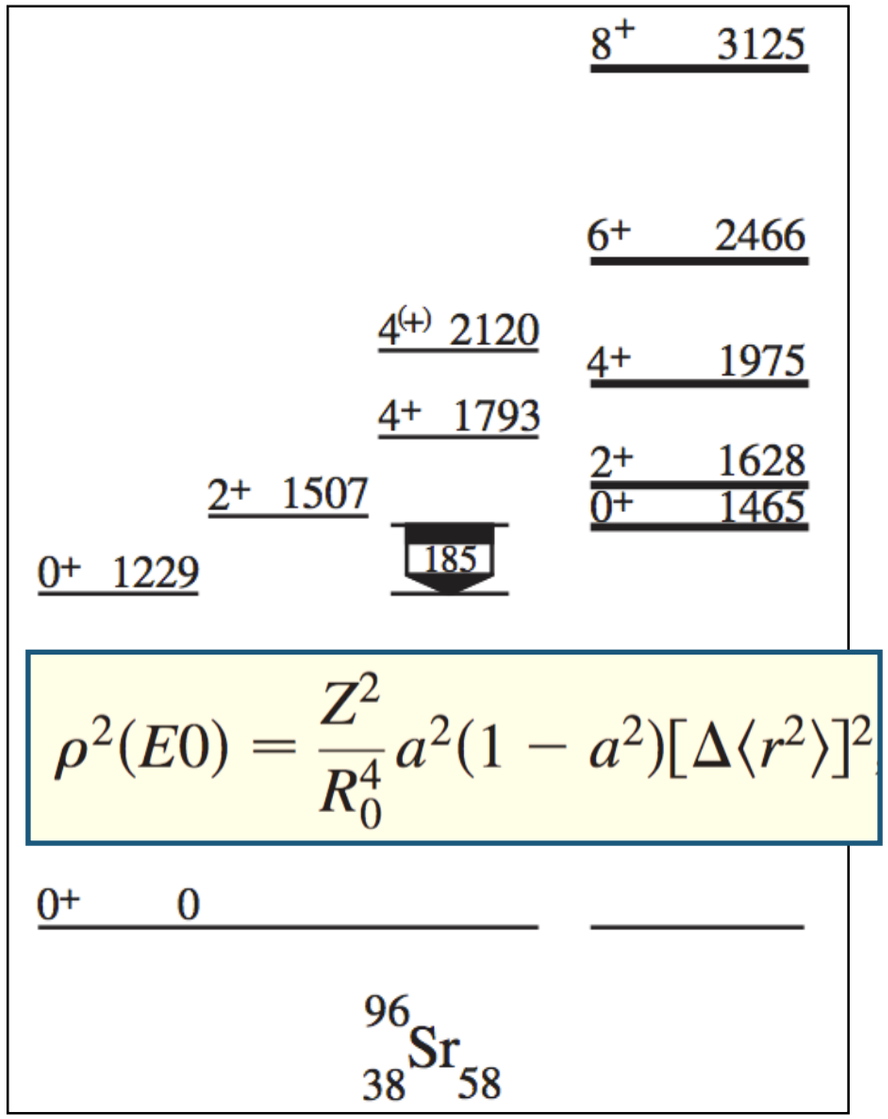

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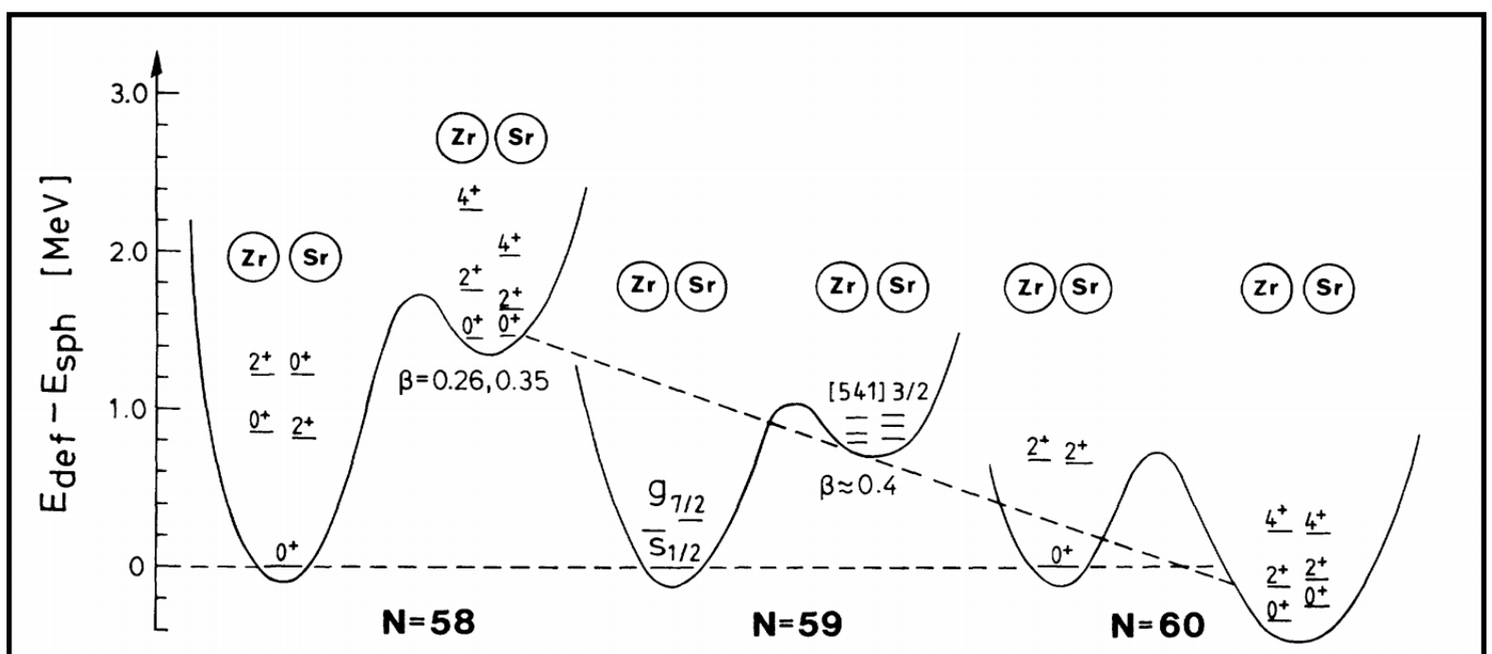
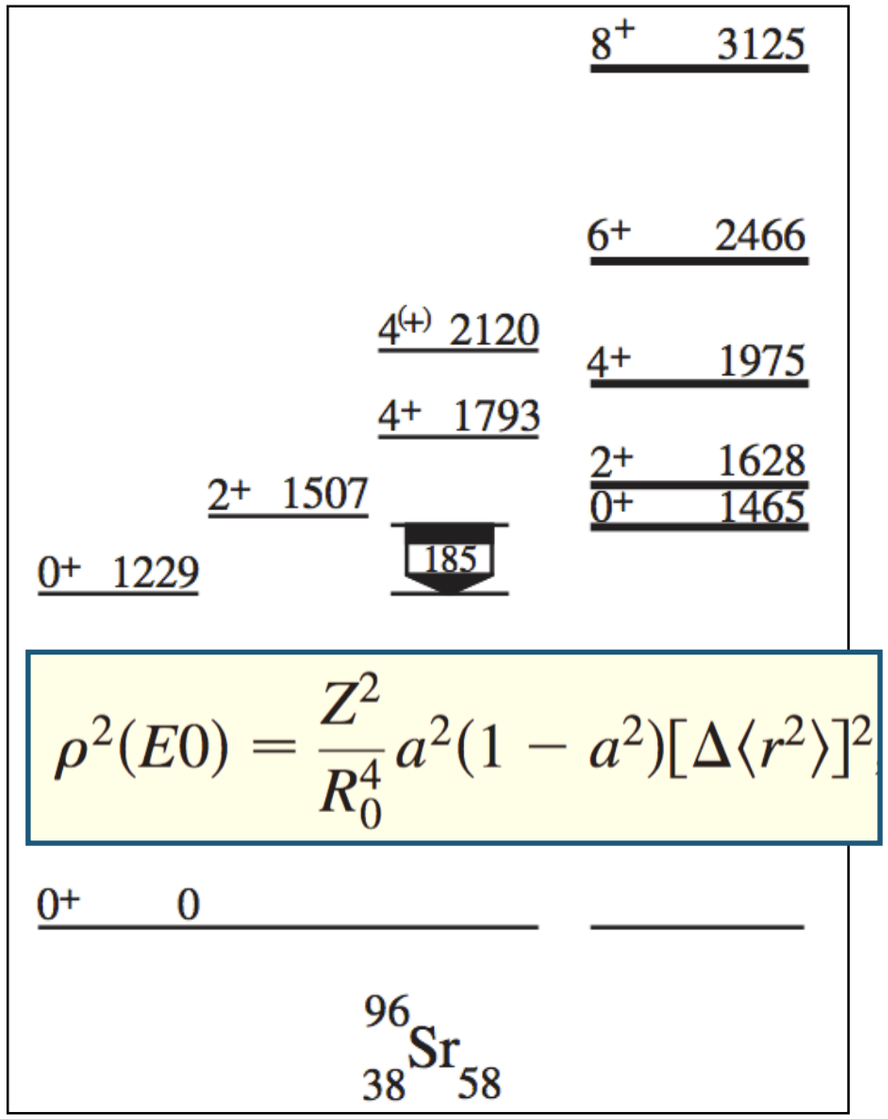


G. Lhersonneau et al., Phys. Rev. C 49, (1994) 1379



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^{94,95,96}Sr(d,p)Sr reactions to study evolution of structure in Sr through low energy single particle states.

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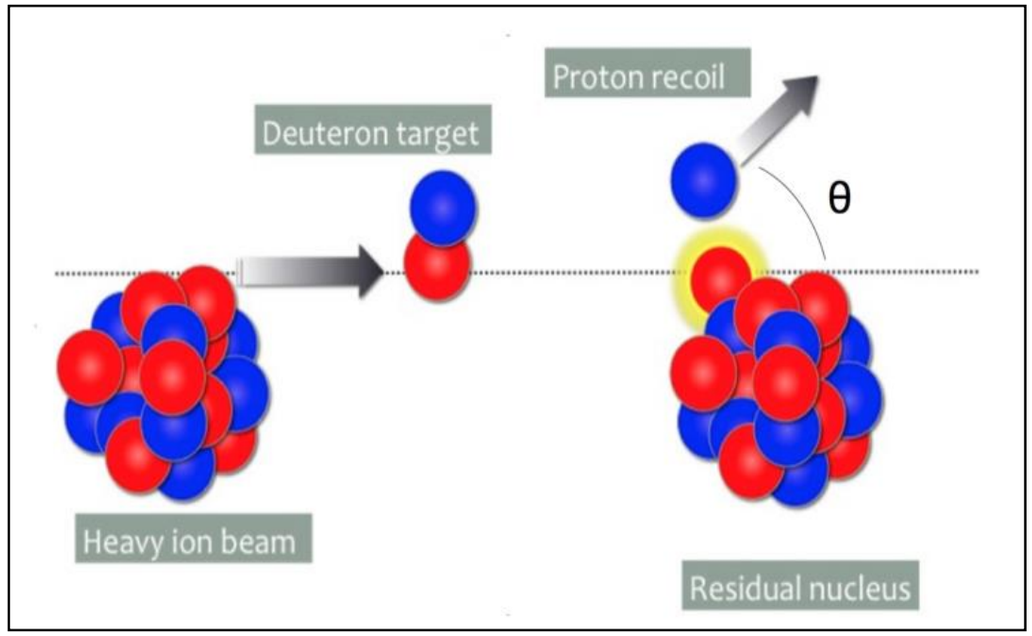
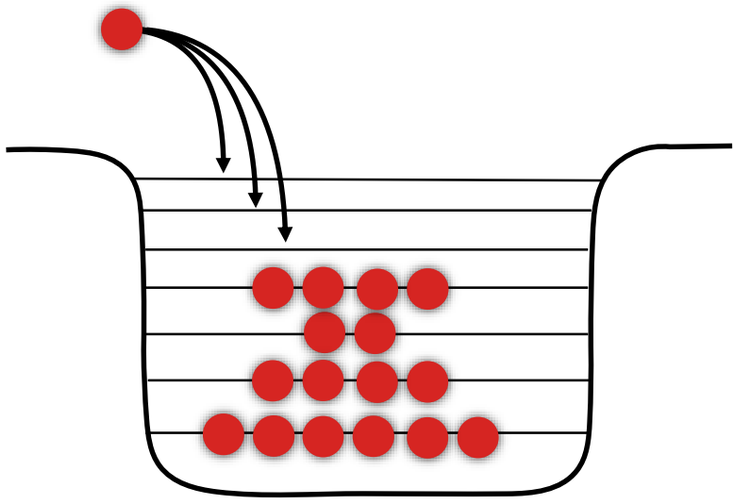


Neutron populates one of the single particle orbitals



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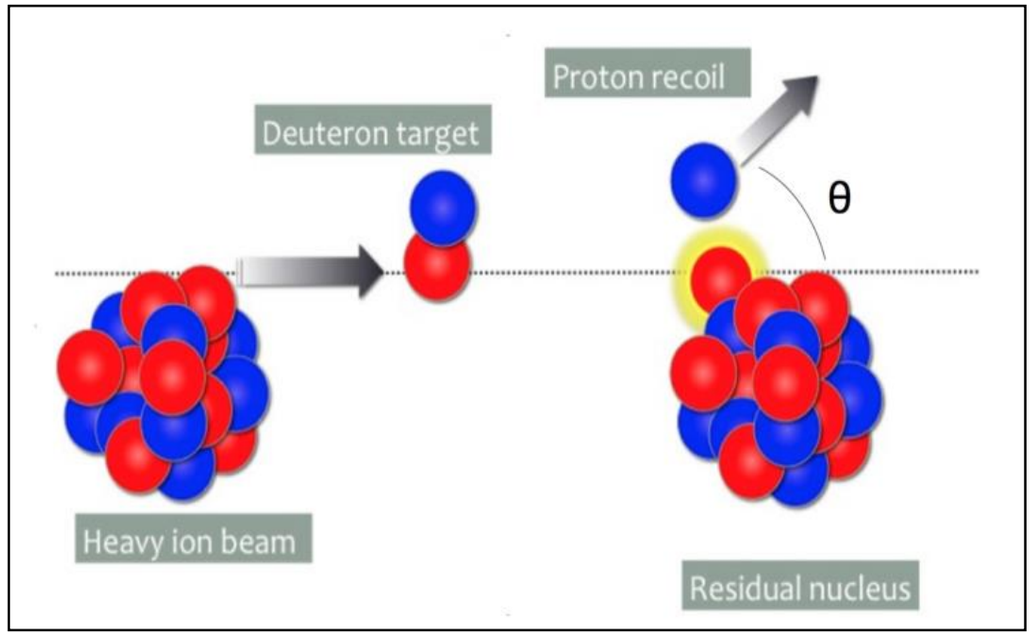

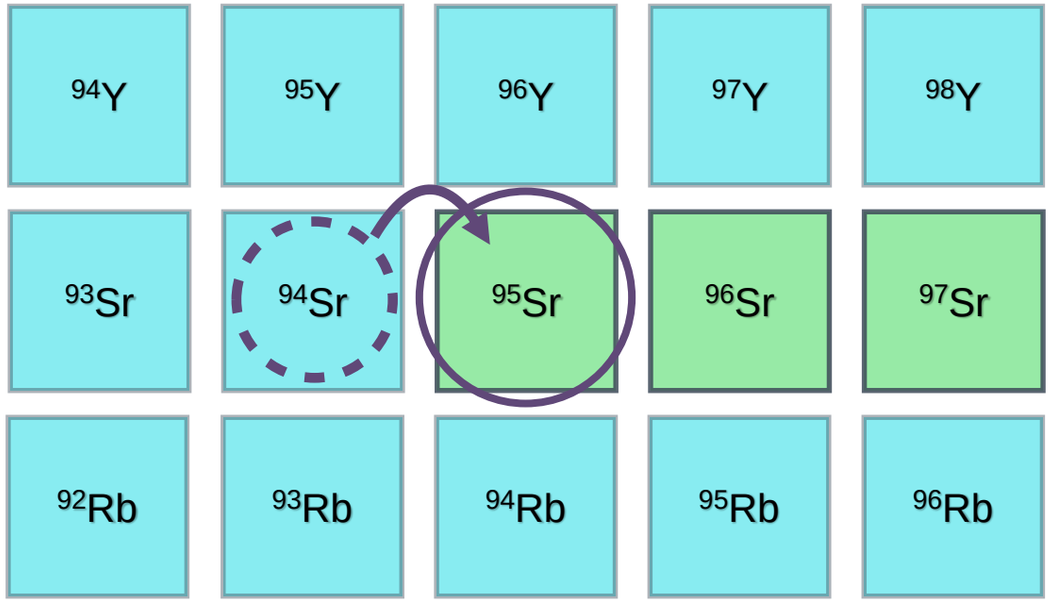

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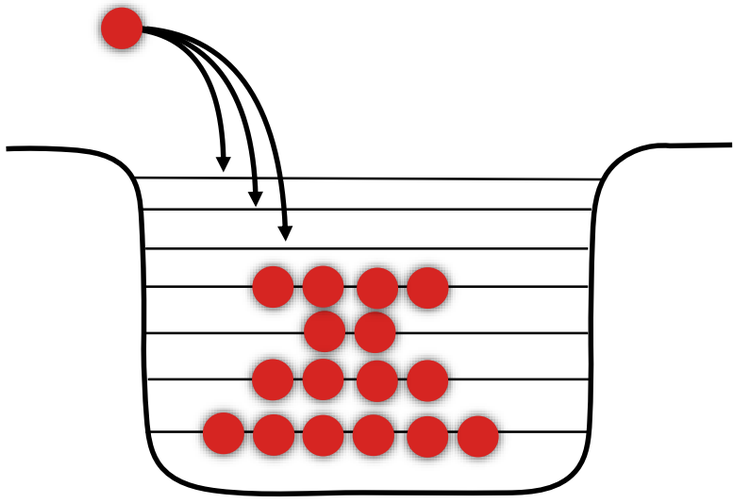

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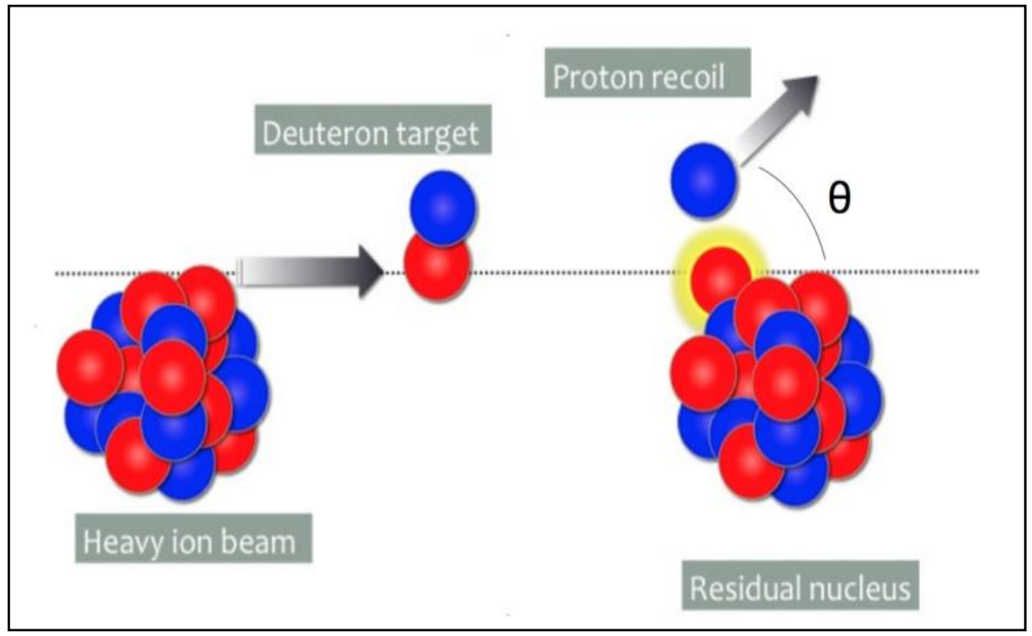

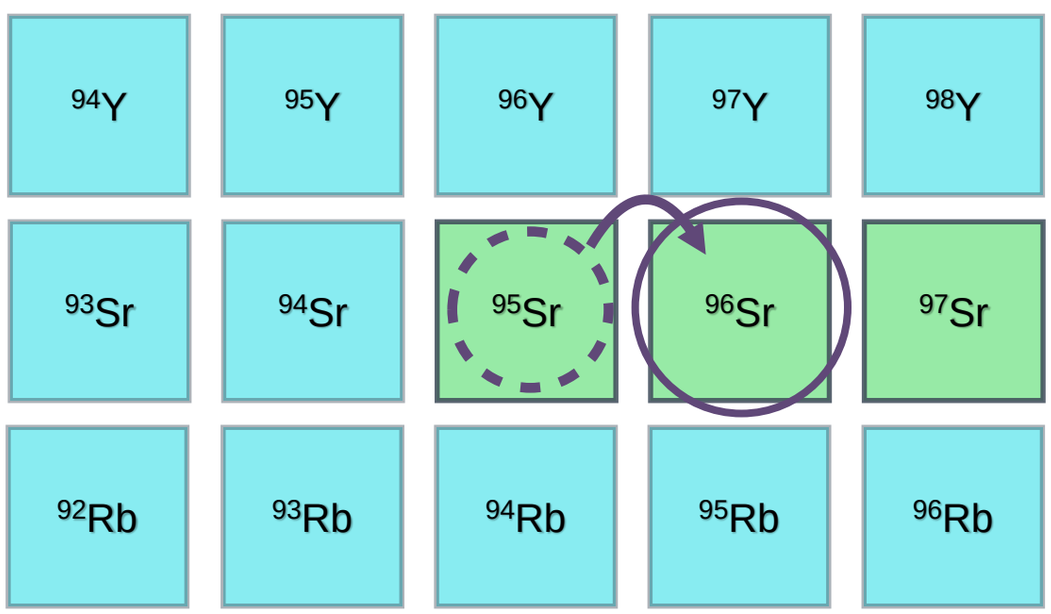

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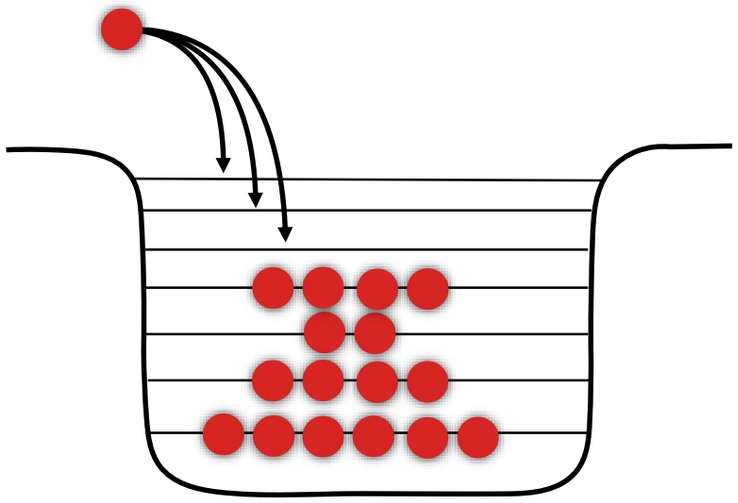

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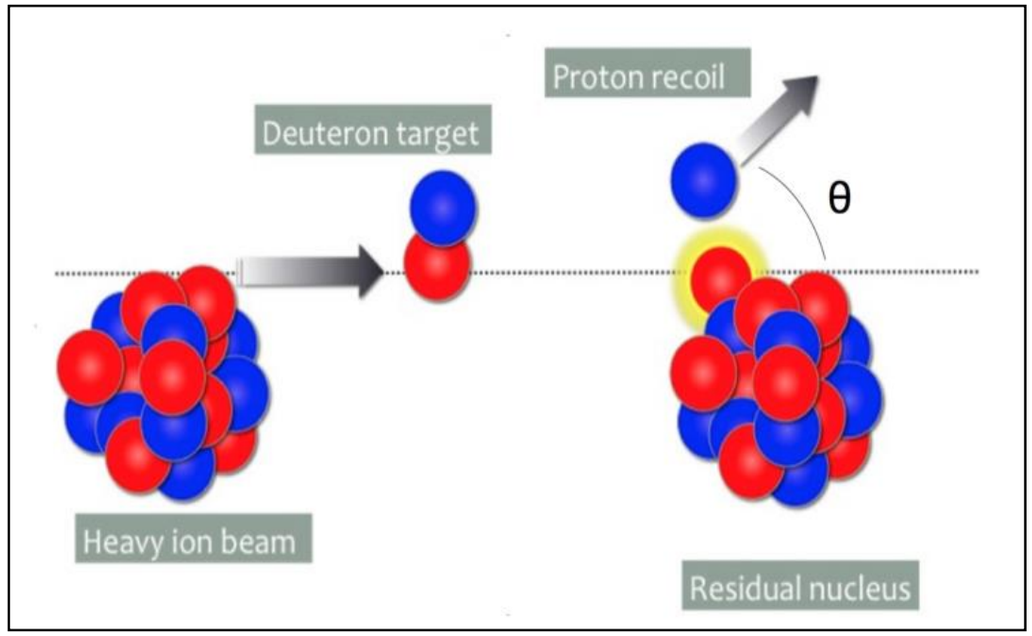

