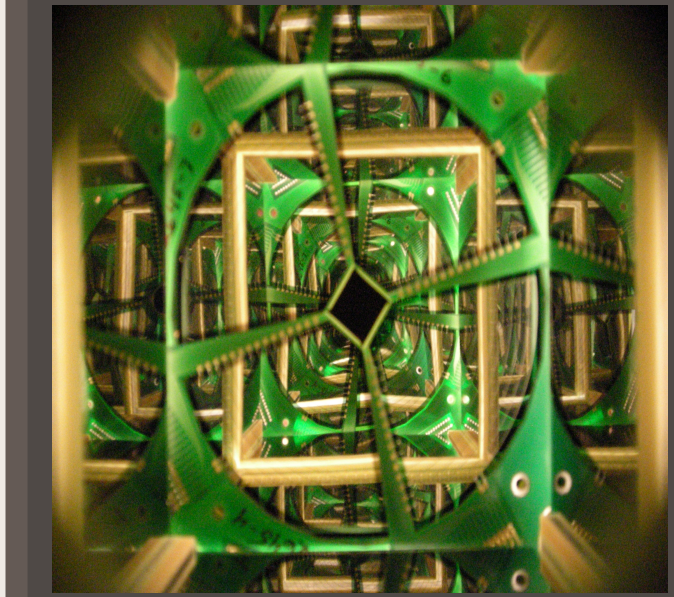
# Shape coexistence in exotic Sr isotopes

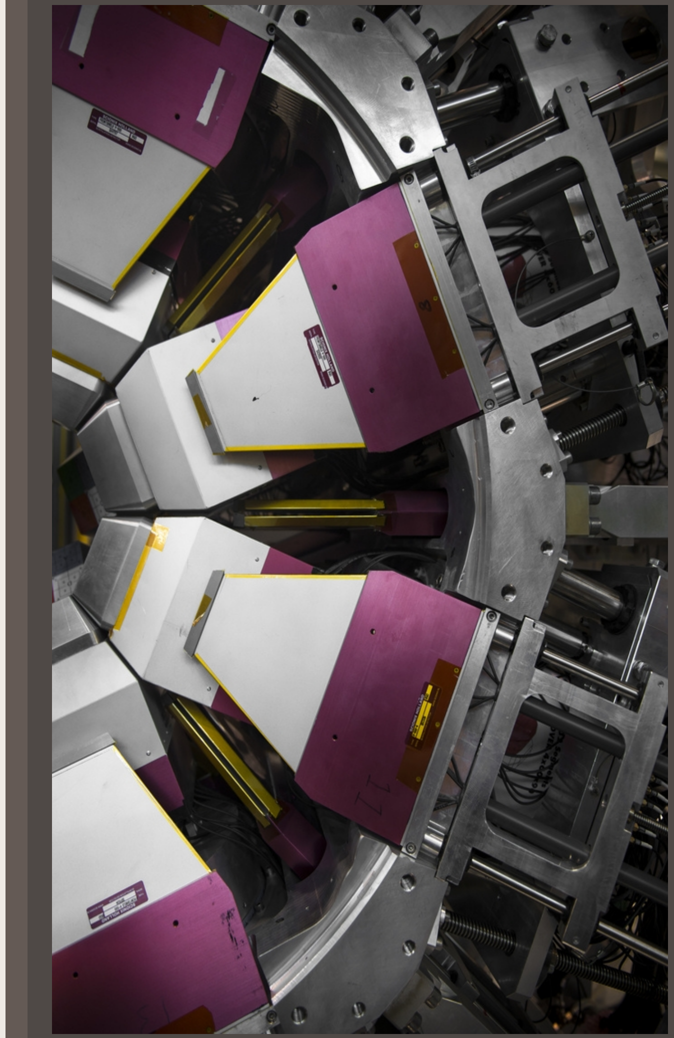
CAP Congress, Tuesday 17th June 2014.

**Steffen Cruz**

*UBC and TRIUMF*

On behalf of the S1389 experimental team

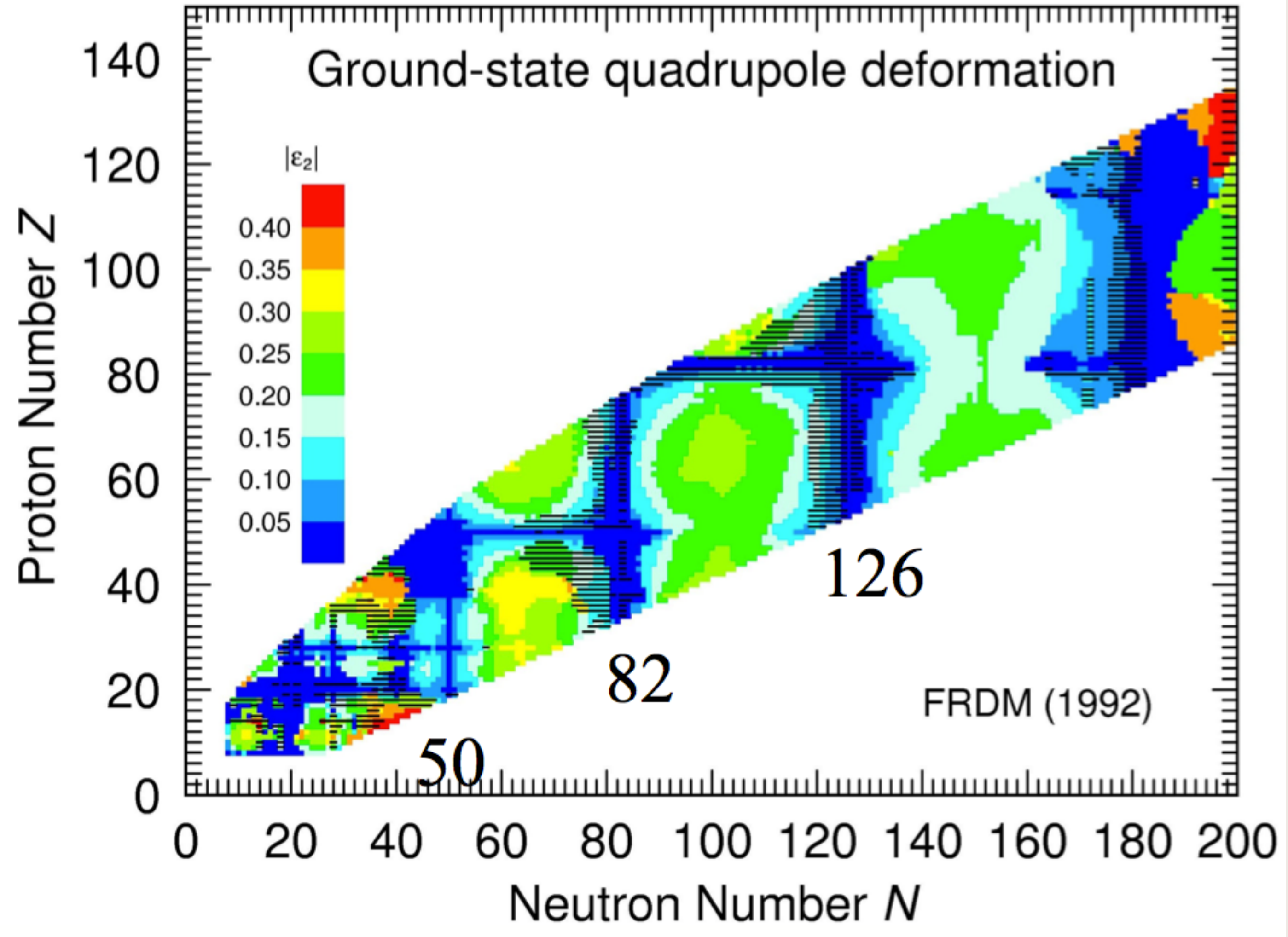




# Theory

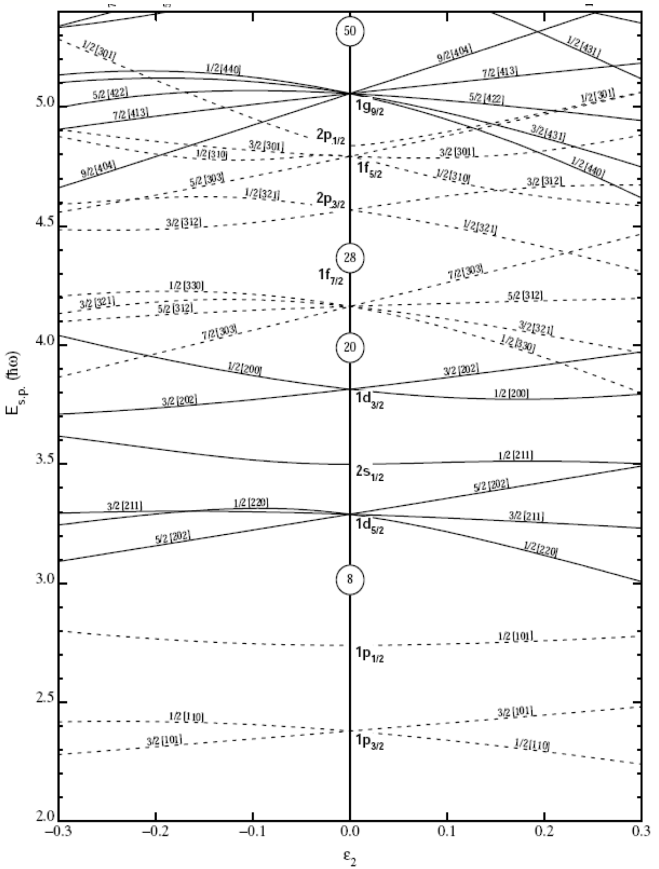
- Shape deformation enables the nucleus to minimize its energy.
- FRDM calculation below shows expected deformation across nuclear chart.

Quadrupole deformation is a measure of nuclear shape.



*P. Moller, J.R. Nix, W.D. Myers and W.J Swiatecki, At. Data Nucl. Data Tables 59, 185 (1995)*

Nilsson model: Different deformations have different single particle configurations



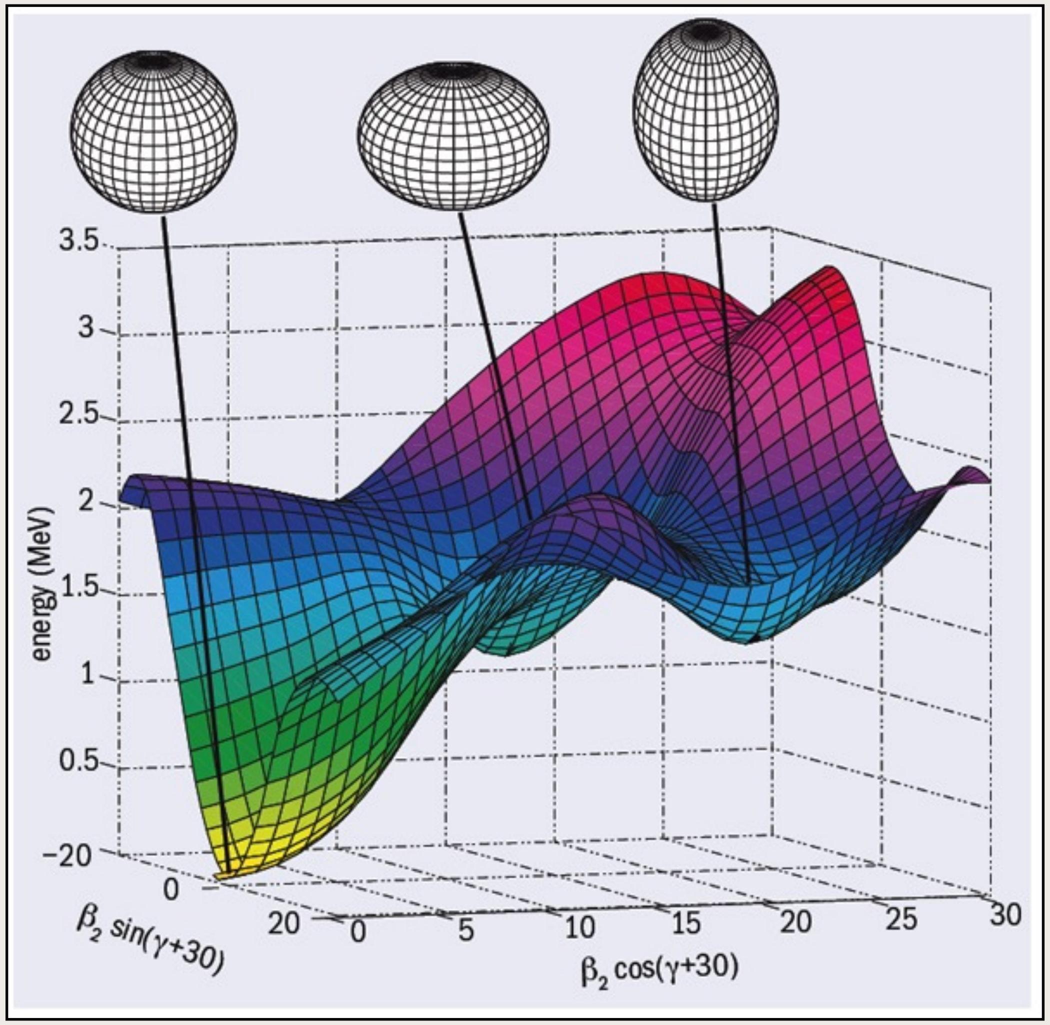
**oblate** **spherical** **prolate**

***Plot source: R.F. Casten***

# Theory

- This calculation of $^{186}$Pb shows how the potential surface has minima close in energy at different shapes.
- The potential minima are produced using different single particle configurations.
- Shape coexistence in nuclei occurs between states with different deformations which can have very close energies.

*$0^+$ state energies in $^{186}$Pb*



Andreyev, A. N., et al., Nature **405**, 430 (2000).

