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ISOLDE Solenoidal Spectrometer

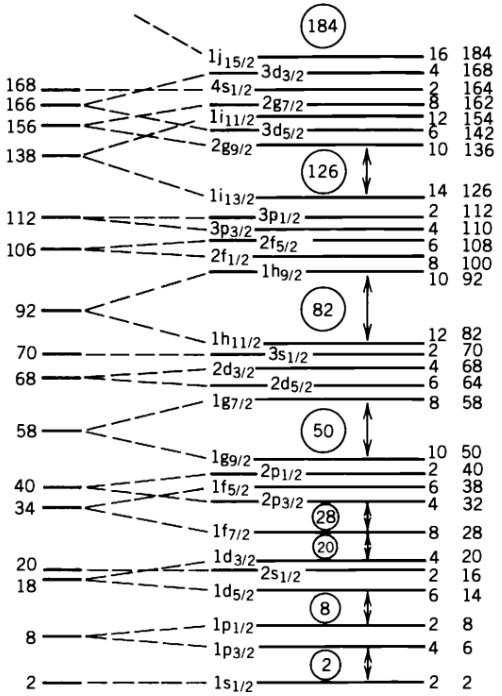
The evolution of single-particle states along N=127 using the d(^{212}Rn, p)^{213}Rn reaction at the ISOLDE Solenoidal Spectrometer (ISS)

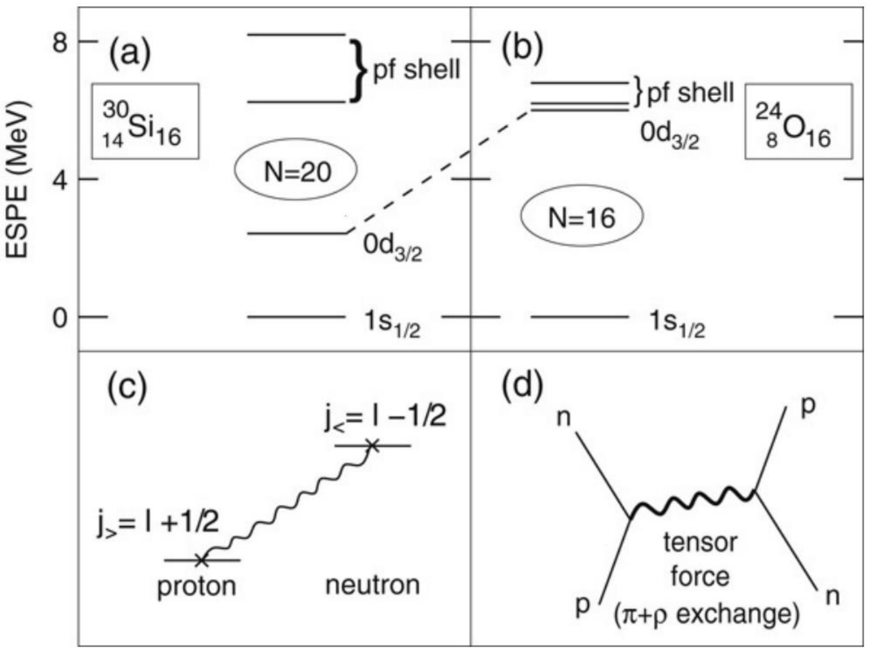
Daniel Clarke
ISOLDE Workshop and Users Meeting 2022

Single-particle evolution in nuclei

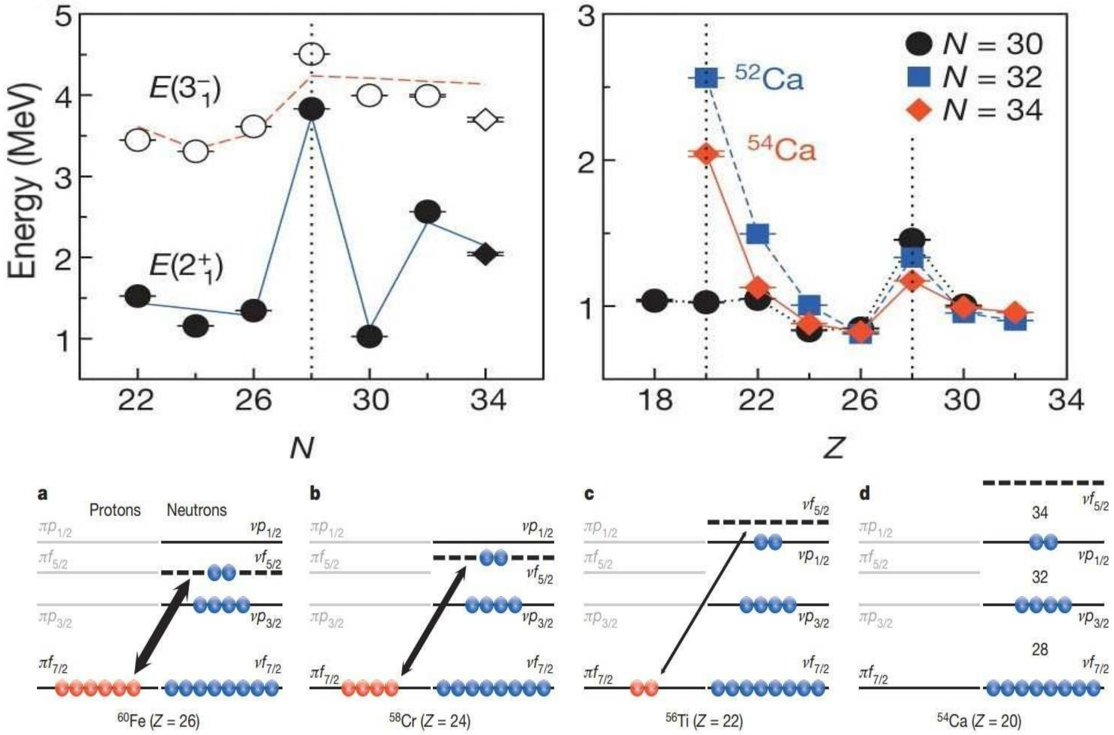
- Far from stability, shell closures have been shown to evolve for systems with imbalances of protons and neutrons

- Studies of light neutron-rich system have led to the discovery of new shell closures





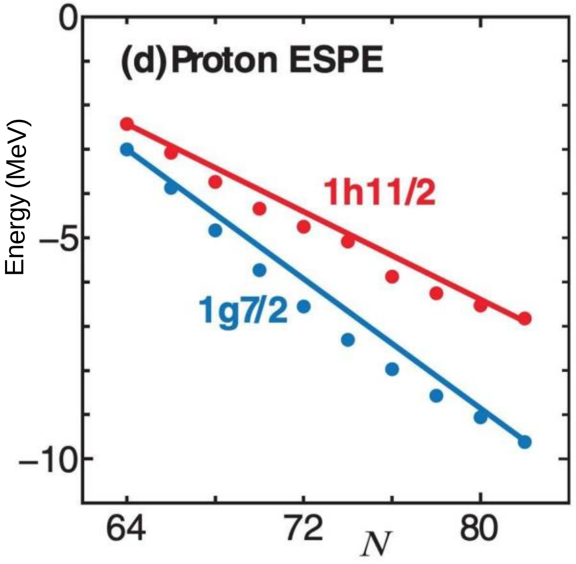
T.Otsuka and D. Abe, Prog. In Particle and Nuclear Physics 59 425 (2007)

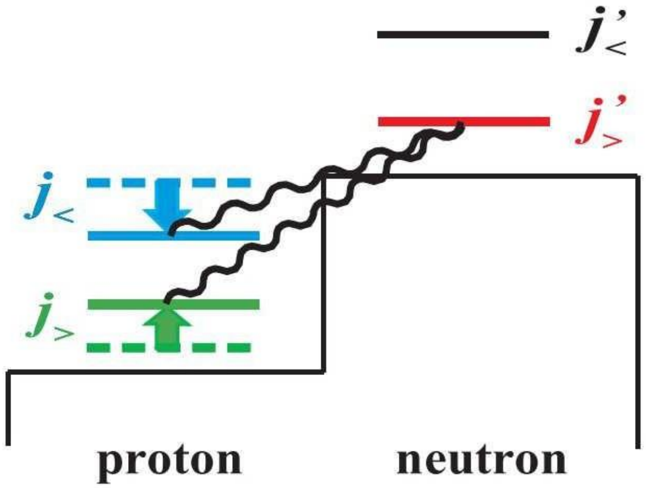


D. Steppenbeck et al, Nature 502 207 (2013)

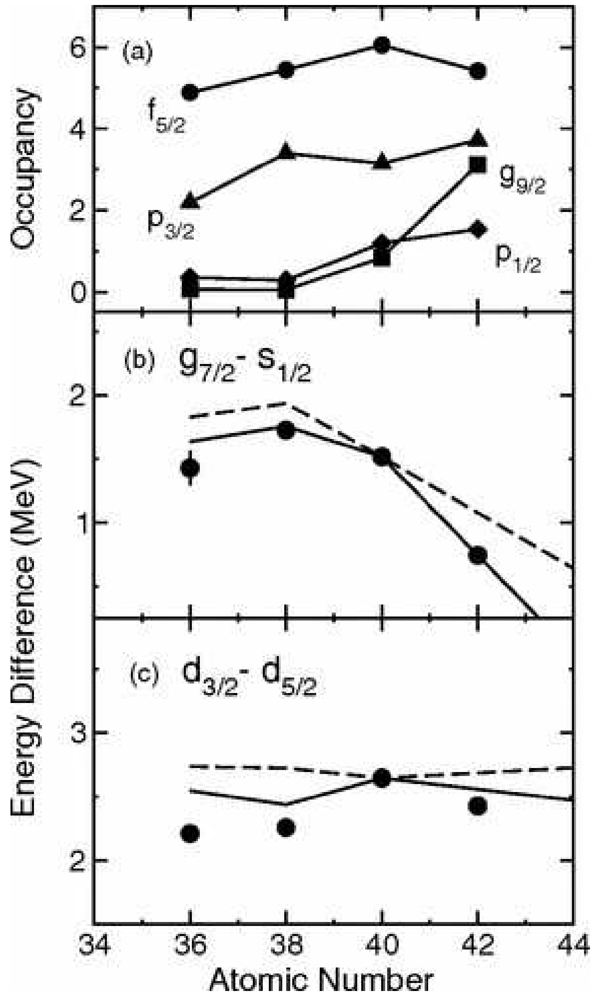
Single-particle evolution – heavy nuclei