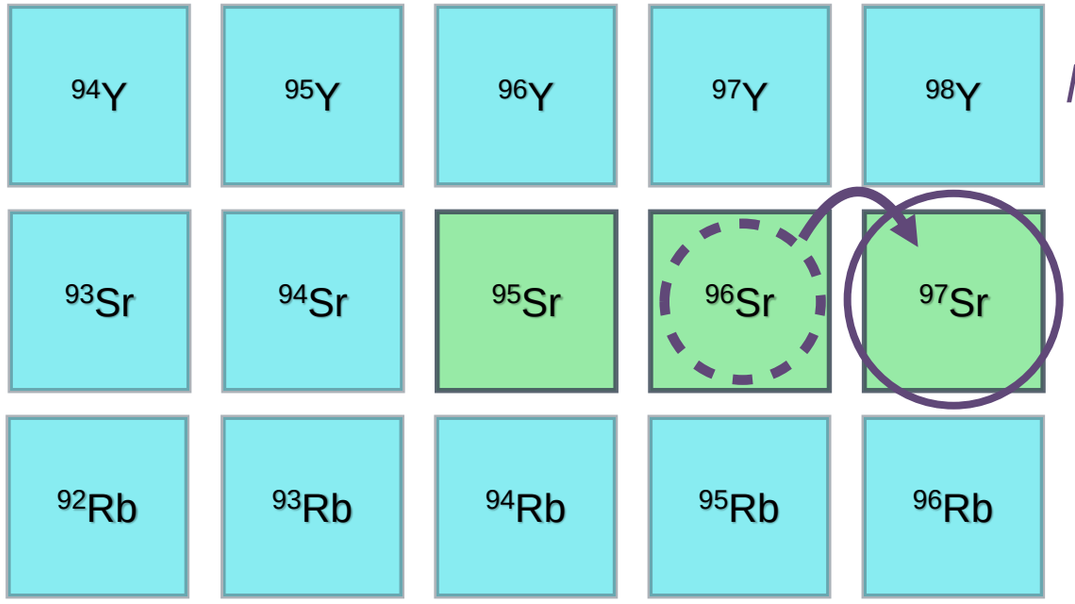

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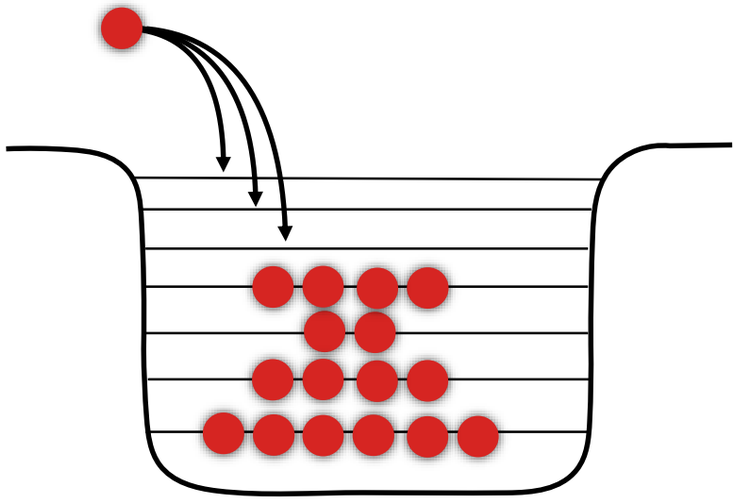
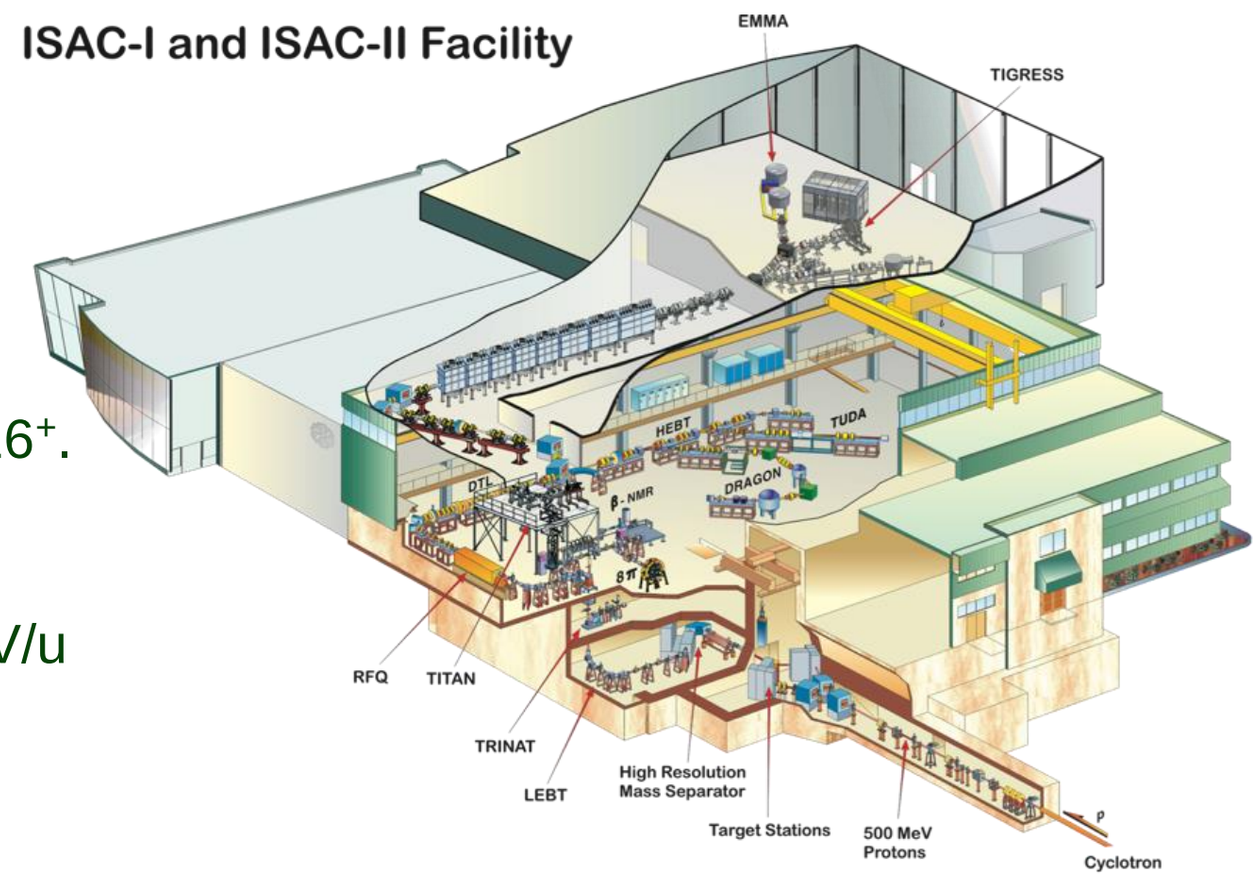


^{95}Sr beam delivery

- A 500 MeV proton beam was impinged on a UCx target.
- Extracted isotopes were laser ionized, mass separated and transported to the Charge State Booster where the isotopes were charge bred to 16^+.
- Ionized beam ($Q=22^+$) was delivered at 5.515 MeV/u to the experiment.



TRIUMF

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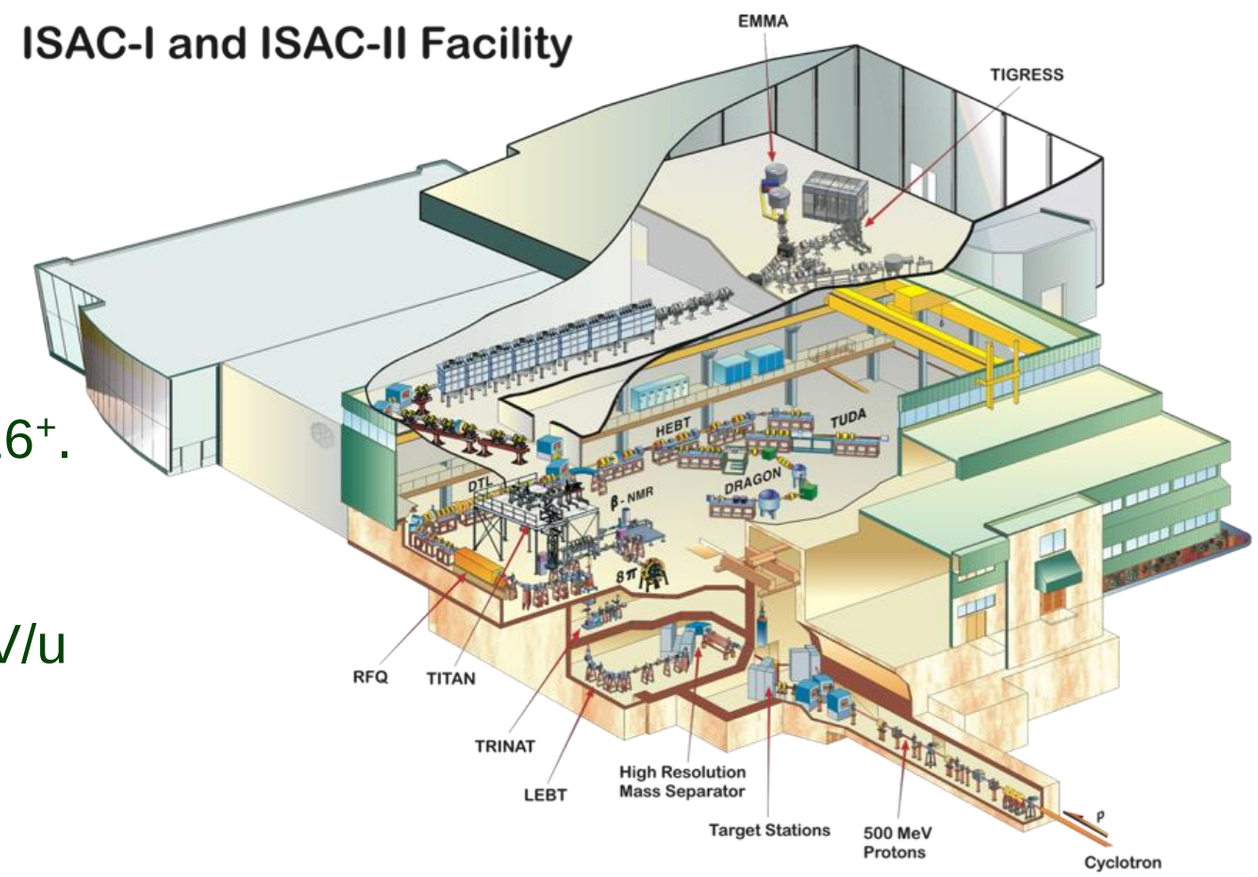
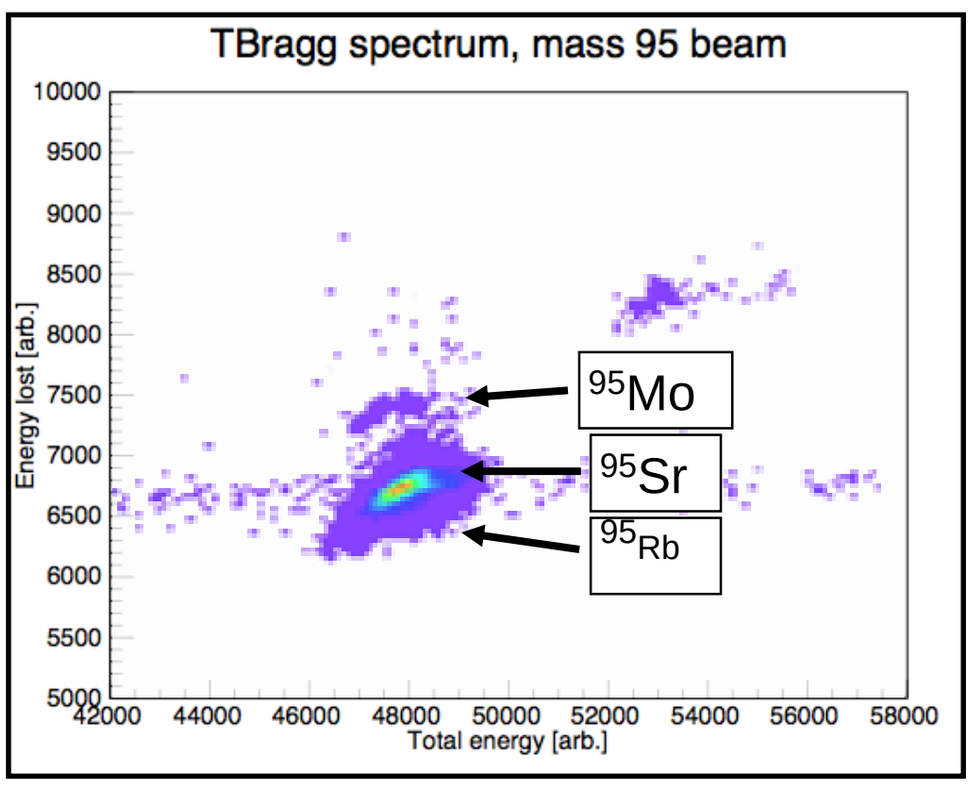




Composition of radioactive beam was ~80% ^{95}Sr.

^{95}Sr with an average intensity of ~10^7 pps was impinged upon a 0.5 mg/cm^2 deuterated polyethylene target (CD_2).

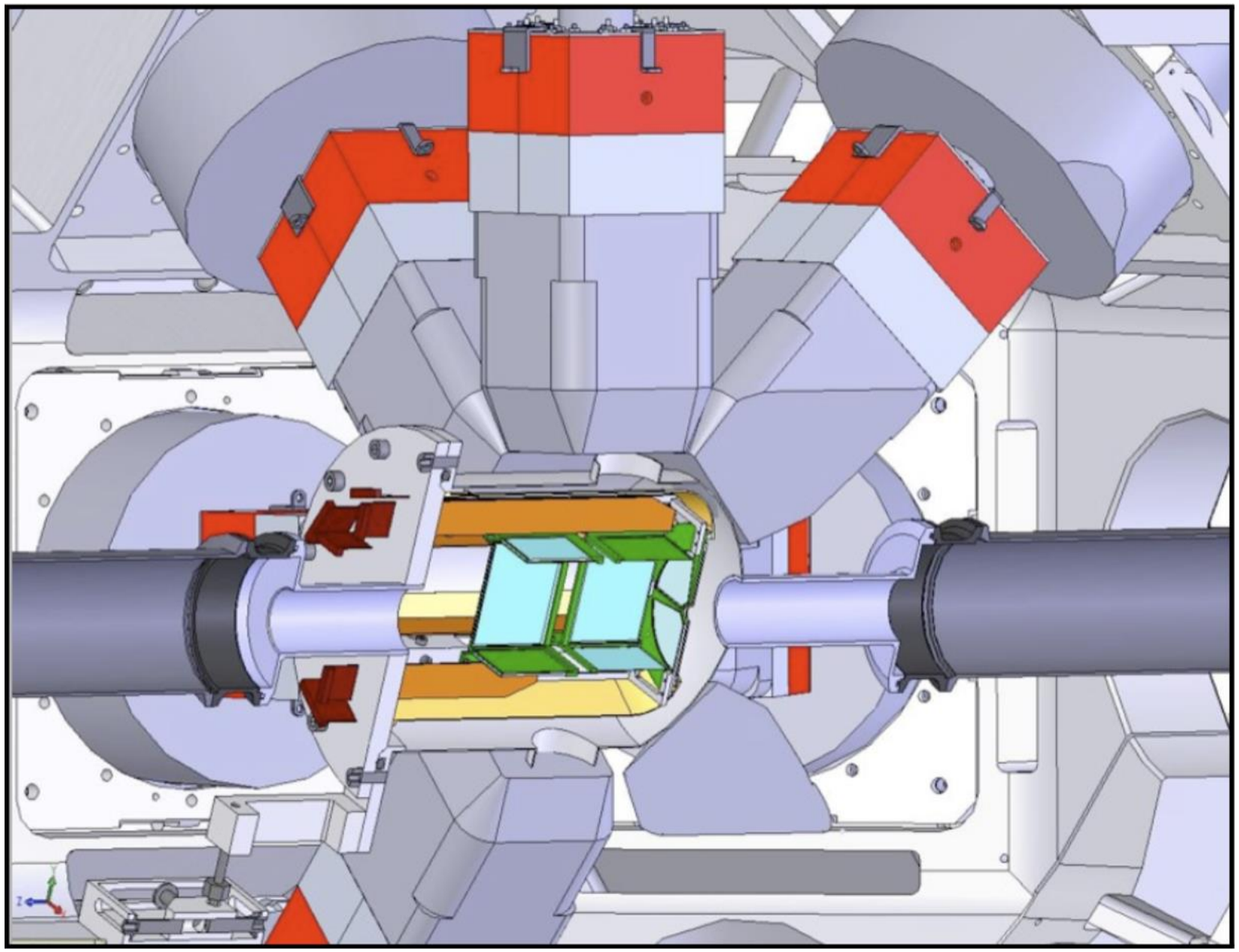
Experimental Station

SHARC

- Highly pixelated Si Detectors
- Efficiency ≈ 80%
- Coverage ≈ 80% of 4π
- Ang. Res. ≈ 1 degree.

TIGRESS

- 12 HPGe Clovers.
- Efficiency (1 MeV) ≈ 10%.
- Coverage ≈ 2π.
- Energy res. (1 MeV) ≈ 2 keV.



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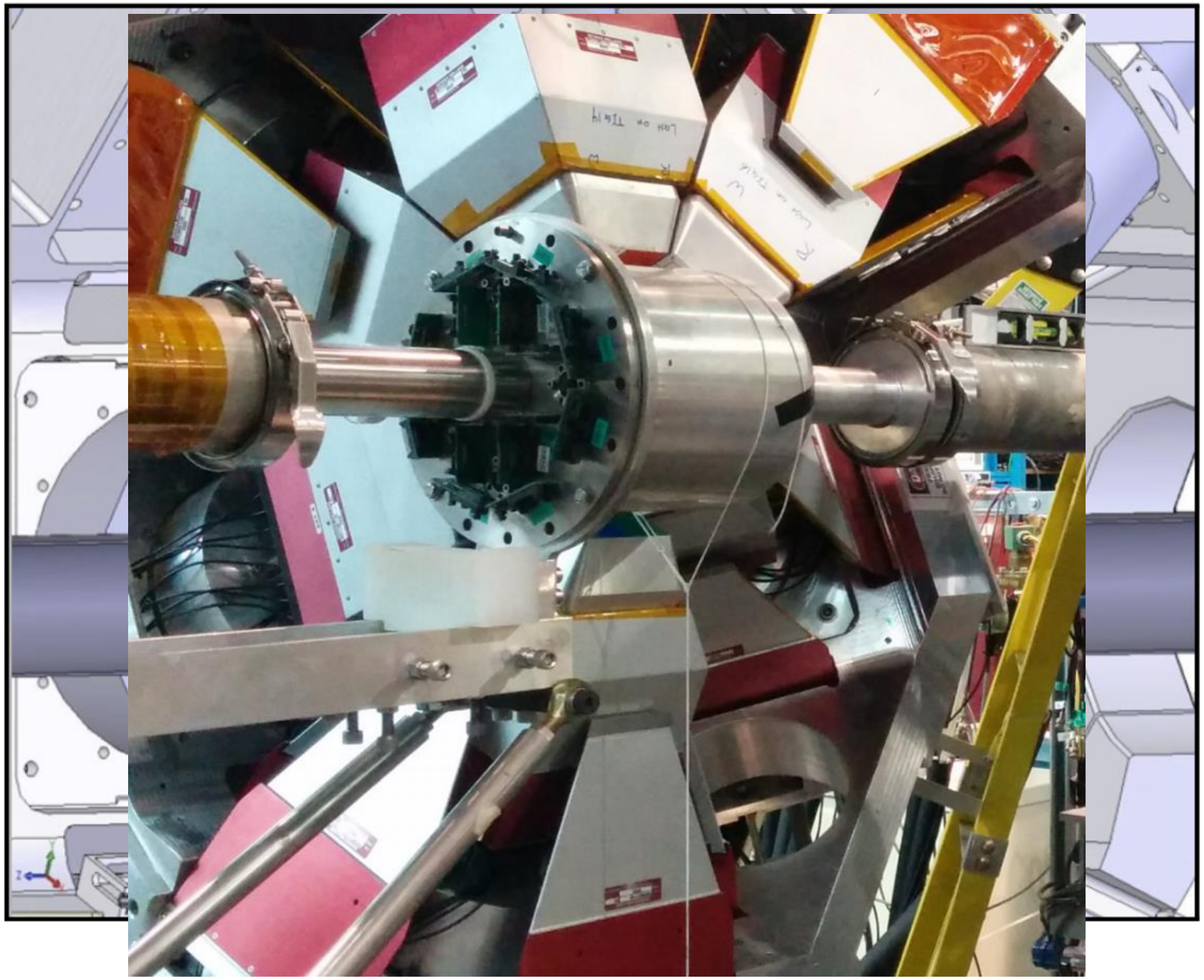

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SHARC Data

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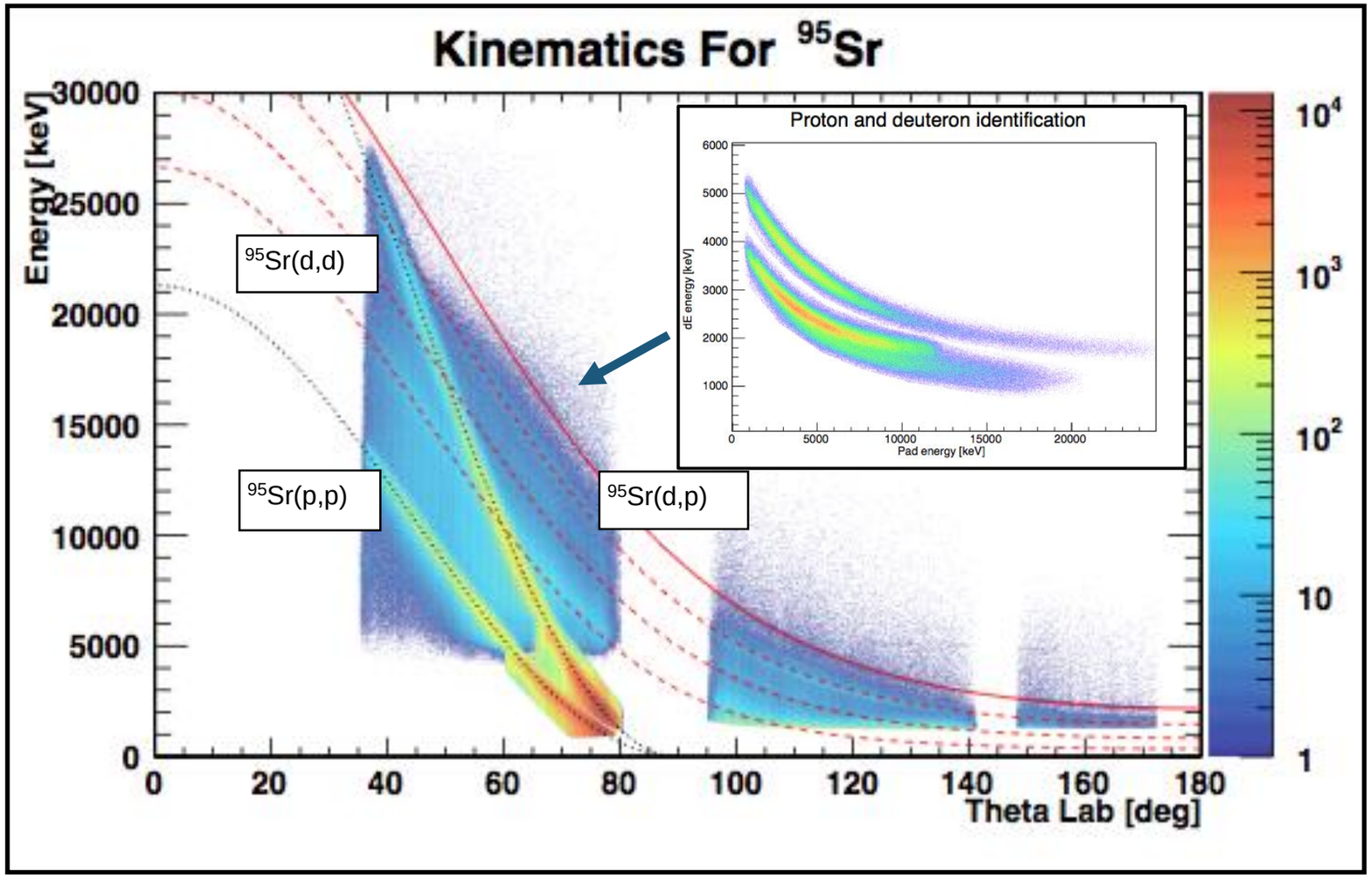
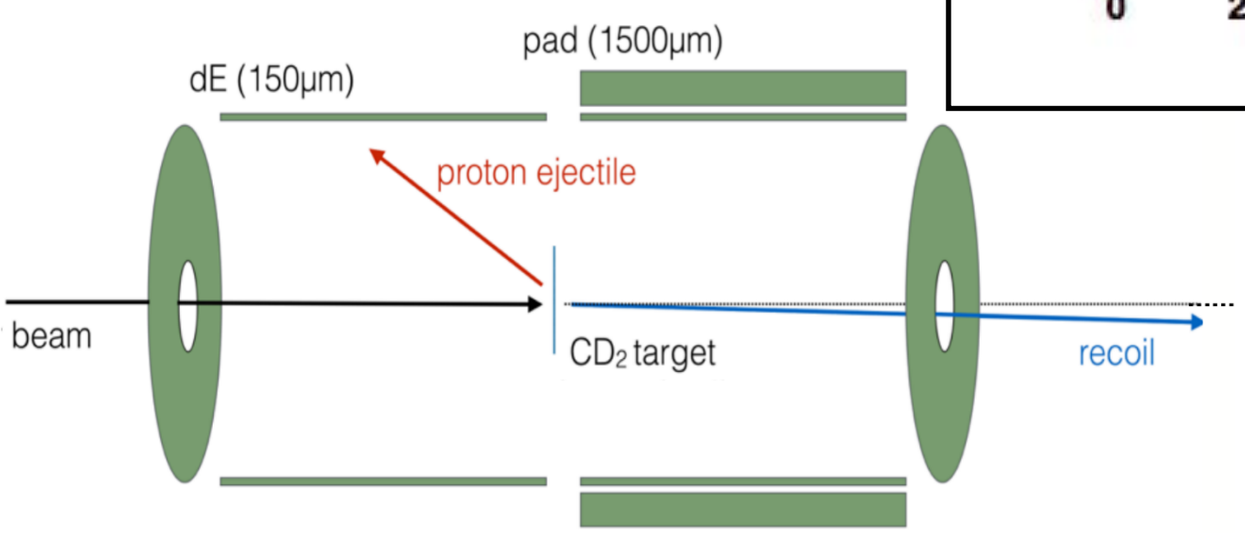
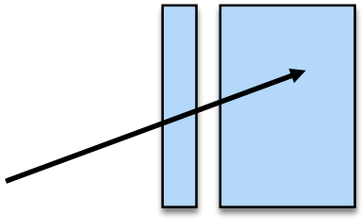
- Below: Excitation energy.
- Poor energy resolution makes extracting ^{96}Sr states difficult.





