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

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Daniel Clarke

ISOLDE Solenoidal Spectrometer

HIE-ISOLDE Physics Workshop 2023

Single-particle evolution in nuclei

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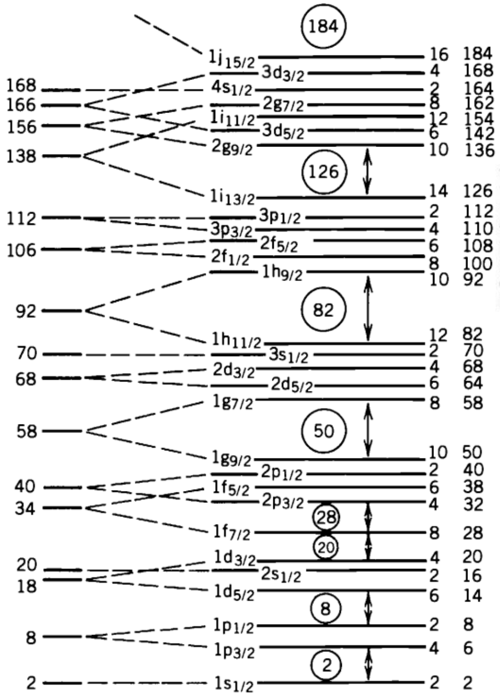
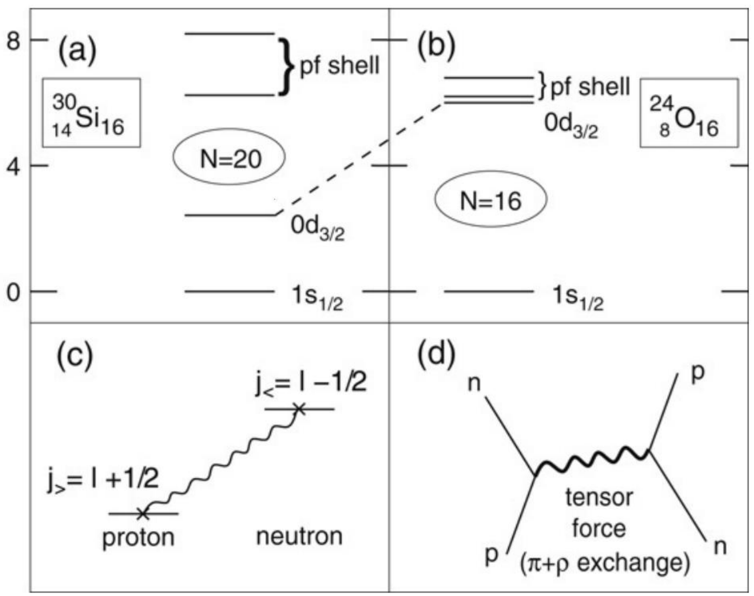
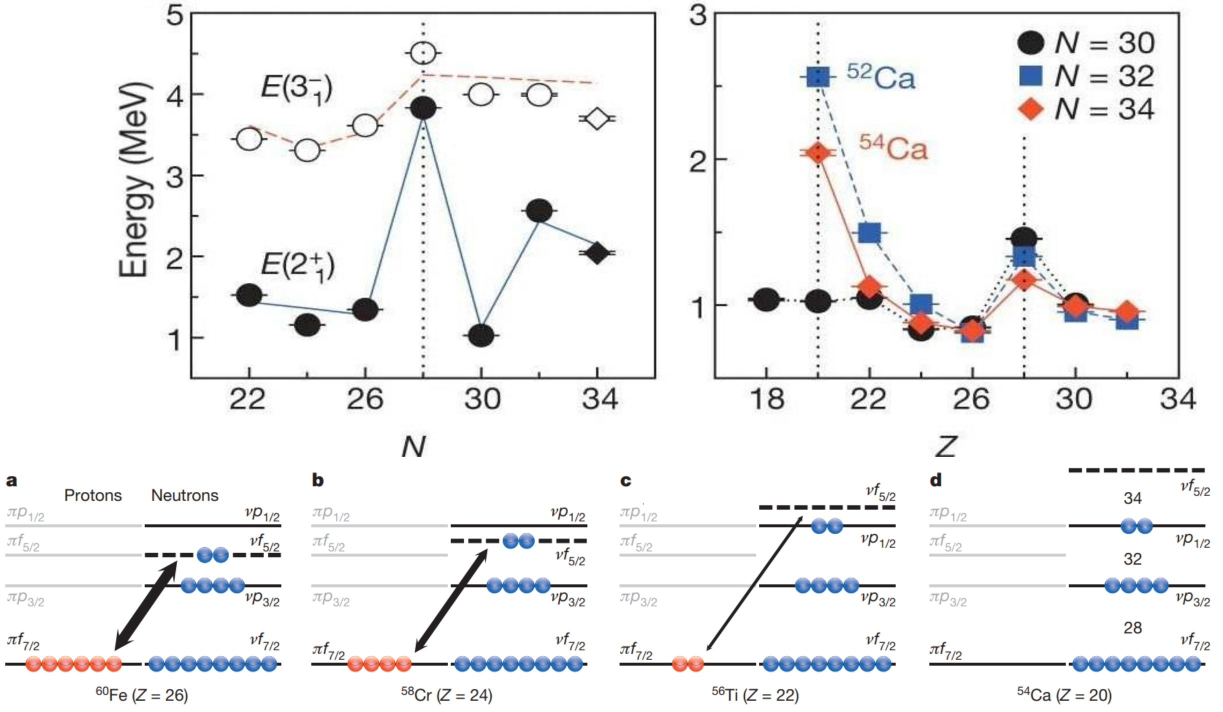
- Far from stability, shell closures have been shown to evolve for systems with imbalances of protons and neutrons