- In heavier stable nuclei trends have also been observed, particularly in high-j states as other high-j states fill with nucleons
- Studying chains of isotopes/isotones near closed shells have pointed to the inclusion of a tensor interaction to explain systematics





Otsuka et al. Phys. Rev. Lett. 95, 232502 (2005)



D.K. Sharp et al, Phys.Rev.C 87 014312 (2013)

Single-particle evolution along N=126

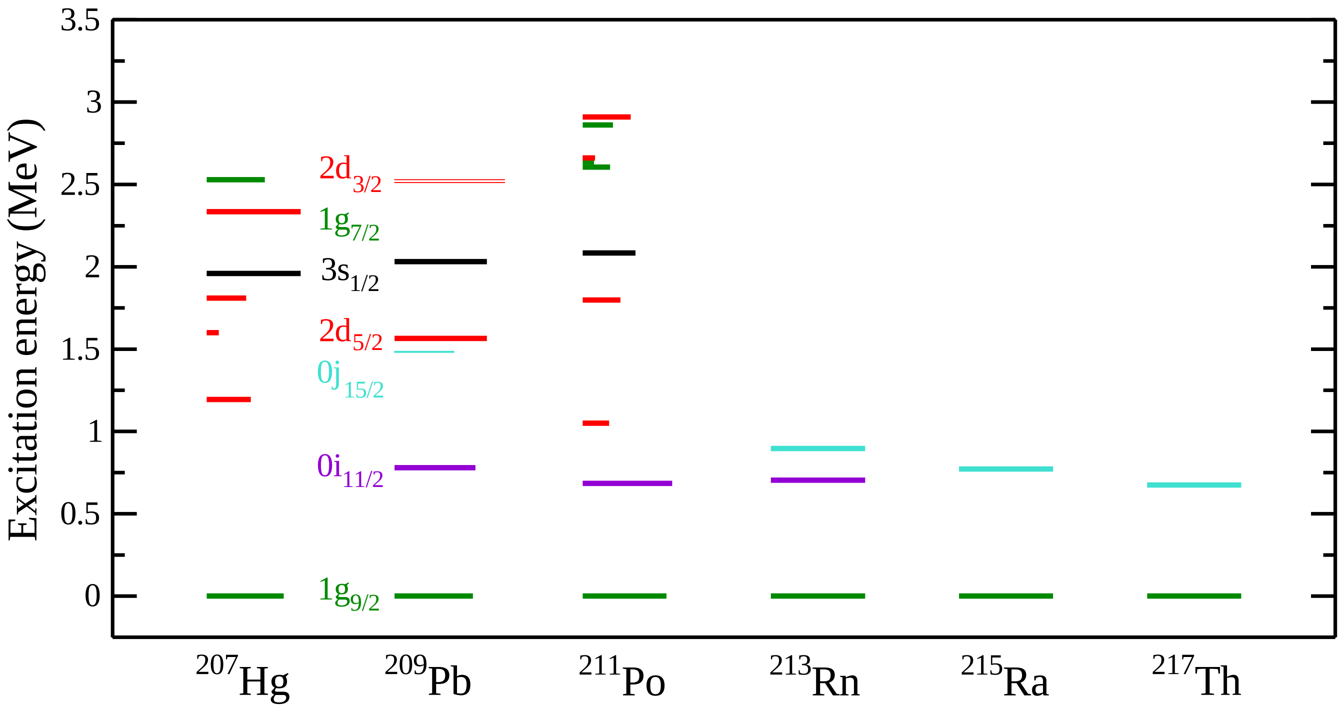
- Radioactive beams at HIE-ISOLDE allow new closed-shell systems to be studied

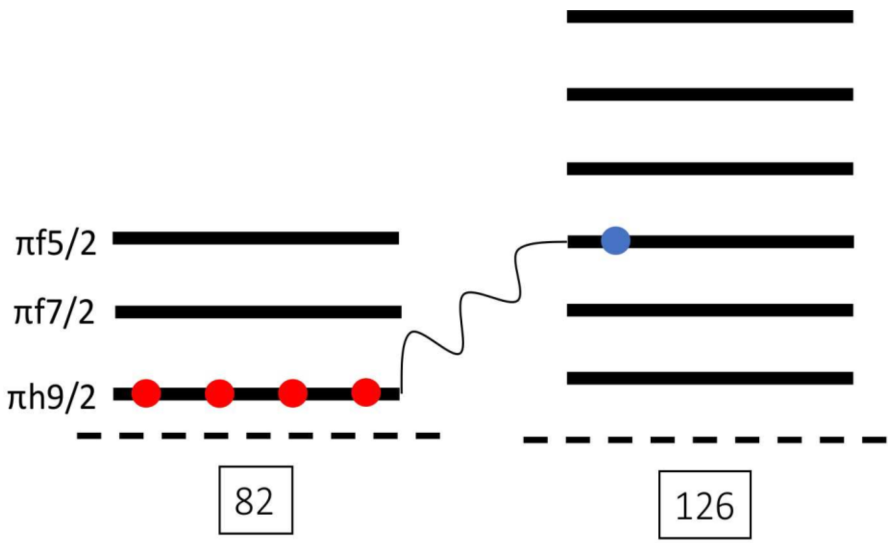
- Studies can be extended to N=126 isotones

- Currently, spectroscopic information on states up to Z=84 (^{211}Po) is known

- The location of nuclei with one neutron outside the N=126 closed shell makes them ideal testing grounds for modern shell-model calculations

- Aim is to probe the strength of neutron orbitals in this region which will be interacting with protons in the $\pi h_{9/2}$ orbital





Direct transfer reactions – inverse kinematics

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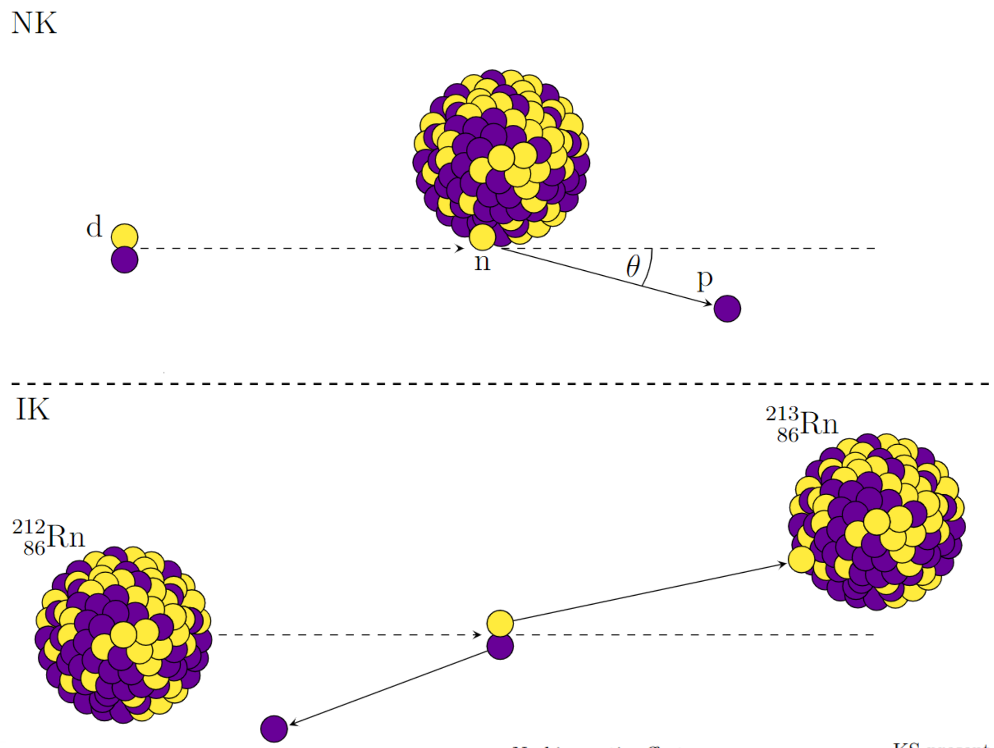
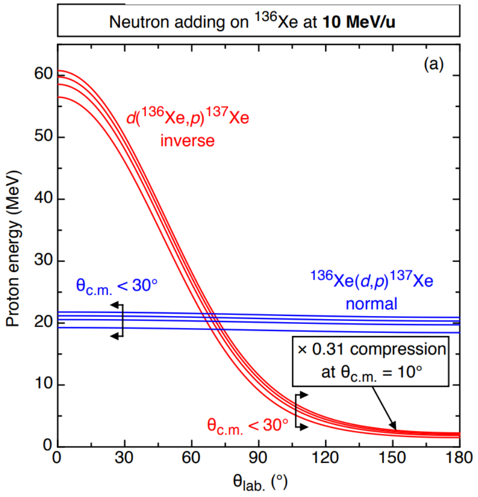
- Information:
  - Yields - cross sections
  - θ - angular momentum
  - Proton energy - excitation energy of nucleus.