Particle identification used through dE-E detector arrangement



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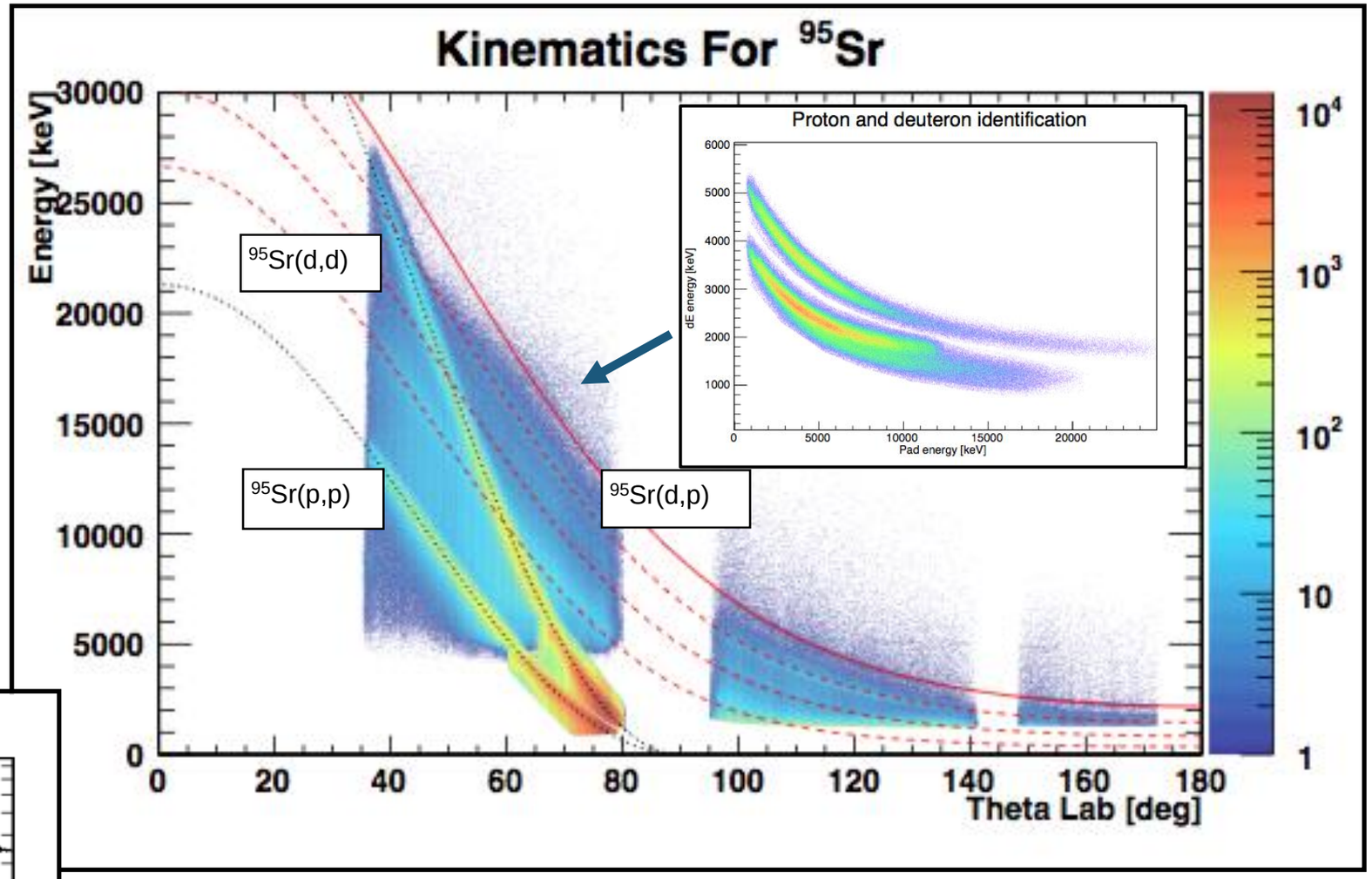

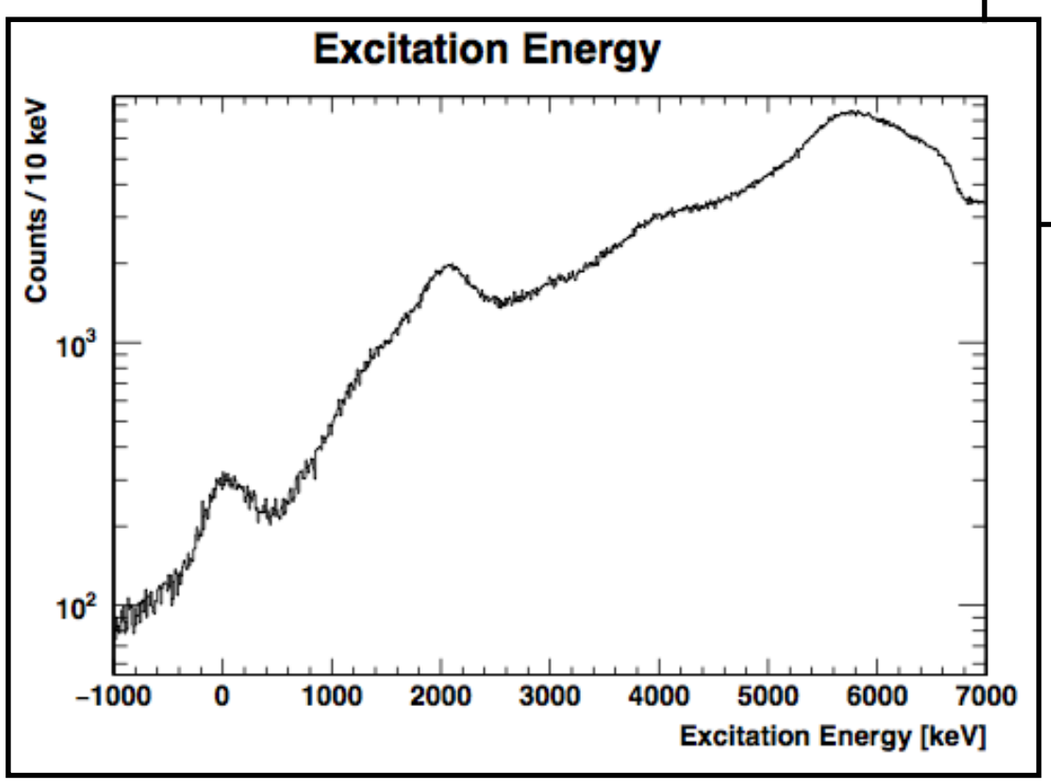

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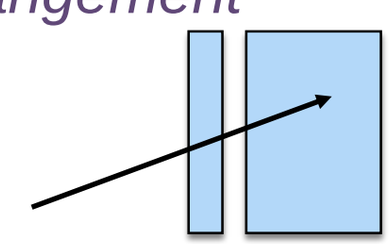

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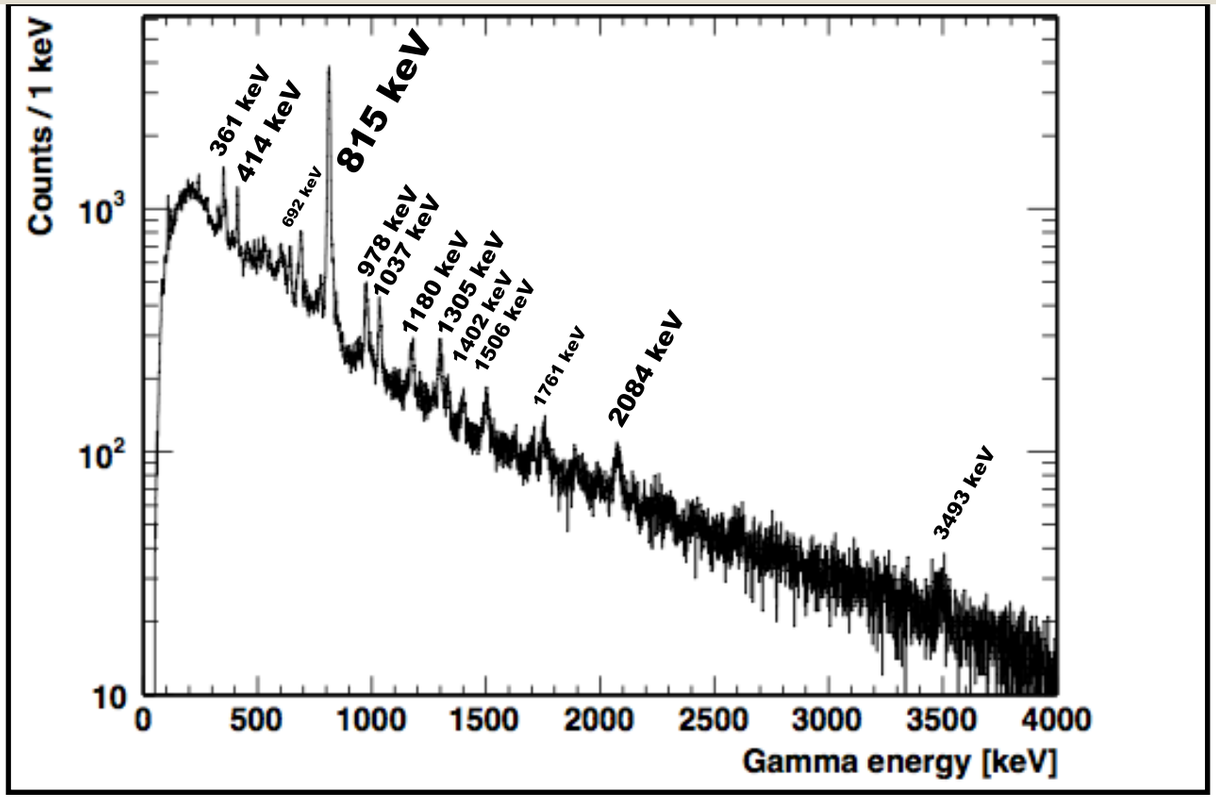

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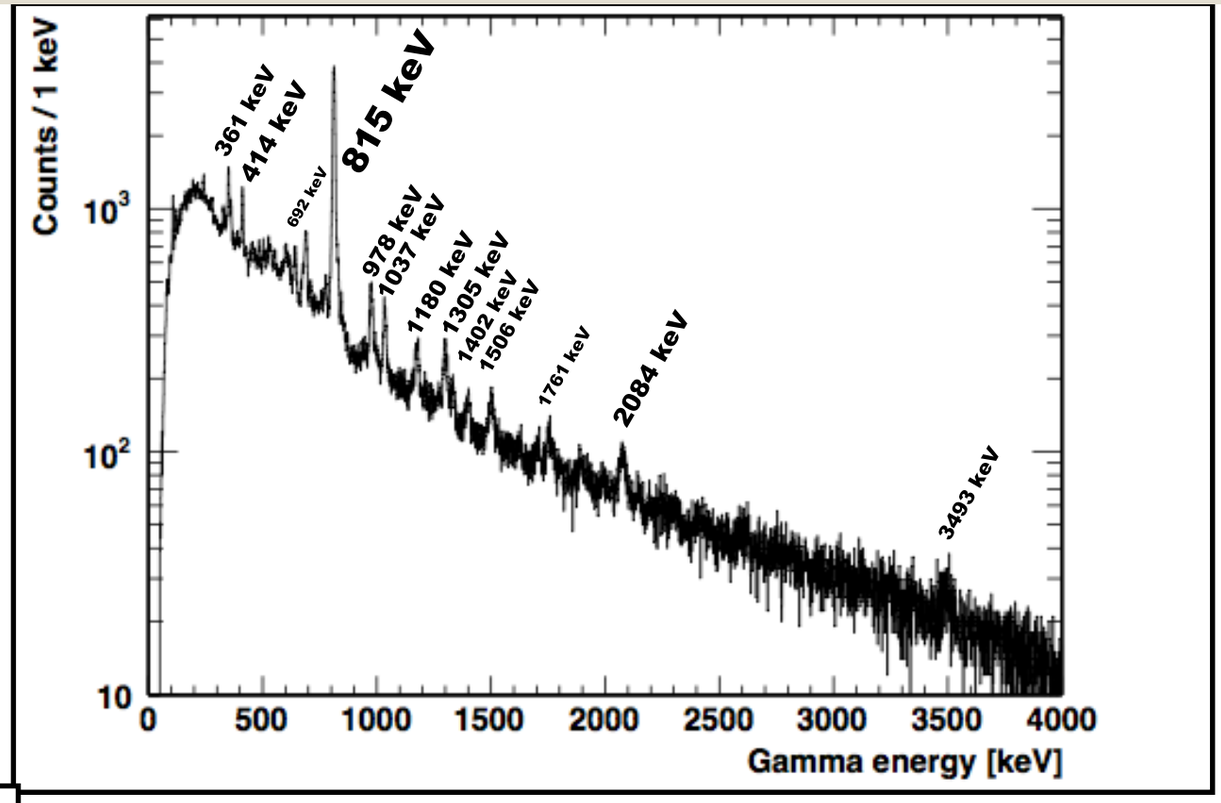

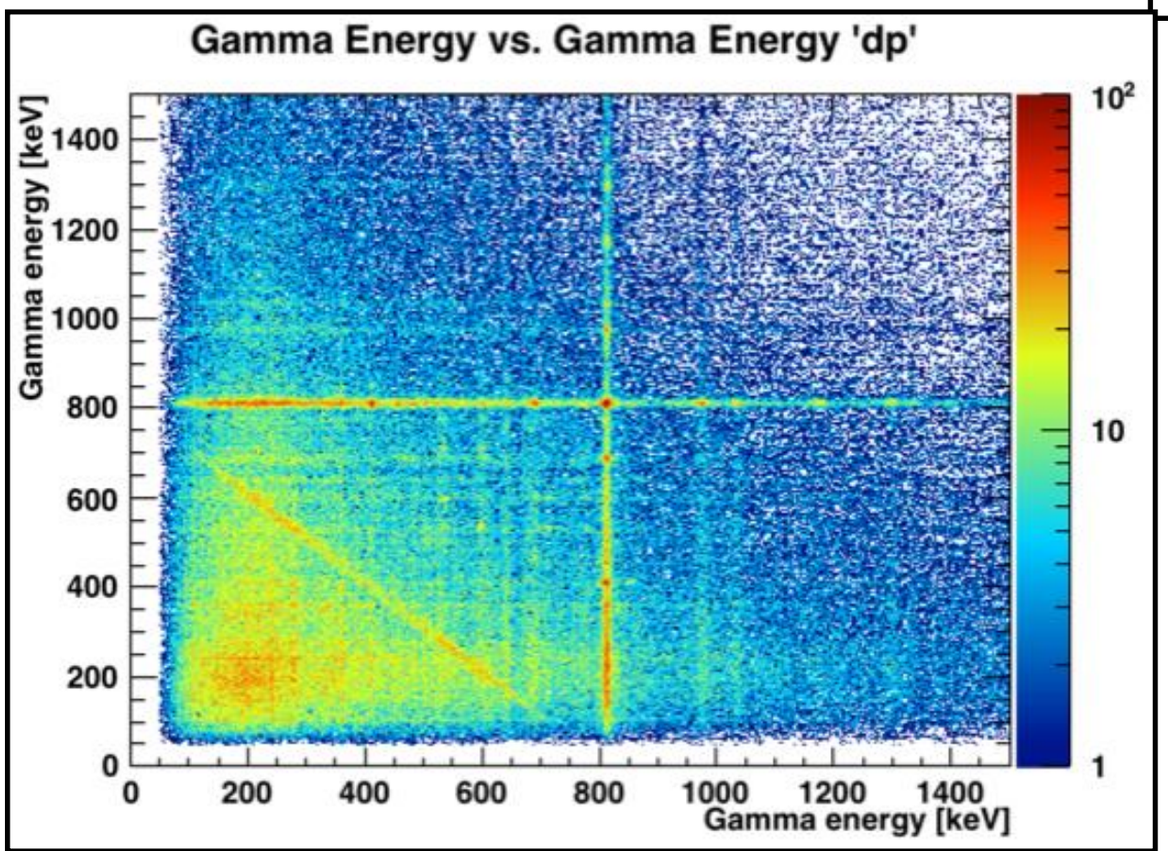

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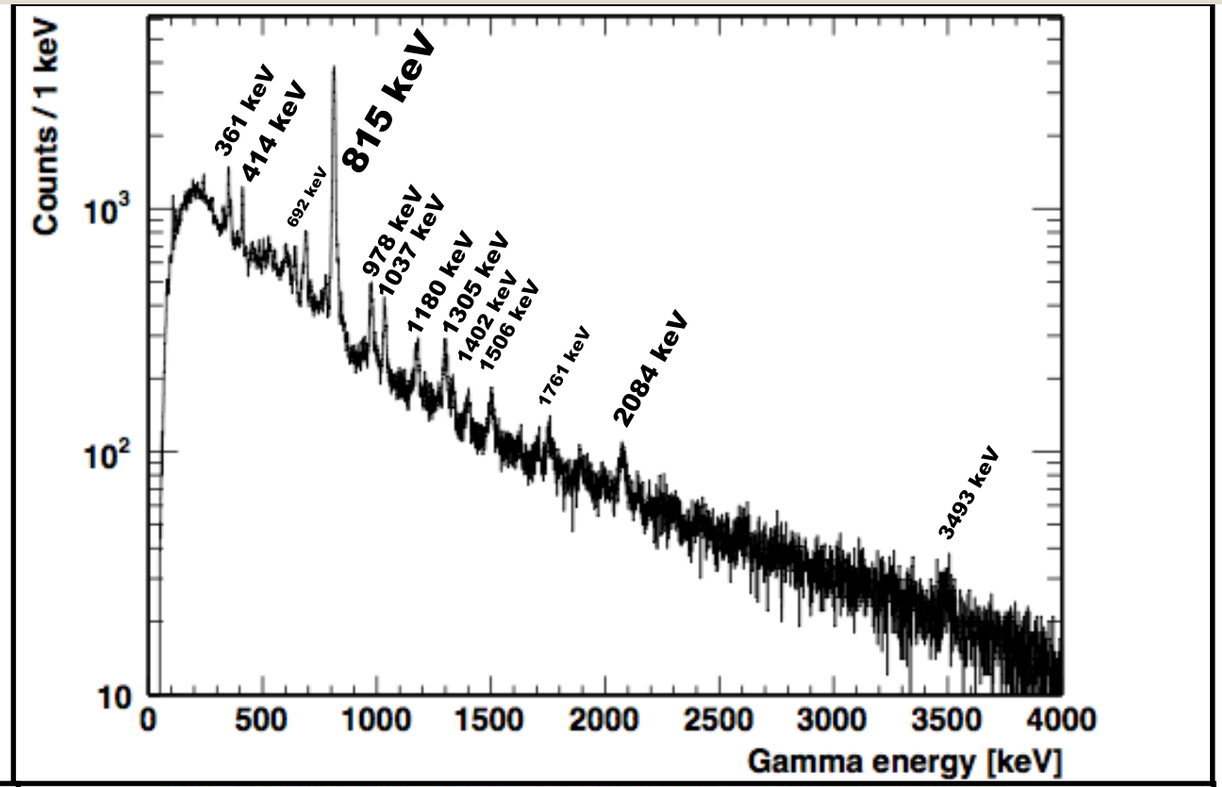