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





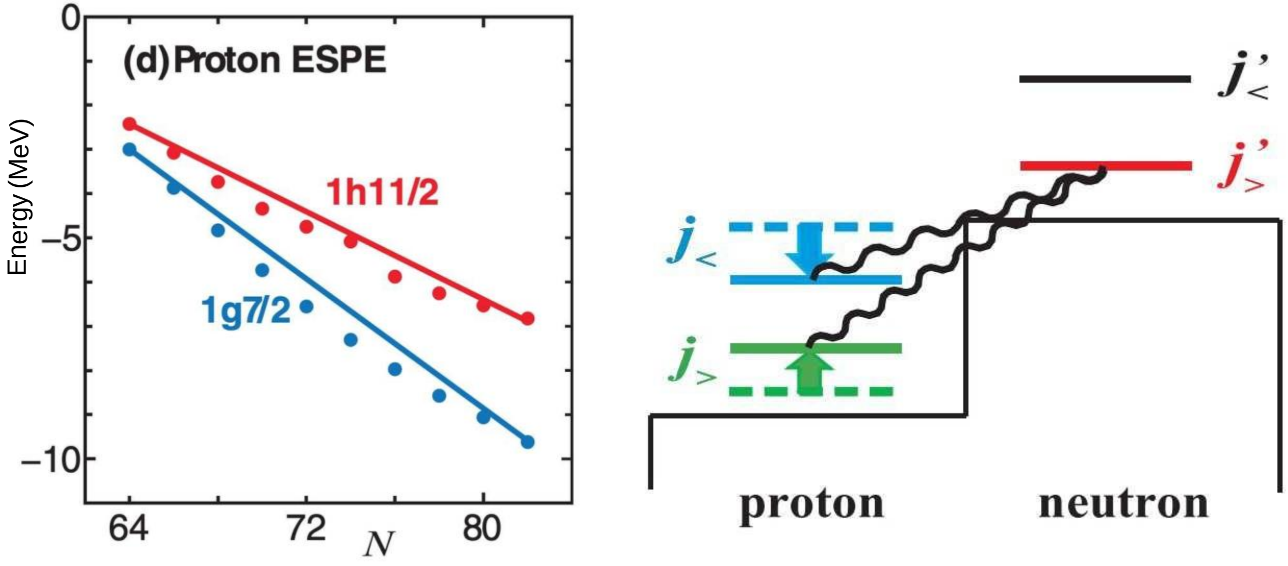
T. Otsuka, et al., Phys. Rev. Lett. 87 (2001) 082502



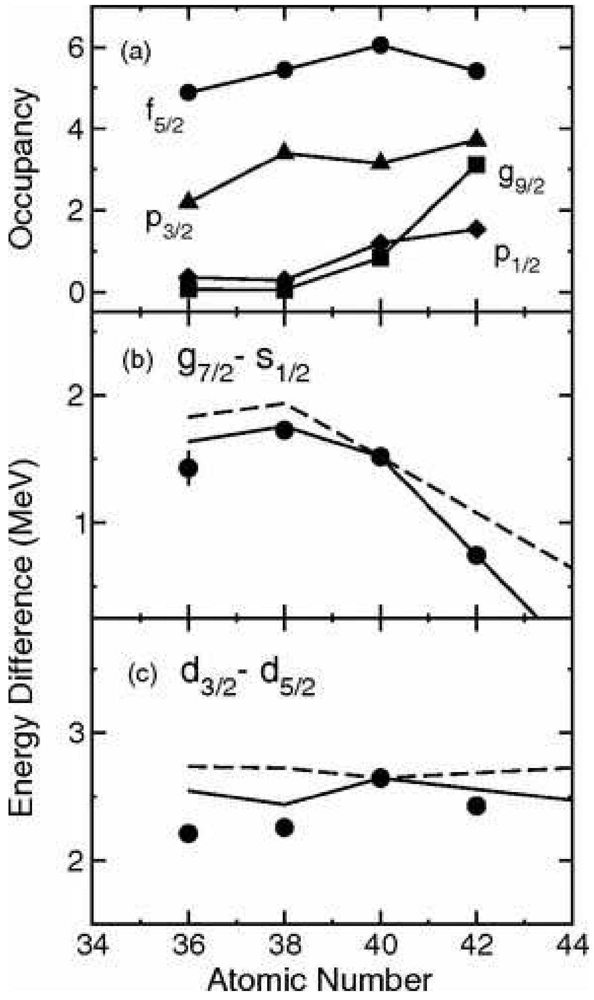
D. Steppenbeck et al, Nature 502 207 (2013)