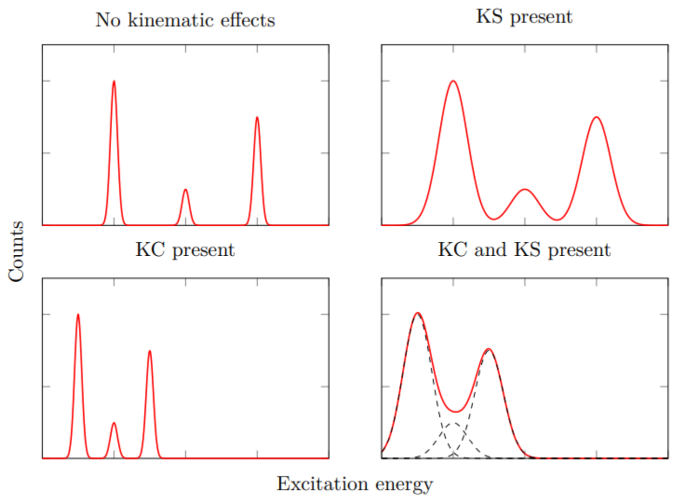
- d(^{212}Rn, p)^{213}Rn:
  - Need to consider lab to CM transformations

- Problems:
  - Kinematic compression – reduces energy difference between states
  - Kinematic shift – broadens peaks





B P Kay et al 2012 J. Phys.: Conf. Ser. 381 012095



P. T. MacGregor, Ph.D. Thesis (2021)

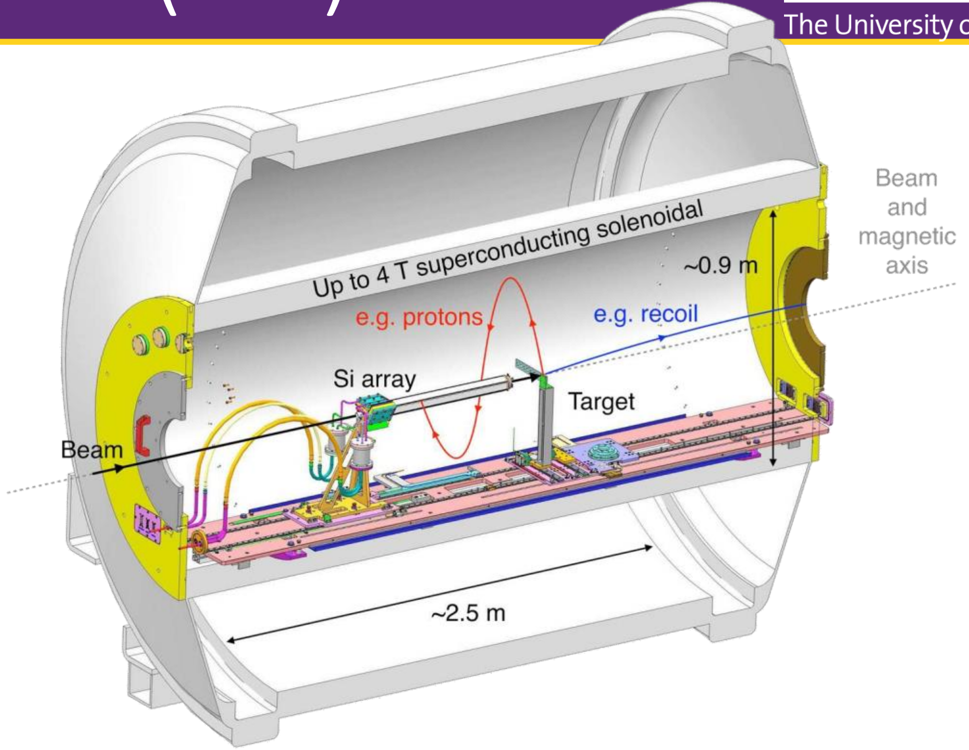
ISOLDE Solenoidal Spectrometer (ISS)

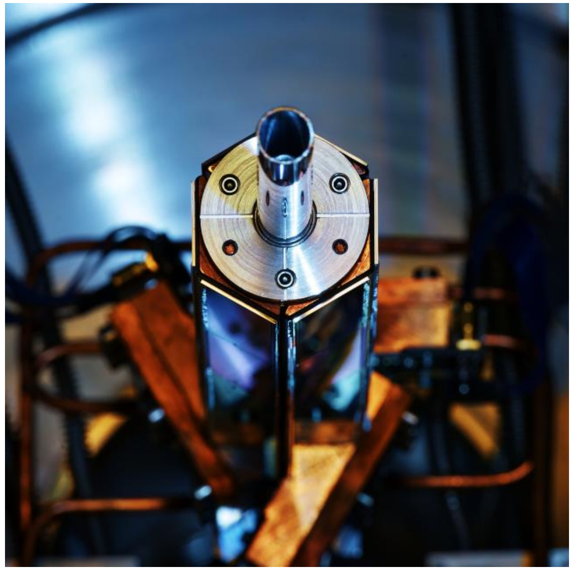
- Potential solution using a solenoid (2.5 T).
- Particles from target follow helical orbits and return to the axis after one cyclotron period

$$T_{cyc} = \frac{2\pi r}{v_\perp} = \frac{2\pi m}{qB}$$

- Measure protons in position-sensitive array
- Position, $E_{lab} \propto E_{cm}$.
- No compression in the solenoid – better resolution

$$E_{\rm cm} = E_{\rm lab} + \frac{m}{2} V_{\rm cm}^2 - \frac{m V_{\rm cm} z}{T_{\rm cyc}}$$





HIE-ISOLDE

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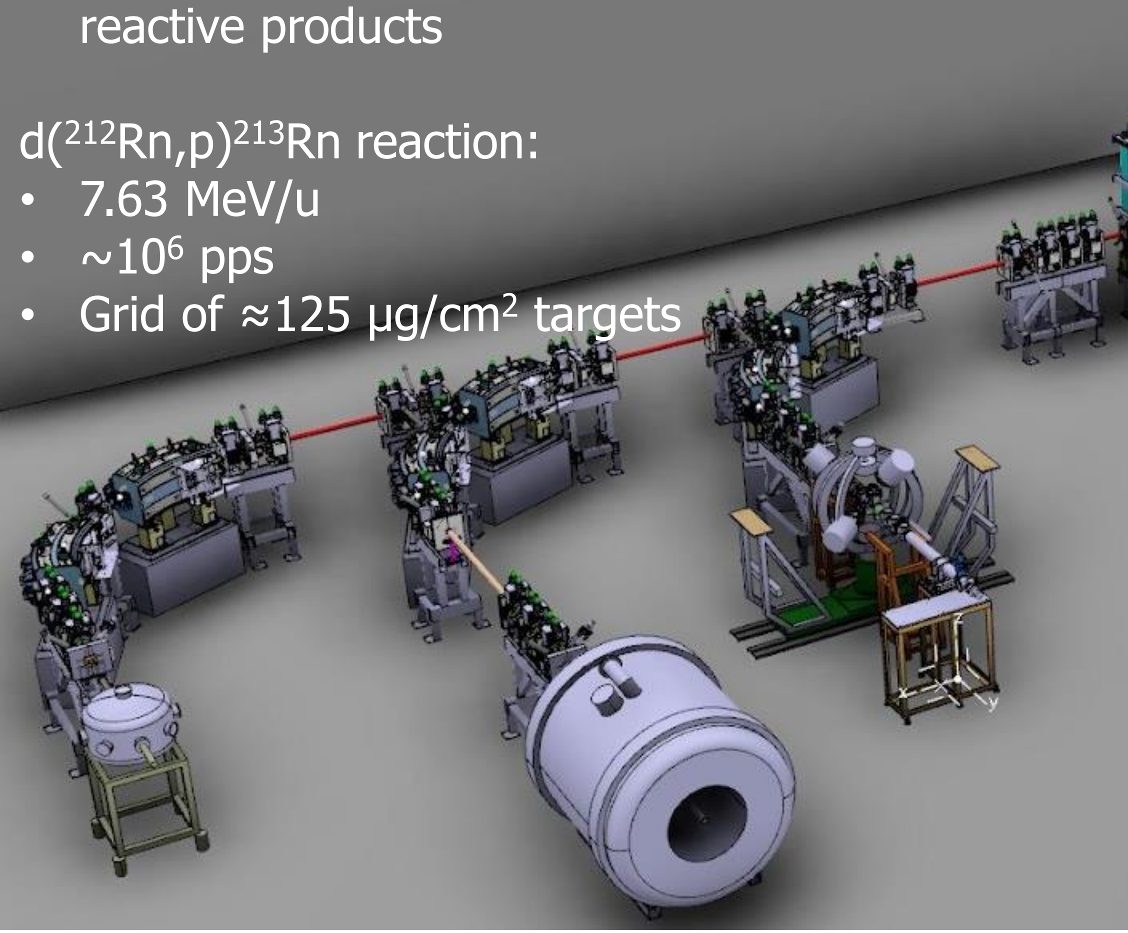
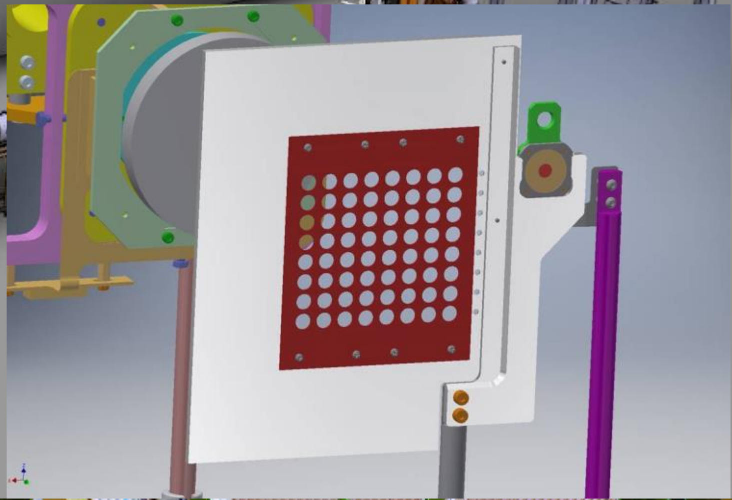
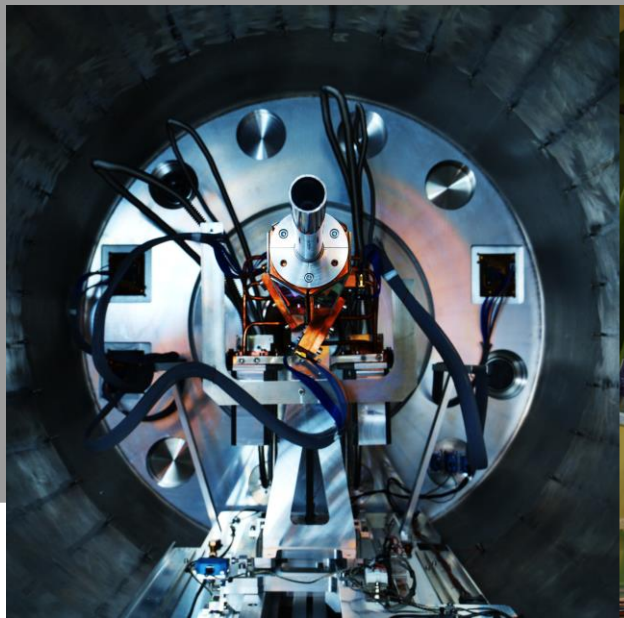
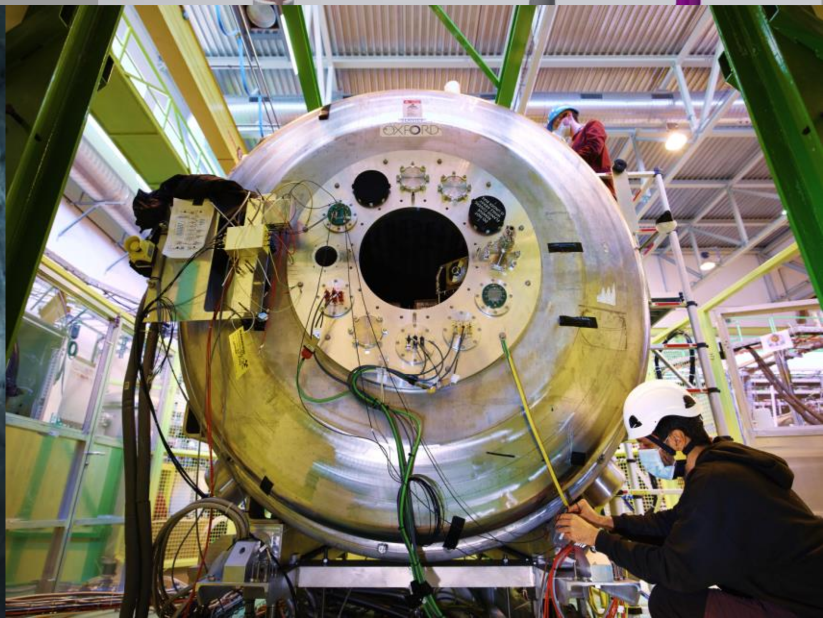
Experimental details:
- Protons from the PSB impinged on a heated UC_x target
- VADIS ion-source
- Transfer line between ion source and target cooled to capture reactive products