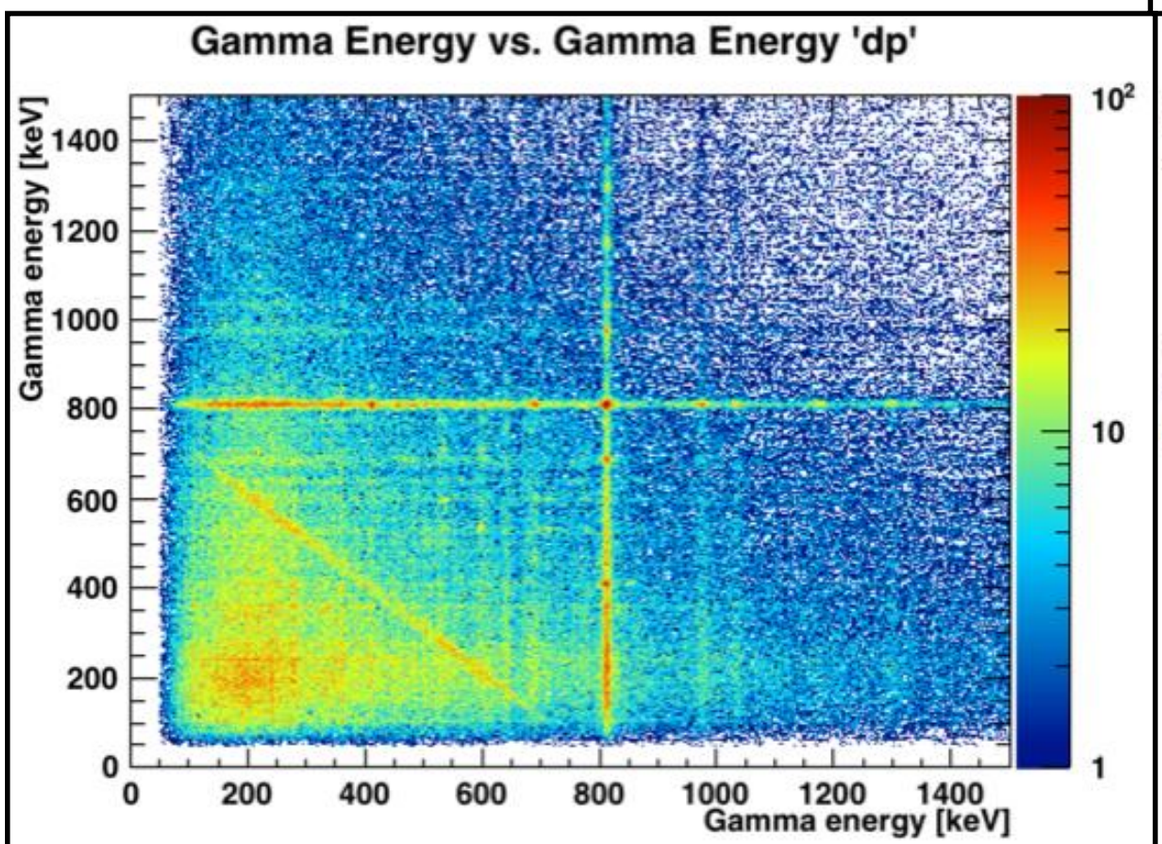

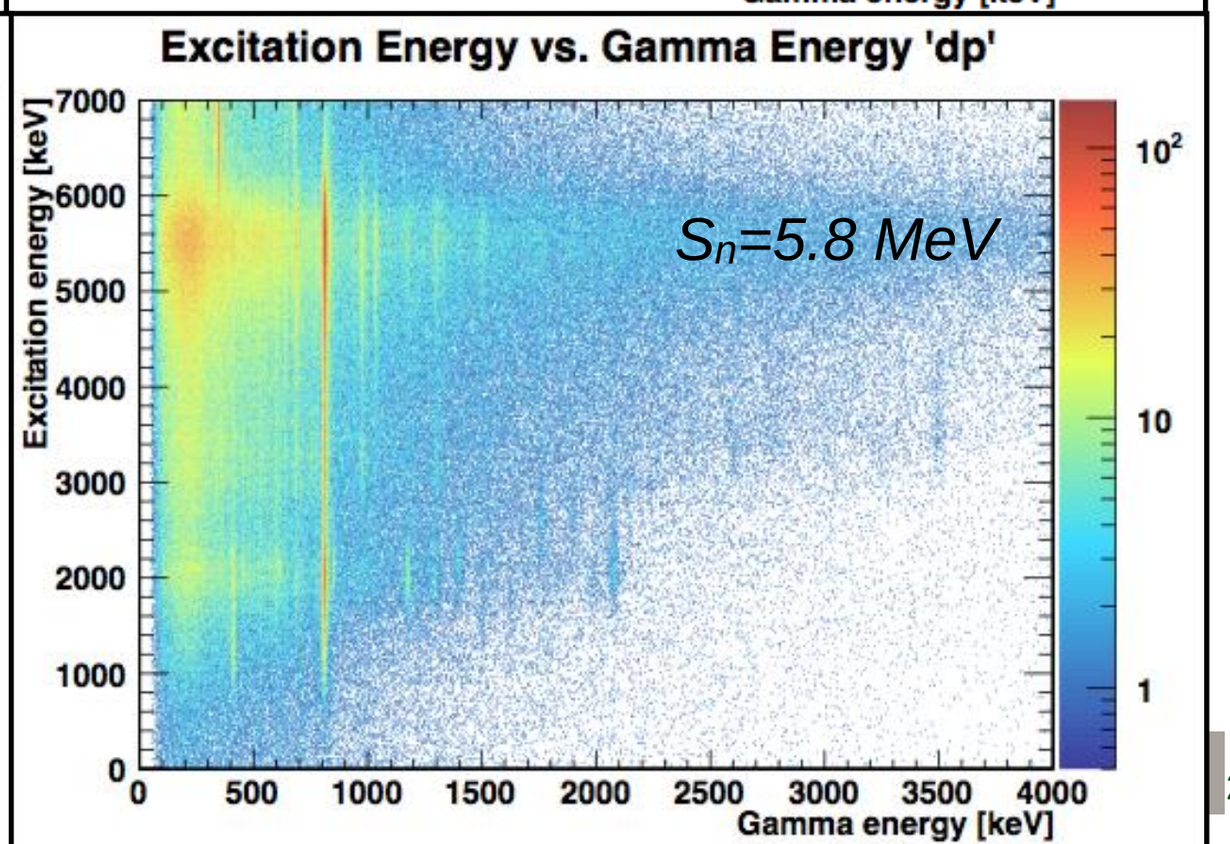

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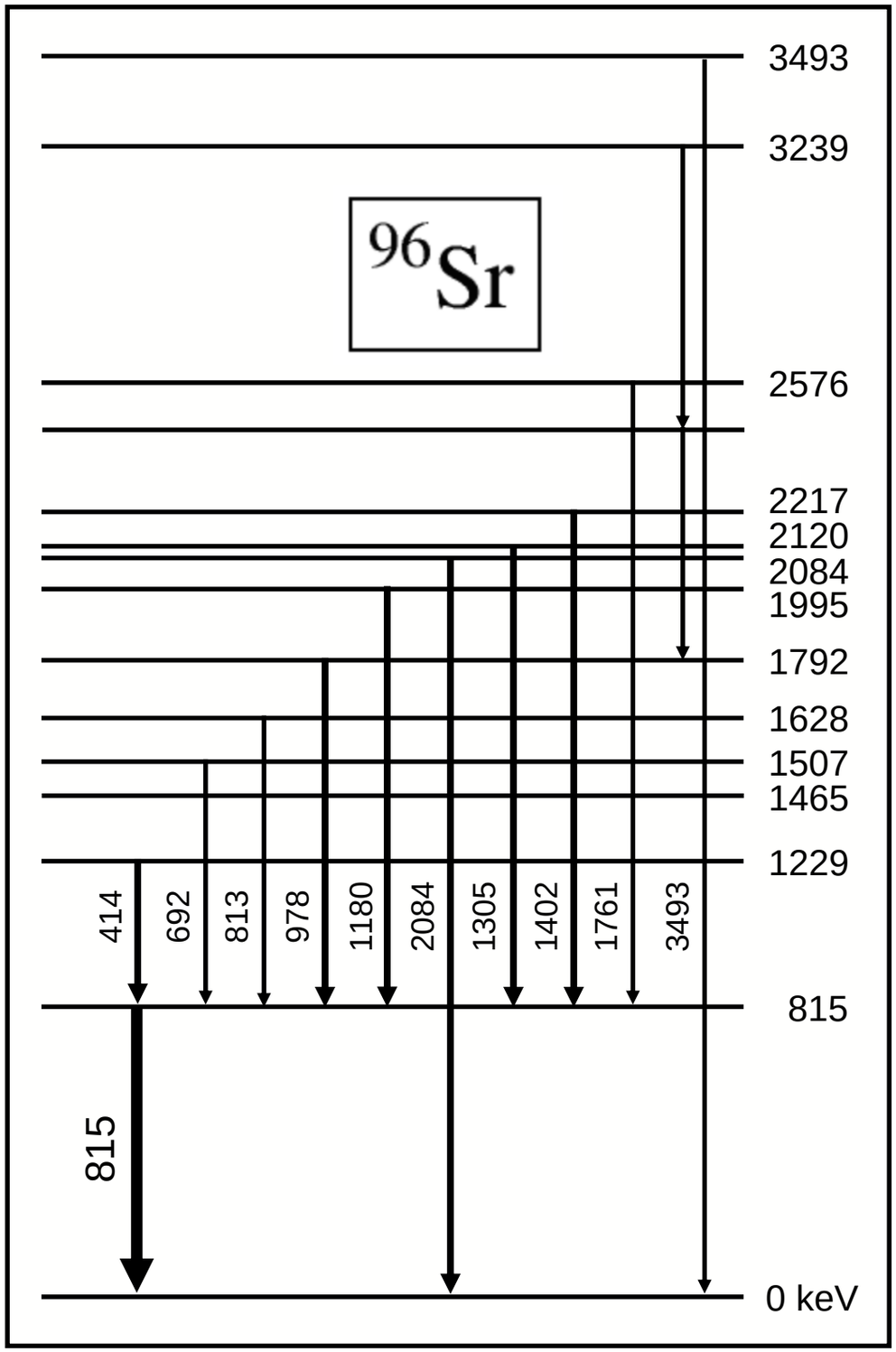

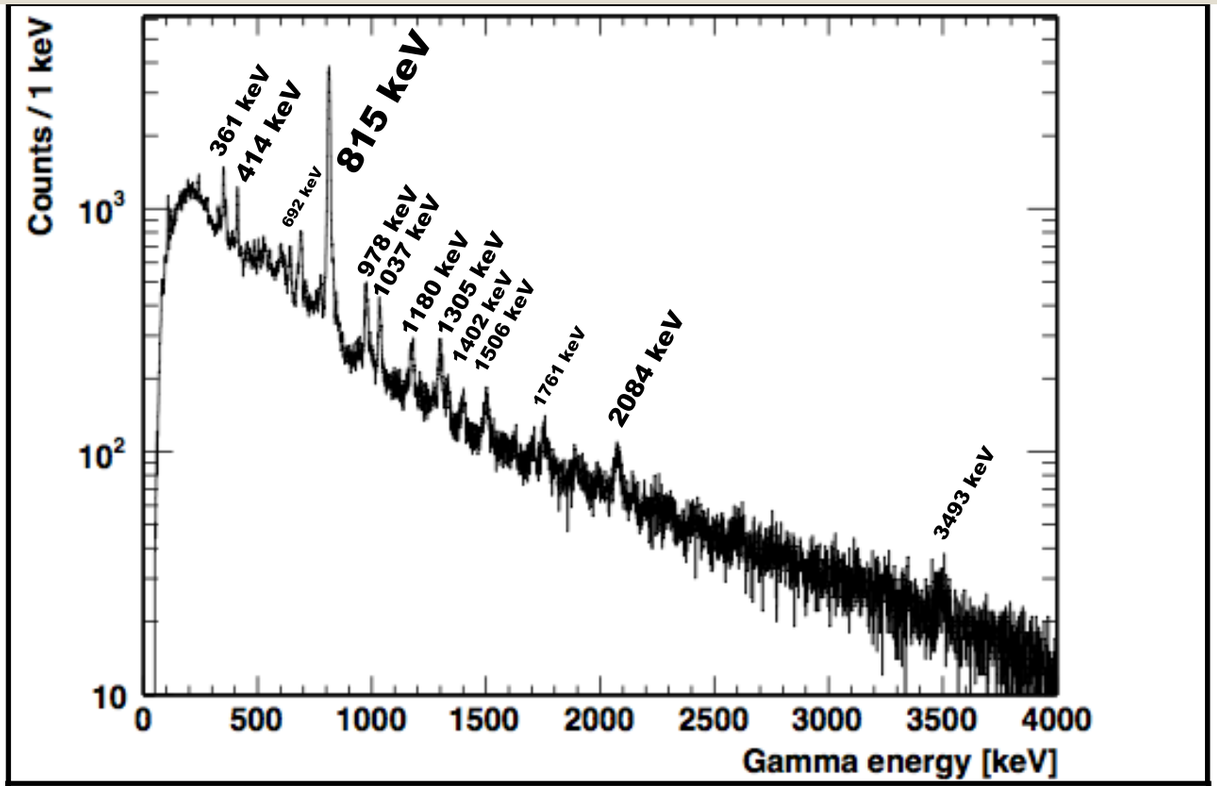

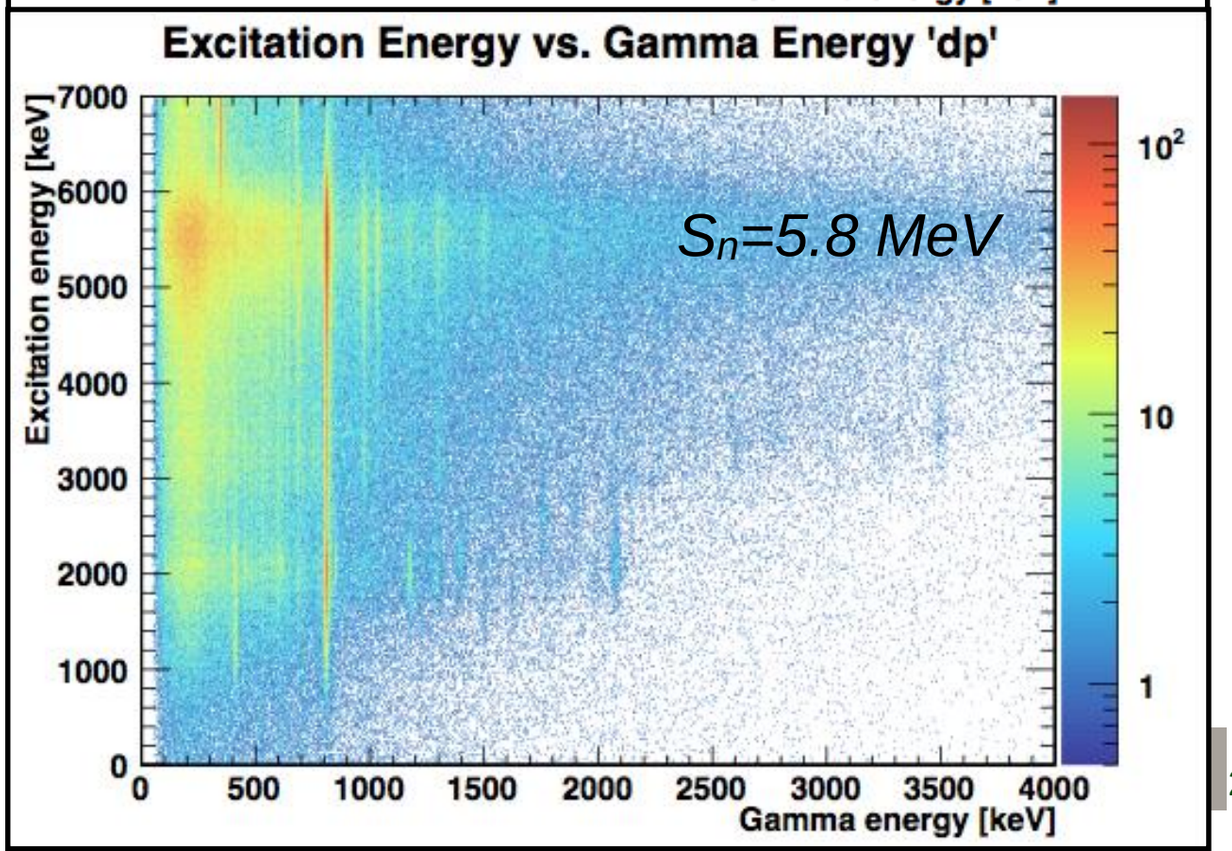

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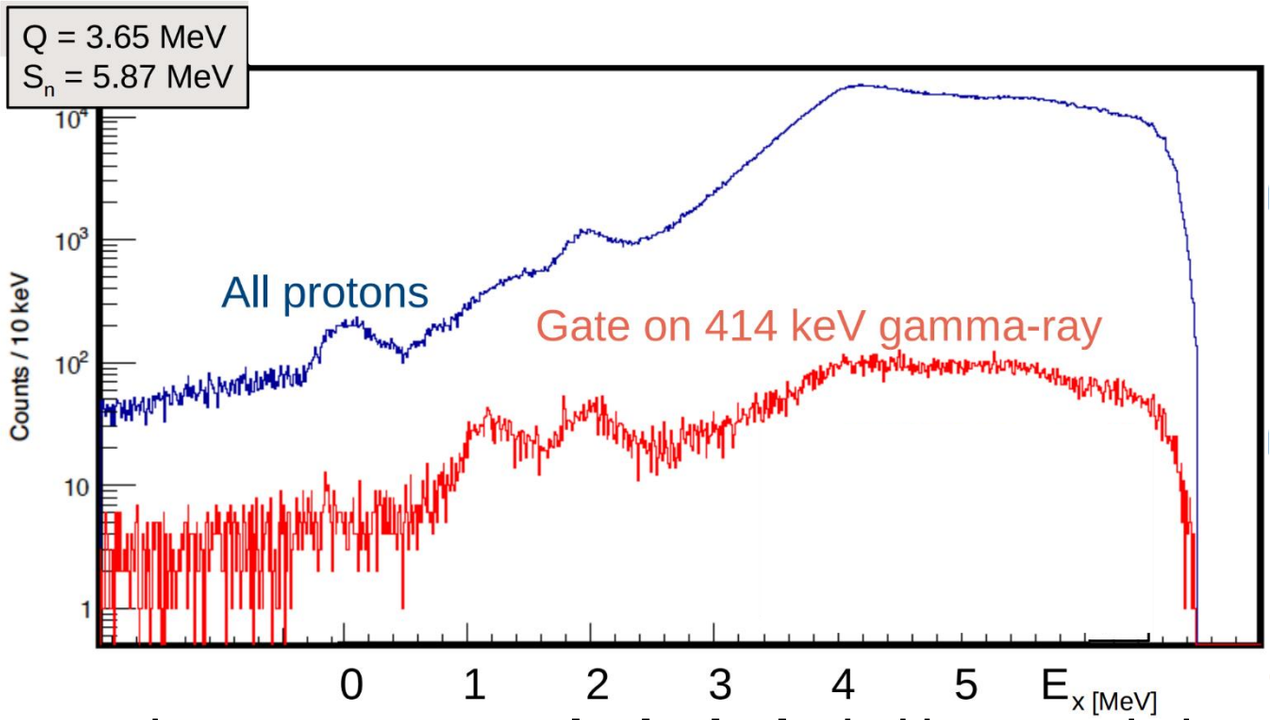
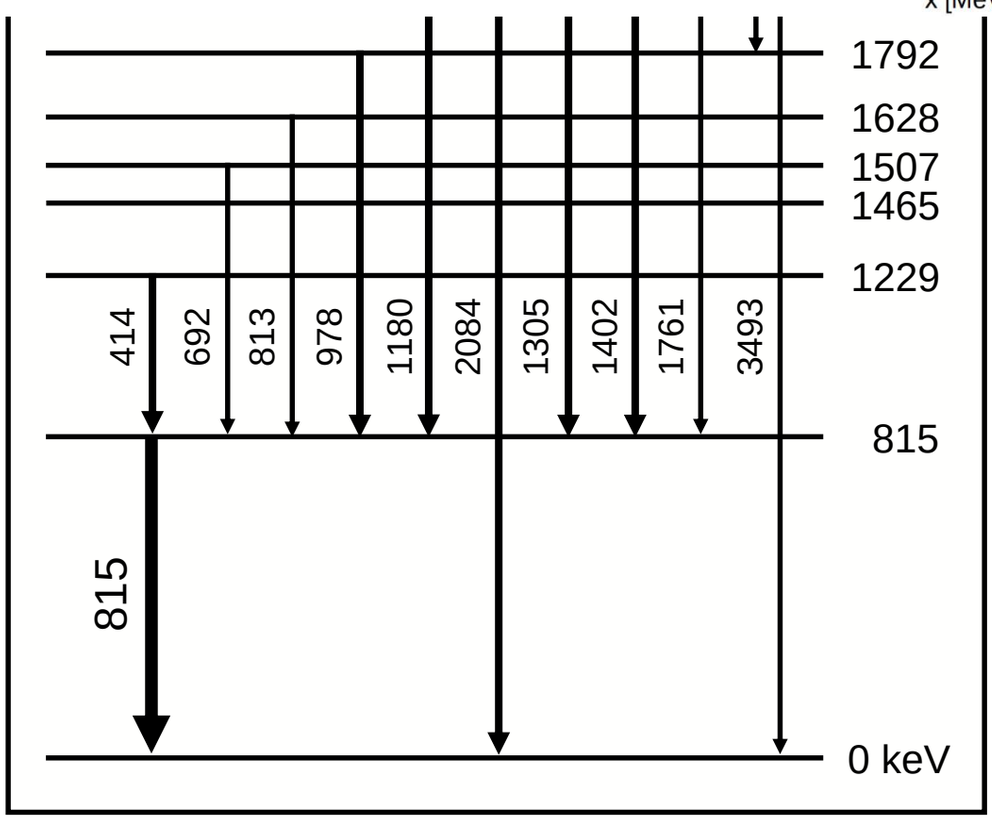
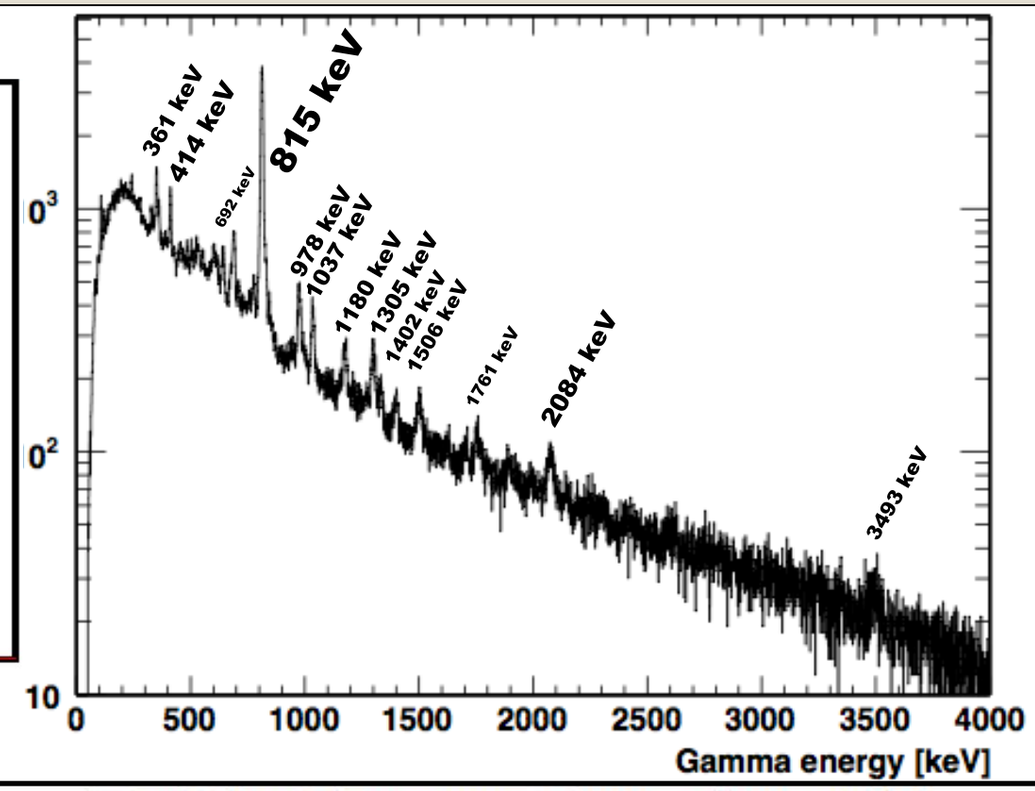
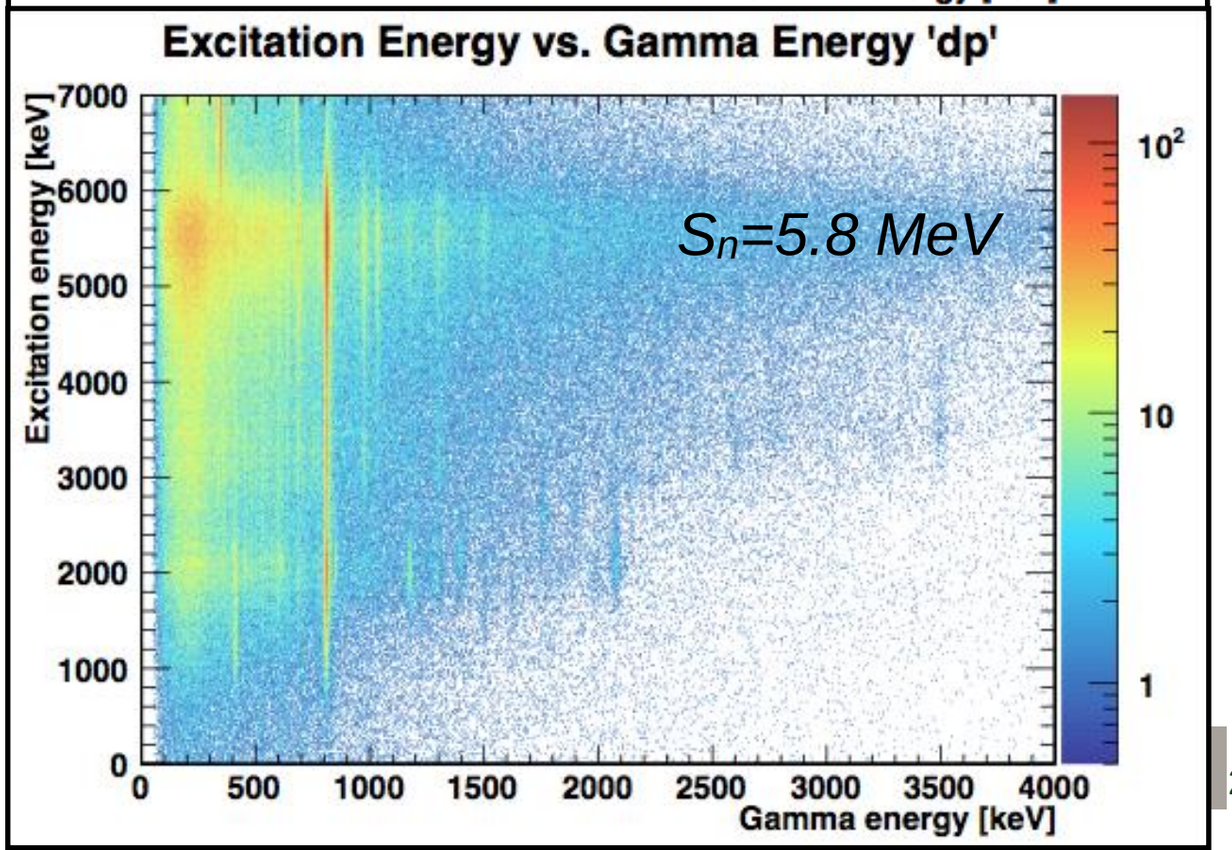