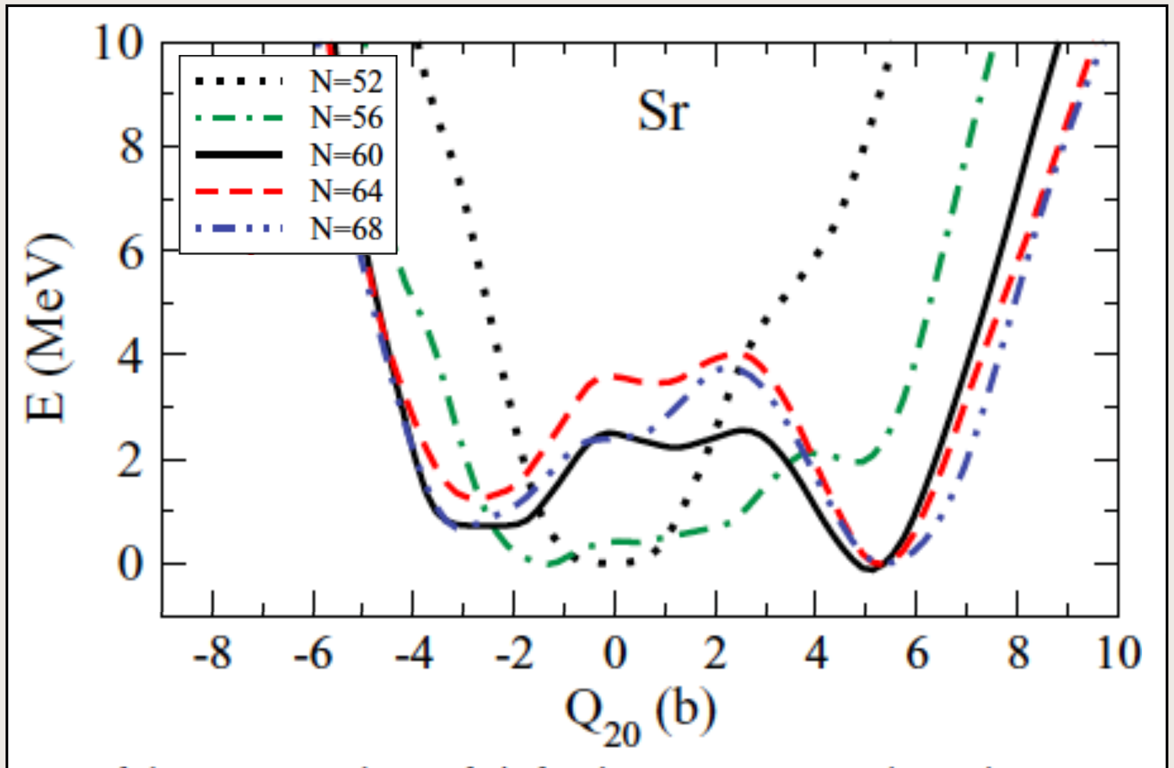
Onset of deformation is driven by **single particle levels**

# Theory

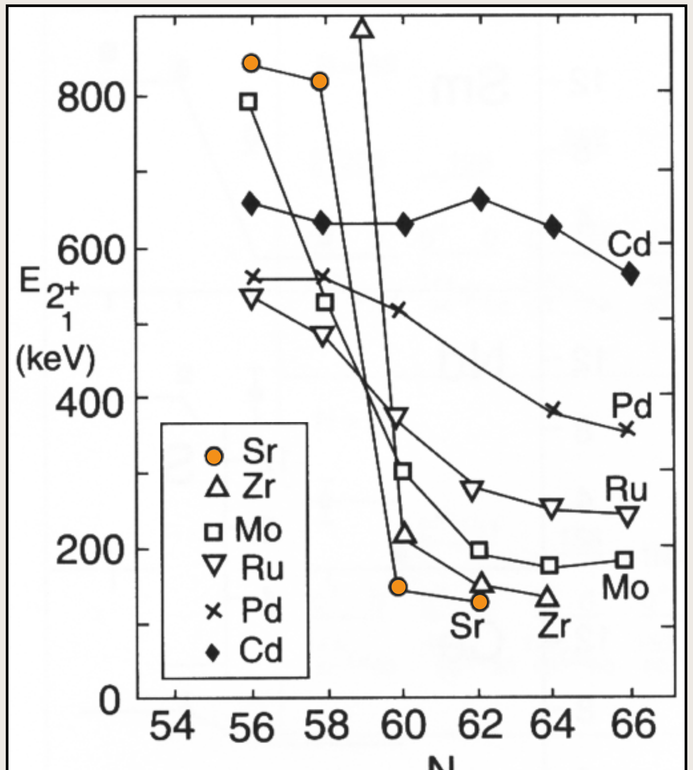
- State of the art (beyond mean field) calculations predict binding energy as a function of deformation.
- Measurements of single particle levels in $^{95,96}$Sr essential for a detailed description of this transitional region.

***Predicted***

*Binding energy curves predict almost degenerate potential minima at N = 60.*



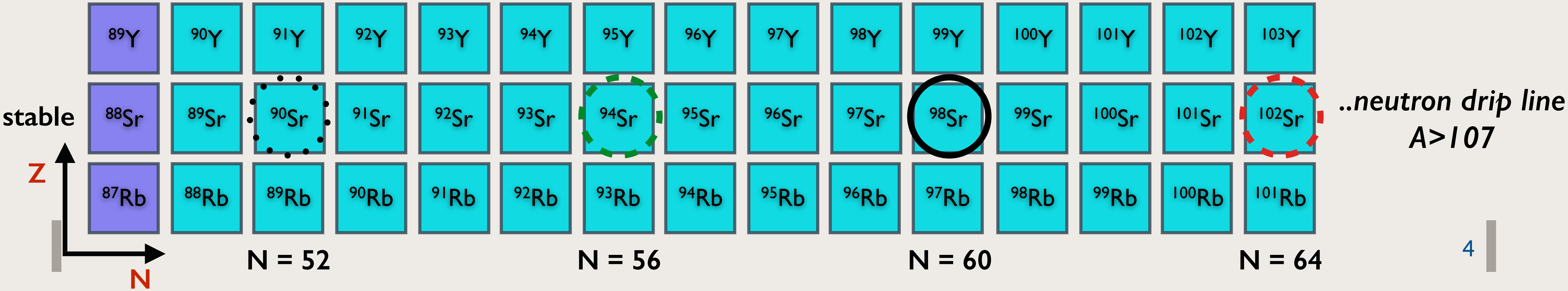
*R. Rodríguez-Guzmán et al. / Physics Letters B 691 (2010) 202–207*



***Source: R.F. Casten***

***Observed***

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



| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $^{89}$Y | $^{90}$Y | $^{91}$Y | $^{92}$Y | $^{93}$Y | $^{94}$Y | $^{95}$Y | $^{96}$Y | $^{97}$Y | $^{98}$Y | $^{99}$Y | $^{100}$Y | $^{101}$Y | $^{102}$Y | $^{103}$Y |
| stable | $^{88}$Sr | $^{89}$Sr | $^{90}$Sr | $^{91}$Sr | $^{92}$Sr | $^{93}$Sr | $^{94}$Sr | $^{95}$Sr | $^{96}$Sr | $^{97}$Sr | $^{98}$Sr | $^{99}$Sr | $^{100}$Sr | $^{101}$Sr | $^{102}$Sr |
| | $^{87}$Rb | $^{88}$Rb | $^{89}$Rb | $^{90}$Rb | $^{91}$Rb | $^{92}$Rb | $^{93}$Rb | $^{94}$Rb | $^{95}$Rb | $^{96}$Rb | $^{97}$Rb | $^{98}$Rb | $^{99}$Rb | $^{100}$Rb | $^{101}$Rb |

N = 52 N = 56 N = 60 N = 64

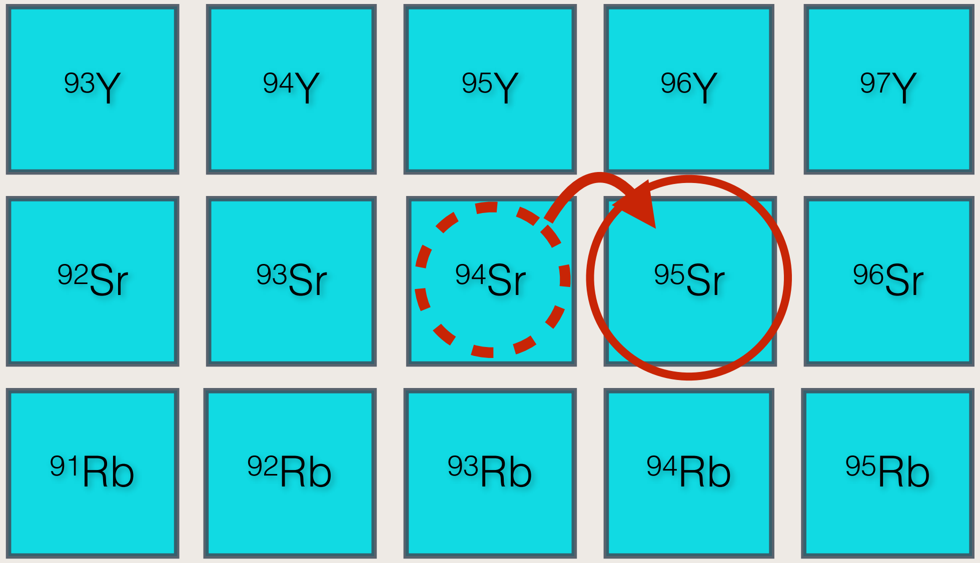
*..neutron drip line A>107*

# Experiment

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

## Aims

- Measure energies of excited states (single particle energies).
- Measure angular momentum transfer of $^{95}$Sr states (dσ/dΩ).
- Measure cross section, which gives a orbital occupation number.



| | | | | |
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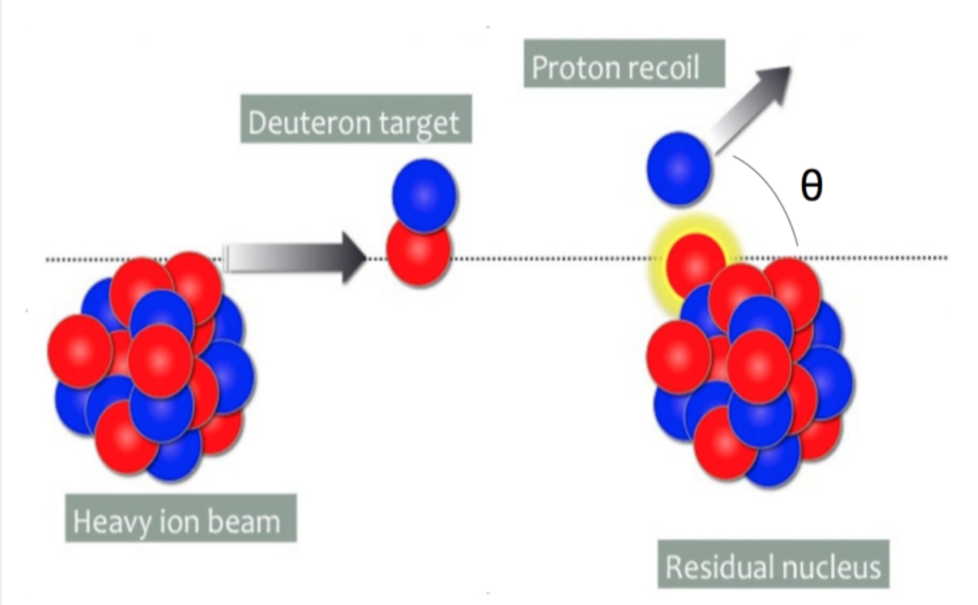
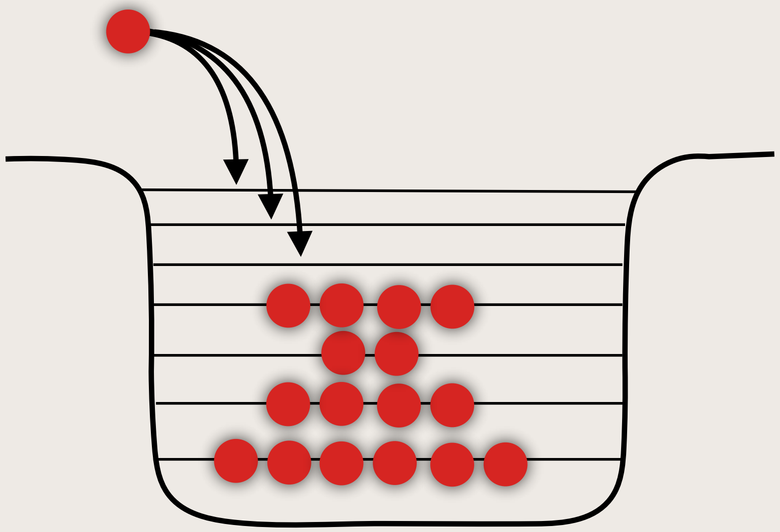
| $^{91}$Rb | $^{92}$Rb | $^{93}$Rb | $^{94}$Rb | $^{95}$Rb |