d(^{212}Rn,p)^{213}Rn reaction:
- 7.63 MeV/u
- $\sim 10^6$ pps
- Grid of $\approx$125 µg/cm^2 targets



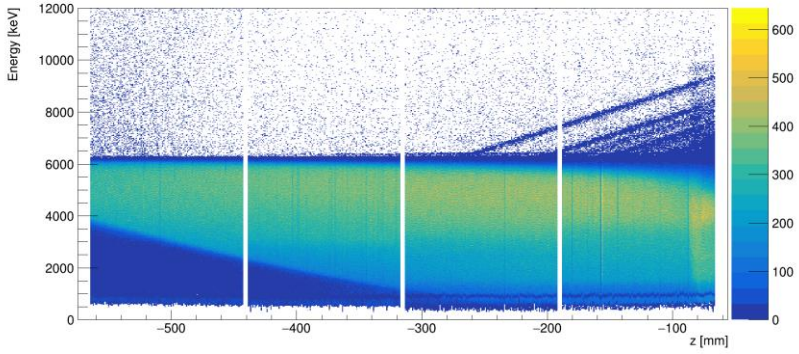






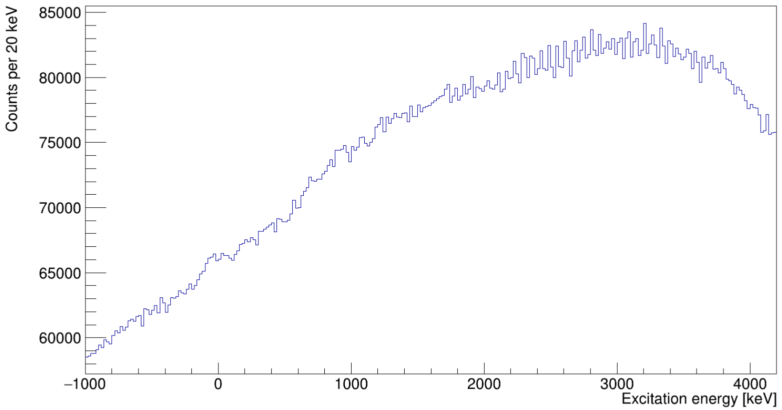
https://hie-isolde-project.web.cern.ch/hie-isolde-project