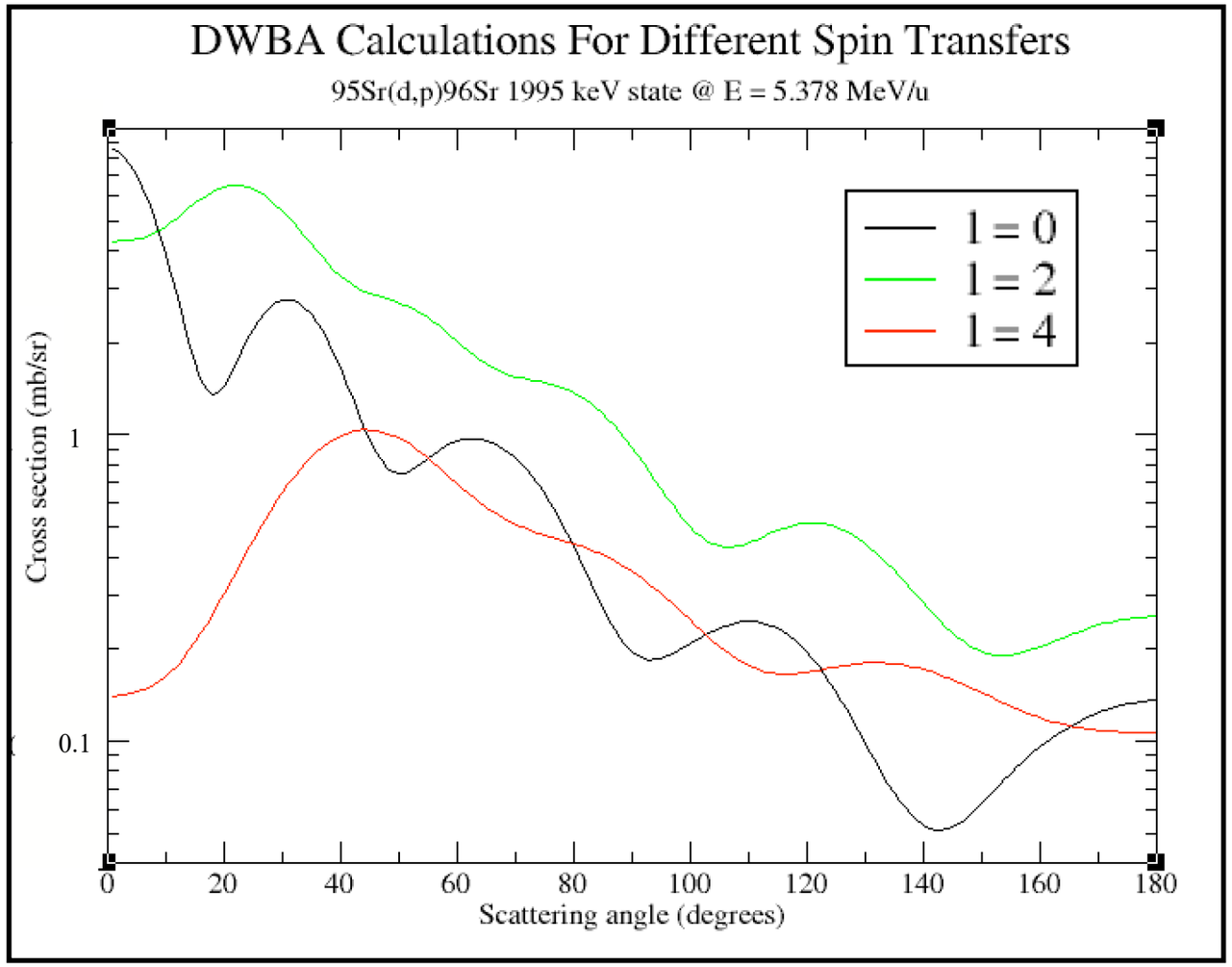


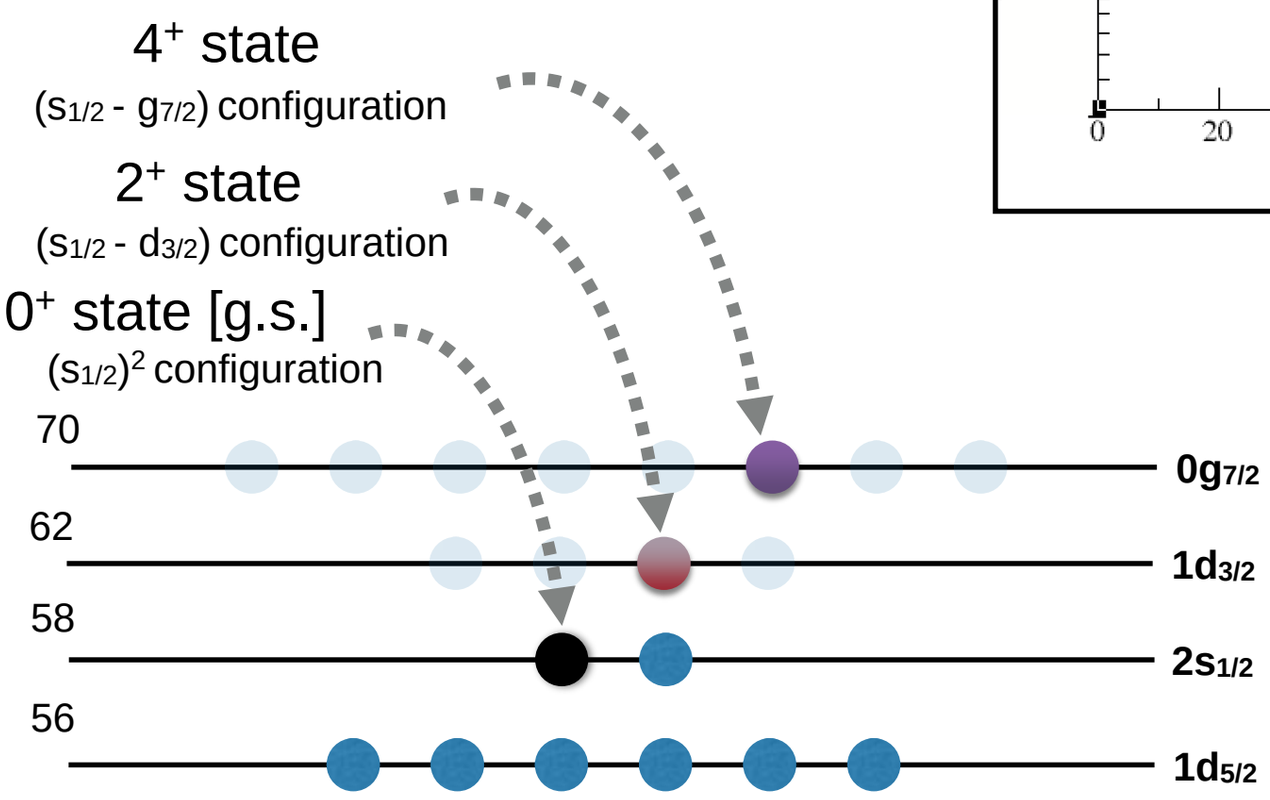




Expected Cross Sections

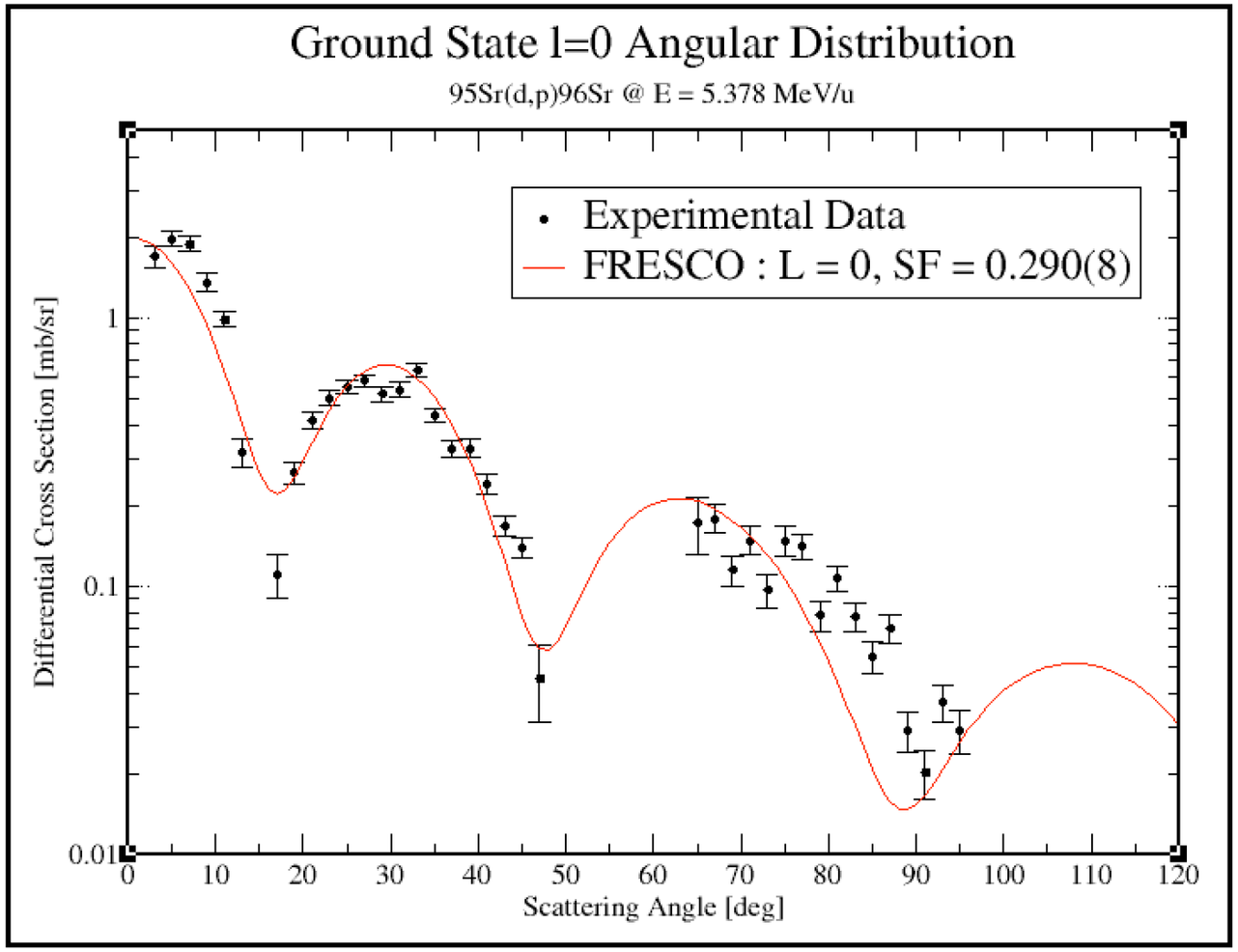
- Assume pure **ν**[$s_{1/2}$] state for the ^{95}Sr ground state and calculate angular distributions using FRESCO.
- Spectroscopic factors for 0^+ states will tell us about the $[s_{1/2}]^2$ component of their single particle configurations.

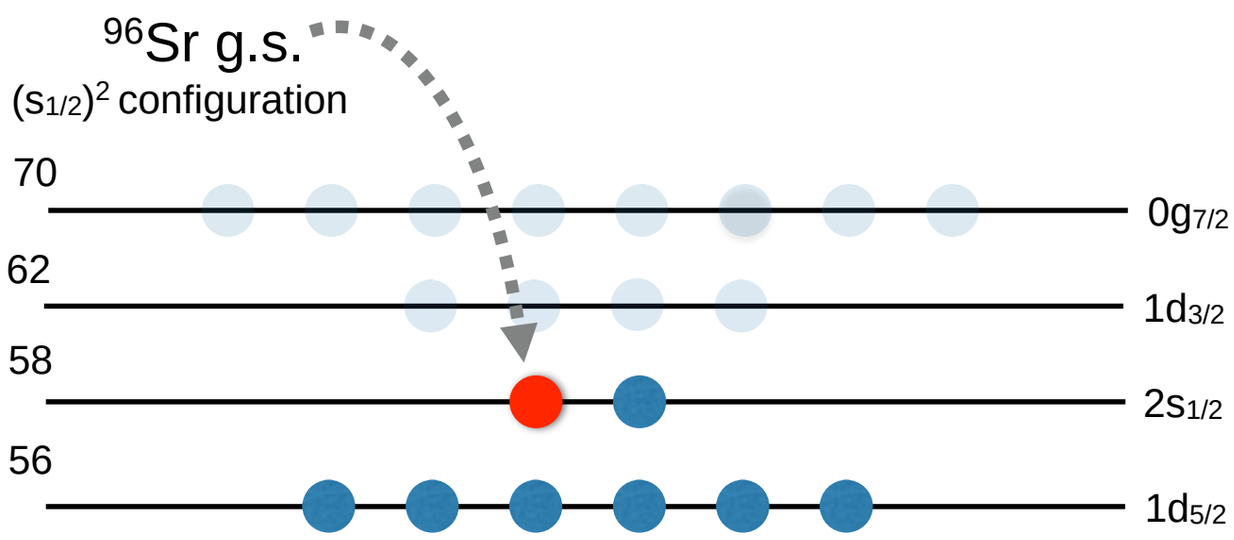




^{96}Sr 0^+ Ground State

- Clear ℓ=0 character.
- Spectroscopic factor of ~0.29 tells us that the ^{96}Sr ground state is not pure $[s_{1/2}]^2$ configuration.
- Pair scattering of neutrons in ^{95}Sr would affect the cross section for this reaction.
- Shell model calculations for ^{95,96}Sr to follow shortly.





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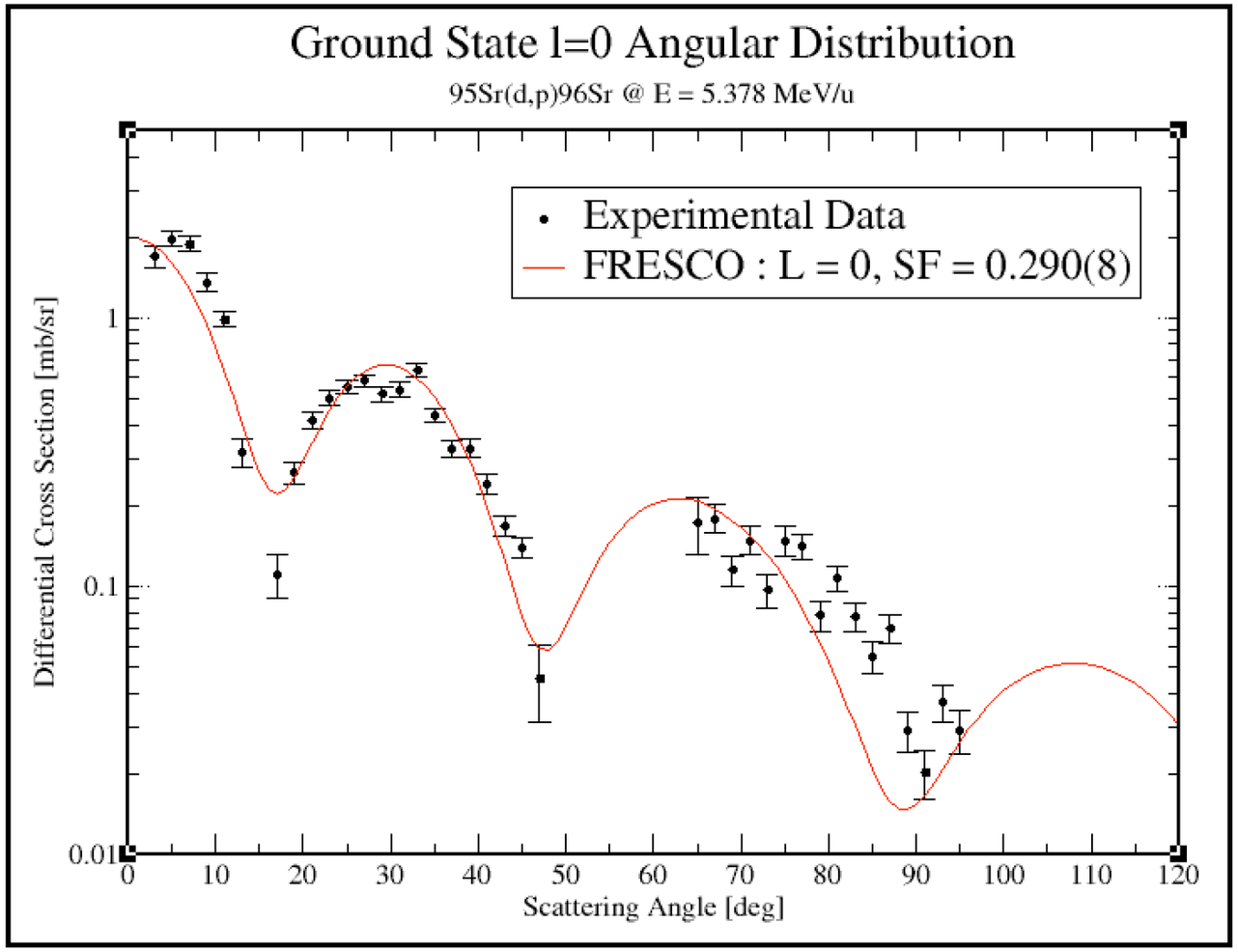
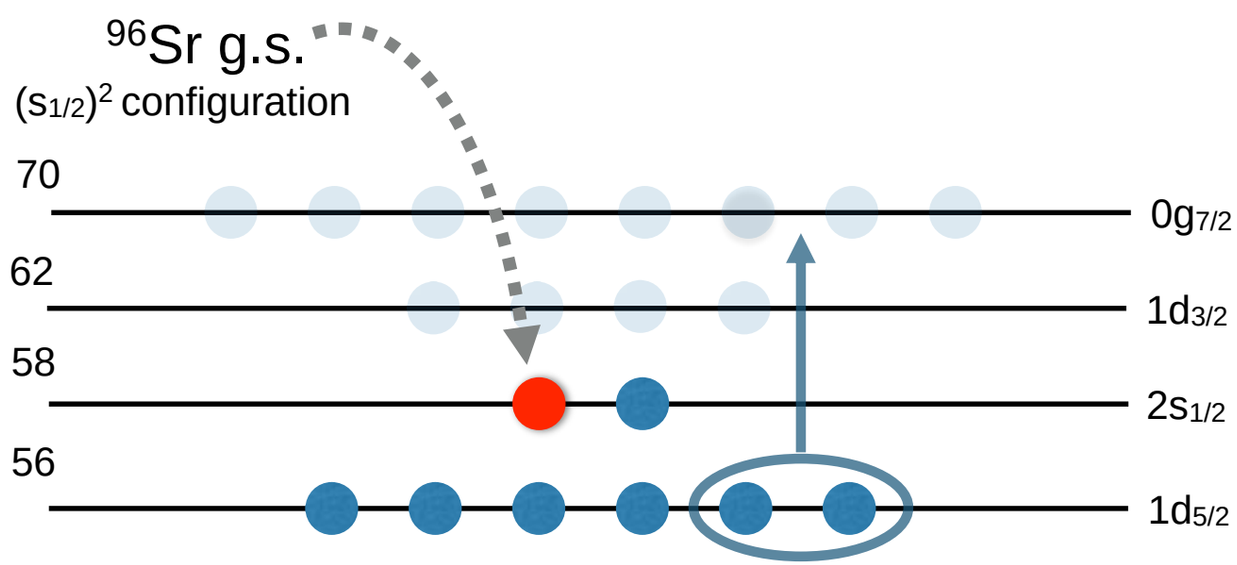
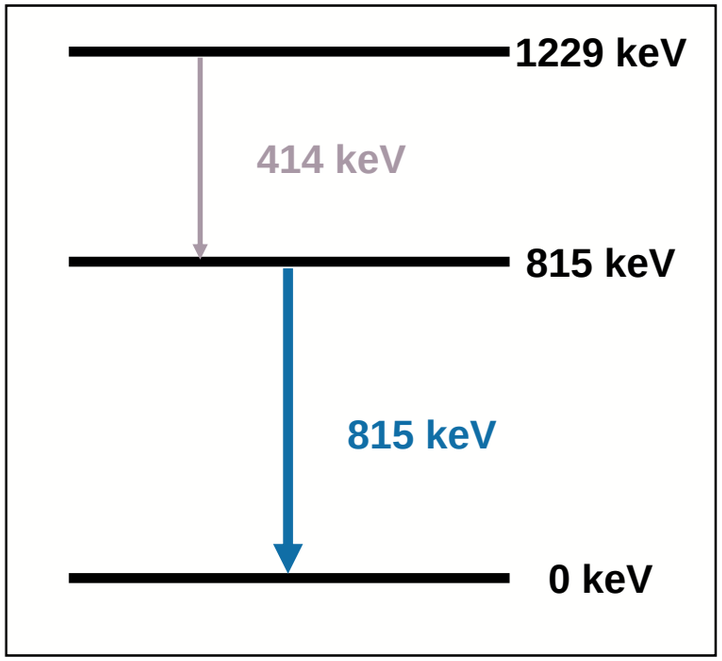
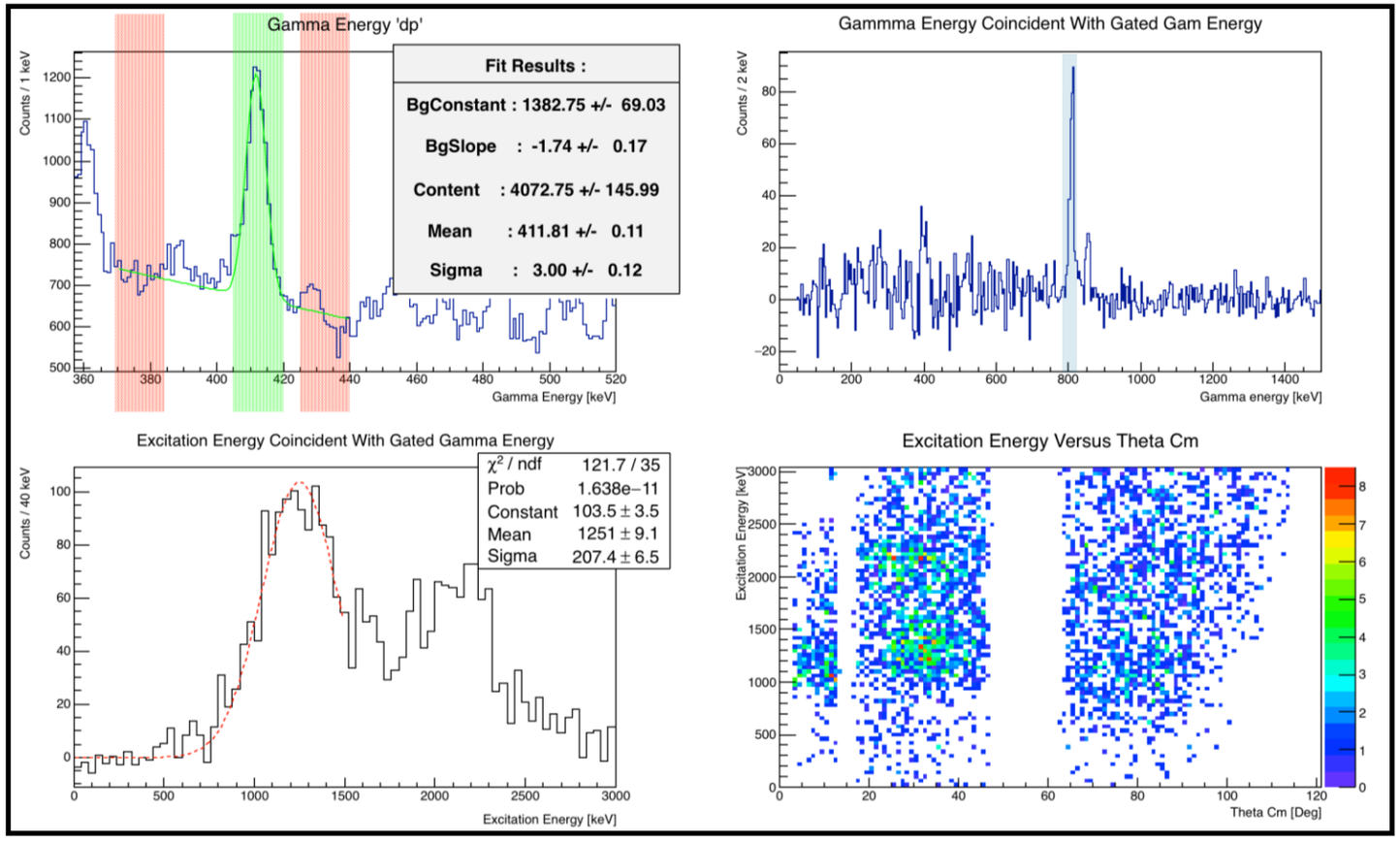




1229 keV 0^+ State

- TIGRESS gate used on 414 keV transition to select 1229 keV state.
- Clear ℓ=0 character in angular distribution.
- Spectroscopic factor determined to be 0.456(3).