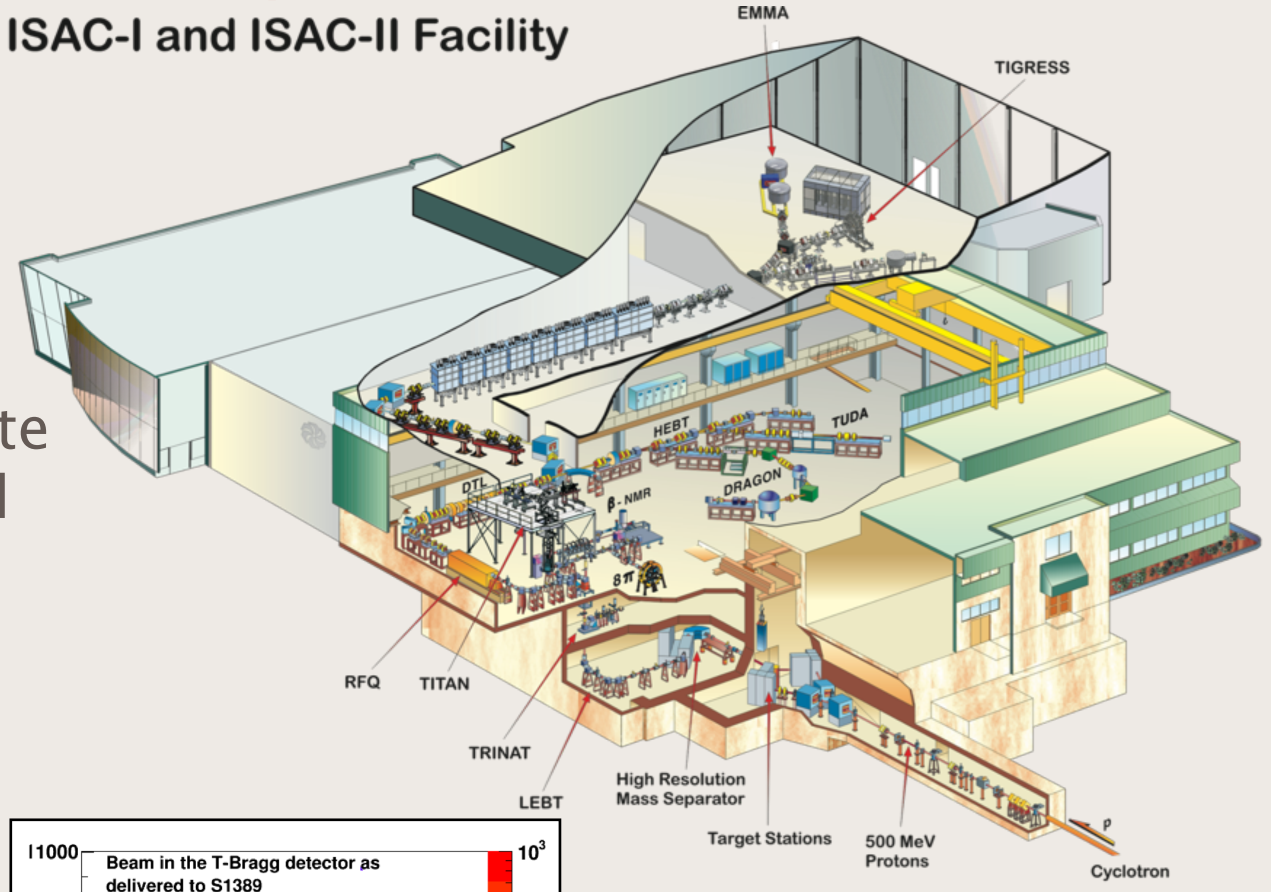


*Neutron populates one of the single particle orbitals*



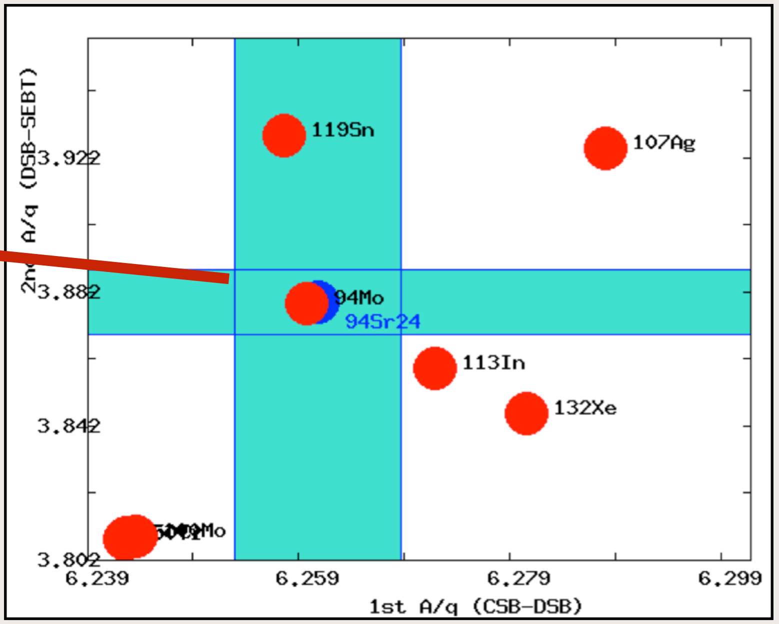
# Experiment

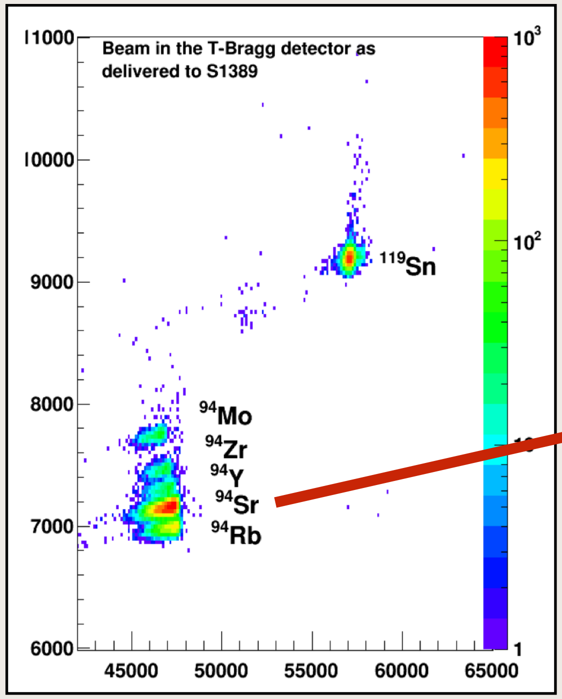
*July-August 2013 TRIUMF successfully delivered first high mass rare isotope beam to ISAC-II for a nuclear structure experiment.*



- 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 $15^+$.
- Ionized beam ($Q=22^+$) was delivered at 5.5 MeV/u to the experiment.

*A/q selection makes isotope separation possible*





*Our beam!*

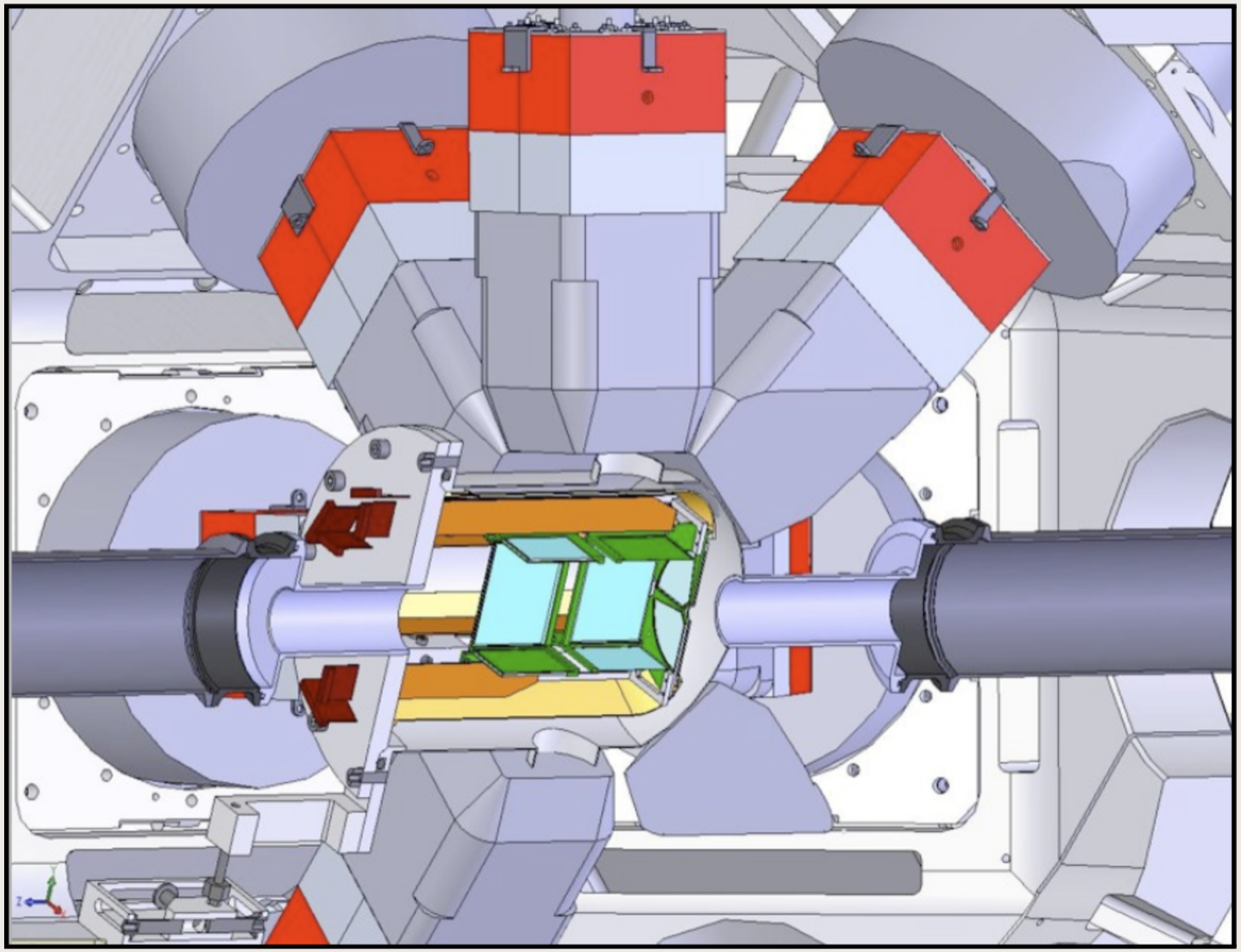
# Experiment

## SHARC

- A Silicon detectors.
- Efficiency ≈ 80%.
- Coverage ≈ 80% of 4π.
- Ang. res. ≈ 1°.

## TIGRESS

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



**$^{94}$Sr with an intensity of approximately 30,000 pps was impinged upon a 0.5 mg/cm$^2$ deuterated polyethylene target (CD2).**

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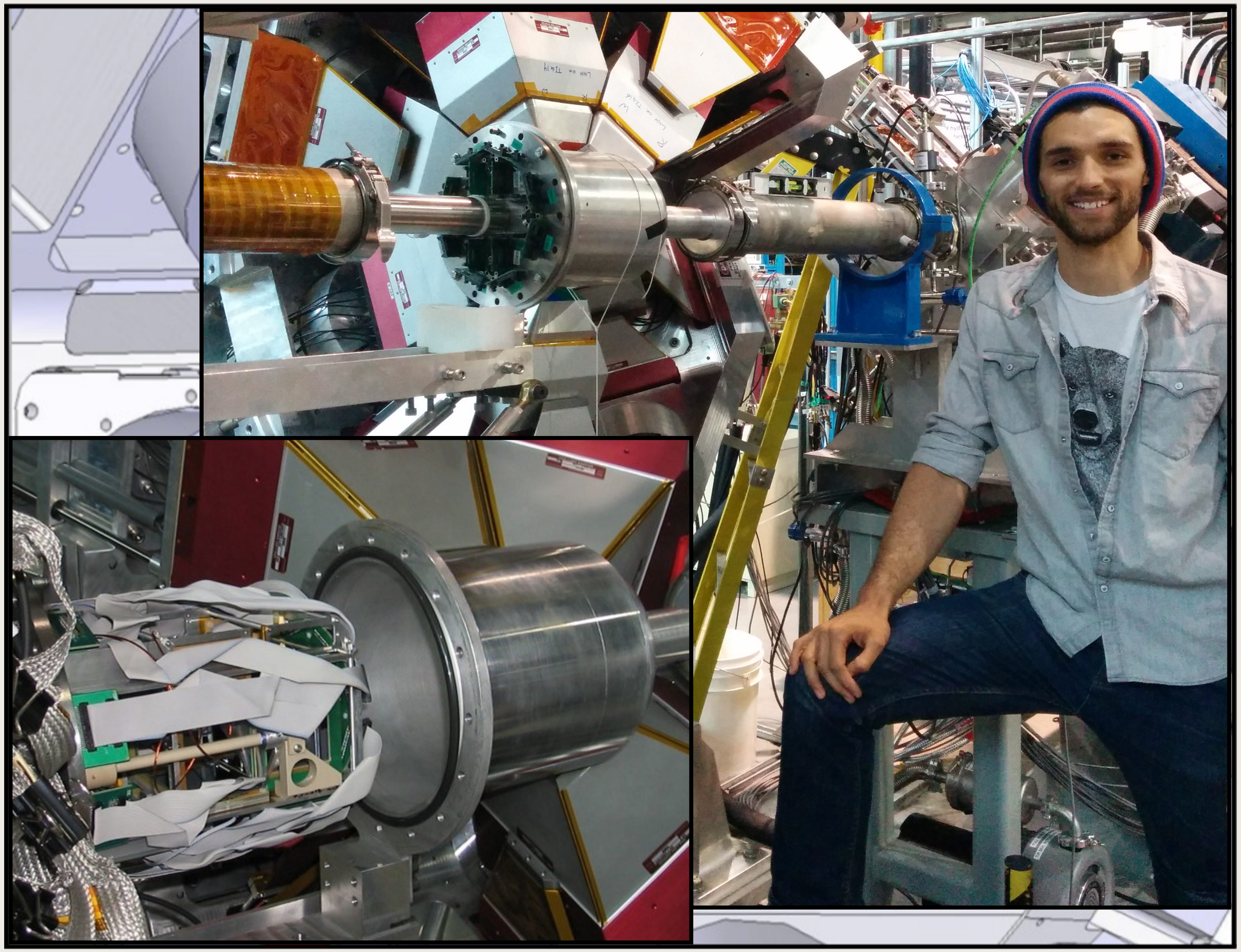

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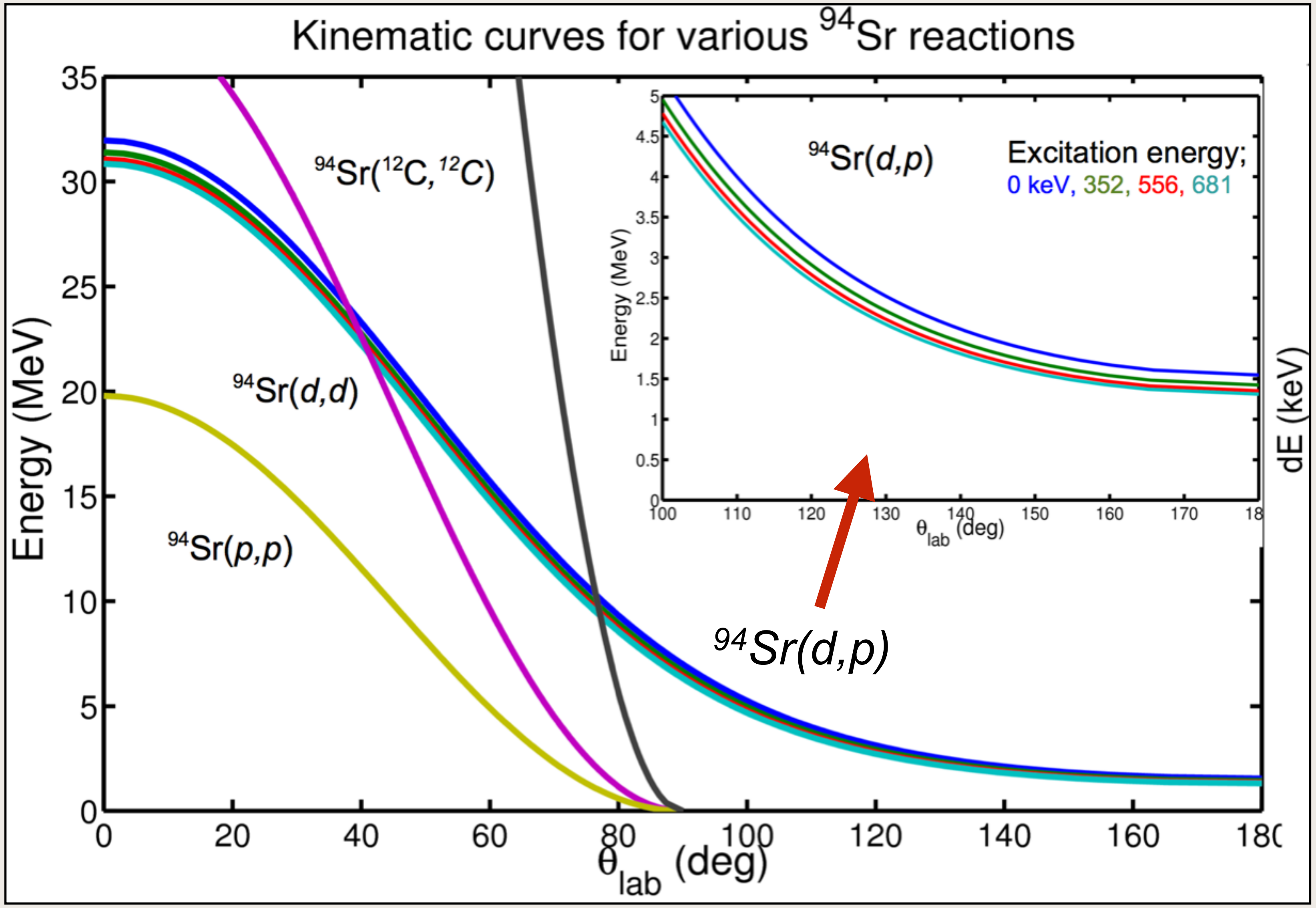
# Experiment