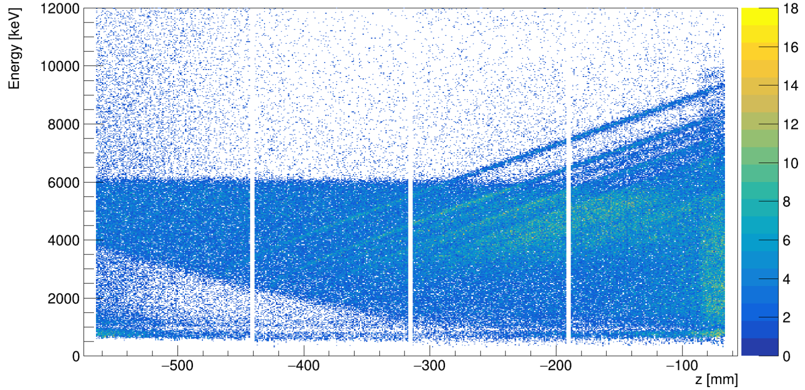
Preliminary data analysis



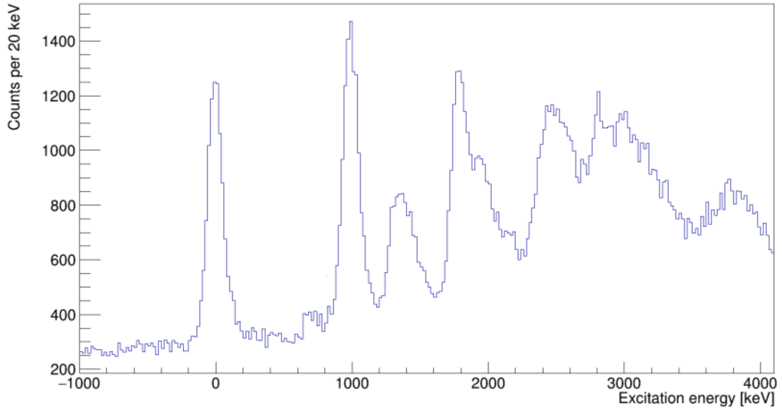
Singles

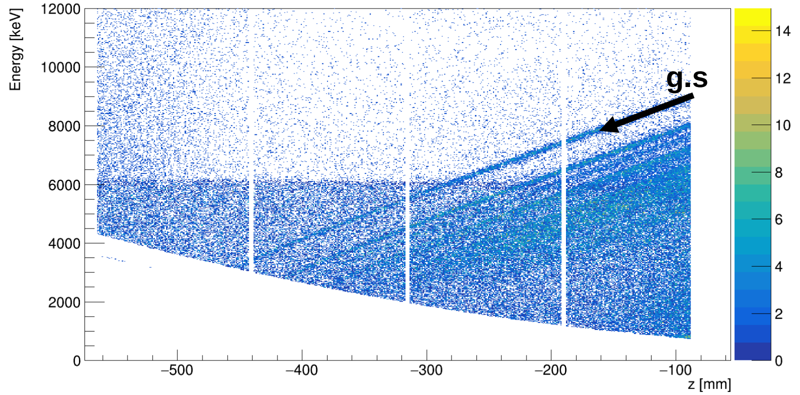
Large α background





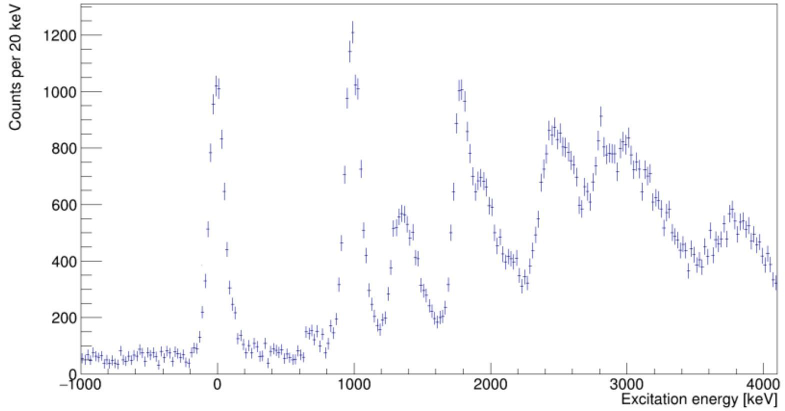
Gating on EBIS-on time



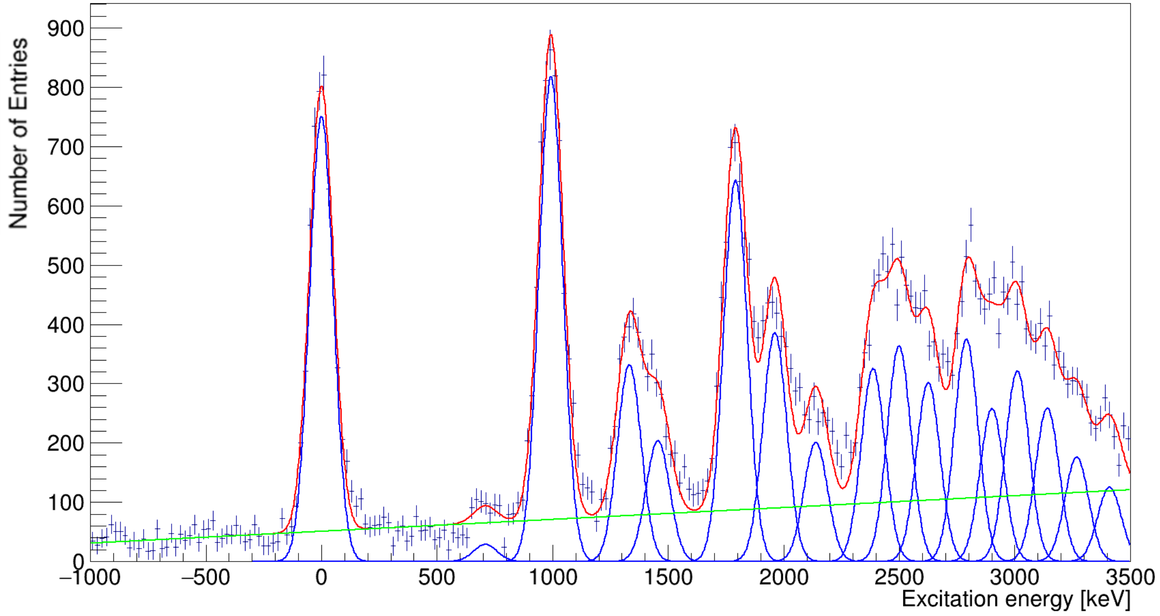


Subtracting EBIS-off time

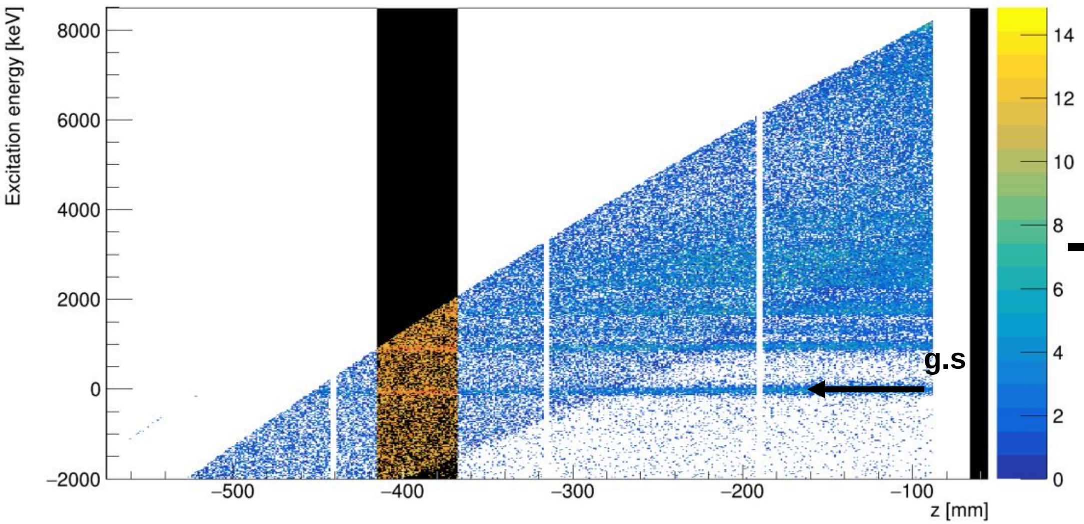
θ_{cm} and z cuts

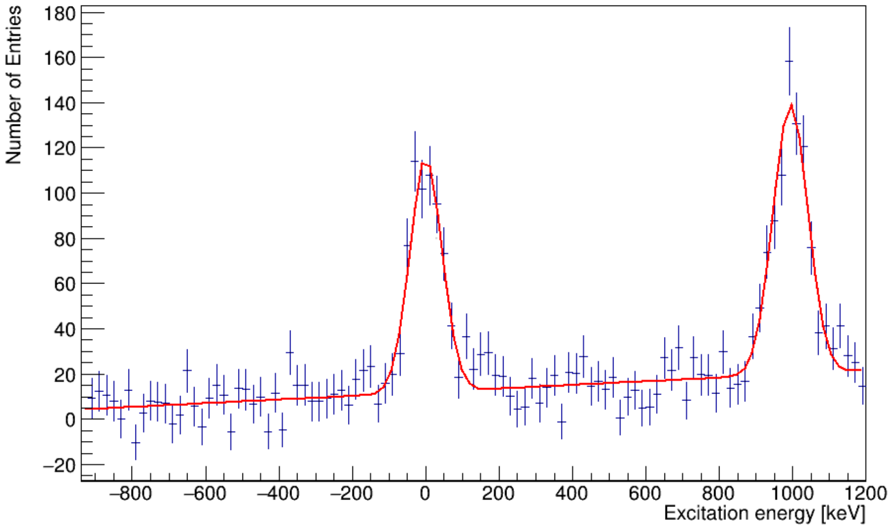


Preliminary excitation energy spectrum



- Resolution of 120 keV FWHM
- Identified 17 states in ^{213}Rn up to 3.5 MeV
- Projected excitation energies vs z
- Regions in z map to θ_{cm}
- Extracted yields of states
- Measured cross sections

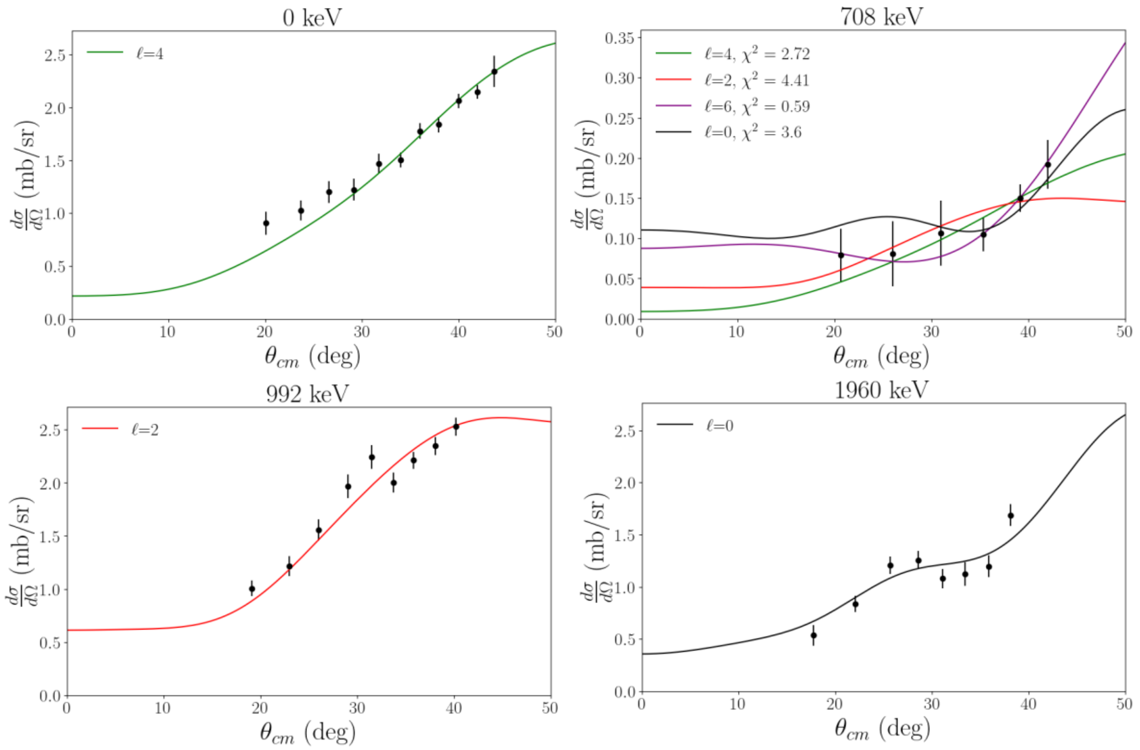




$$\frac{d\sigma}{d\Omega} = \frac{Y}{N_B N_T \Delta\Omega \xi}$$

Preliminary angular distributions

- PTOLEMY used to calculate angular distributions
- Measured angular distributions compared to calculations and assignments made for states up to 2.1 MeV