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 has pointed to the inclusion of a tensor interaction to explain systematics



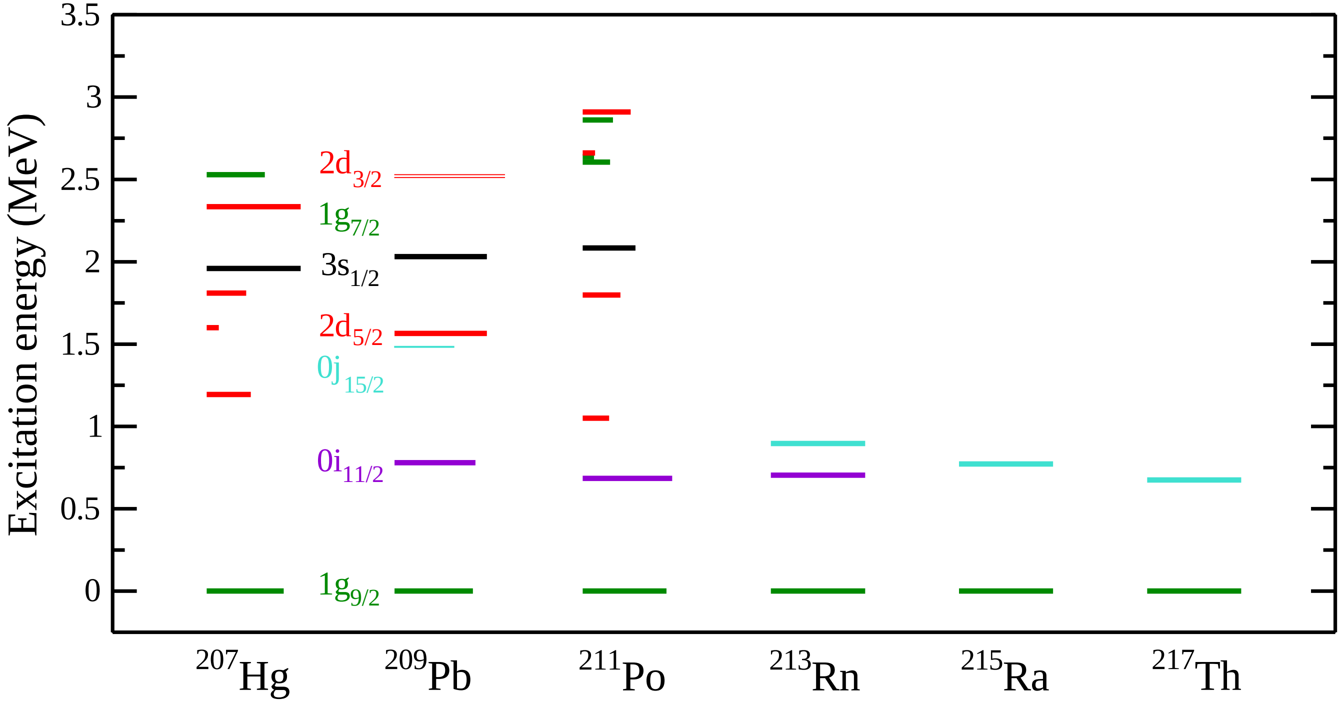
Otsuka et al. Phys. Rev. Lett. 95, 232502 (2005)

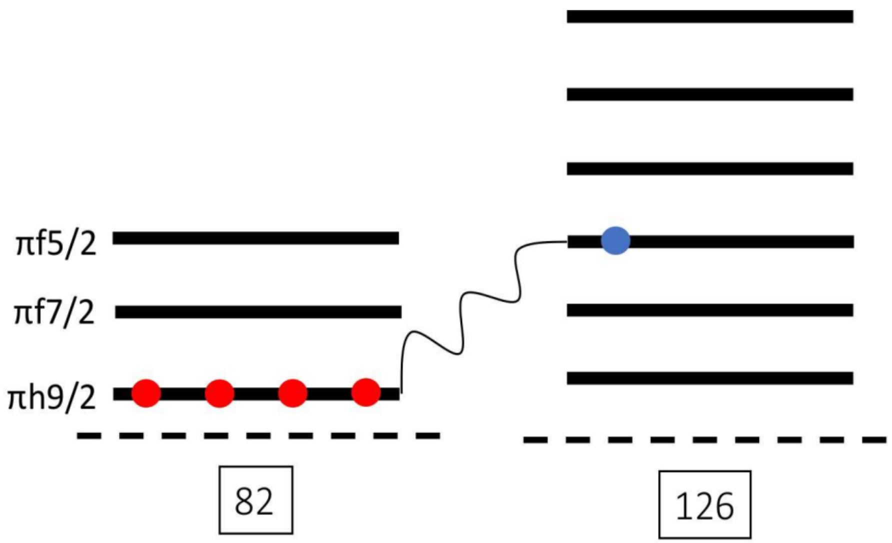


D.K. Sharp et al, Phys.Rev.C 87 014312 (2013)