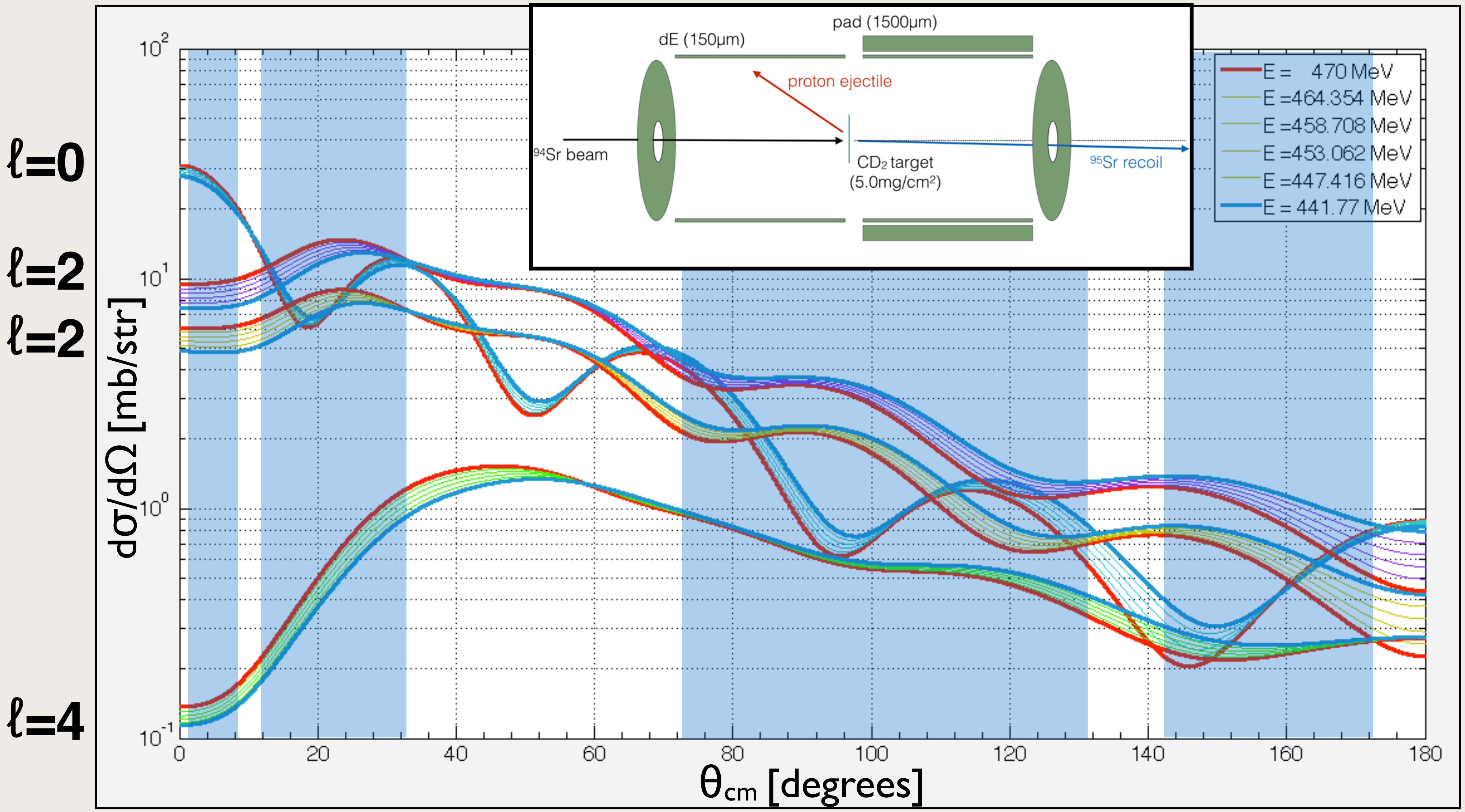
- TIGRESS and SHARC detectors used to enable proton-gamma coincidence measurements.
- Inverse kinematics and other energy losses gives excited state energy resolution ~ 200 keV.



*Individual $^{95}$Sr states cannot be resolved using SHARC only*

# Experiment

- Proton intensities are different between states and vary with θ.
- Reaction code (FRESCO) predicts dσ/dΩ.
- dσ/dΩ can be used to determine angular momentum transfer, ℓ.

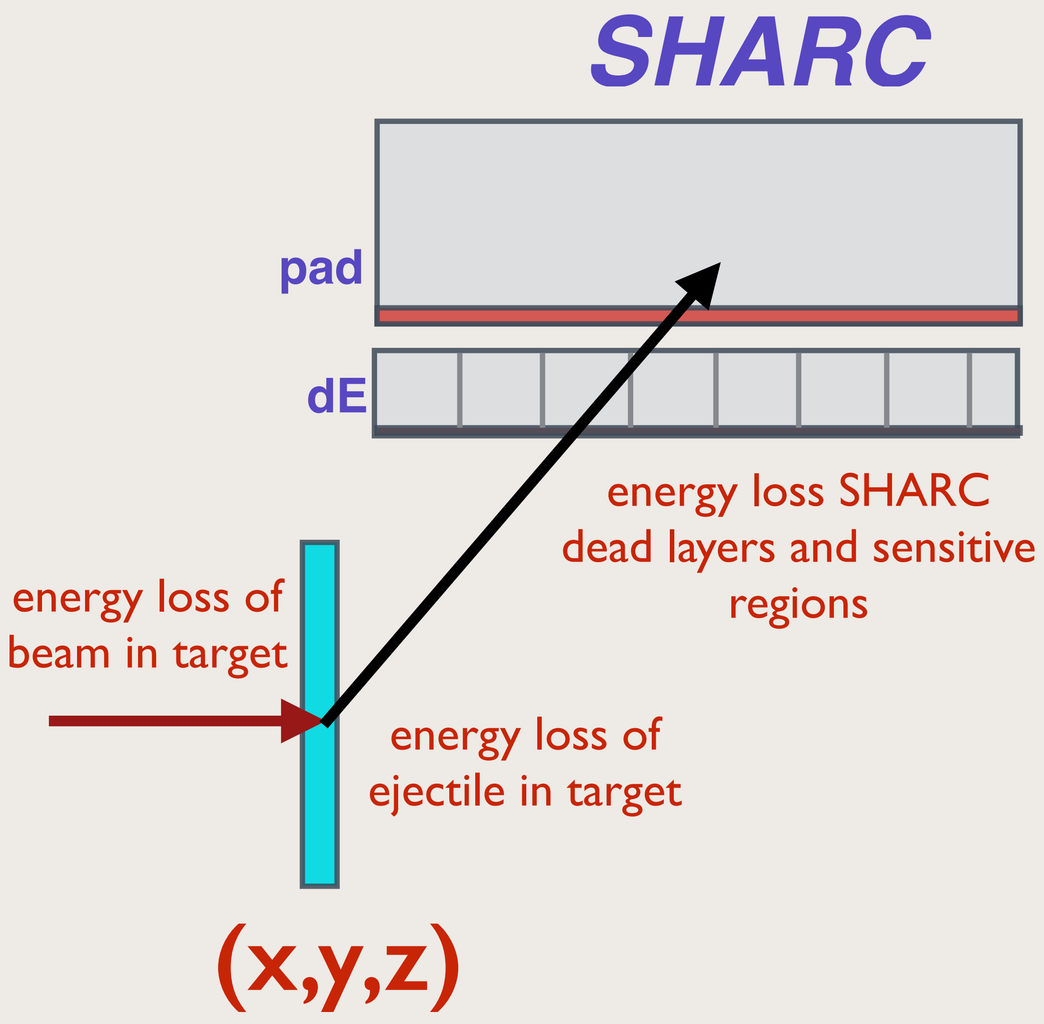


*This predicts the cross section depending on the single particle properties*

*Angular distributions can be measured in shaded angular ranges by SHARC.*

# Calibration challenges

- SHARC calibrated using triple alpha ($^{241}$Am / $^{239}$Pu / $^{244}$Cm) source, >15,000 segments.
- 2mm beam collimator gives SHARC position uncertainty, so fit using data.

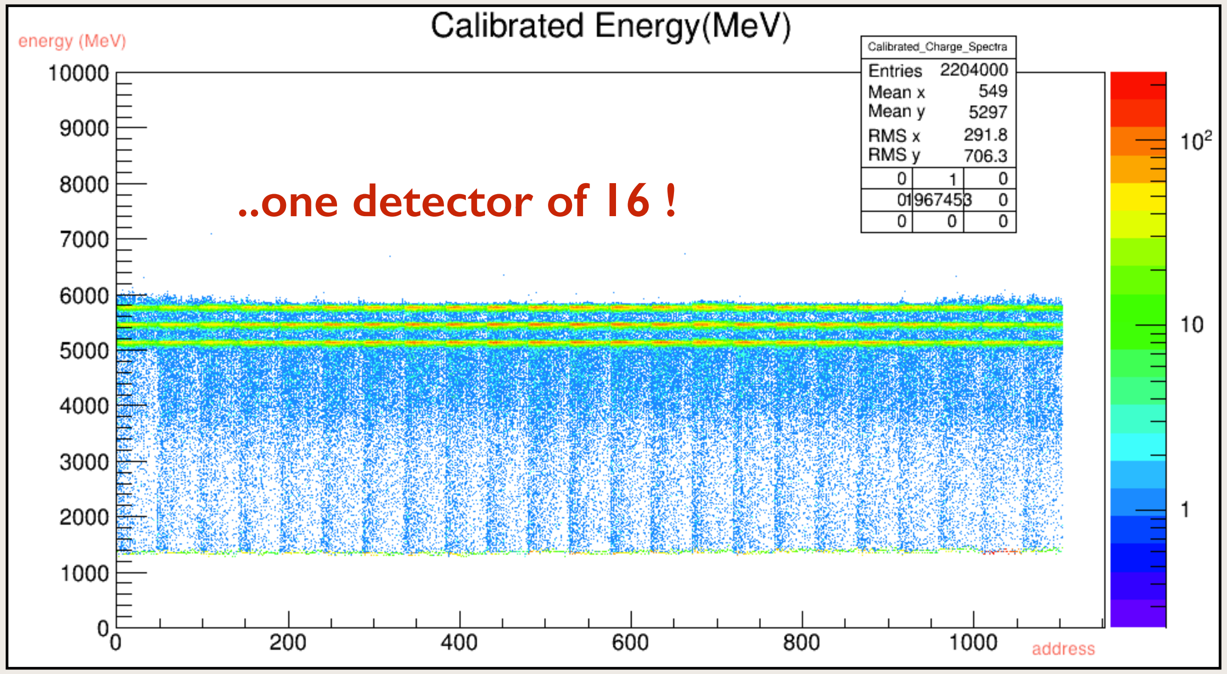


energy loss SHARC dead layers and sensitive regions

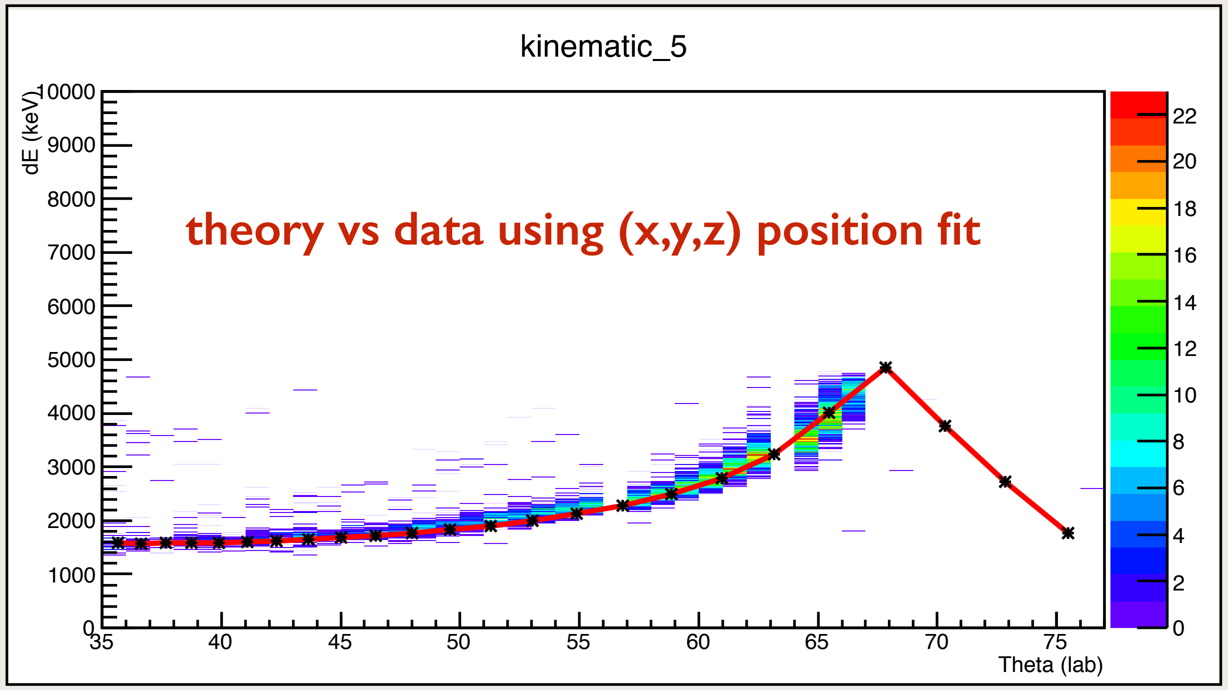
energy loss of beam in target

energy loss of ejectile in target

(x,y,z)



..one detector of 16 !