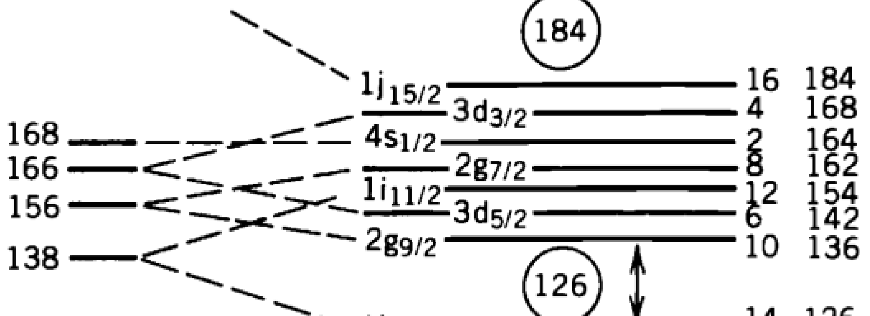
Energy / keV	L	nlj	S
0	4	$2g_{9/2}$	1.00
708(11)	6	$1i_{11/2}$	1.25
992(1)	2		0.31
1330(3)	2/0		0.12/0.22
1454(5)	2/0		0.08/0.16
1790(2)	2		0.26
1960(2)	0	$4s_{1/2}$	0.36
2139(5)	0	$4s_{1/2}$	0.21

L	Orbital	Sum SF
0	$4s_{1/2}$	0.95*
2		0.77*
4	$2g_{9/2}$	1.00

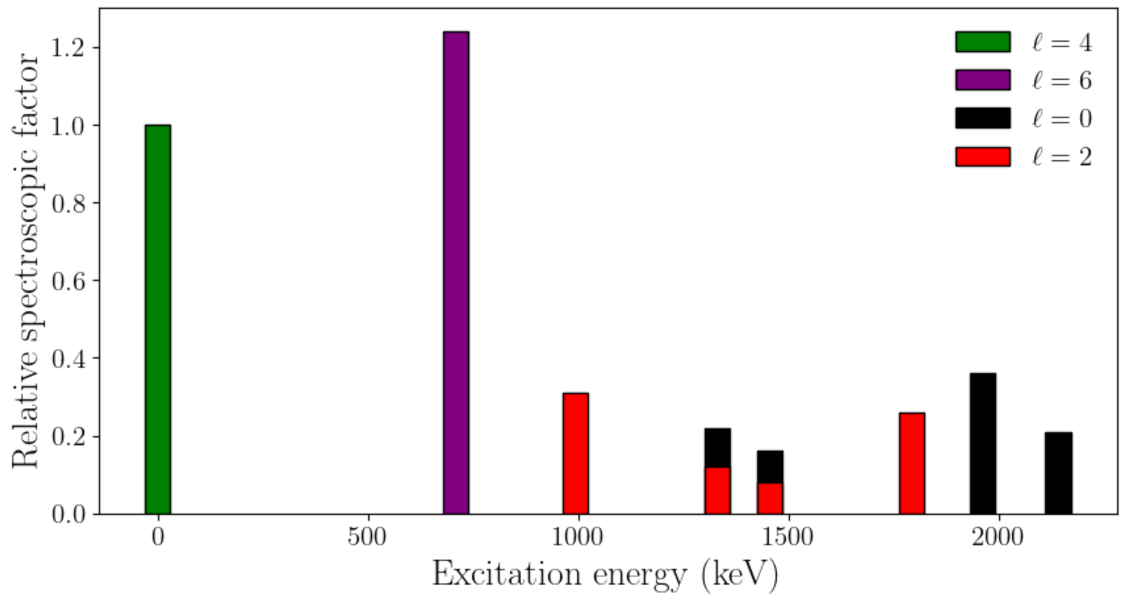
*Summing all ambiguous states

- Relative spectroscopic factors extracted by comparing with DWBA calculations normalized to the $2g_{9/2}$ ground state
- Summed strength should equal one for a completely empty orbital outside a closed shell

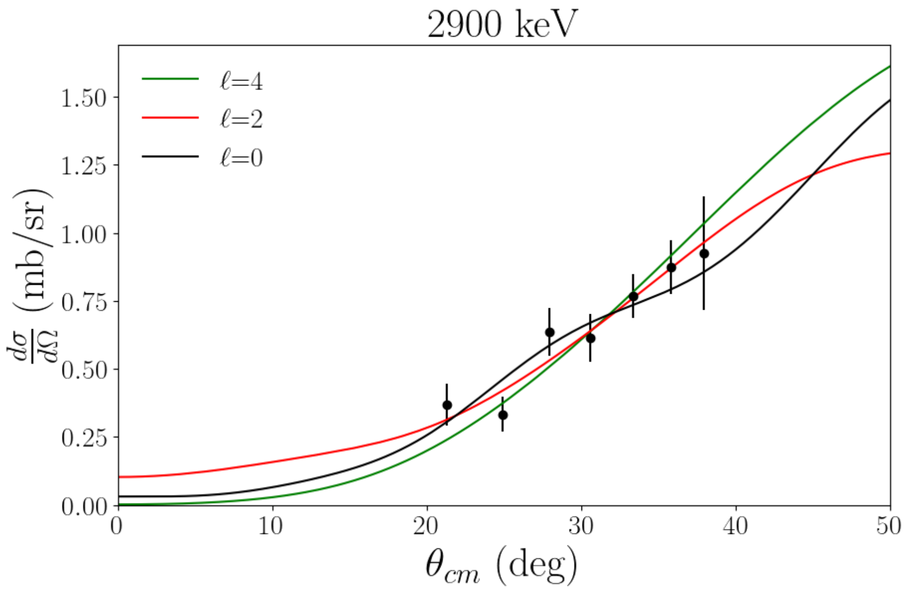
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = S_{ij}\left(\frac{d\sigma}{d\Omega}\right)_{\text{DWBA}}$$



Preliminary spectroscopic factors

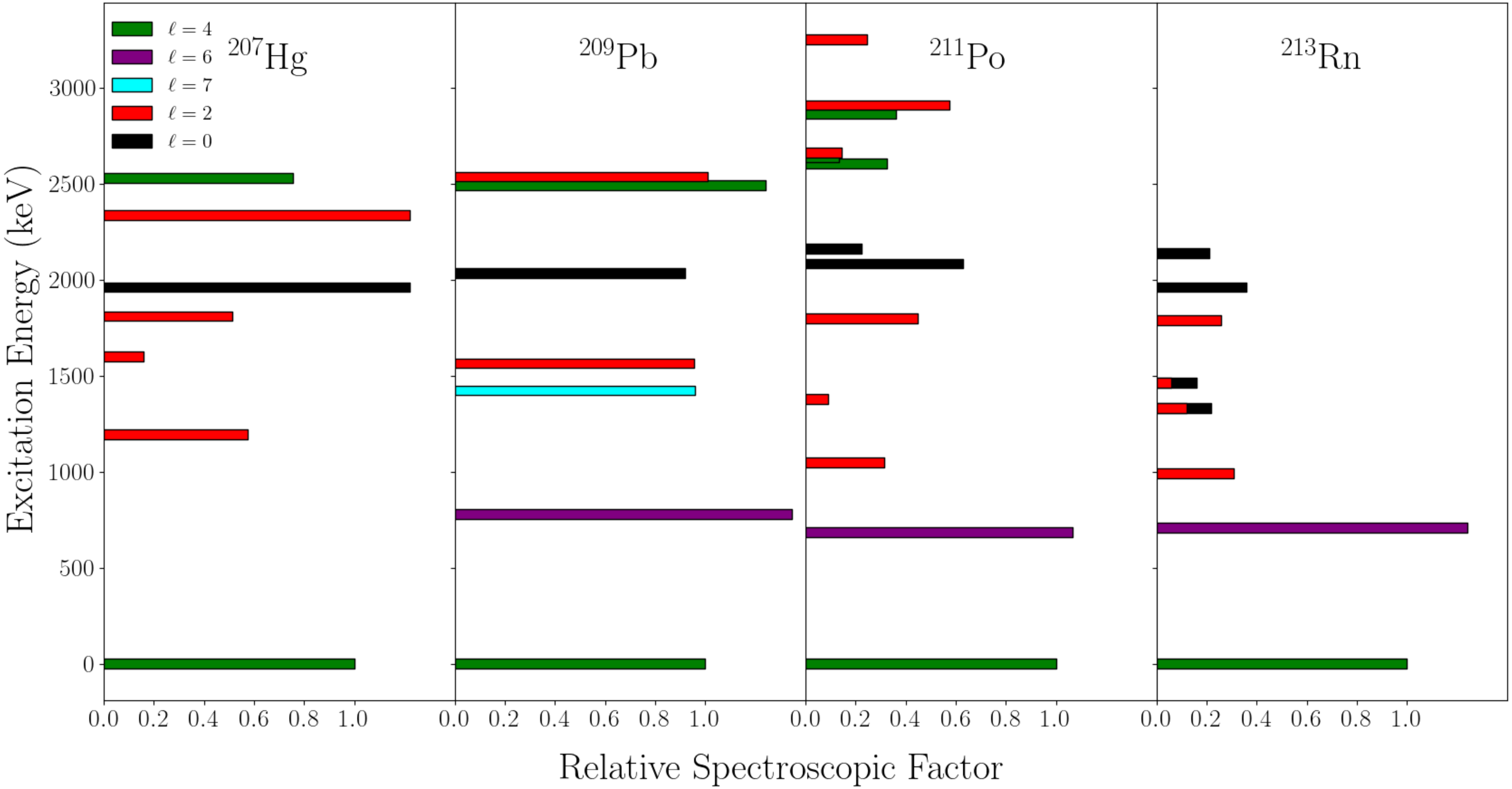


- Assuming ground state is a pure single-particle state



- Challenging to assign states above 2.1 MeV
  - Larger uncertainties for cross sections
  - θ angle coverage decreases with excitation energy
  - PTOLEMY calculations become more similar