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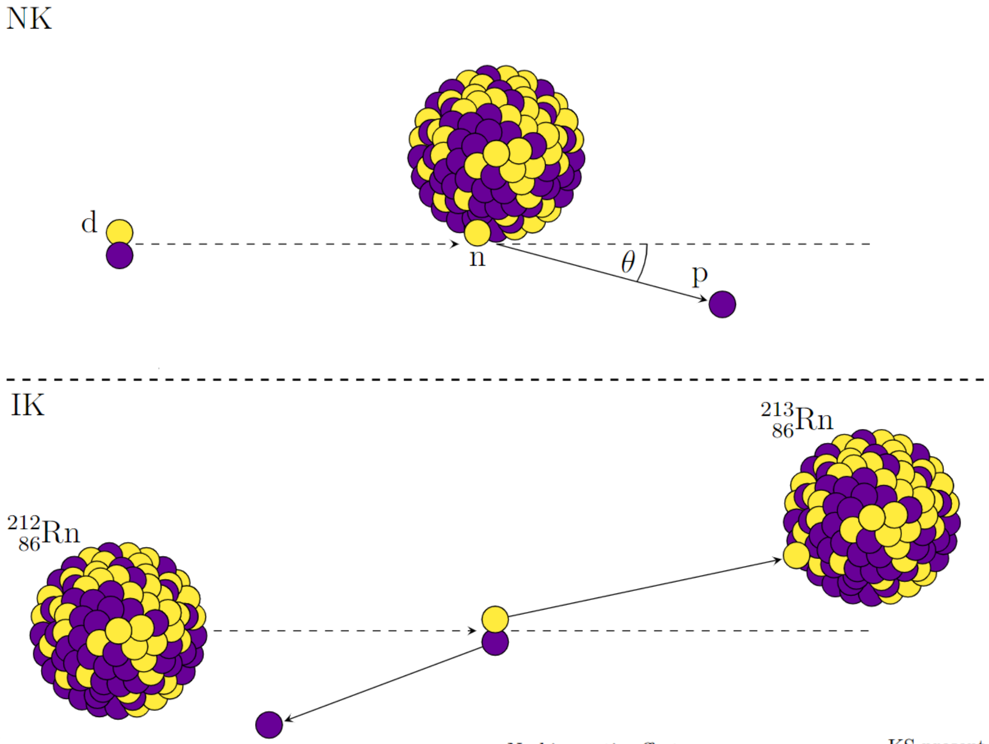
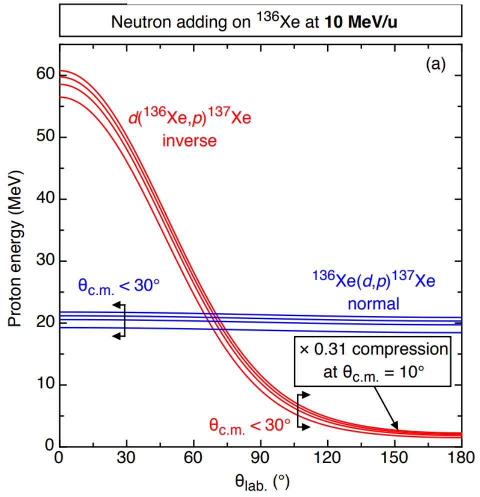
- Information:
  - Yields - cross sections
  - θ - angular momentum
  - Proton energy - excitation energy of nucleus

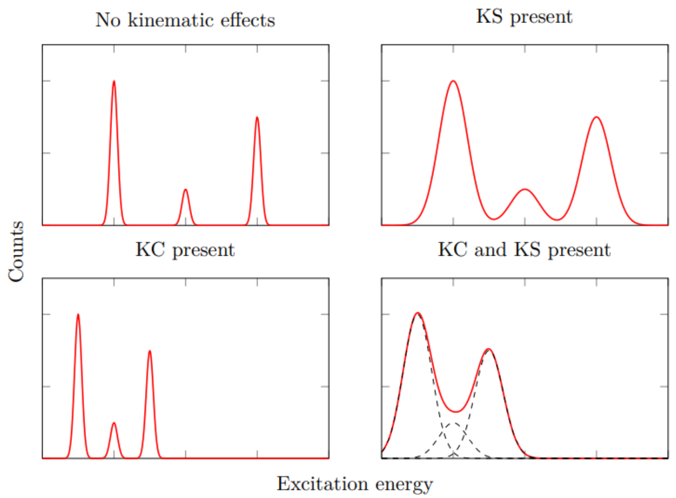
- d(^{212}Rn, p)^{213}Rn:
  - Need to consider lab to CM transformations

- 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)