theory vs data using (x,y,z) position fit

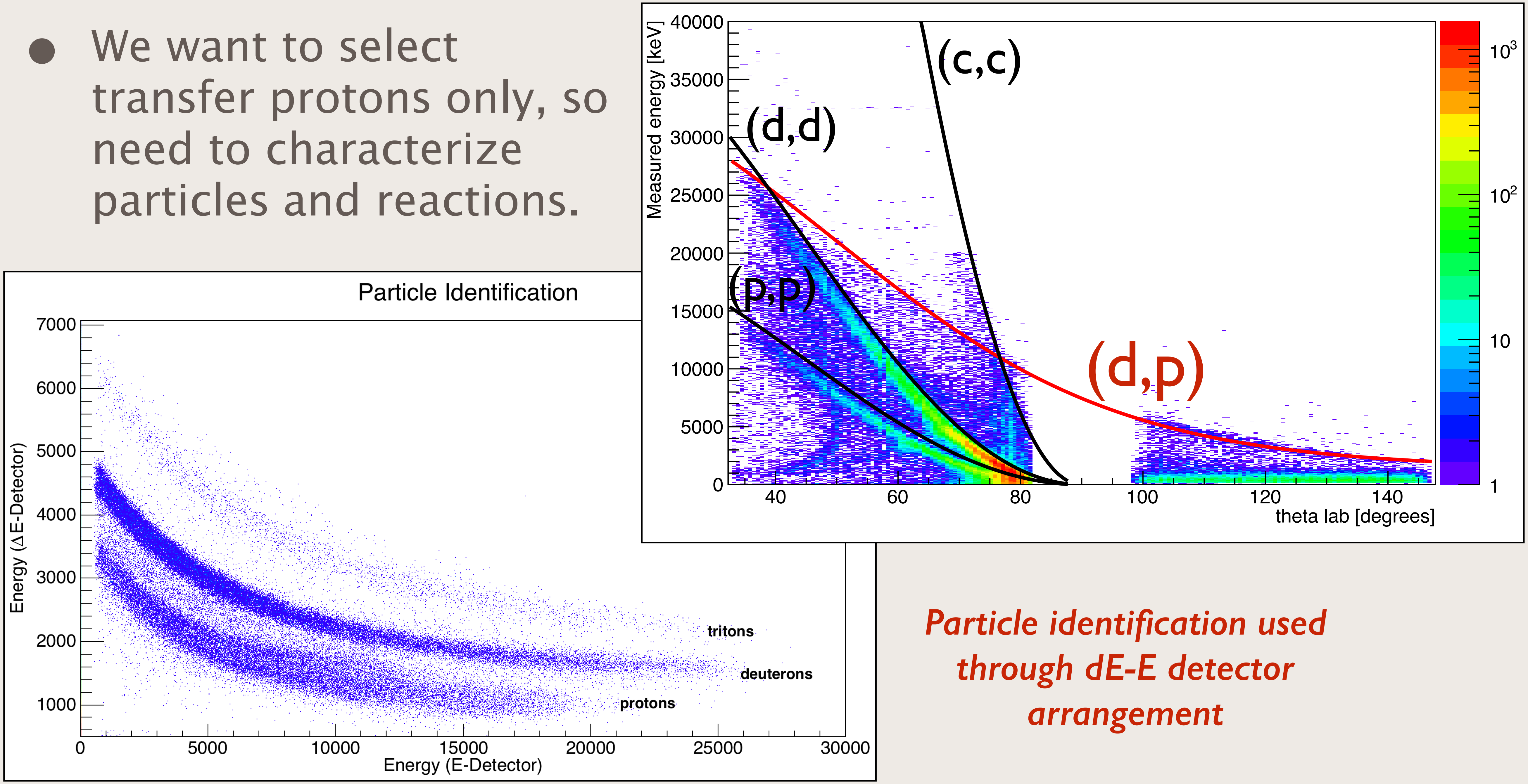
*Compare expected energy measured with data to determine position of target during experiment*

# Ongoing analysis

- We want to select transfer protons only, so need to characterize particles and reactions.

*Forward angles - lots of reaction channels (e.g. elastic)*

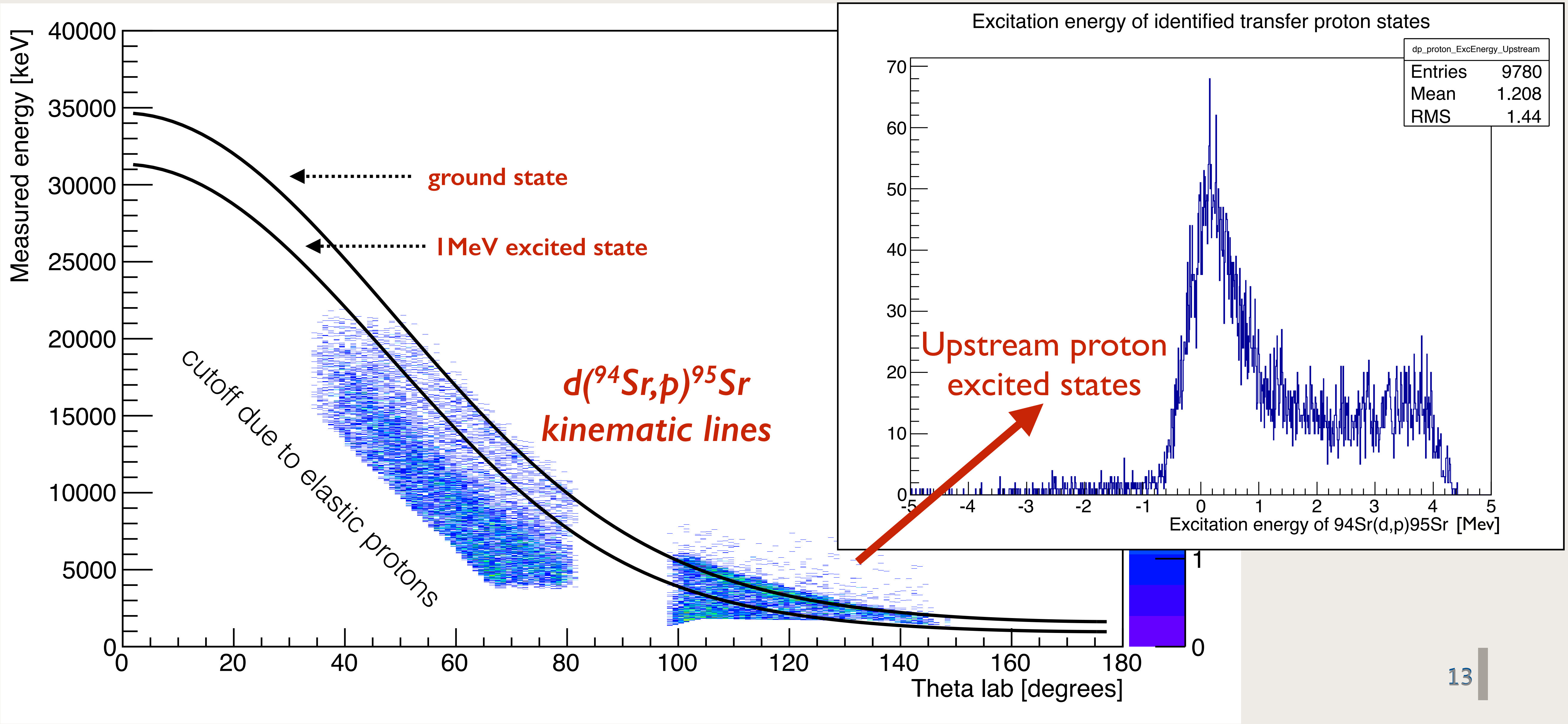
*Backward angles - transfer protons*



*Particle identification used through dE-E detector arrangement*

# Ongoing analysis

- Use PID and kinematic cuts to select transfer protons for analysis.
- Reconstruct excitation energy using kinematics.



ground state

1MeV excited state

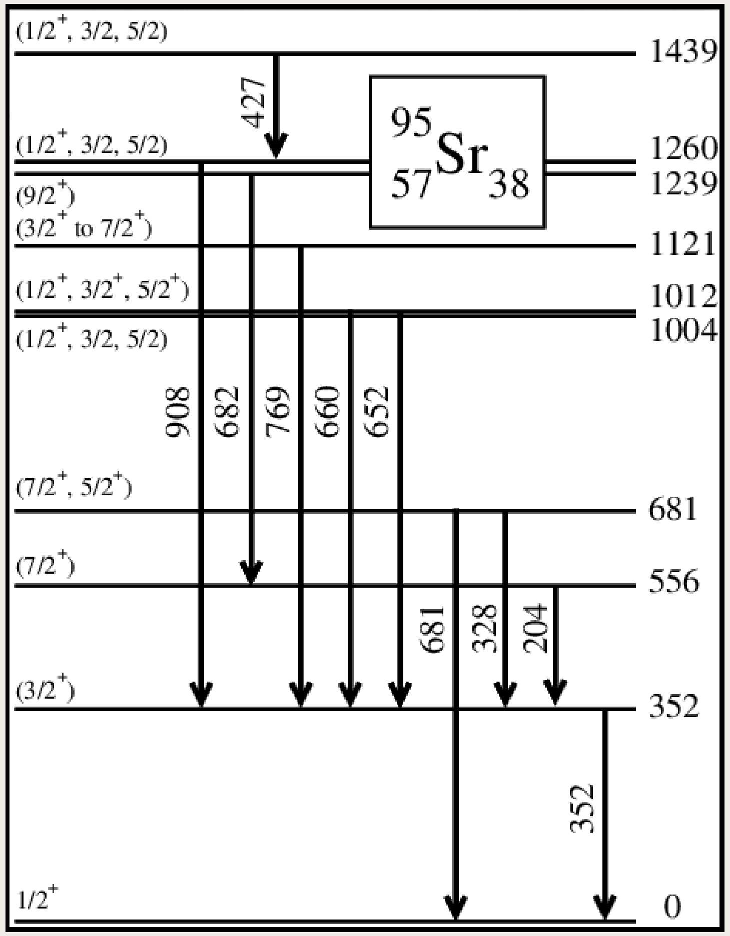
*d($^{94}$Sr,p)$^{95}$Sr kinematic lines*

cutoff due to elastic protons

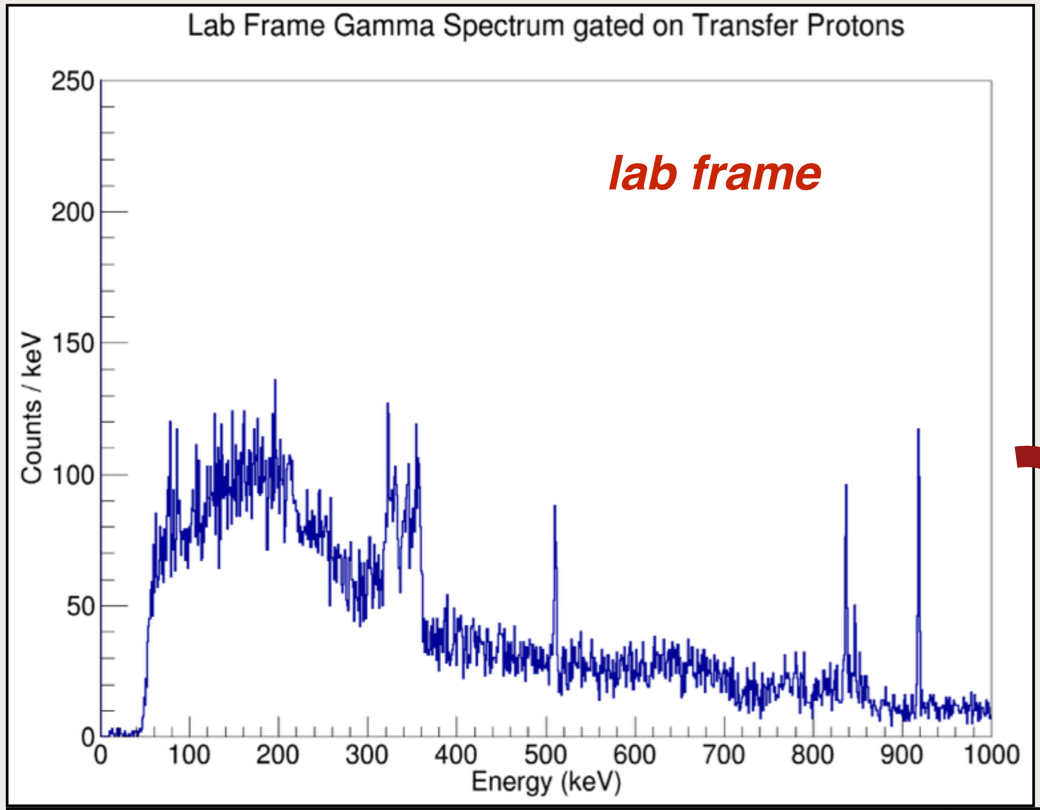
Upstream proton excited states

# Ongoing analysis

- Doppler corrected gamma spectra gated on transfer protons.
- Evidence for direct population of $^{95}$Sr states.