Systematics



T. L. Tang *et al.* Phys. Rev. Lett. **124**, 062502 (2020)
G. Muehllehner *et al.* Phys. Rev. **159**, 1039 (1967)
T.S. Bhatia *et al.* Nuclear Physics A, **104** (1979)

Conclusions

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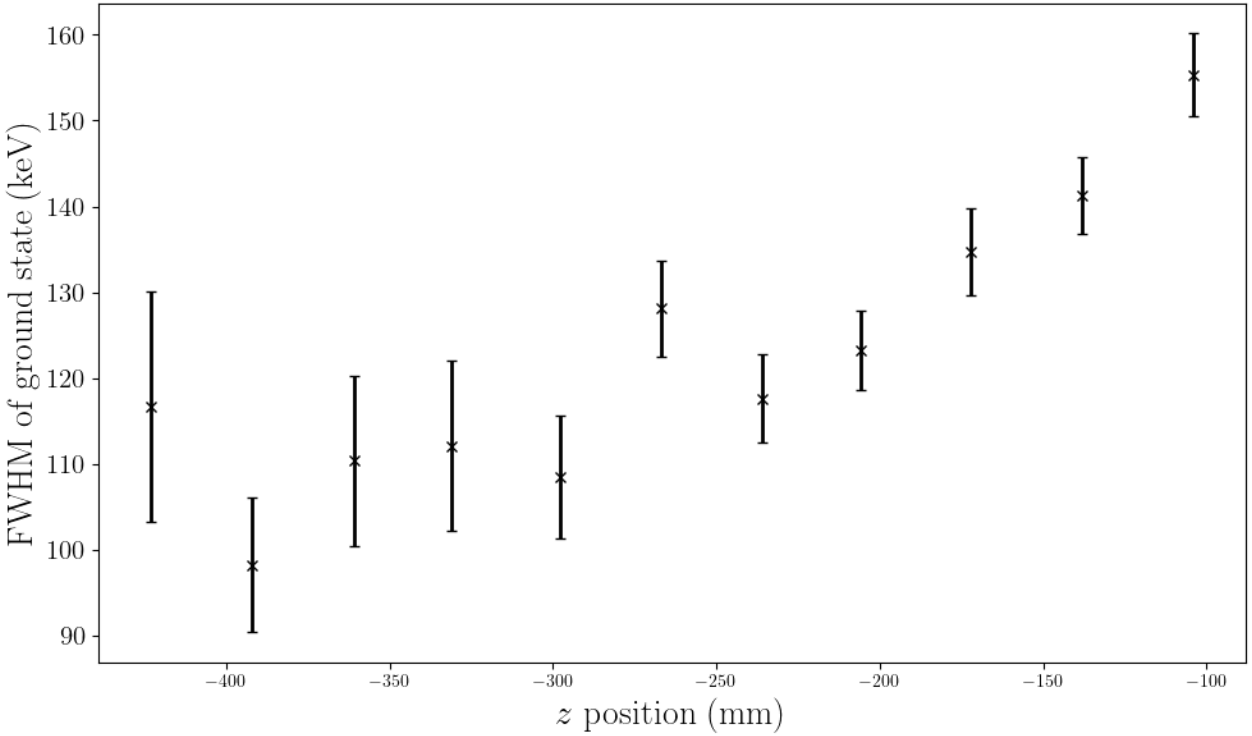
- 17 new states identified in ^{213}Rn
- Preliminary ℓ transfer assignments have been made up to 2.1 MeV
- Extracted relative spectroscopic factors for these states
- Compare to modern shell-model DFT calculations (Gianluca Colò, Università degli Studi di Milano)

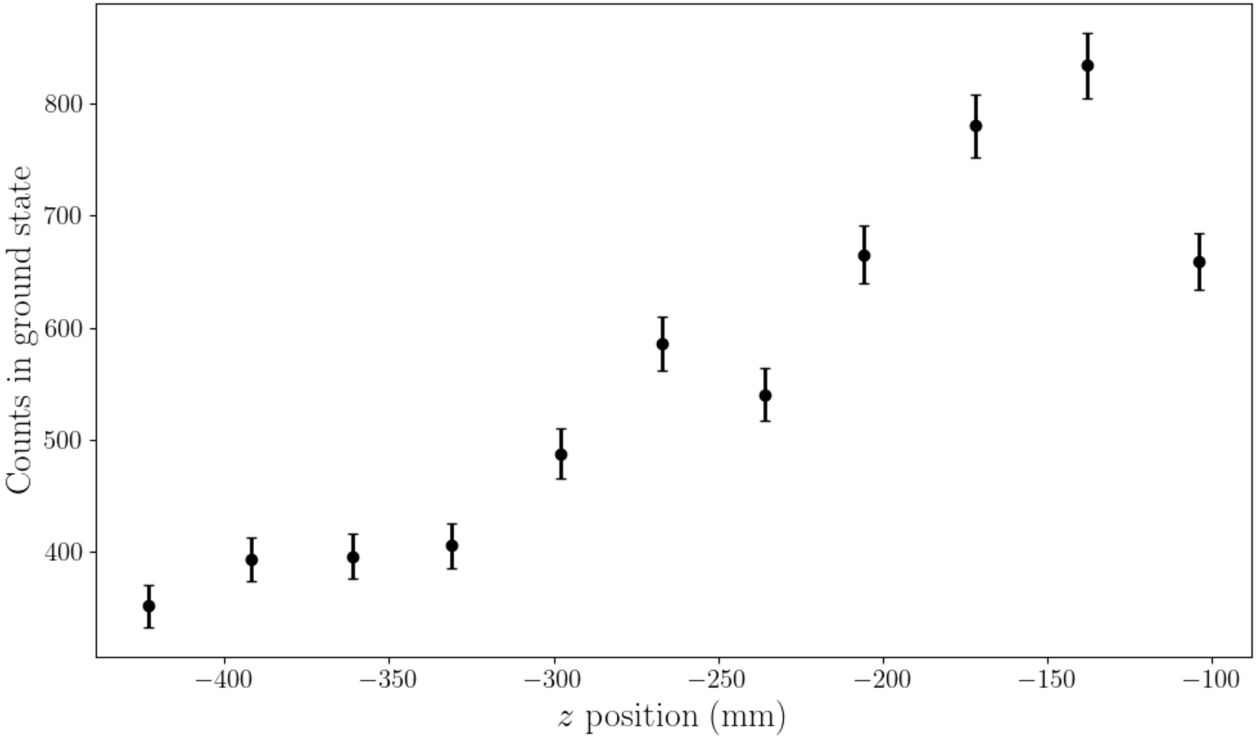
ISOLDE Solenoidal Spectrometer

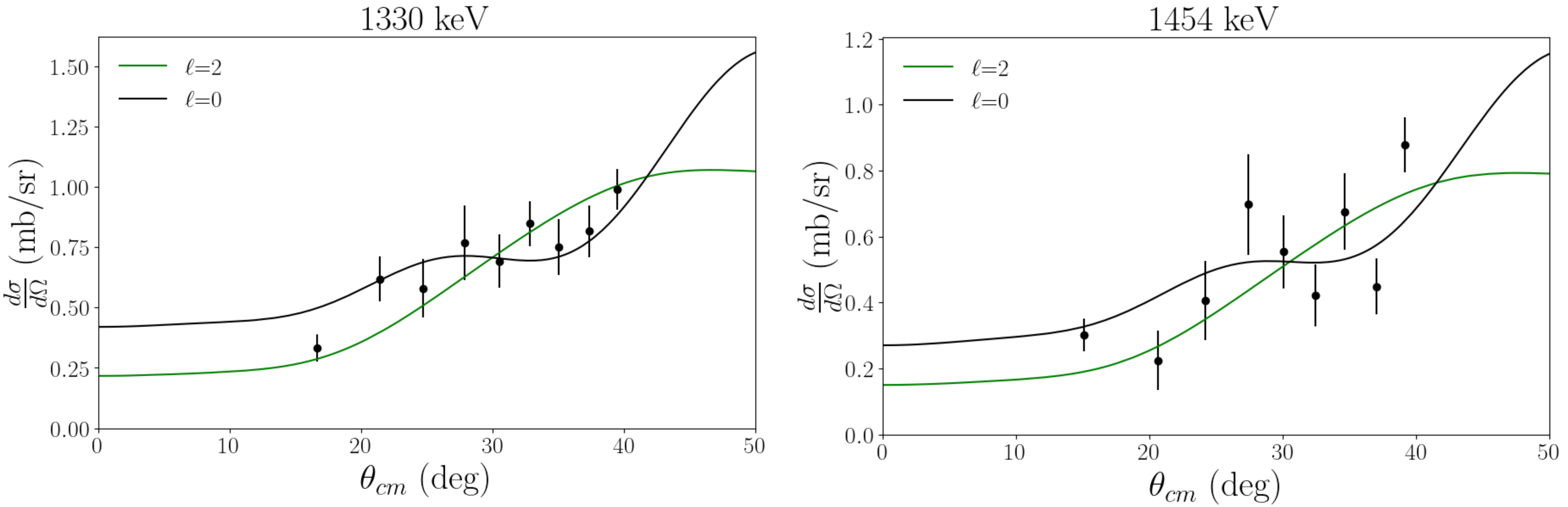
Science and Technology Facilities Council