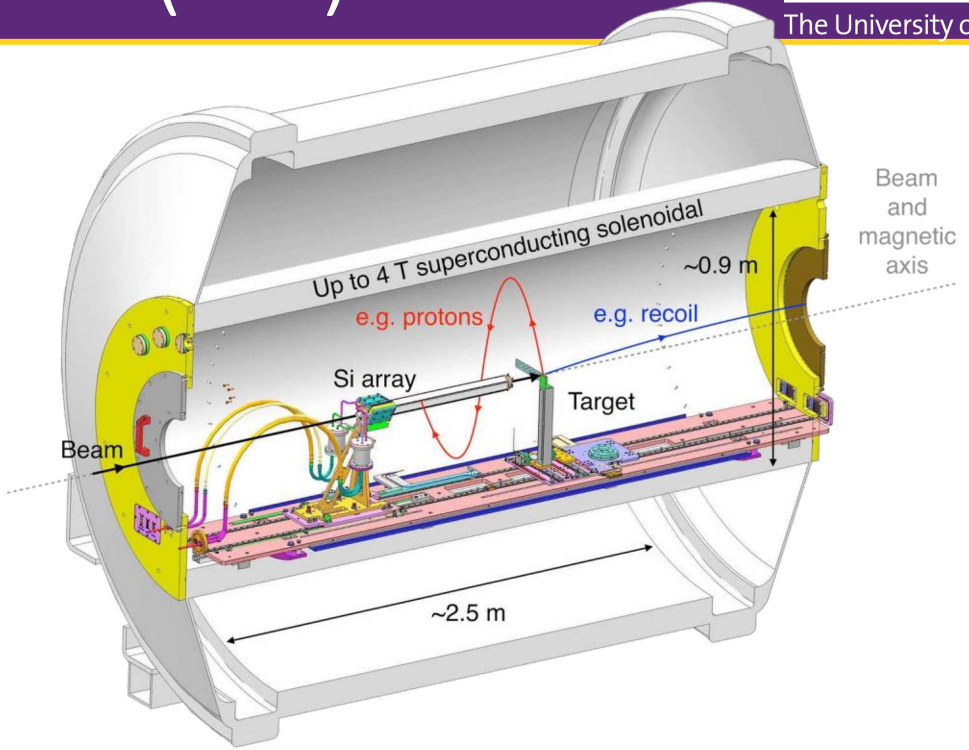
ISOLDE Solenoidal Spectrometer (ISS)

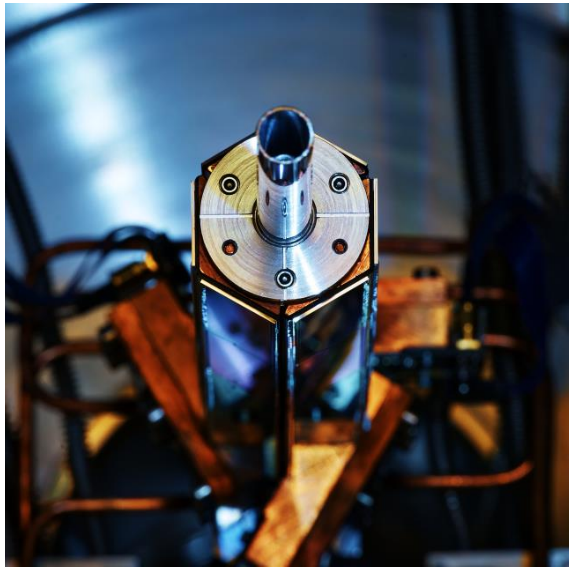
- Potential solution using a solenoid (2.5 T)
- Particles from target follow helical orbits and return to the axis after one cyclotron period