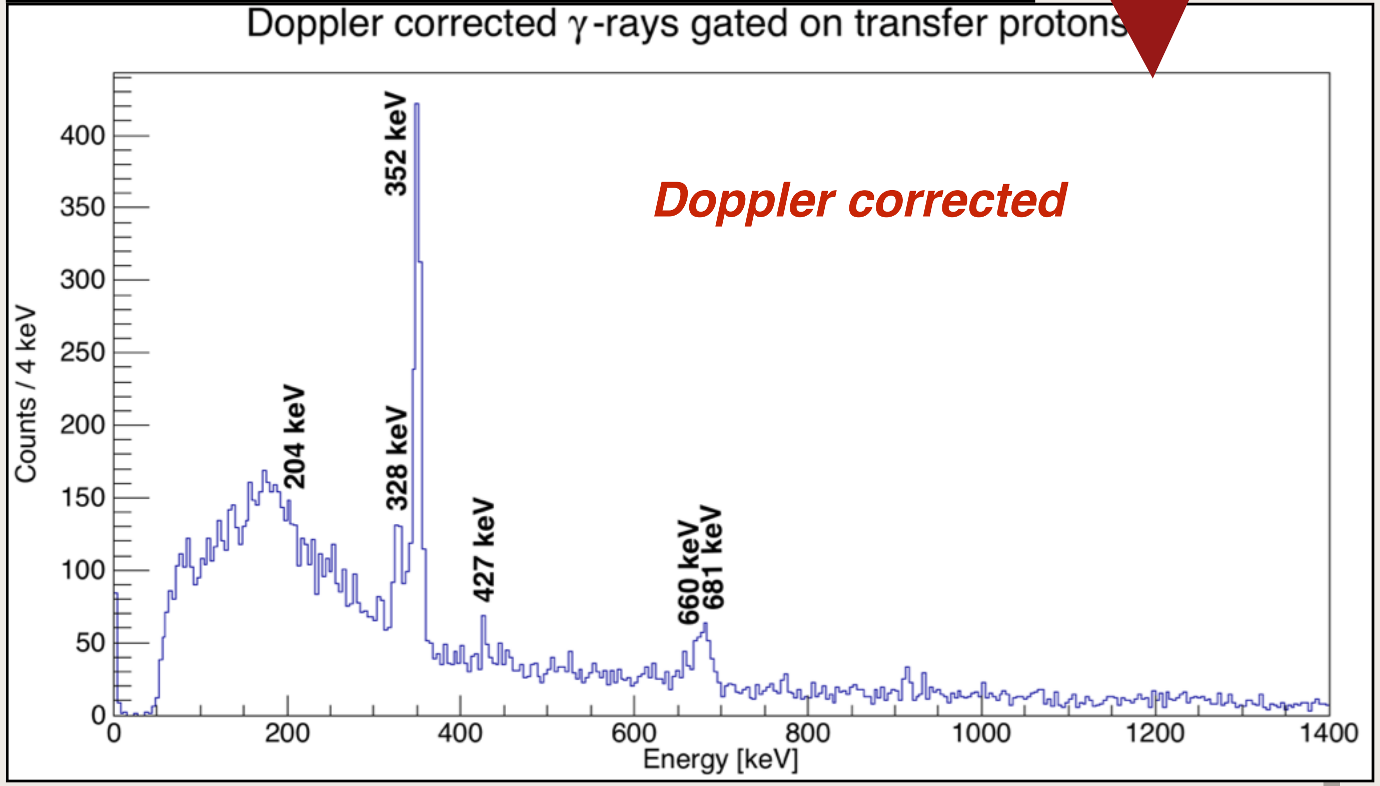


Adapted from NNDC.bnl.gov



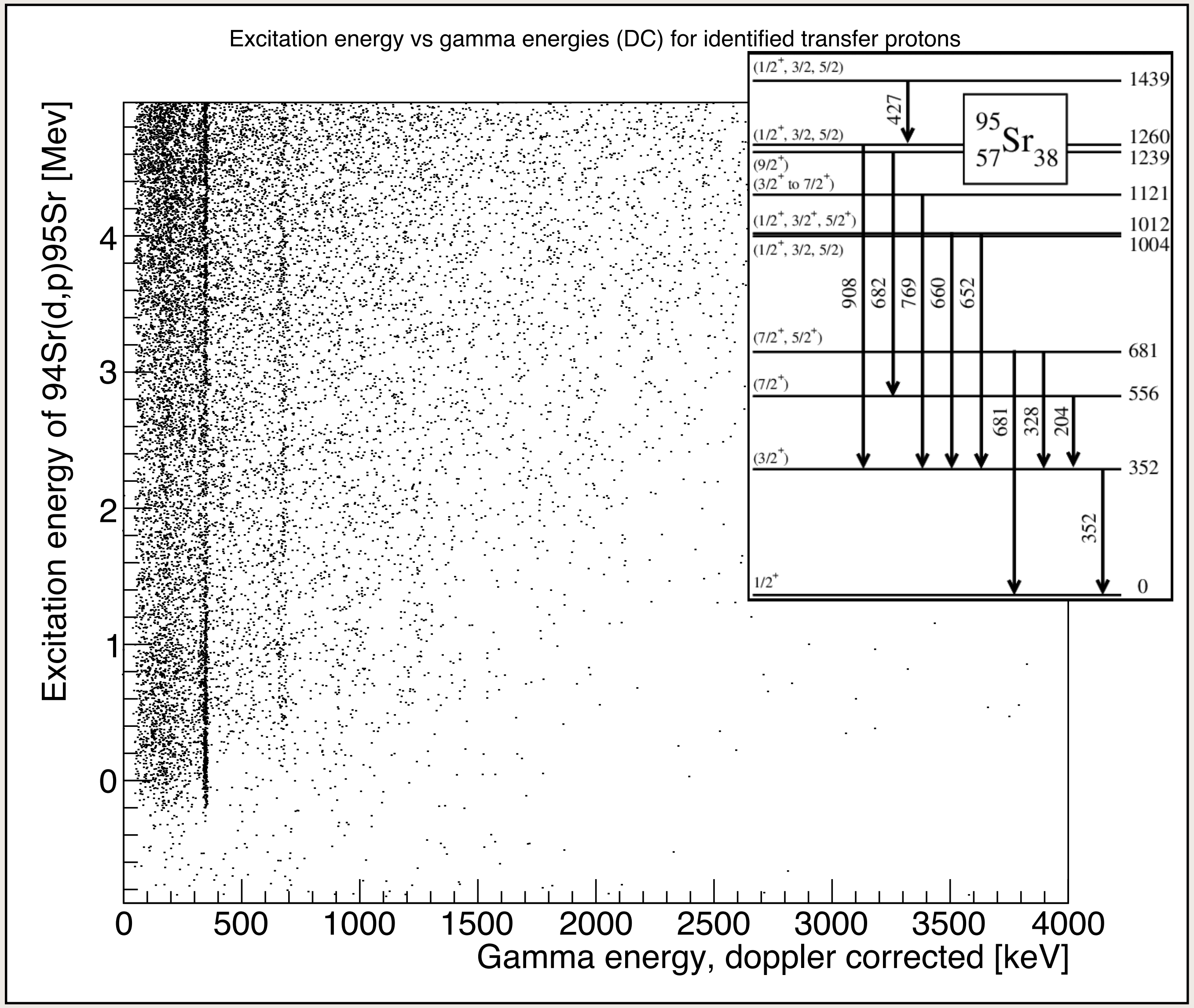
**Account for the fact that gamma source is not at rest**

$E' = E\,(1 - \beta \cos\theta)\,\gamma$



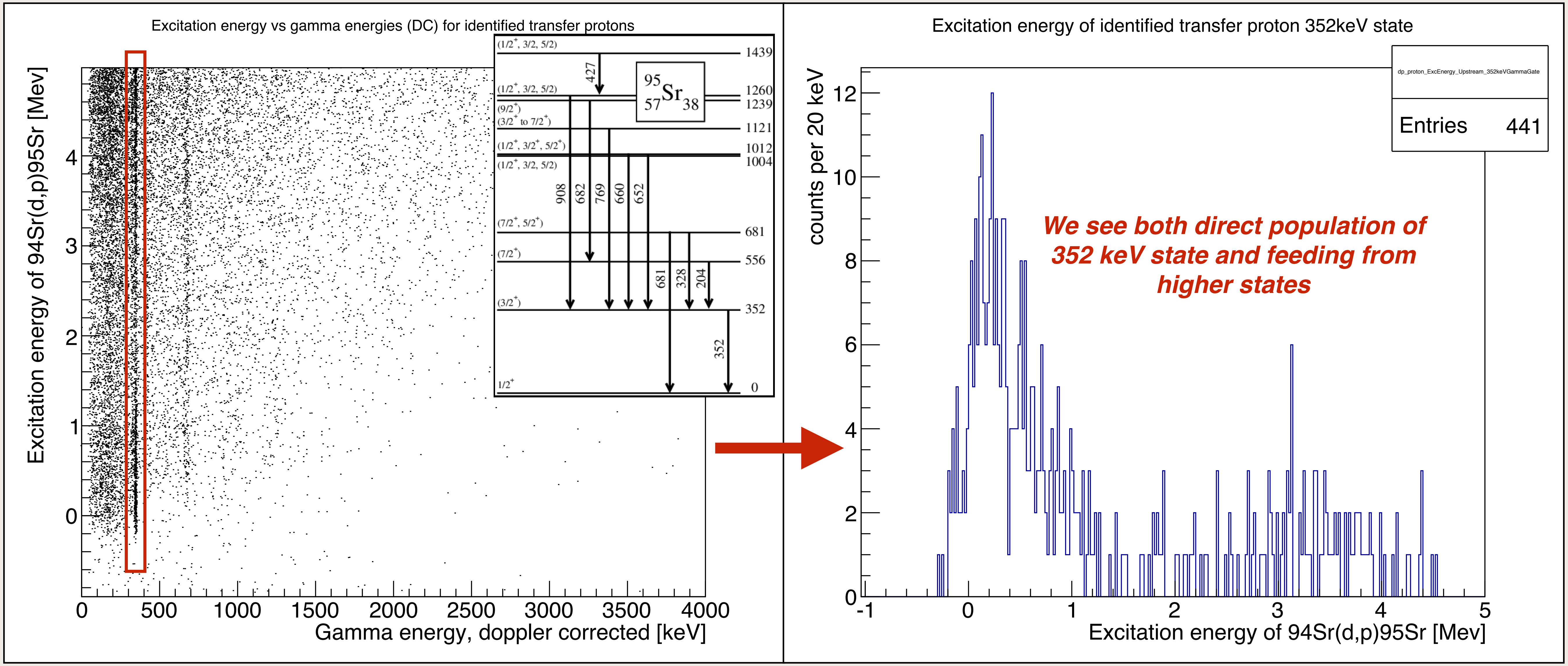
# Ongoing analysis

*Gate on transfer proton states using gamma coincidences.*



# Ongoing analysis

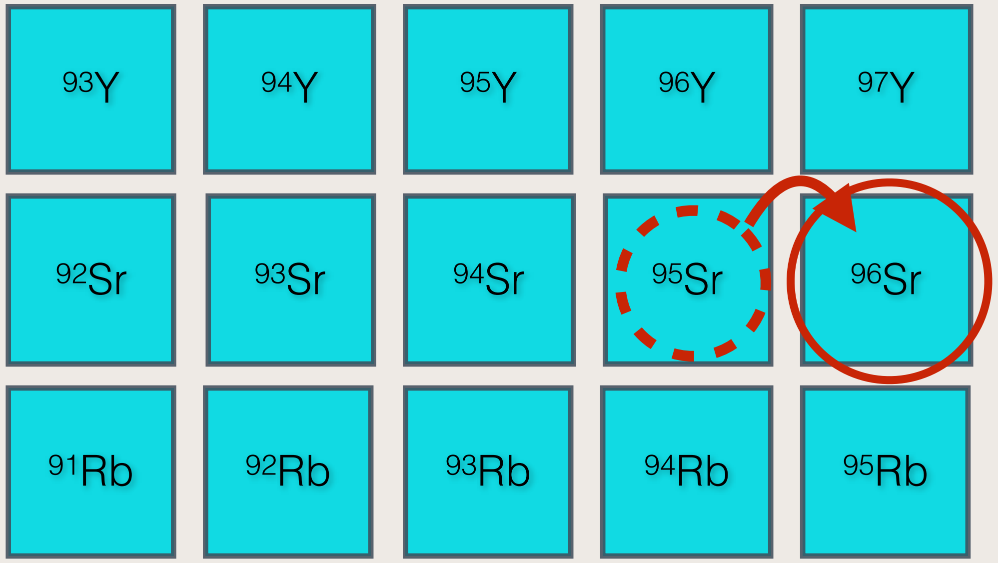
## *Gate on transfer proton states using gamma coincidences.*



***We see both direct population of 352 keV state and feeding from higher states***

# Looking to the future

- Extract angular distributions.
- Measure absolute cross sections.
- Determine single particle occupations and compare to theoretical calculations.
- Continue high mass Sr(d,p) campaign with $^{95}$Sr beam (begins next week!).



| | | | | |
|---|---|---|---|---|
| $^{93}$Y | $^{94}$Y | $^{95}$Y | $^{96}$Y | $^{97}$Y |
| $^{92}$Sr | $^{93}$Sr | $^{94}$Sr | $^{95}$Sr | $^{96}$Sr |
| $^{91}$Rb | $^{92}$Rb | $^{93}$Rb | $^{94}$Rb | $^{95}$Rb |

# THANK YOU FOR LISTENING

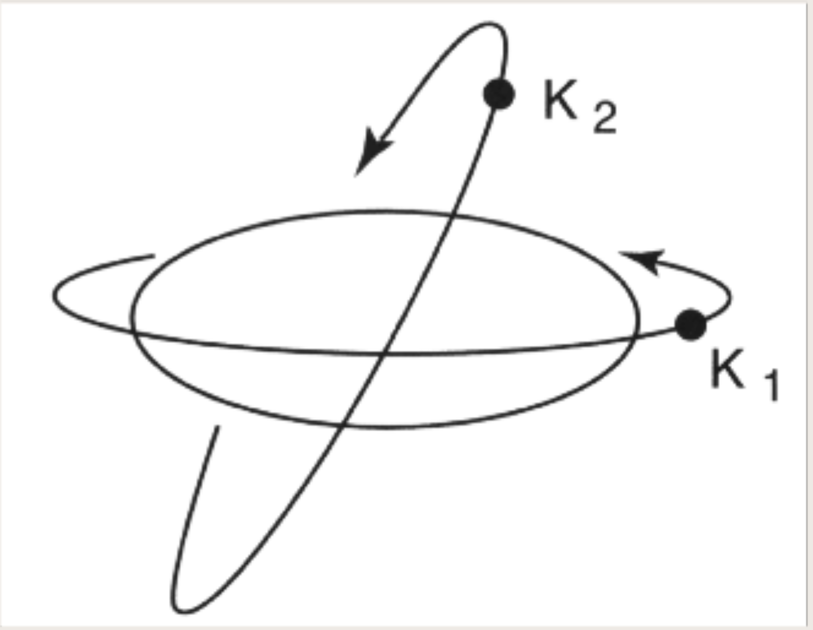
many thanks to;