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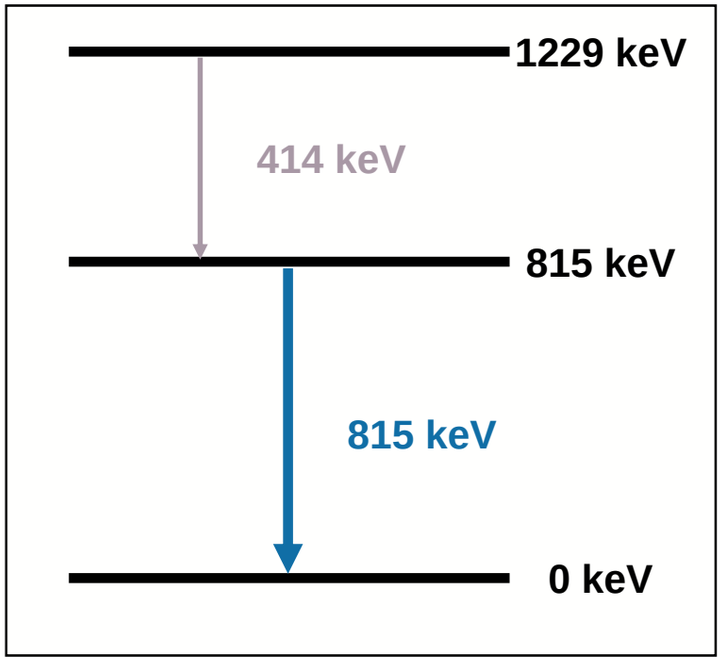
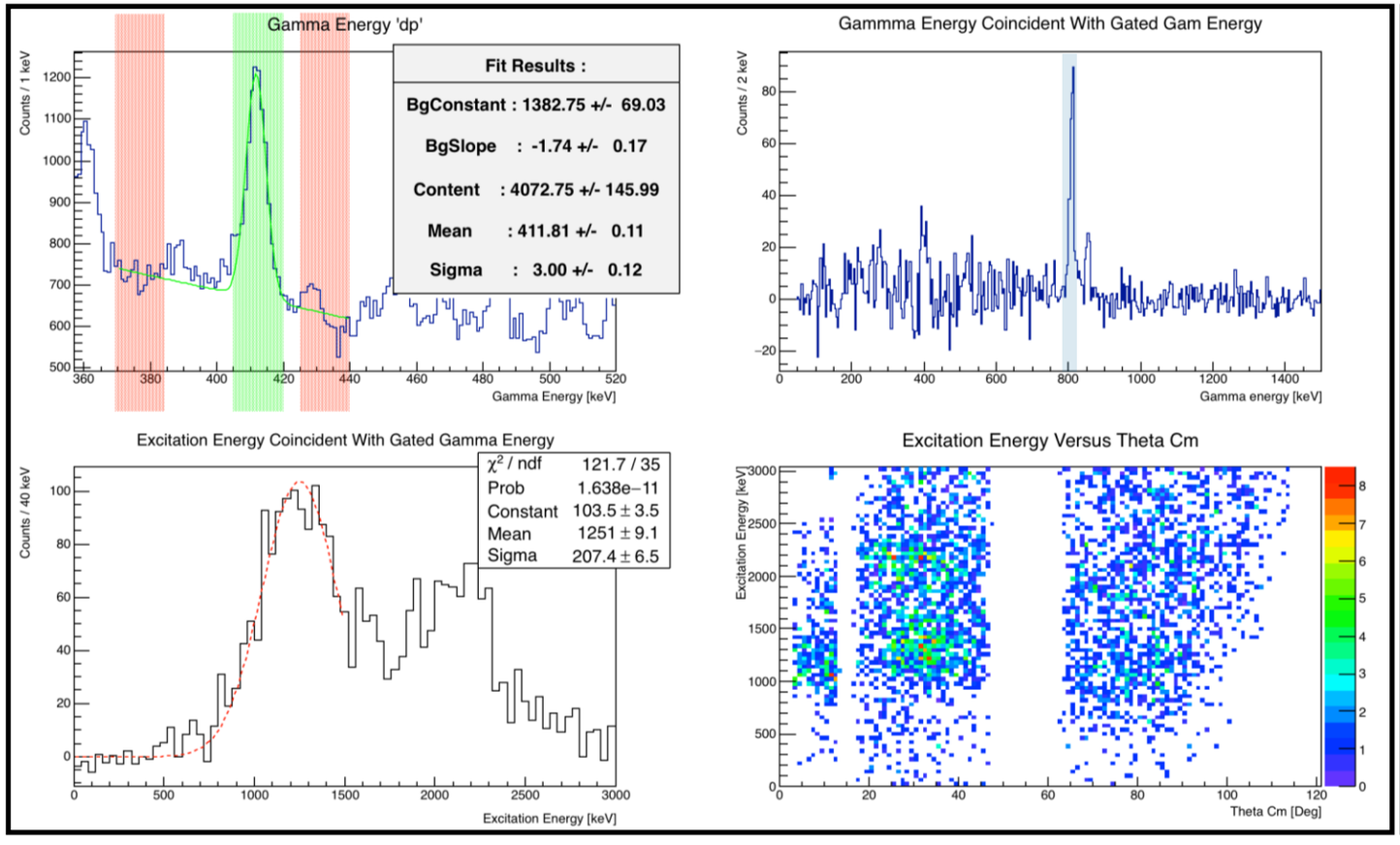
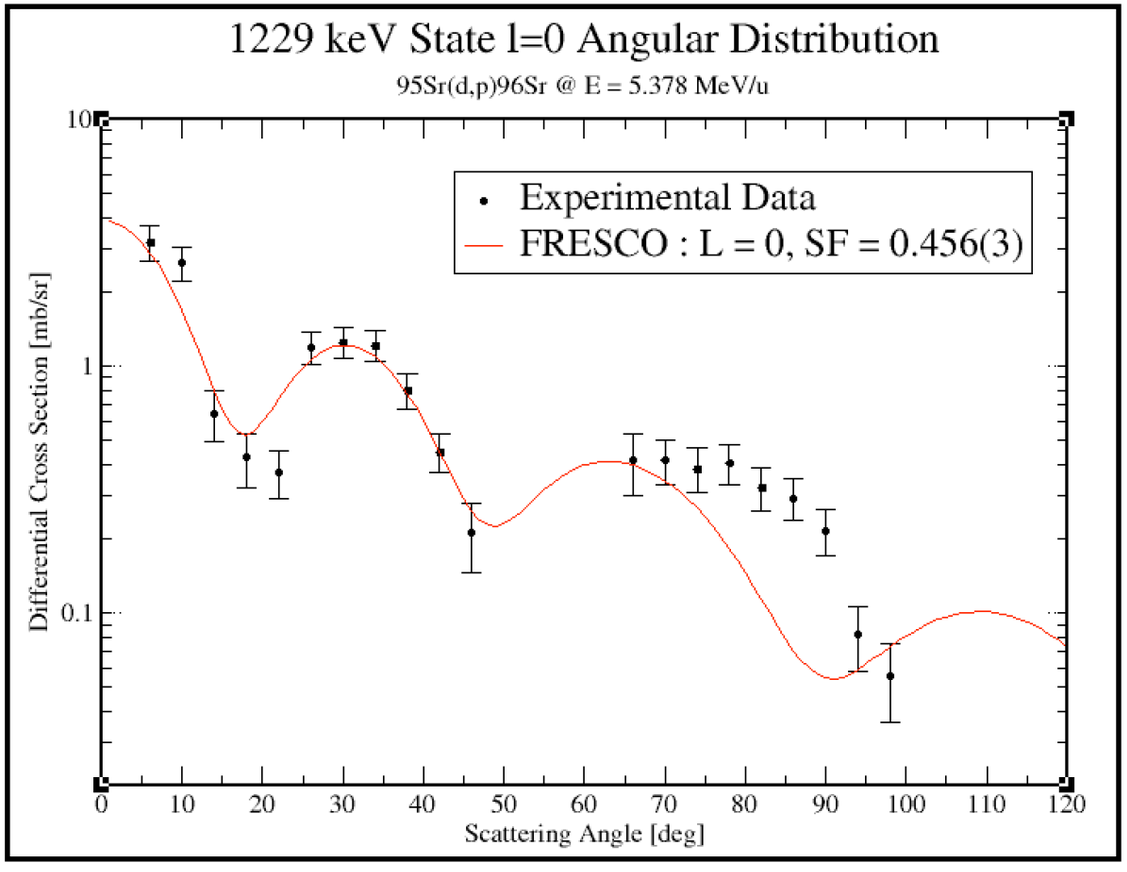
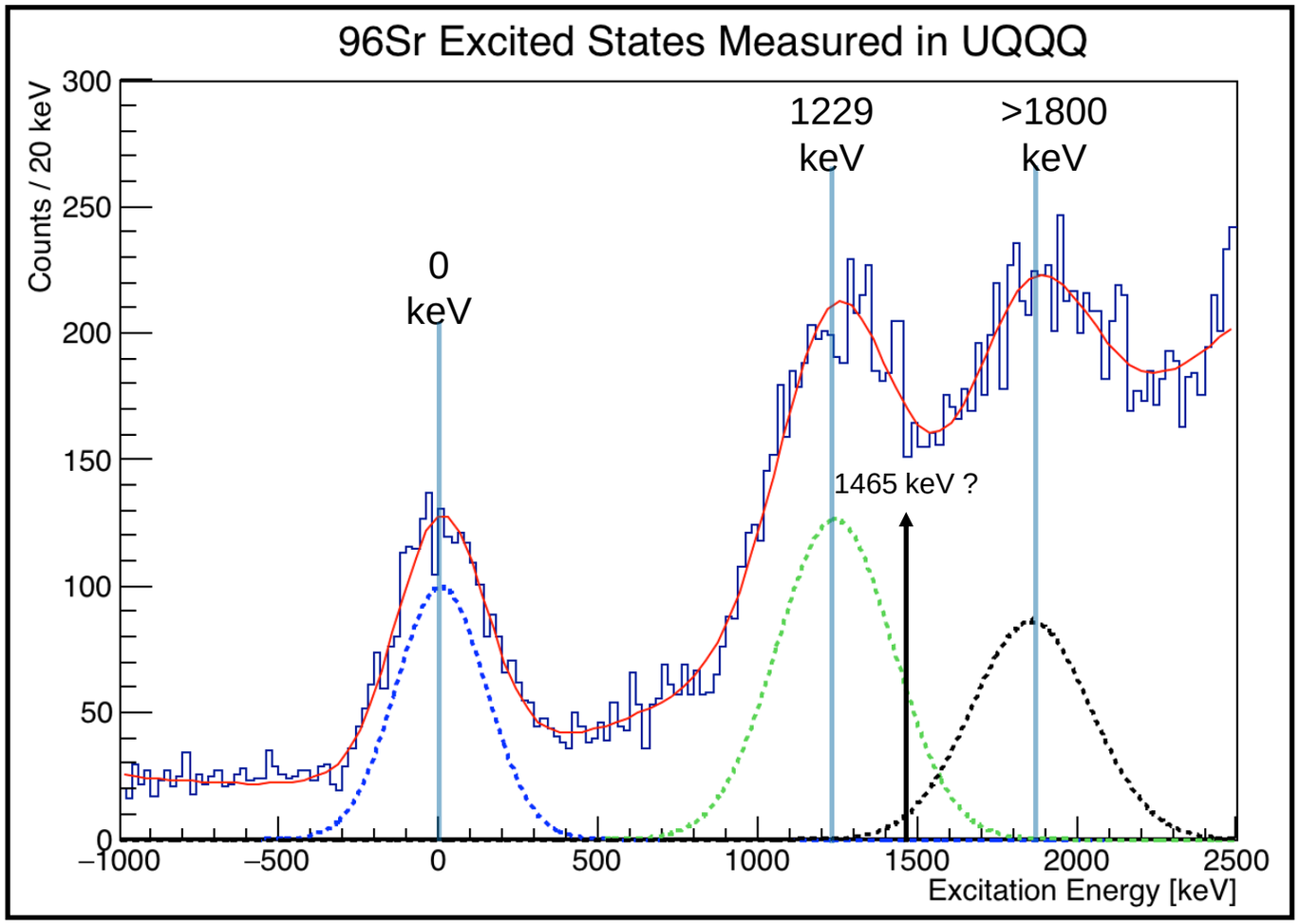






1465 keV 0^+ State

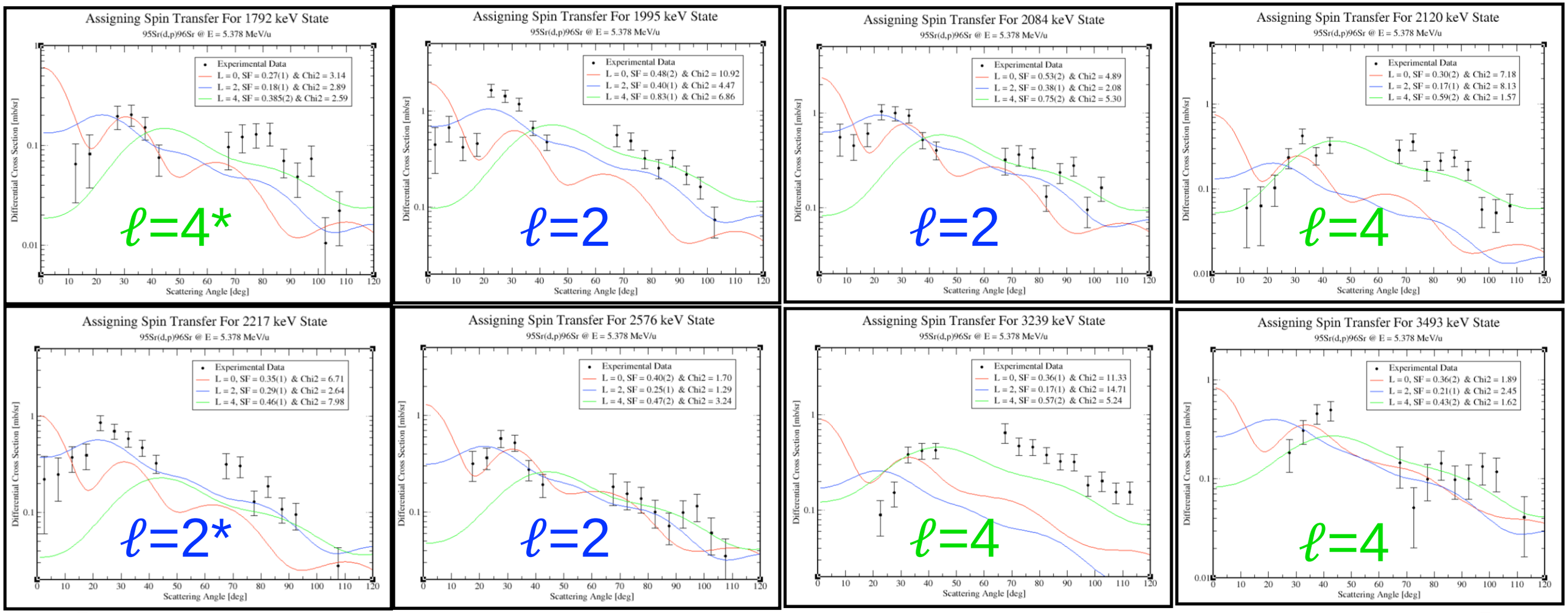
- 0^+ state populations strengths can be compared in UQQQ detector.
- Spectrum can be fit using known resolutions and measured cross sections in this angular range.
- 0_3^+ cross section indicates much smaller $[s_{1/2}]^2$ contribution.
- This suggests a different structure.



$$\rho^2(E0) = \frac{Z^2}{R_0^4} a^2(1 - a^2)[\Delta\langle r^2\rangle]^2$$

Additional Populated States

- Spectroscopic factor and χ^2 extracted for each state assuming ℓ=0,2,4.
- Preliminary SFs and spin assignments shown below.



* State spin assigned in previous studies. Out results are in agreement.

Summary and Outlook

- ^{94,95,96}Sr are first high mass (A>30) accelerated beam at TRIUMF.
- Population strengths of low energy 0^+ states in ^{96}Sr have been measured.
- 0_1^+ and 0_2^+ strongly populated, while 0_3^+ not observed.
- We have begun working with SM experts towards large scale calculations.
- ^{94}Sr(d,p) and ^{96}Sr(d,p) analysis in progress
- ^{94}Sr(t,p) next month at TRIUMF.

THANK YOU FOR LISTENING

Many thanks to S1389 Collaboration;

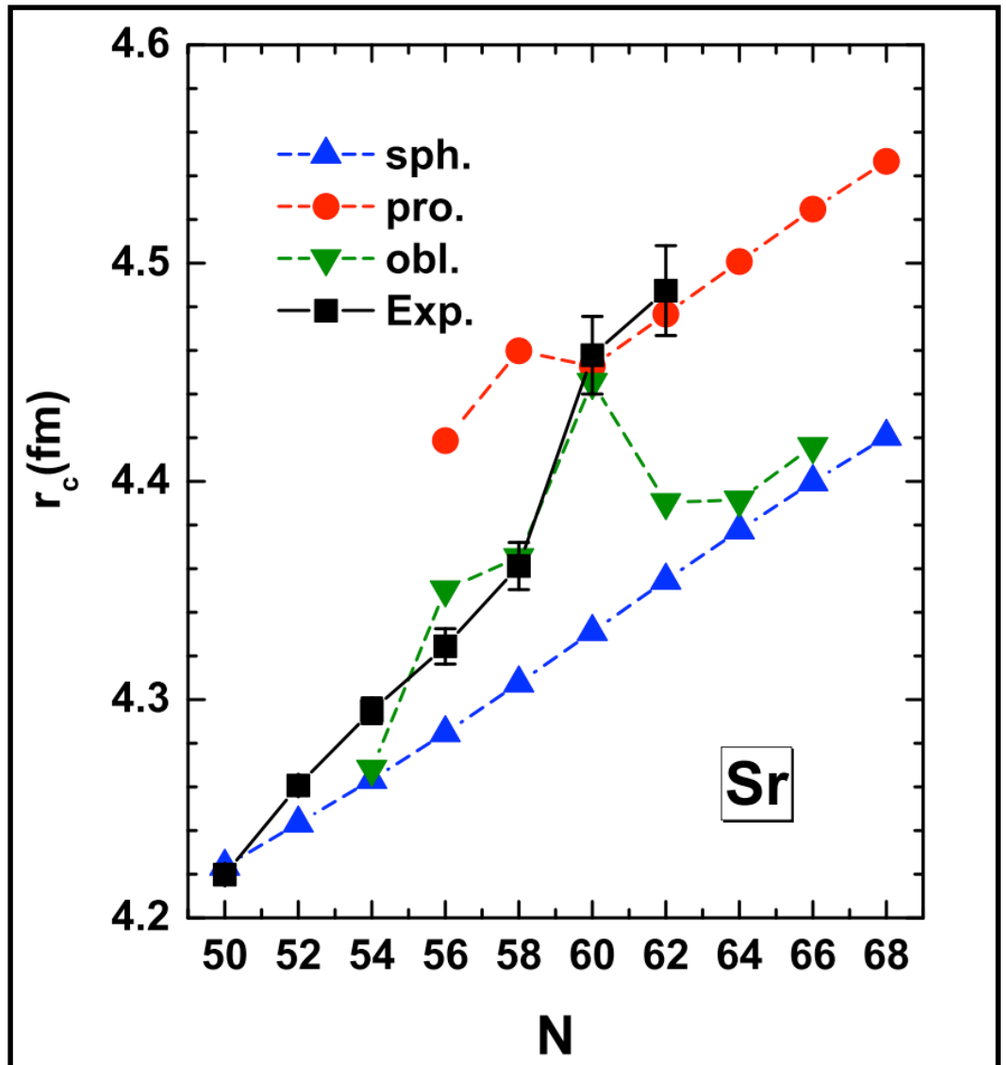
S. Cruz[1], R. Krücken[1,2], K. Wimmer[3], F. Ames[2], C. Andreoiu[4], C. S. Bancroft[3], R. Braid[5], T. Bruhn[2], W. Catford[6], A. Cheeseman[2], D. S. Cross[4], C. Aa. Diget[7], T. Drake[8], A. Garnsworthy[2], G. Hackman[2], R. Kanungo[9], A. Knapton[6], W. Korten[2], K. Kuhn[5], J. Lassen[2], R. Laxdal[2], M. Marchetto[2], A. Matta[6], D. Miller[2], M. Moukaddam[2], N. Orr[10], N. Sachmpazidi[3], A. Sanetullaev[2], N. Termpstra[3], C. Unsworth[2], P. J. Voss[4]

1. University of British Columbia, 2. TRIUMF, 3. Central Michigan University, 4. Simon Fraser University, 5. Colorado School of Mines, 6. University of Surrey, 7. University of York, 8. University of Toronto, 9. Saint Mary's University, 10. LPC Caen.

Theory (changes in radii)

- A dramatic occurrence of evolving shape is seen around Z = 40, N = 60 [1].
- The sudden change in measured radius suggests competing shapes in ground states of Sr isotopes.
- We are investigating how changes in occupations of orbitals affect this transitional region in Sr.