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

- 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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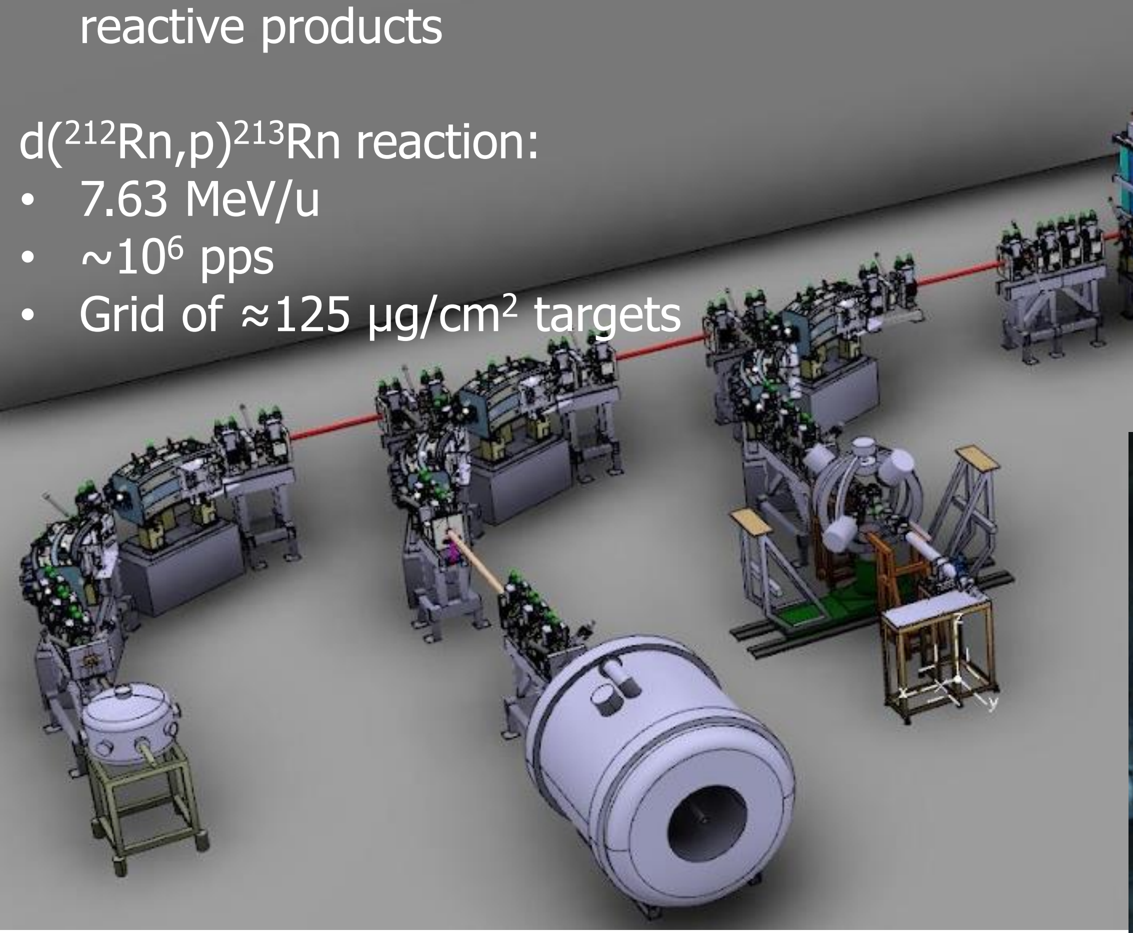
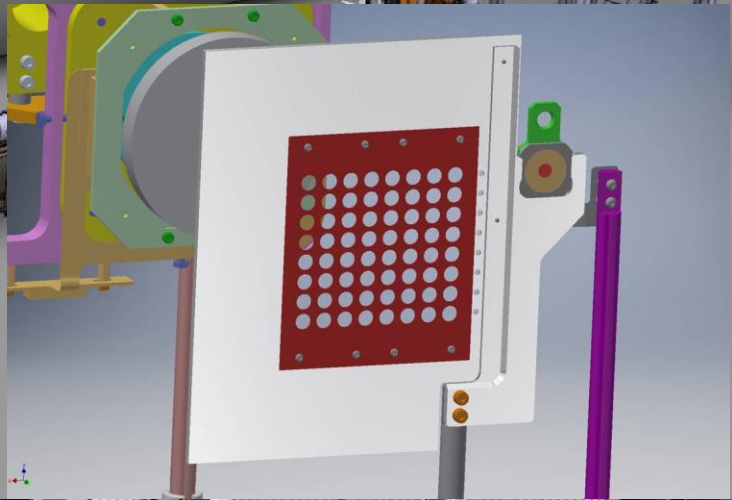
Experimental details:

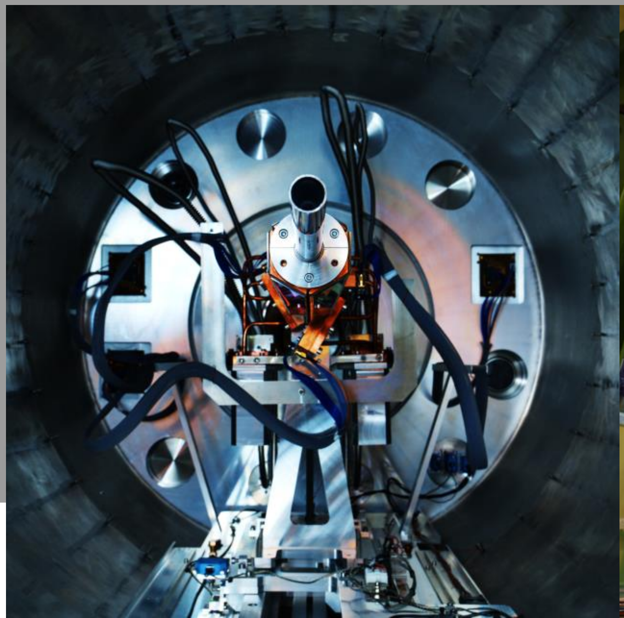
- Protons from the PSB impinged on a heated UC_x target
- VADIS ion-source
- Transfer line between ion source and target cooled to capture reactive products