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

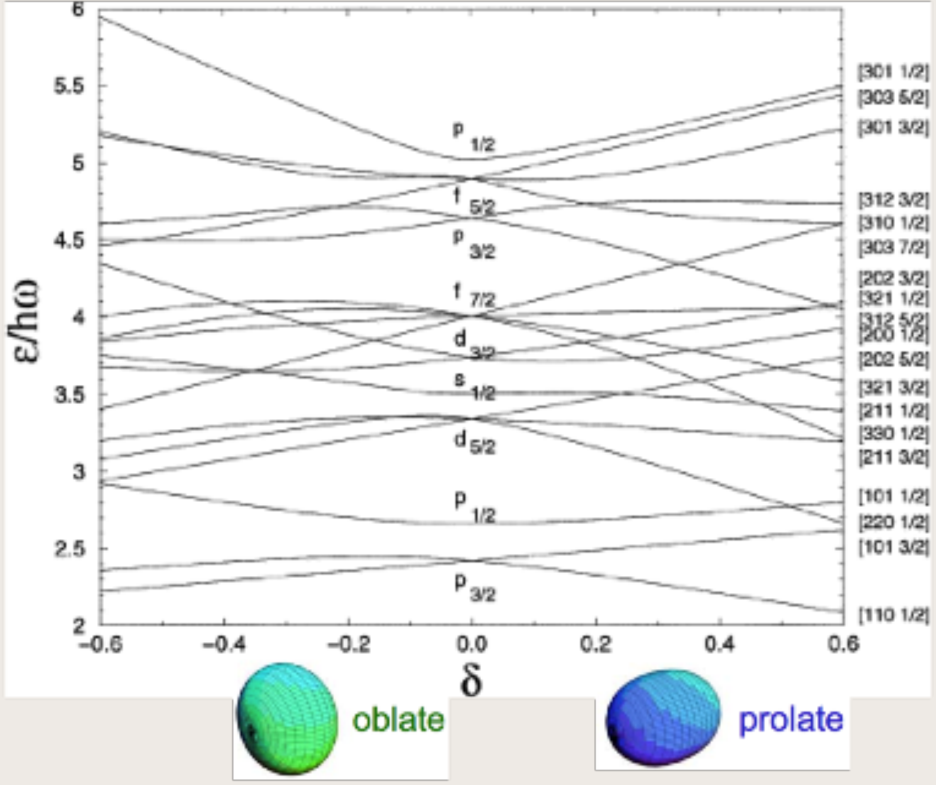
*1. University of British Columbia, 2. TRIUMF, 3. Central Michigan University, 4. Simon Fraser University, 5. University of Toronto, 6. Colorado School of Mines, 7. University of Surrey, 8. LPC Caen.*

# 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



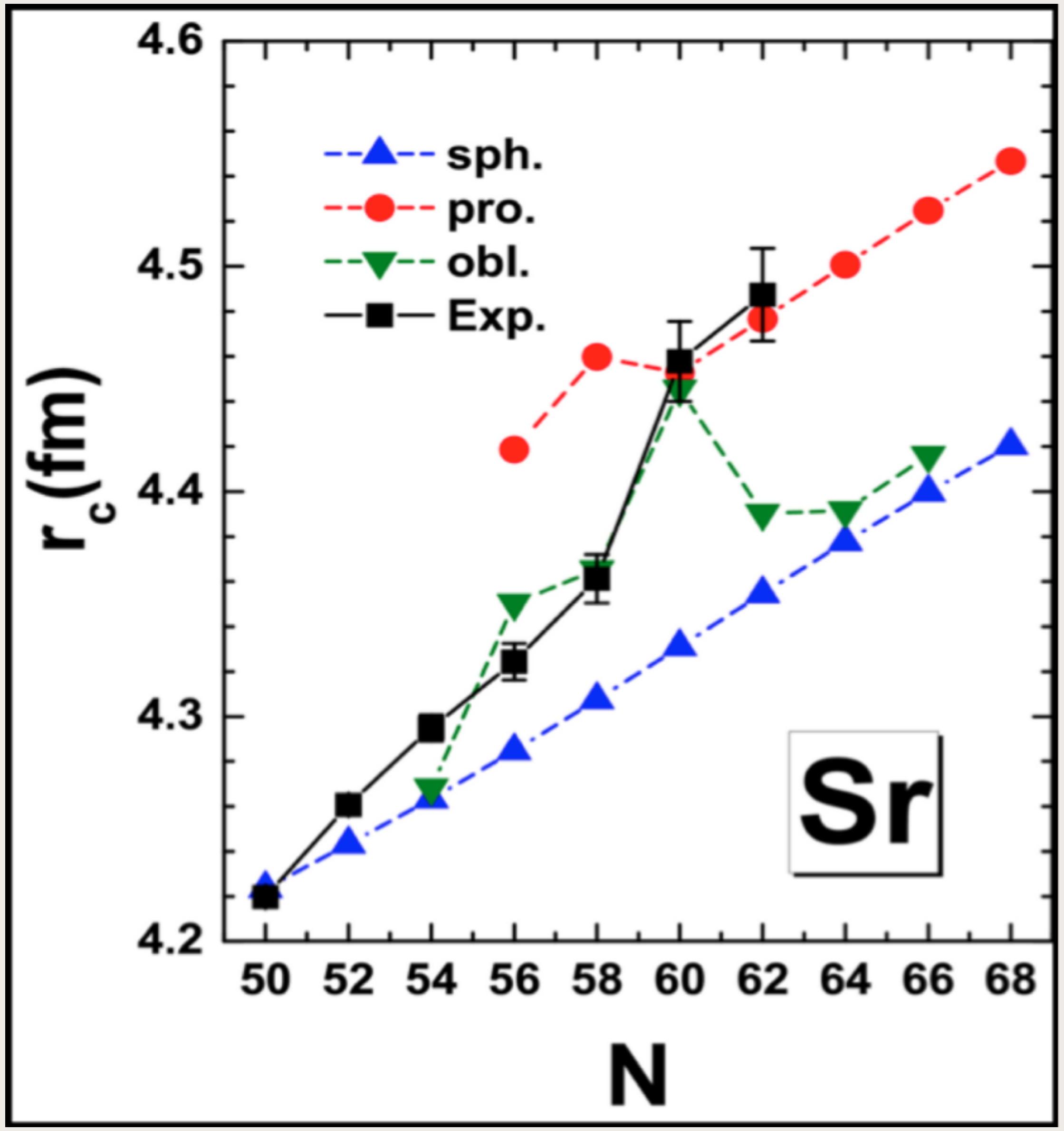
(b) SPE shifts as a function of deformation

TRIUMF

# Theory (changes in radii)

- A dramatic occurrence of evolving shape is seen around Z = 40, N = 60 [1].
- The sudden change in radius suggests competing shapes in ground states of Sr isotopes [2].
- We are investigating how changes in occupations of orbitals affect this transitional region in Sr.

*Changing nuclear radius in even Sr isotopes*

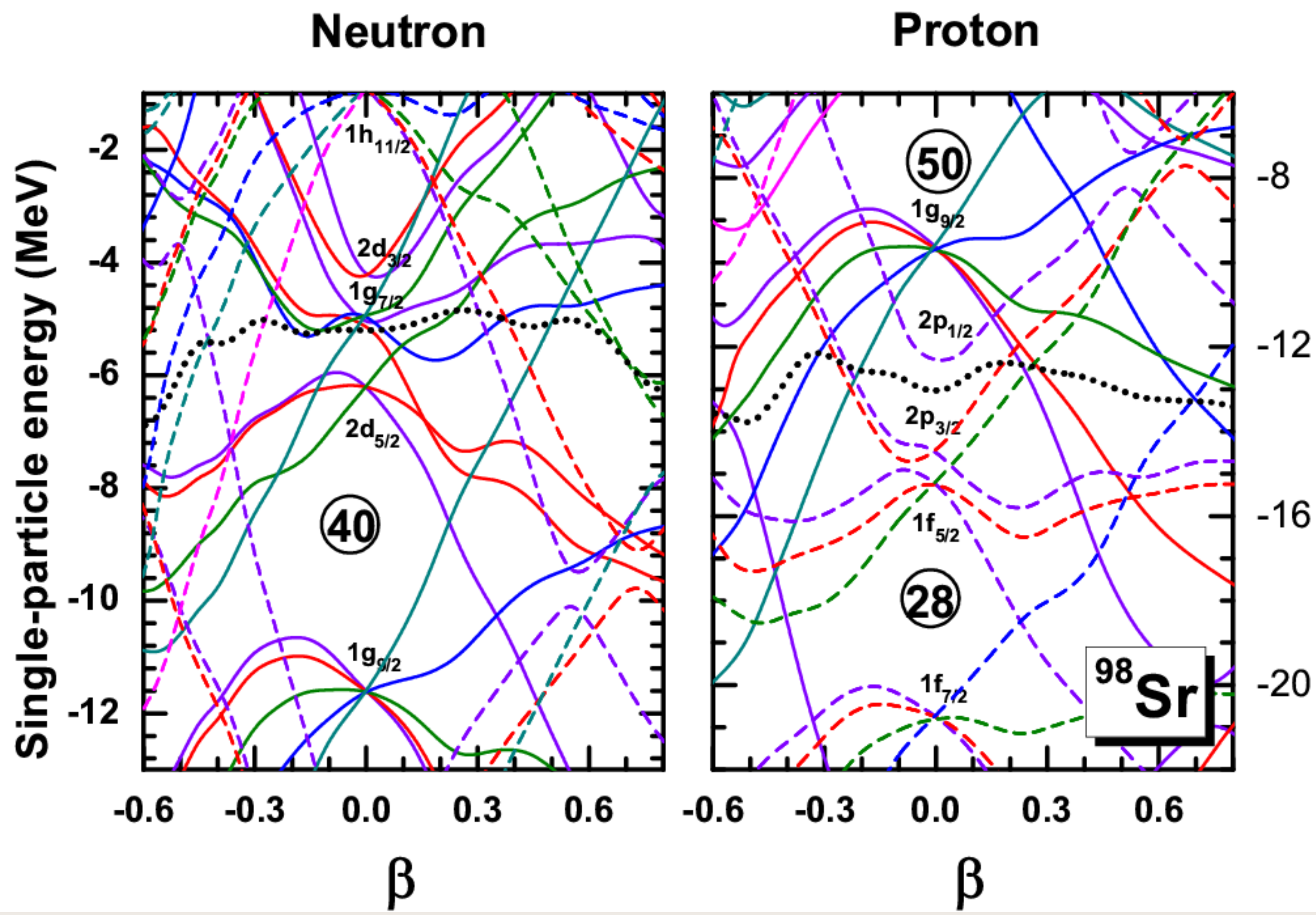


*[1] K. Heyde, J. L. Wood Rev. Mod. Phys. 83, 1467 (2011).*

*[2] Nucl.Phys. A873 (2012) 1-16.*

# 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.



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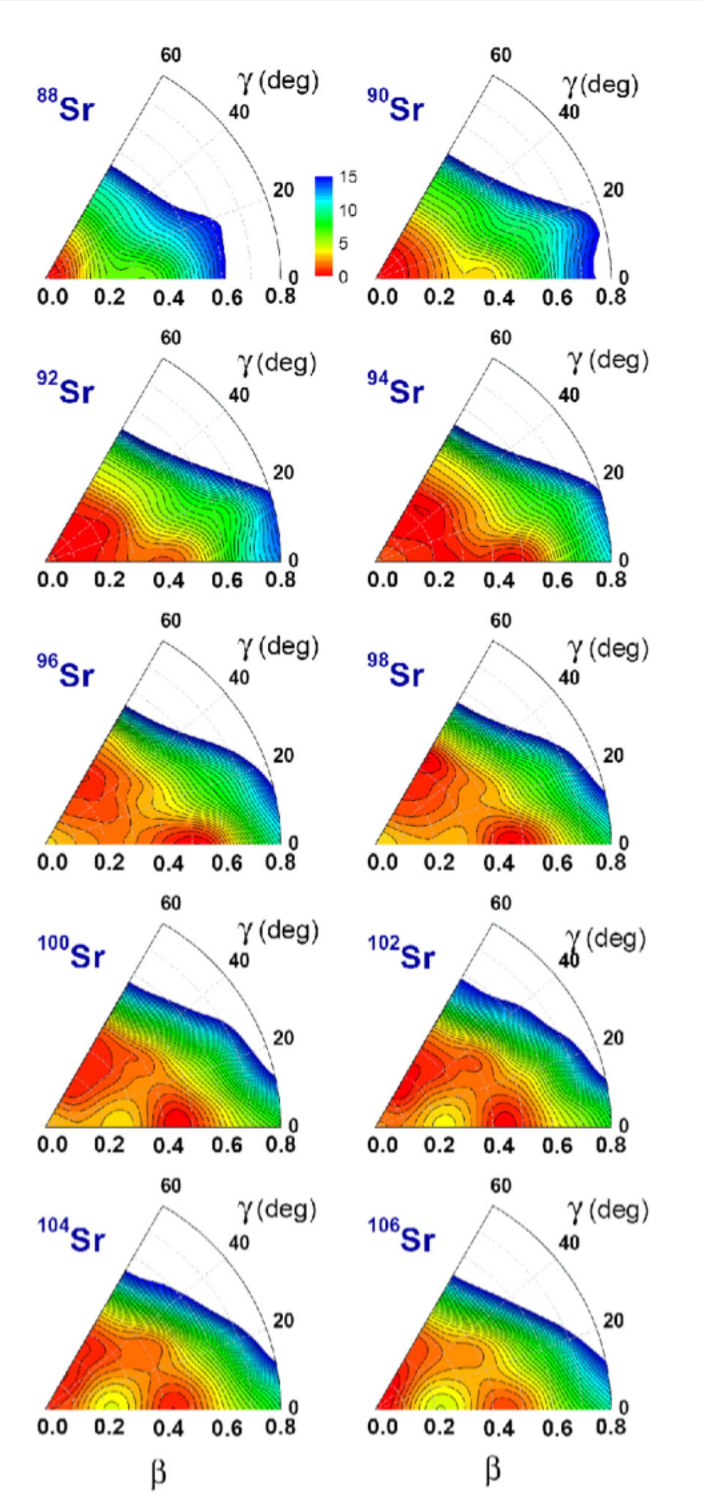
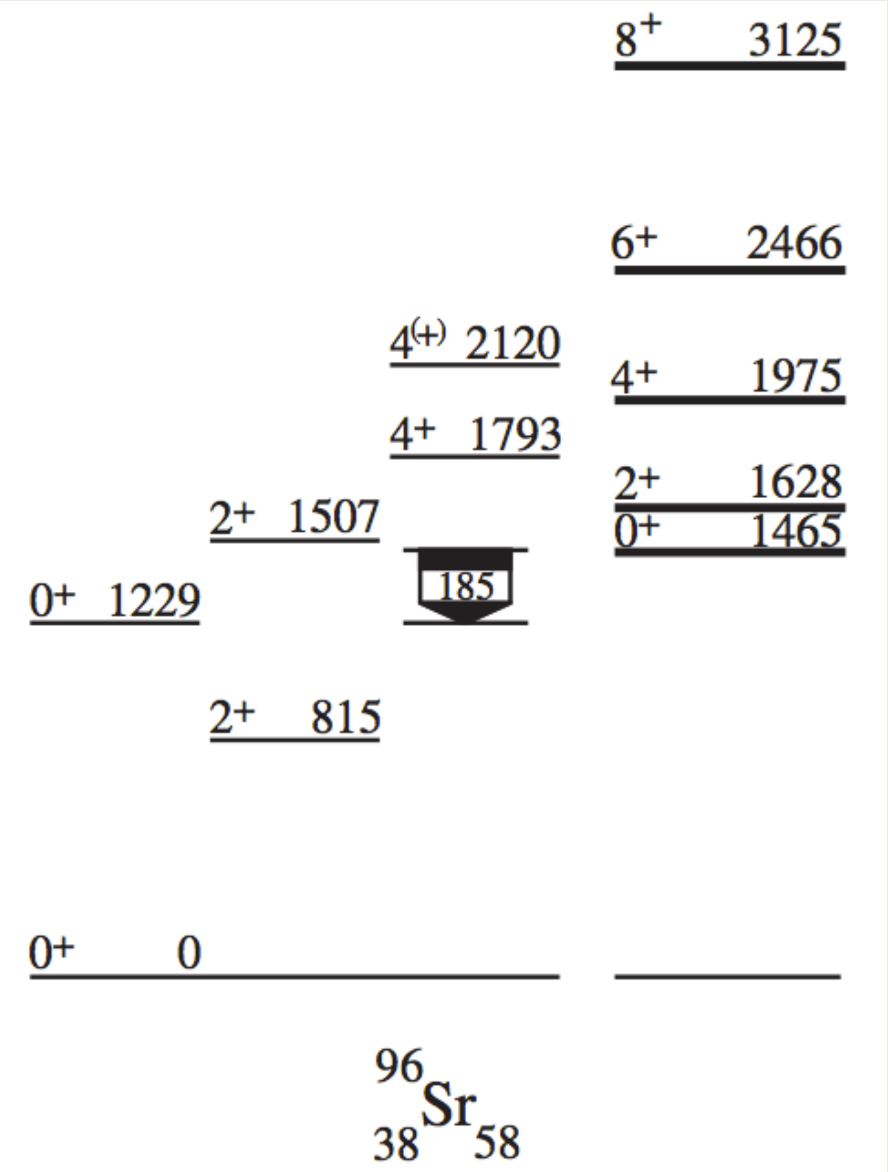


Mei, H. et al. Phys.Rev. C85 (2012)

# Theory (coexisting $0^+$ states)

- The rotational band built on top of the third $0^+$ states at 1465 keV indicates deformation.
- The strong $0^+$ (1465 keV) →$0^+$ (1229 keV) transition is characteristic of coexisting shapes.
- Coexistence is next seen in $^{98}$Sr.