Changing nuclear radius in even Sr isotopes

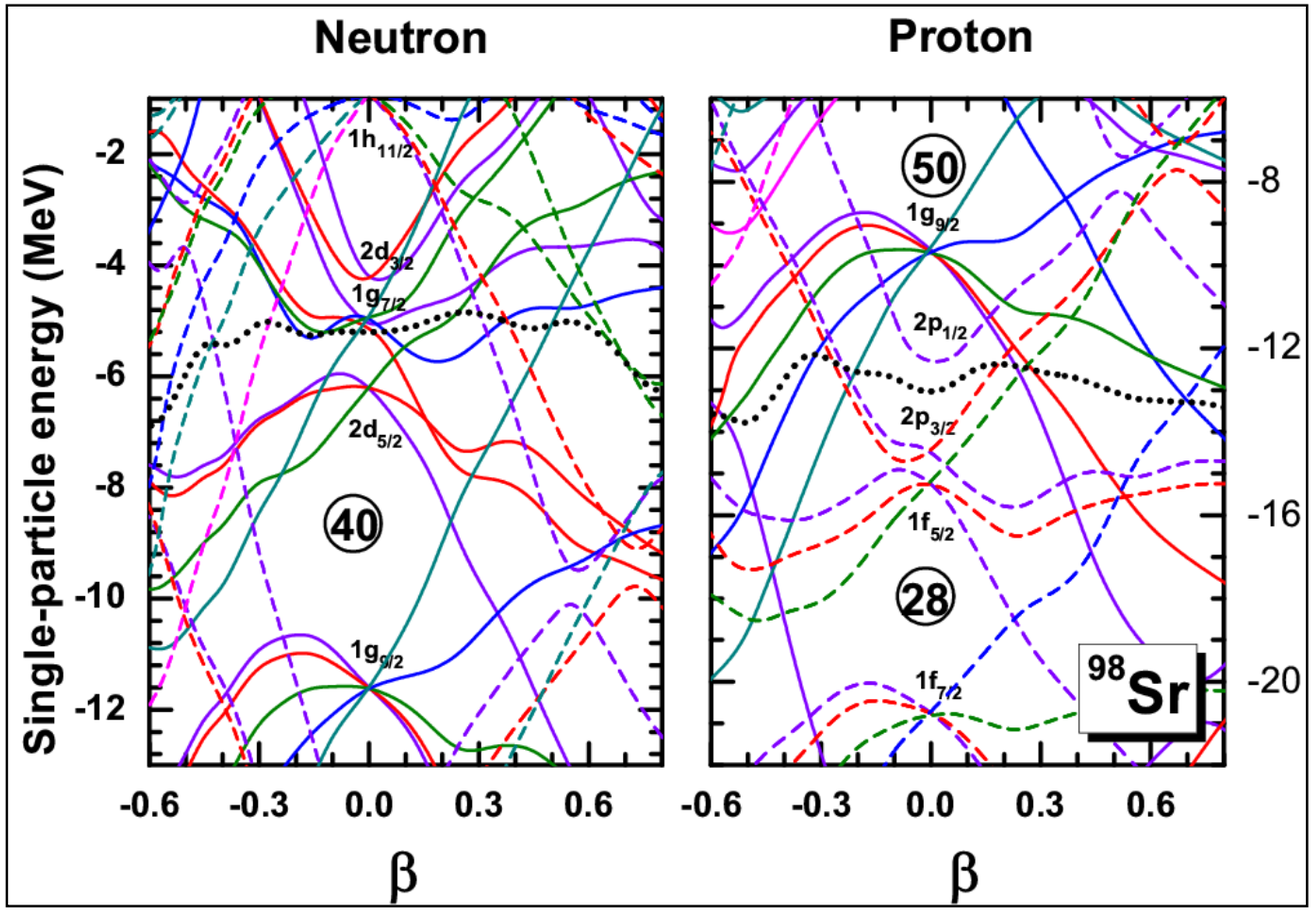


J. Xiang et al. / Nuclear Physics A 873 (2012) 1–16

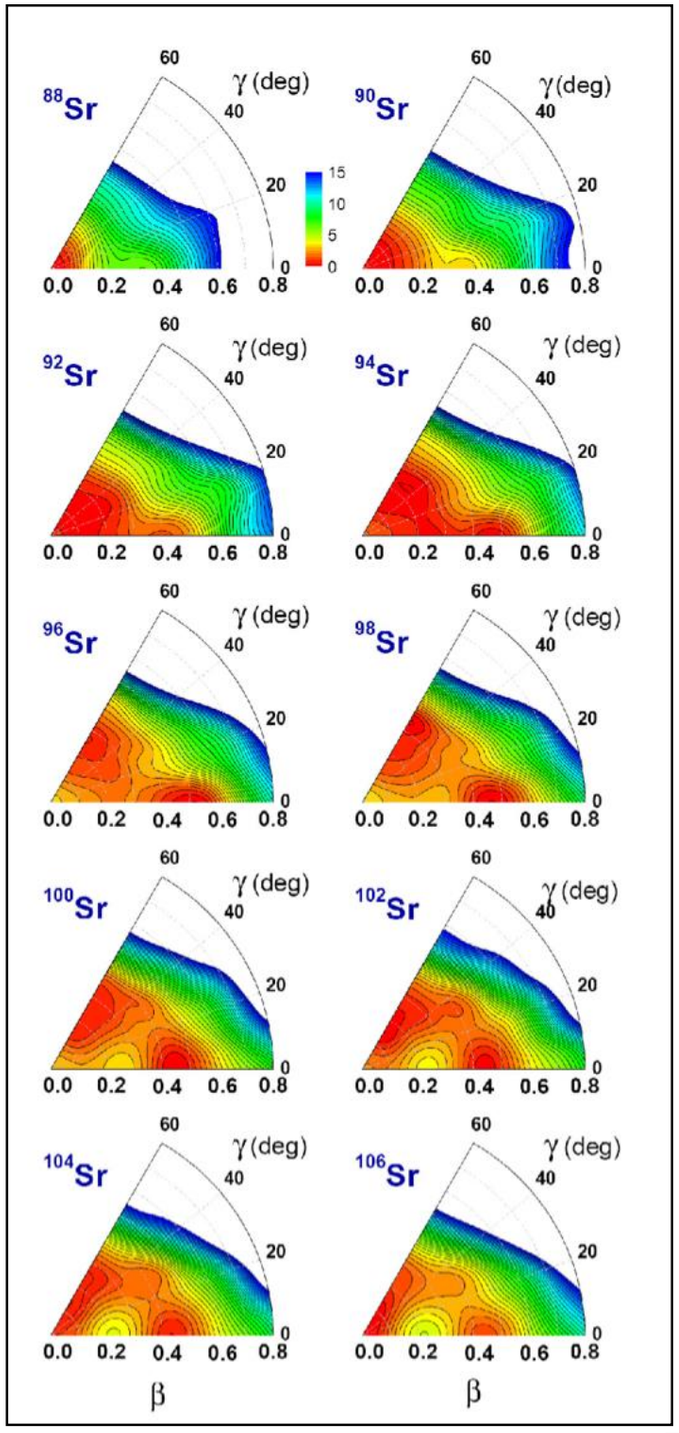
[1] K. Heyde, J. L. Wood Rev. Mod. Phys. 83, 1467 (2011).

Theory (Sr calculations)

- Relativistic mean-field Skyrme-Hartree-Fock calculations of the structure of strontium predict coexisting shapes.
- The dots denote the corresponding Fermi energy levels.



Nucl.Phys. A873 (2012) 1-16



Mei, H. et al. Phys.Rev. C85 (2012)

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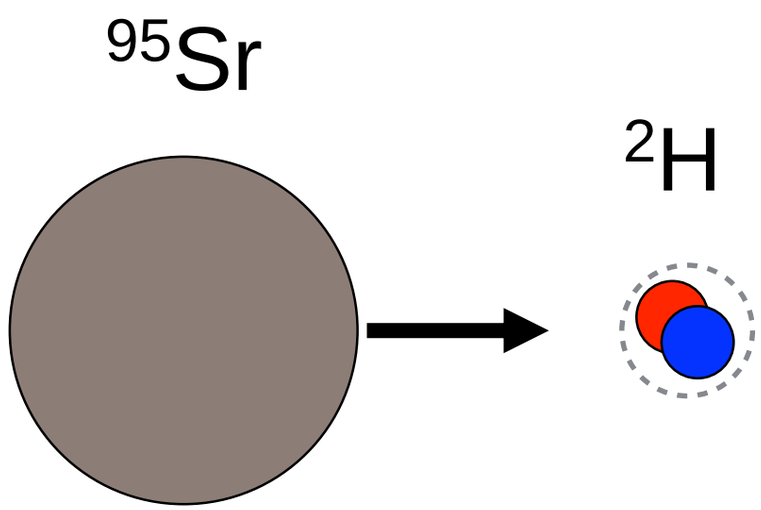
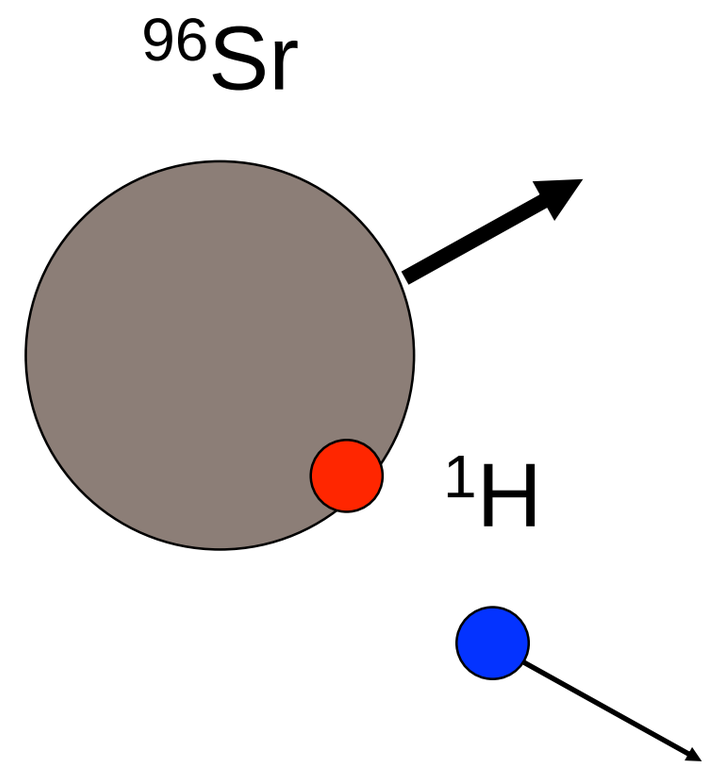
Elastic Channels





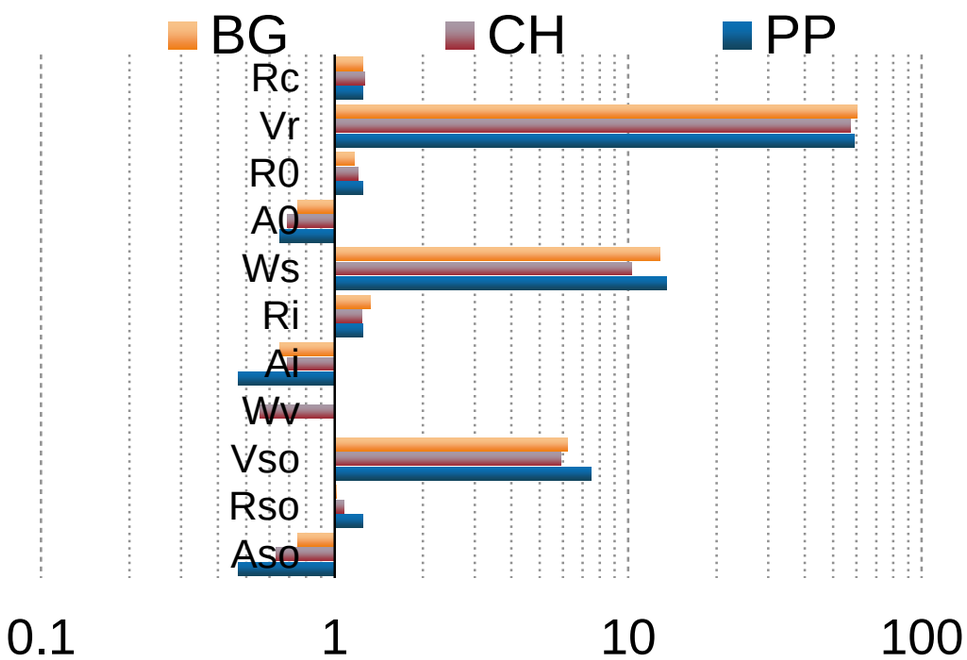
^{95}Sr(d,d) data provides distorted waves in **incoming** ^{95}Sr(d,p) channel

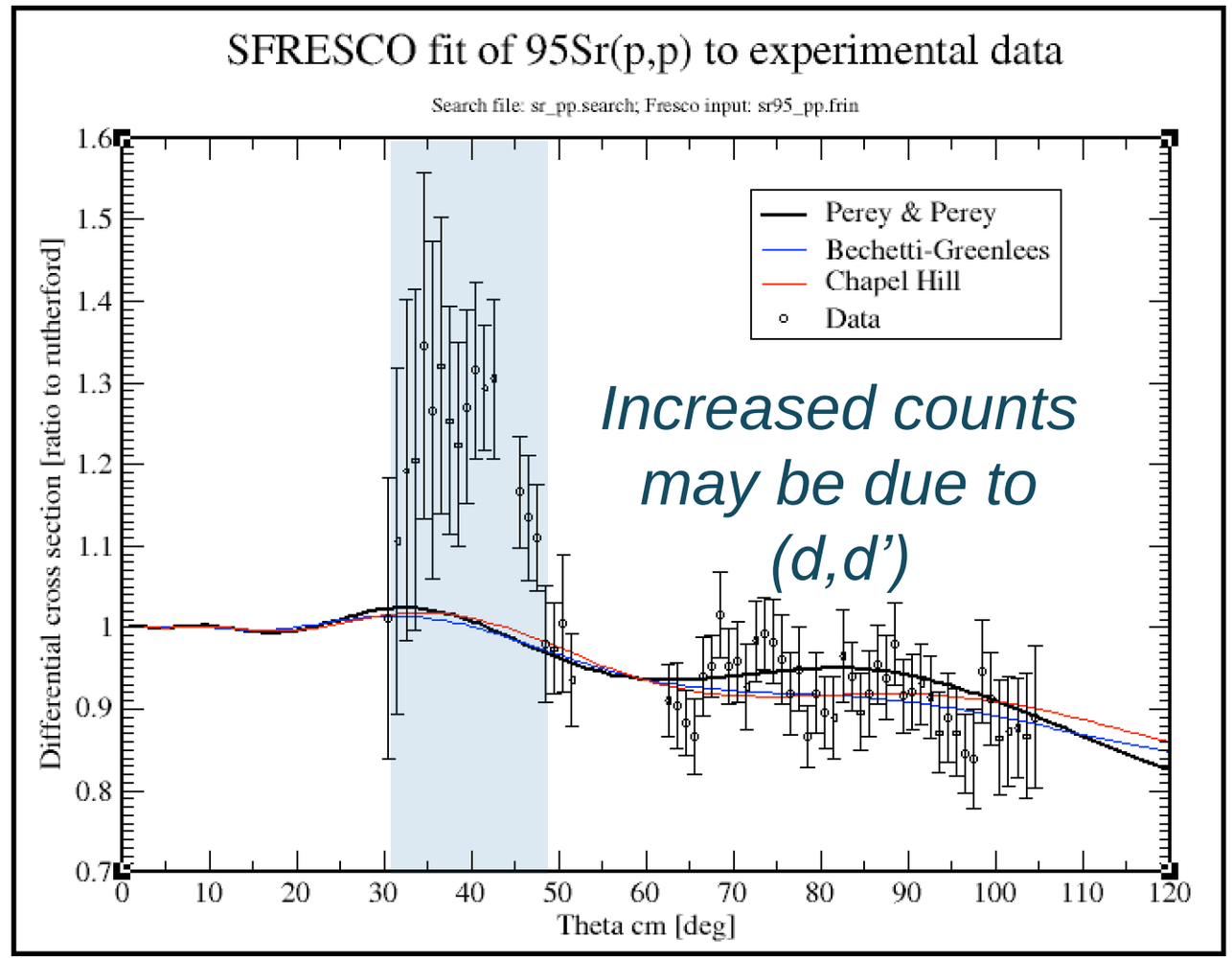
^{95}Sr(p,p) data provides distorted waves in **outgoing** ^{95}Sr(d,p) channel

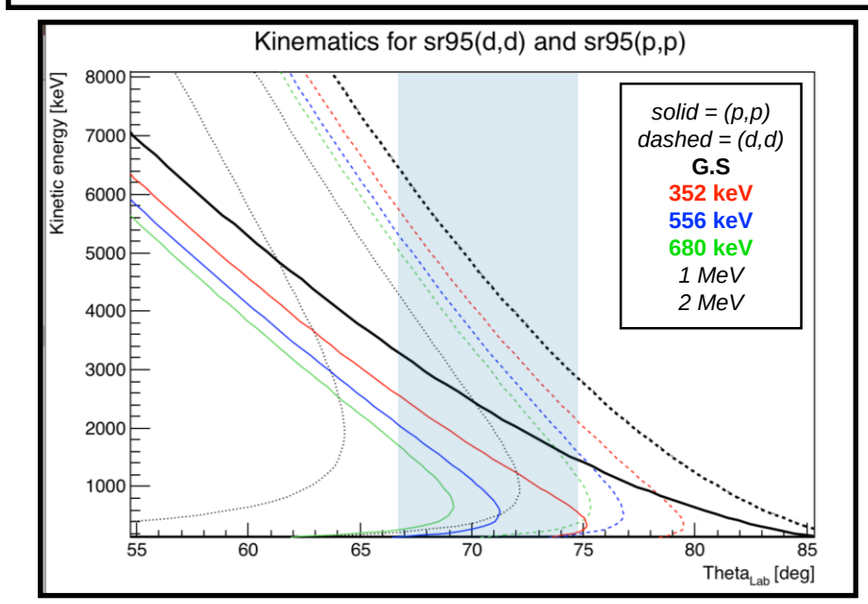
Assume ^{95}Sr(p,p) has ~ the same optical model parameters as ^{96}Sr(p,p)

(p,p) Cross Sections

- All OM parameter sets predict similar angular distributions for (p,p).





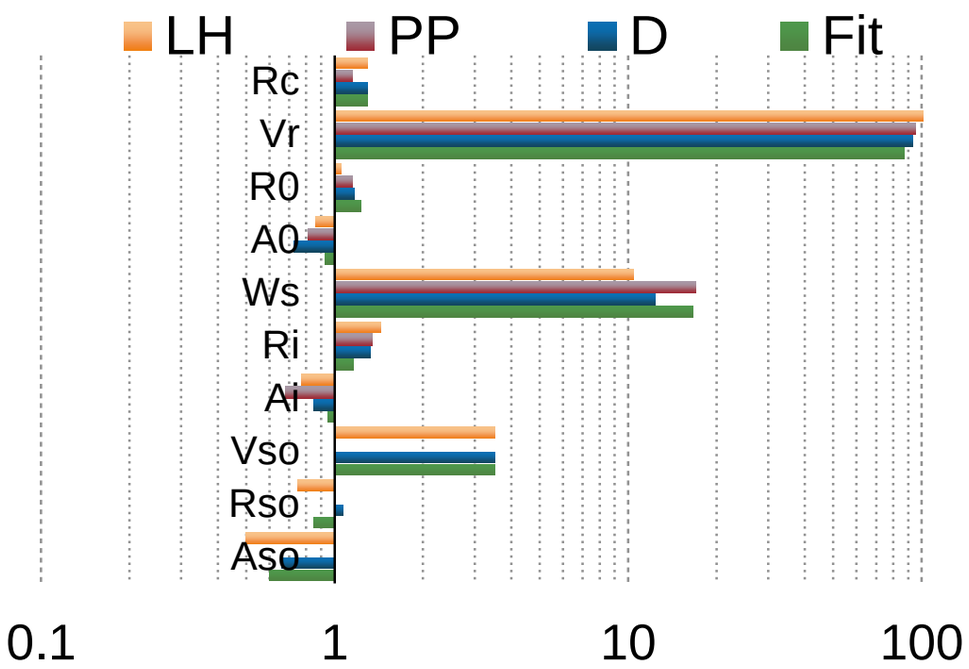


Optical potentials for DWBA

[1] Bechetti-Greenlees (A>40 20<E<50 MeV)
Phys Rev 182 (1969) 1190
[2] Chapel-Hill 89 Global set (A>40 E>10 MeV)
Phys Rep 201 (1991) 57
[3] Perey (E<20MeV) see: ADNTD 17 (1976) p6

(d,d) Cross Sections

- All OM parameter sets predict similar angular distributions for (d,d).



Optical potentials for DWBA

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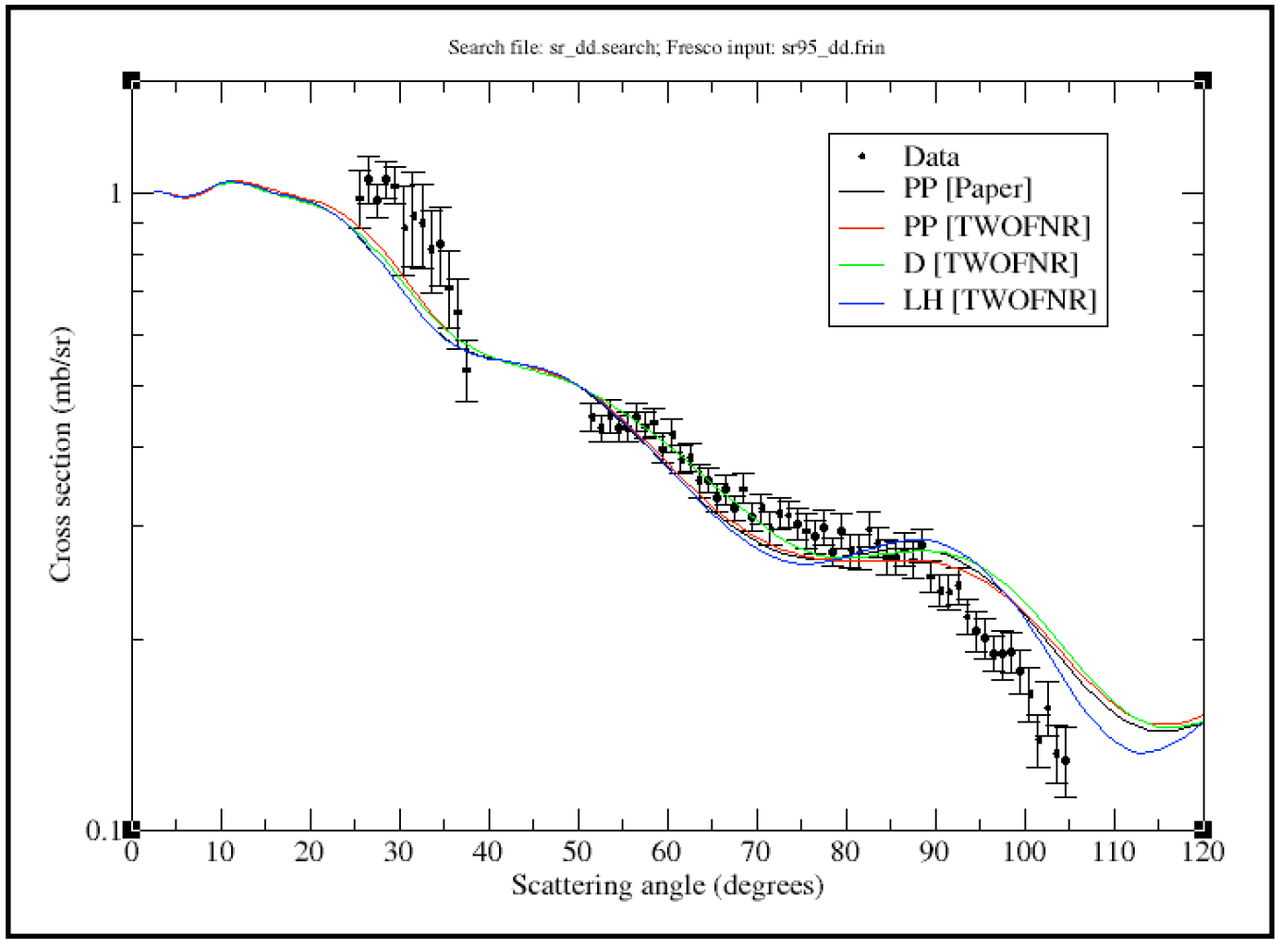
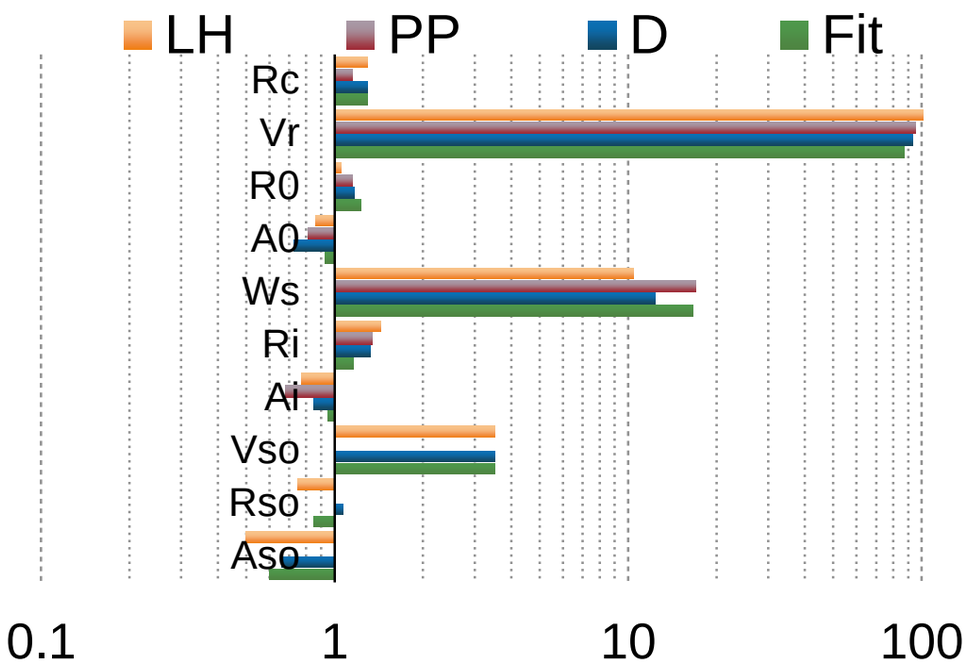
see: ADNTD 17 (1976) p6
[2] Perey-Perey (12<E<25 MeV) no spin-orbit
see: ADNTD 17 (1976) p6
[3] Daehnick Global (A>27 12<E<90 MeV)
Phys. Rev. C 21, 2253 (1980)



Theory is in good agreement with data.

(d,p) Cross Sections

- All OM parameter sets predict similar angular distributions for (d,p).