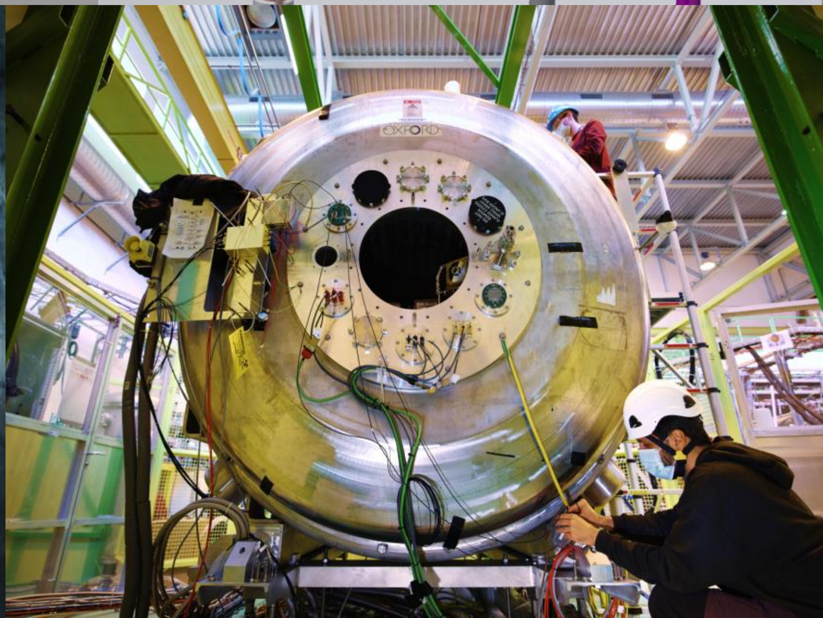
d(^{212}Rn,p)^{213}Rn reaction:

- 7.63 MeV/u
- ~10^6 pps
- Grid of ≈125 μg/cm^2 targets









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

Preliminary data analysis

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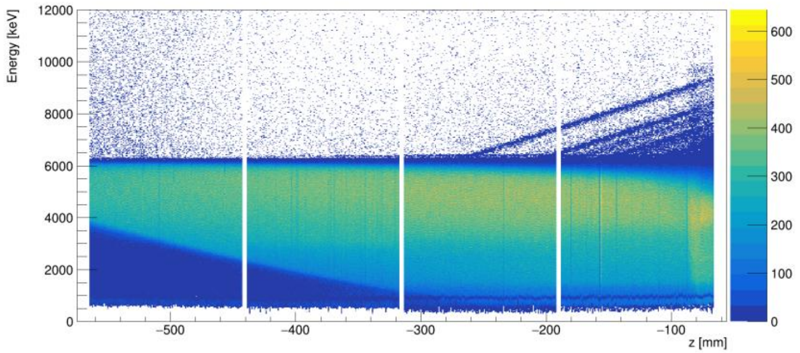
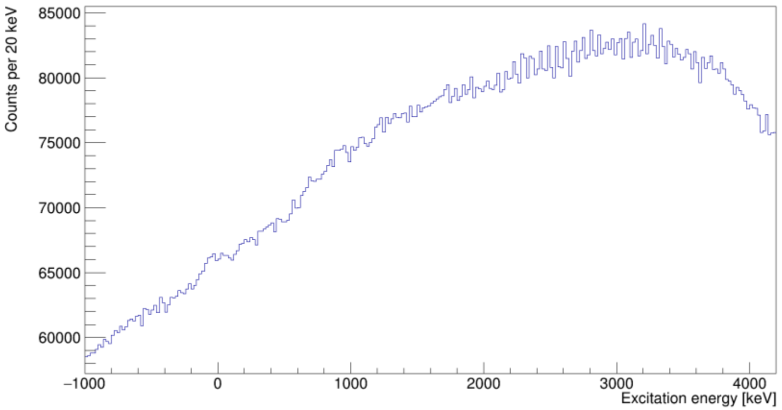
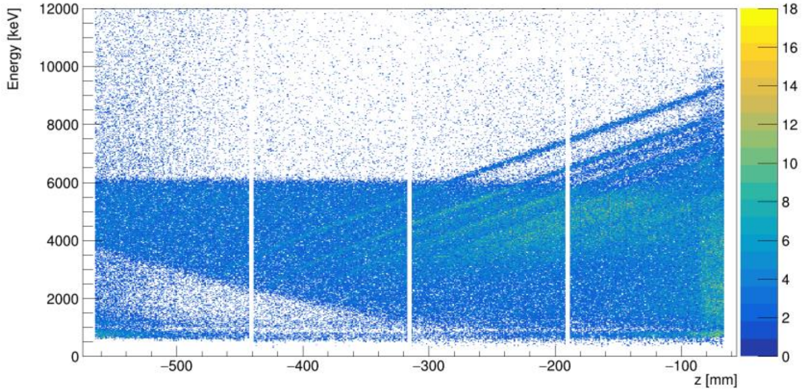