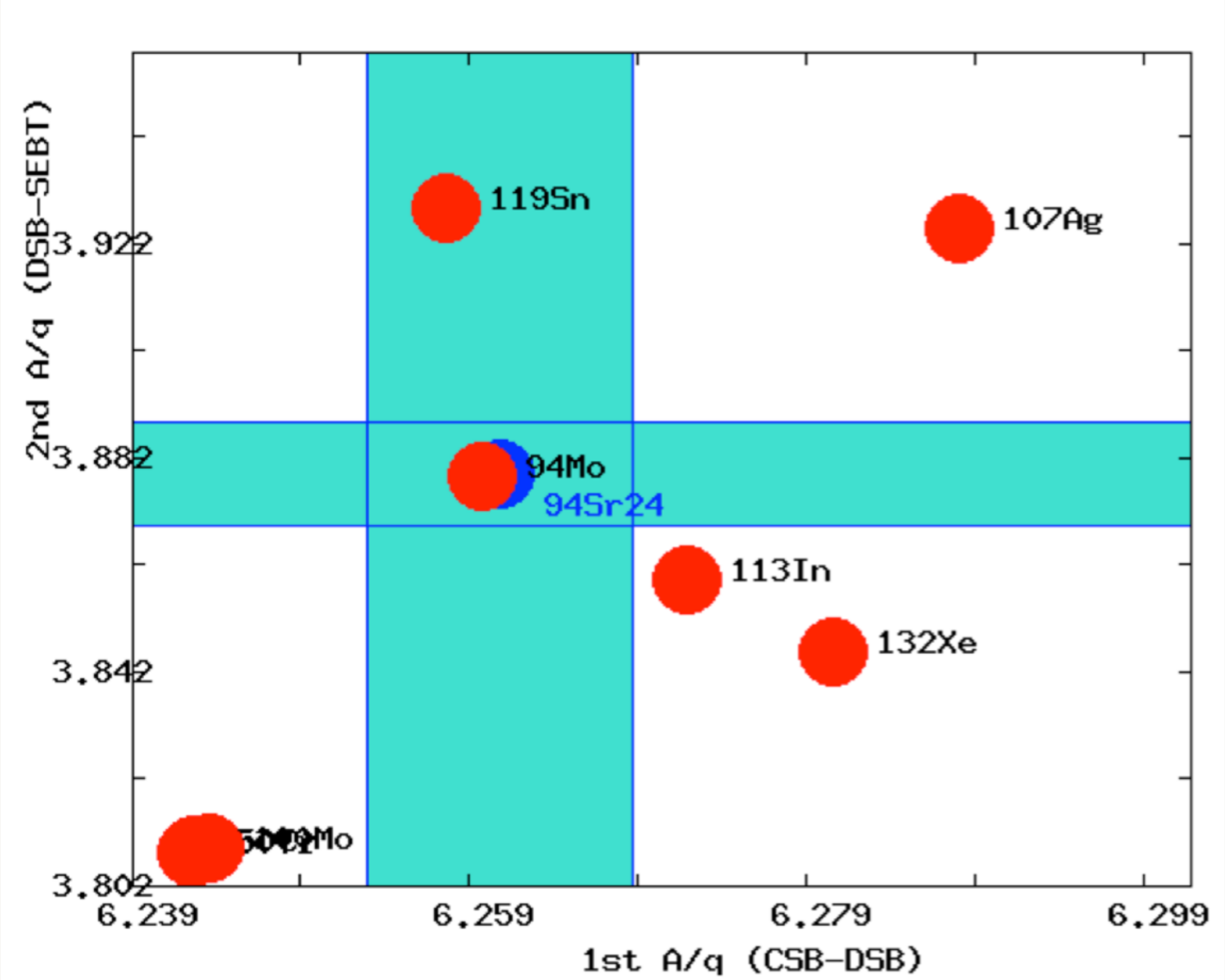
*Shape coexistence in atomic nuclei [Rev. Mod. Phys. 83, 1467 (2011)]*

# Experiment (selection techniques)

- 15⁺ A/Q minimises contamination of beam.

- Anticipated (on target);
  - 2e5 p.p.s. of $^{94}$Sr
  - 1e5 p.p.s. of $^{94}$Rb
  - 1e6 p.p.s. of $^{94}$Mo

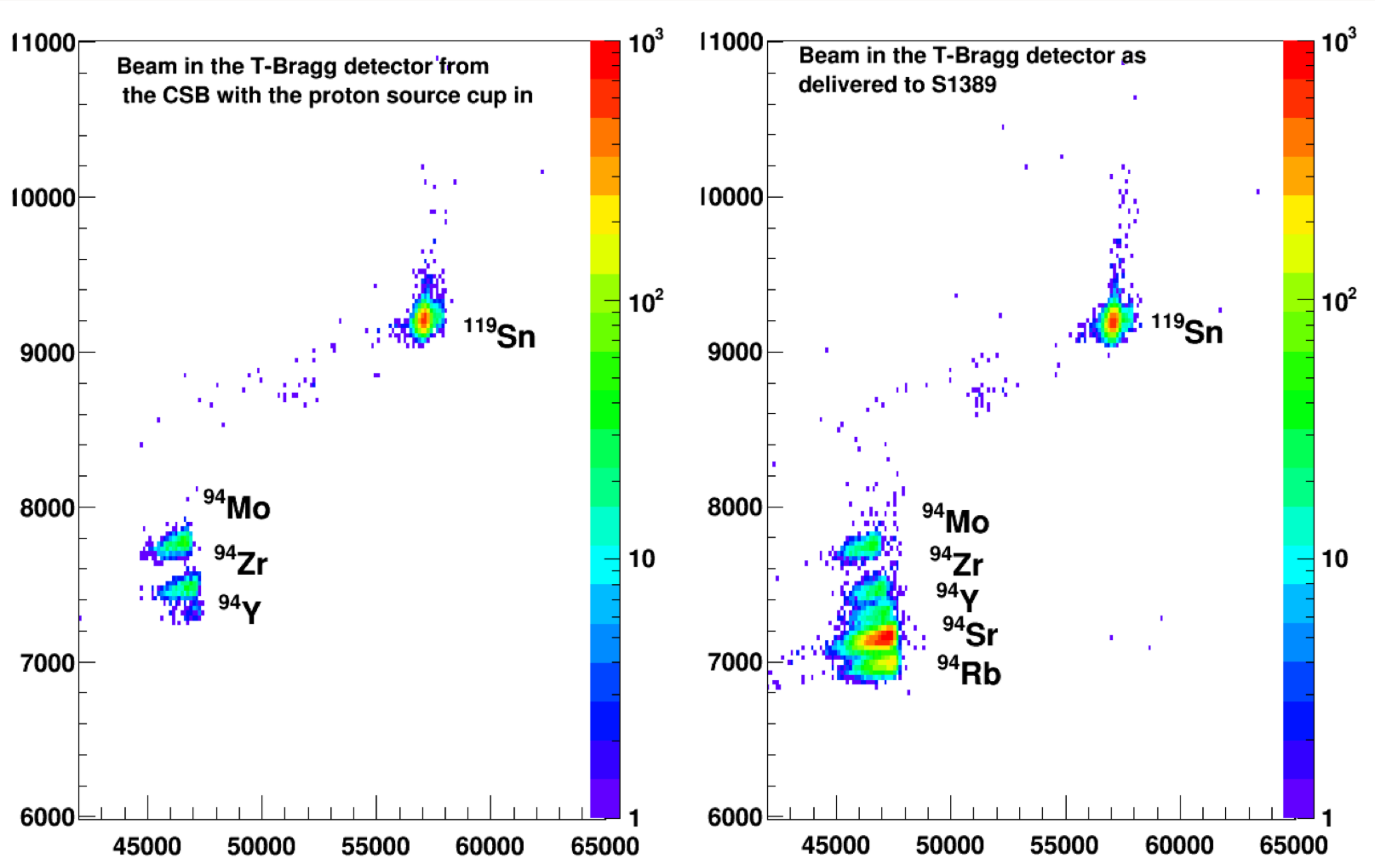
- Measured (on average);
  - $^{94}$Sr 50% of total beam
  - approx. 30,000 p.p.s. $^{94}$Sr



# Experiment (beam composition)

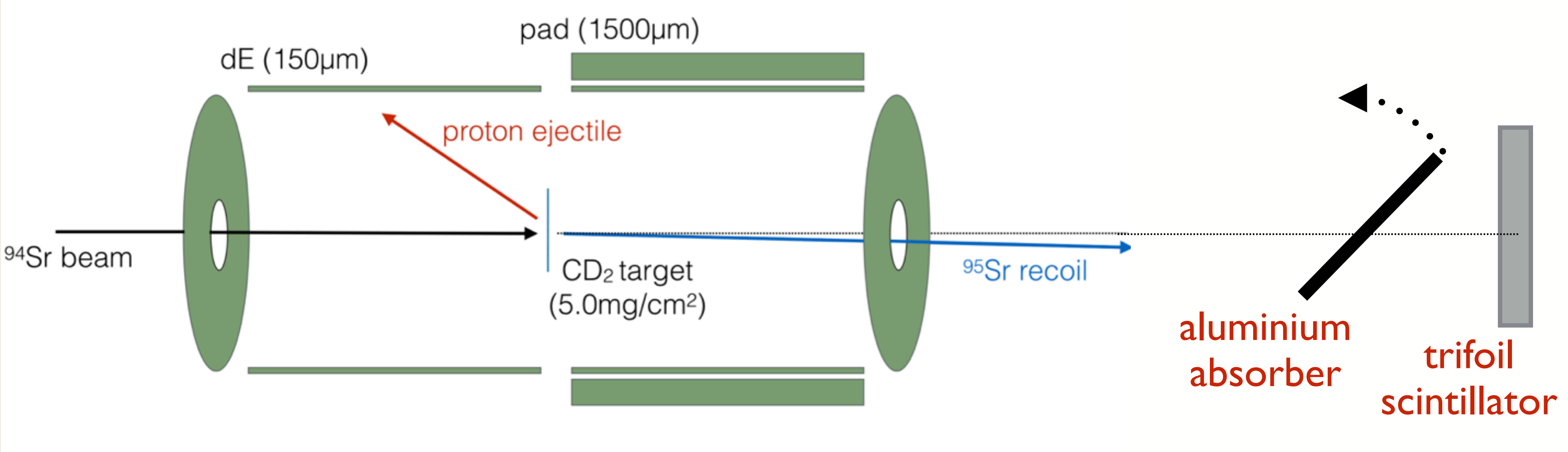
- The main component in the spectrum is the radioactive $^{94}$Sr beam, the major contaminant is $^{119}$Sn.

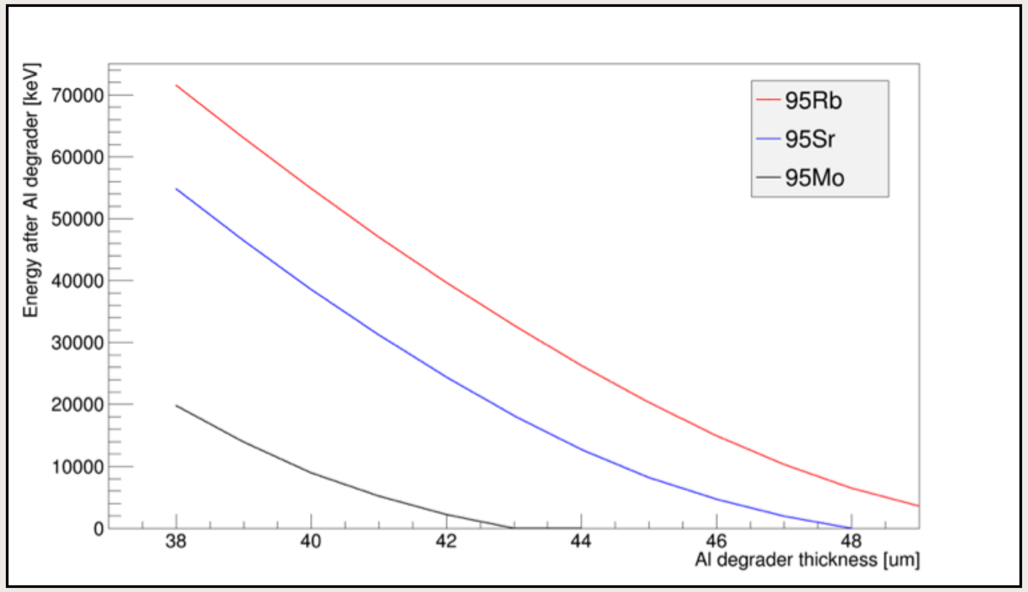
- The measurement of the beam composition has been repeated several times during the experiment, the composition of the beam was stable throughout the experiment.



# Experiment (trifoil veto)

- Beam contaminants with A>94 or Z>38 were suppressed using a scintillator-degrader configuration called the trifoil





If trifoil detects a signal, search for signals in TIGRESS and SHARC.

During analysis we can use timing gates to make use of this veto