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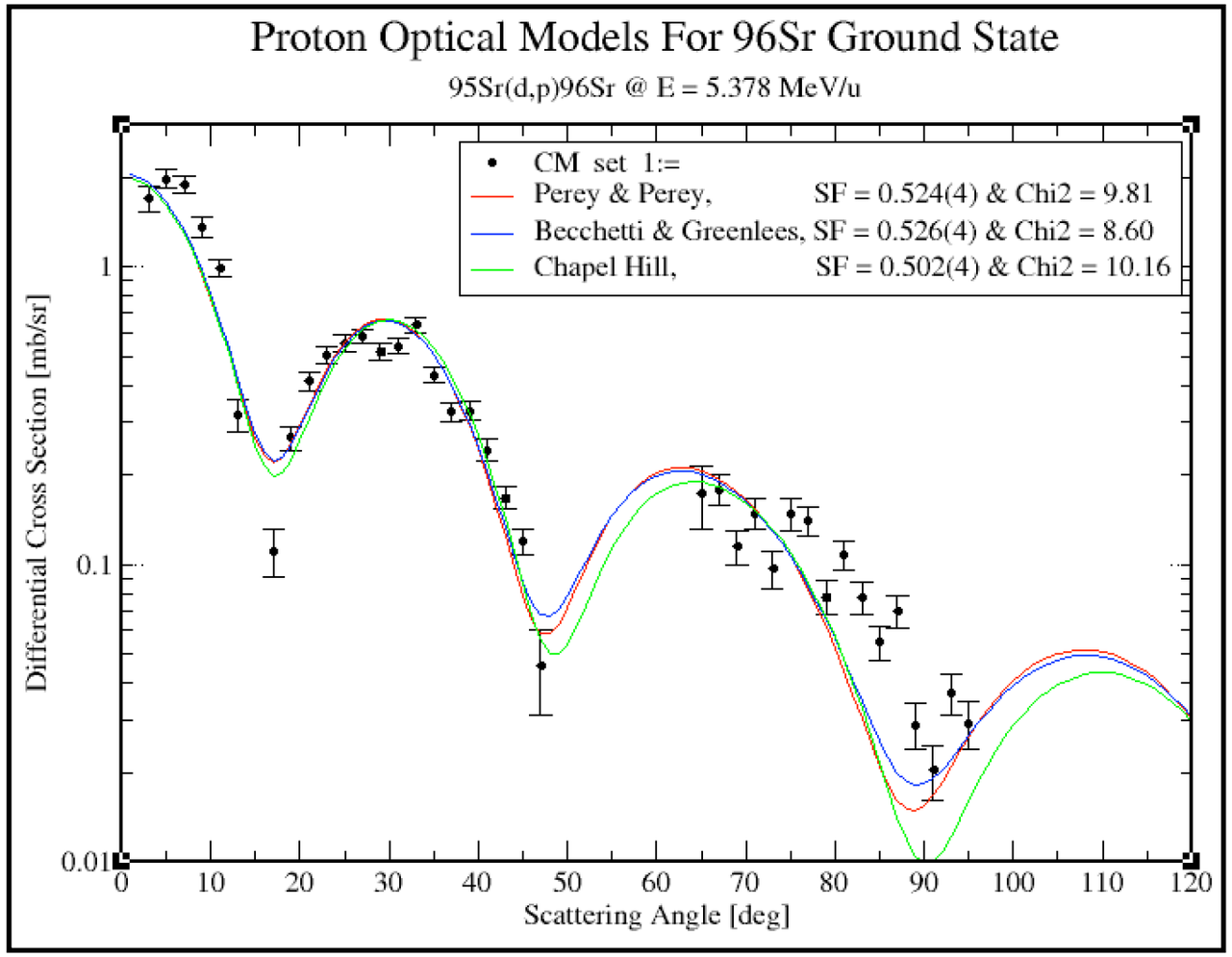


Theory is in good agreement with data.

SM Calculations

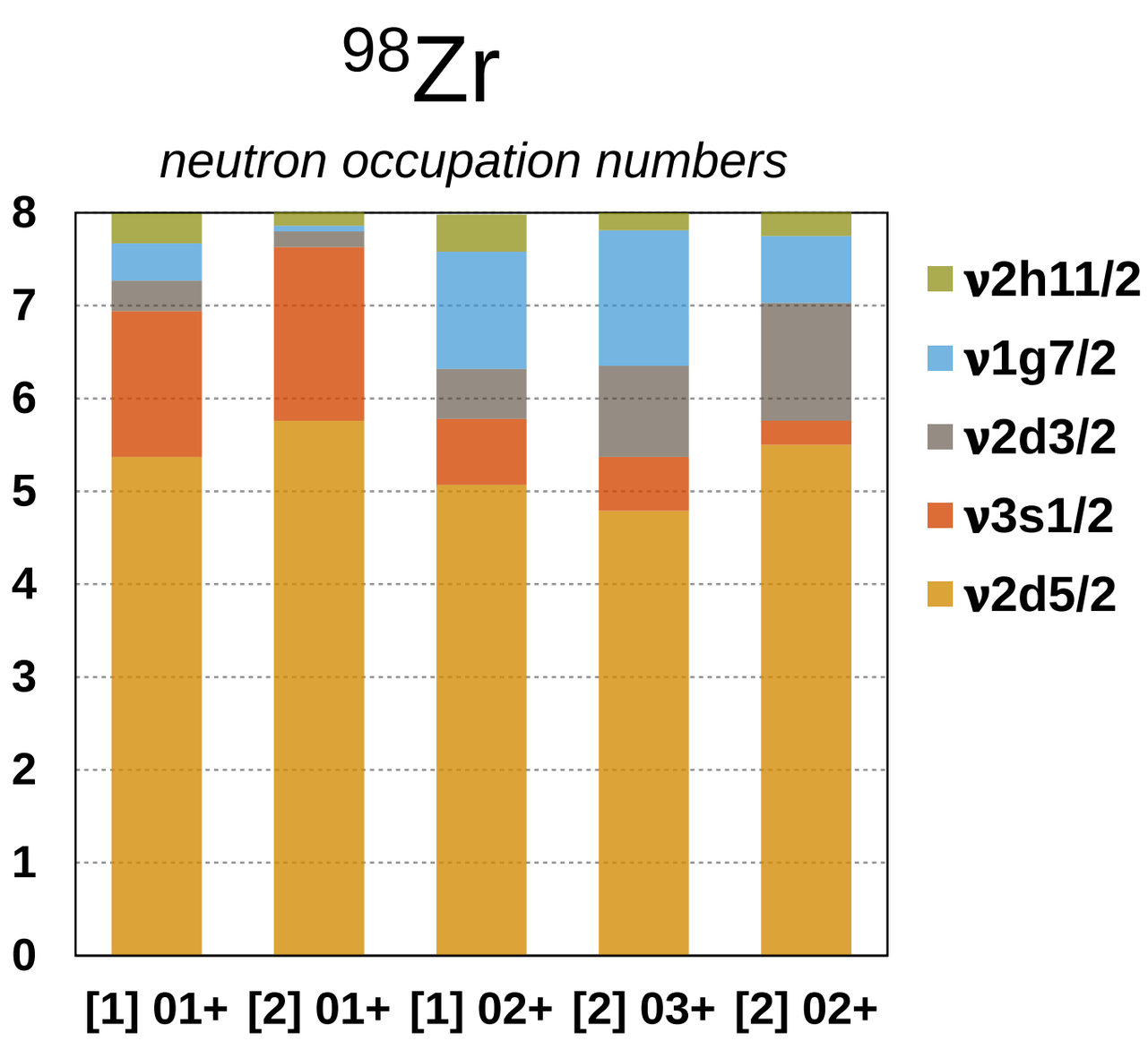
^{98}Zr

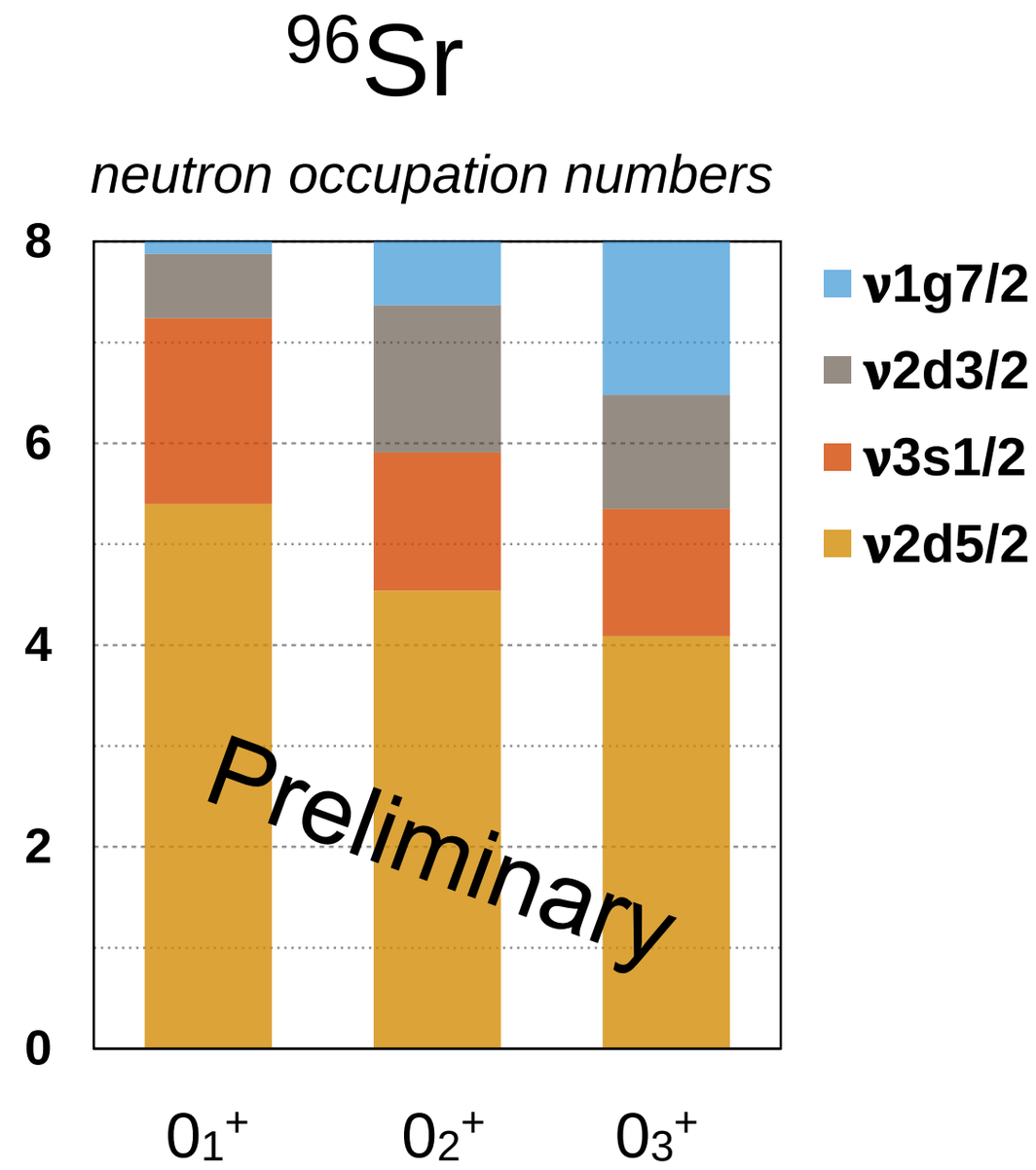
N	J^π	$d_{5/2}$	$s_{1/2}$	$g_{7/2}$	$d_{3/2}$	$h_{11/2}$
58	0_1^+	5.37	1.57	0.40	0.33	0.32
	0_2^+	5.07	0.71	1.26	0.54	0.40

- Occupations from K. Sieja's ^{98}Zr calculations shows dominant $(s_{1/2})^2$ character in ground state 0_1^+ and dominant $(g_{7/2})^2$ character with some $s_{1/2}$ component in first excited 0_2^+.

- Conclusion: 1465 keV ^{96}Sr state is likely the equivalent state as the 0_2^+ state in ^{98}Zr.

SM Calculations

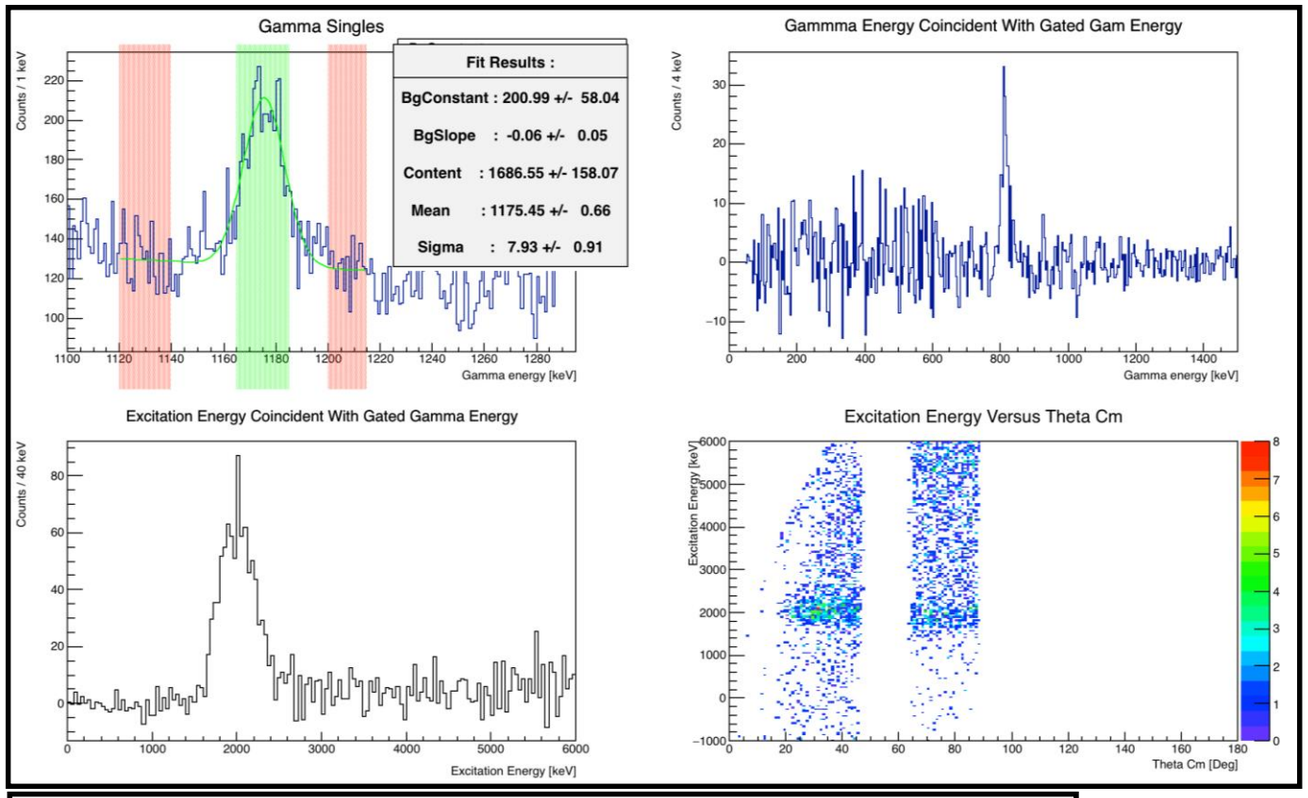


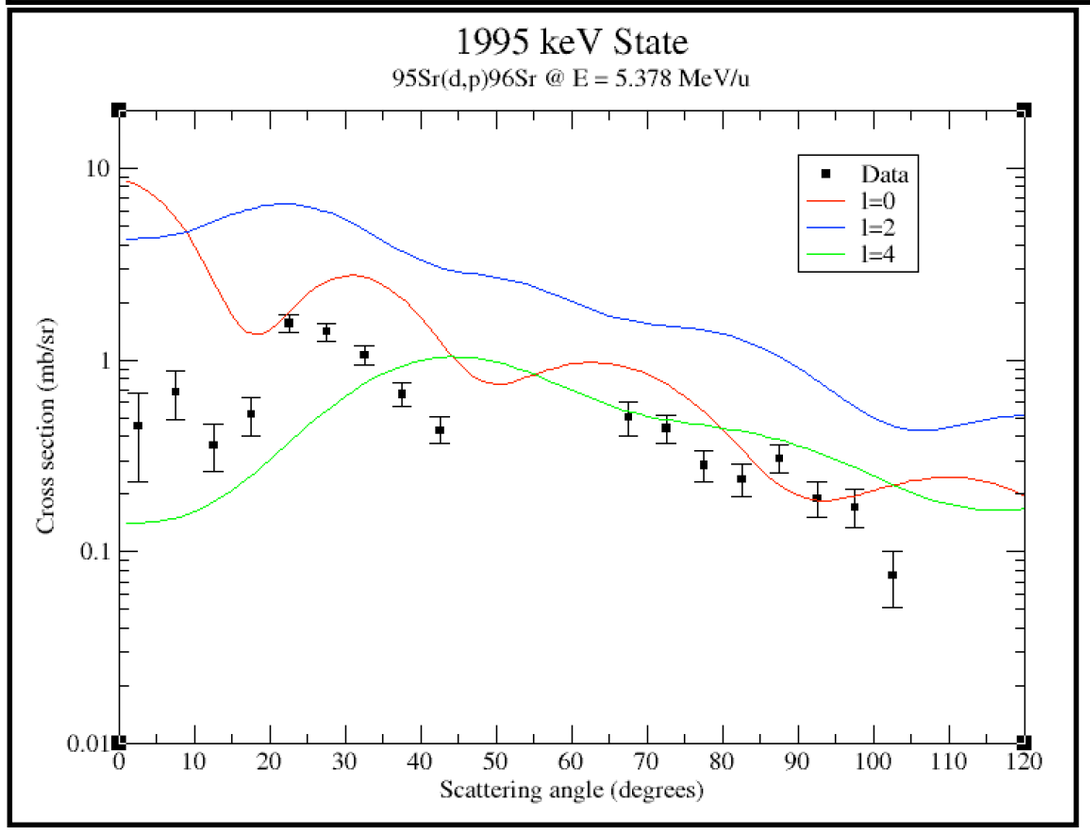


[1] A Holt ^{88}Sr core
[2] K. Sieja ^{78}Ni core

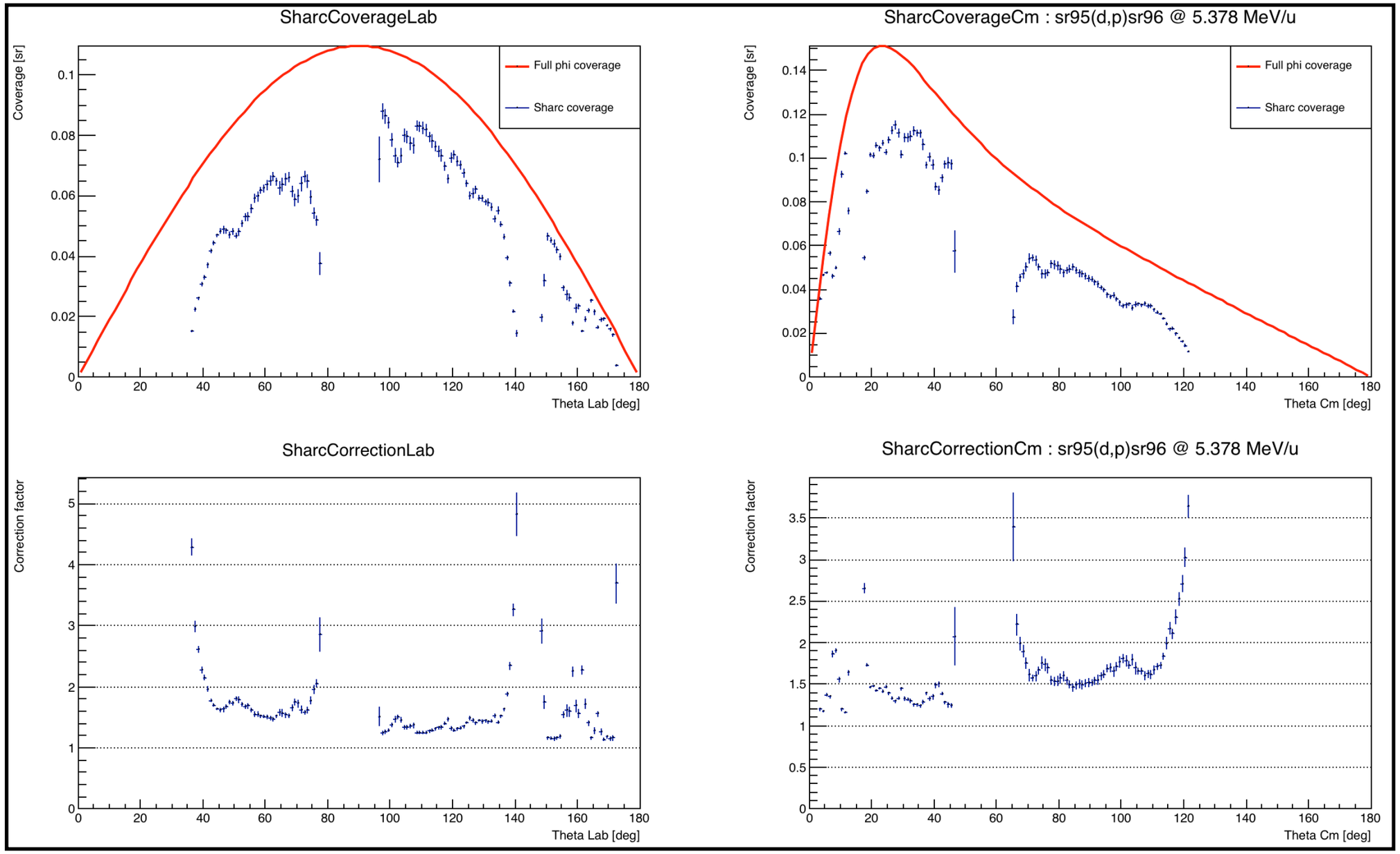
Additional Populated States

- A Number of other states were also strongly populated and so the angular distributions were also extracted.
- Example shown is analysis for 1995 keV state (spin unassigned).
- Normalized data is shown with DWBA calculations.
- Gamma gated on 1176 keV transition to 815 keV (2^+) first excited state.
- Strong ℓ=2 character.





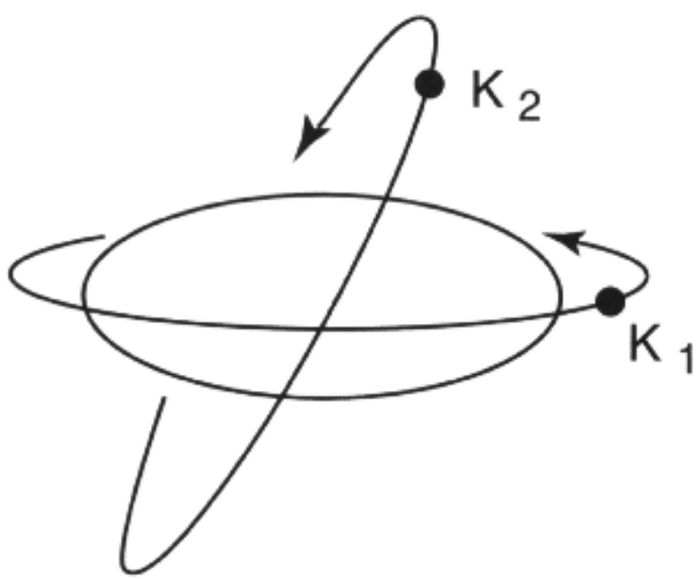
Detector Coverage



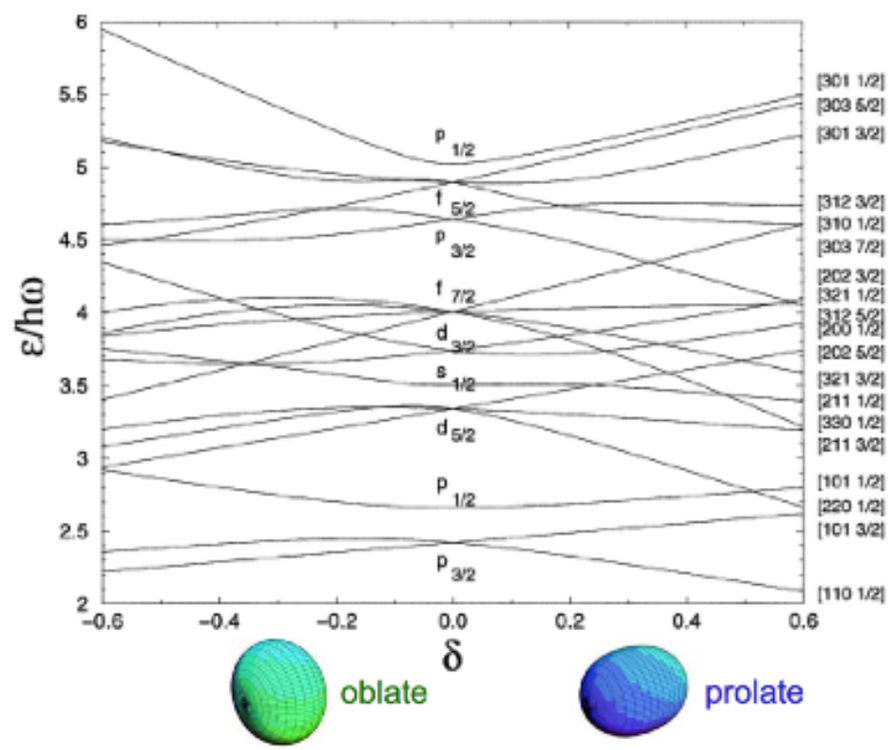
Theory (deformed mean field)

§ In the presence of a deformed mean field potential, single particle energies are shifted.

§ The delicate energy balance between spherical and deformed configurations depends crucially on the size of these energy gaps and the occupations of the single particle levels.



(a) Magnetic substate energy dependence in a deformed nucleus



(b) SPE shifts as a function of deformation

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