Argonne NATIONAL LABORATORY

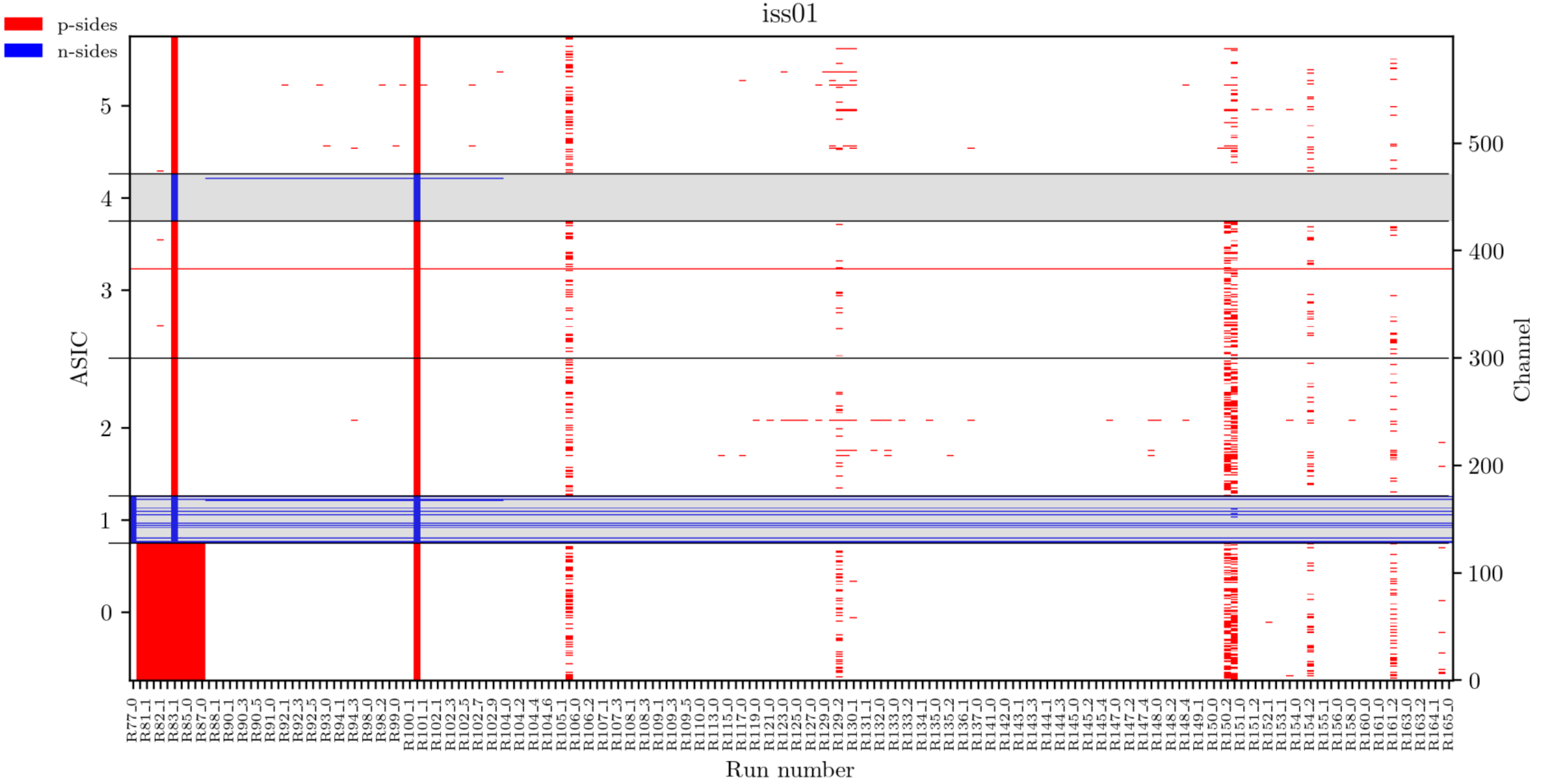
Resolution of the ground state





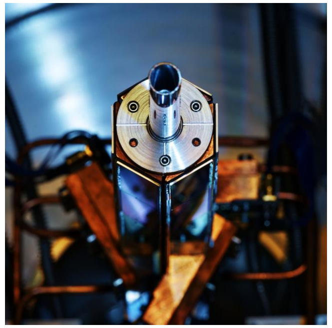

1330 keV
ℓ=2
ℓ=0
dσ/dΩ (mb/sr)
θ_cm (deg)
1454 keV
ℓ=2
ℓ=0
dσ/dΩ (mb/sr)
θ_cm (deg)

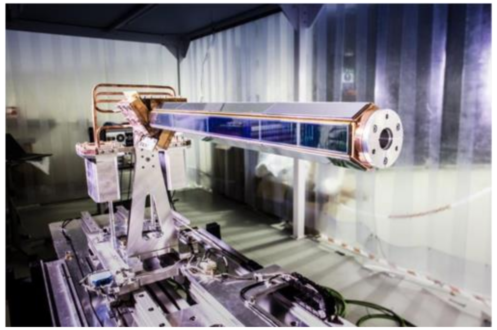
Solid angle corrections



$$\varepsilon_{\mathrm{p}} = \frac{\sum_i \left(\frac{\sum_j I_{ij} N_j}{\sum_j N_j} \right)}{N_{\mathrm{p}}} = \frac{\sum_i \left(\frac{\sum_j I_{ij} N_j}{N_{\mathrm{ELUM}}} \right)}{N_{\mathrm{p}}}$$

$$\varepsilon_{\mathrm{n}} = \frac{\sum_i \left(\frac{\sum_j I_{ij} N_j}{\sum_j N_j} \right)}{N_{\mathrm{n}}} = \frac{\sum_i \left(\frac{\sum_j I_{ij} N_j}{N_{\mathrm{ELUM}}} \right)}{22}$$





Inverse kinematics

Kinematic Compression:

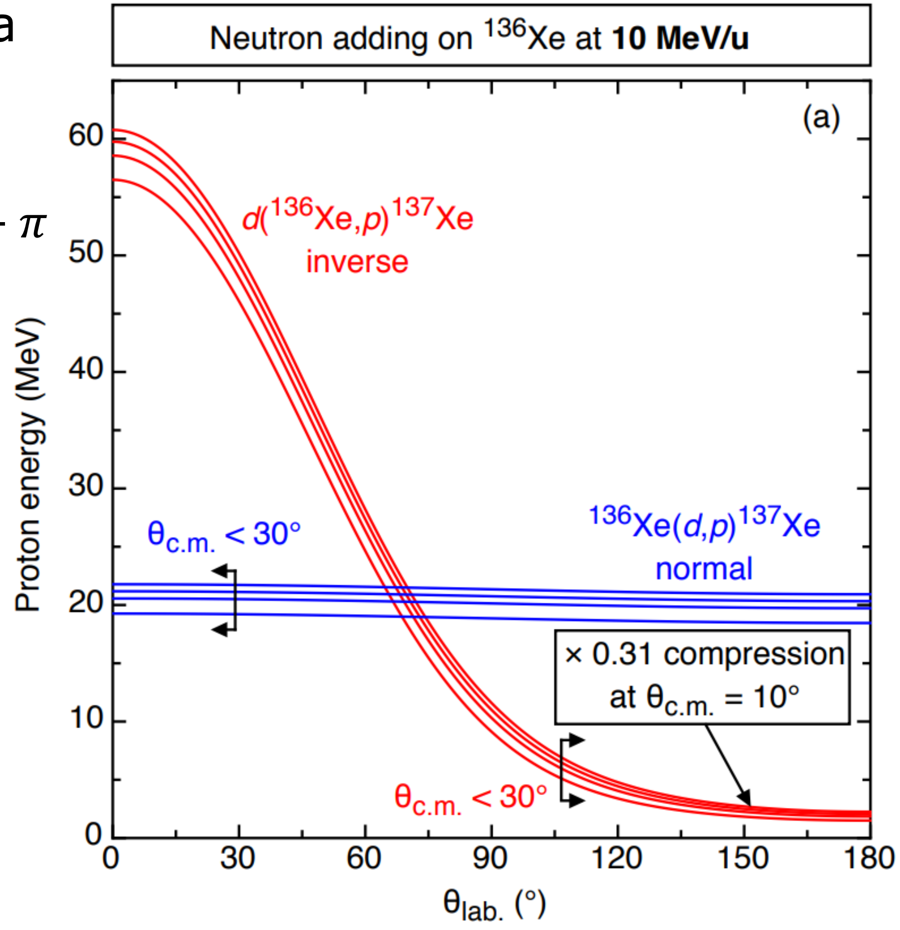
- In IK, the difference in ejectile energy for two states separated by a given excitation energy are compressed together more than in NK.

$$\Delta T_3 = A + B\sqrt{\frac{m_1}{m_2}}\cos\theta_{cm} = A - B\sqrt{\frac{m_1}{m_2}}\cos\eta_{cm} \qquad \eta_{cm} = \theta_{cm} - \pi$$

- Both NK and IK experience this with increasing CoM angle.
- Mass ratio means the affect is worse for IK and states in NK are less affected at small θ_{cm} whereas IK are affected much more.

Kinematic Shift:

- Gradient of proton energy with angle is greater in the inverse case when compared to NK
- Finite angular acceptance allows detection of a range of energies. Peaks are broader in IK



B P Kay et al 2012 J. Phys.: Conf. Ser. 381 012095