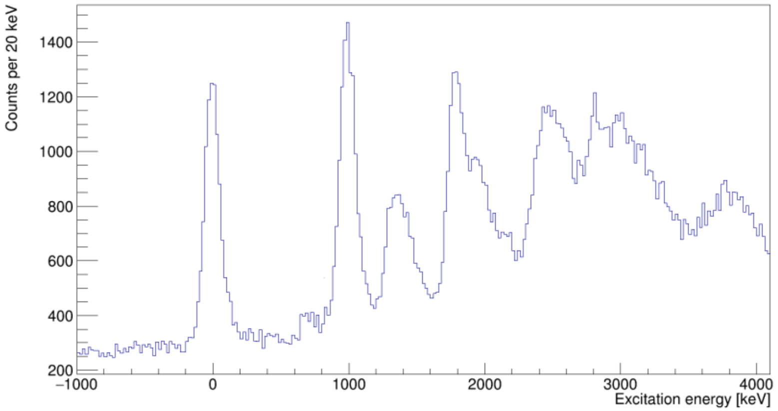
Singles

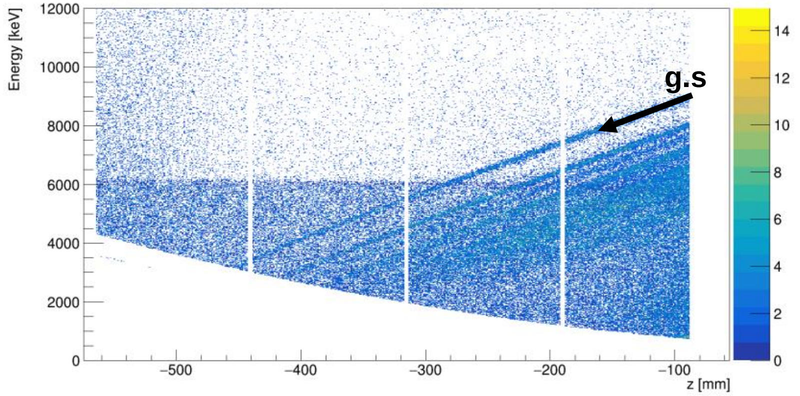
Large α background





Gating on EBIS-on time

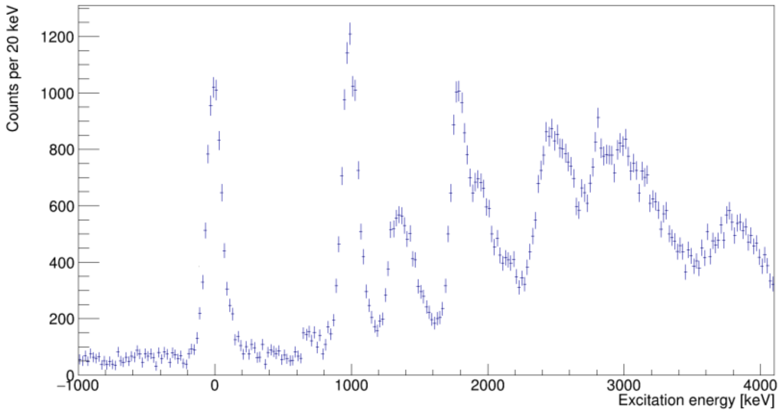




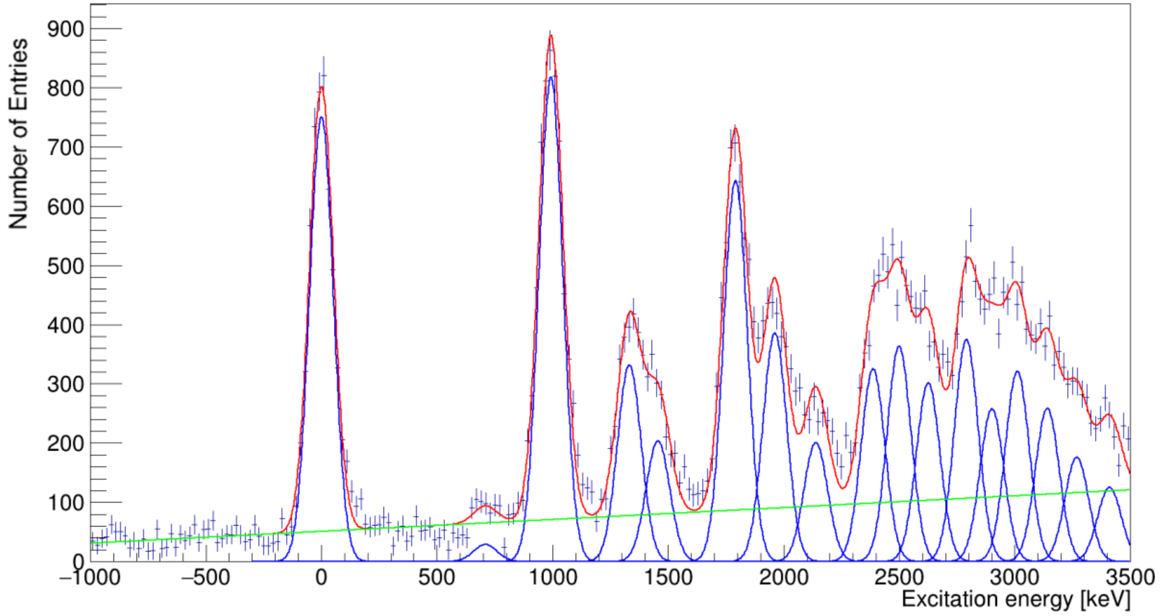
Subtracting EBIS-off time

θ_{cm} cuts - removes knees

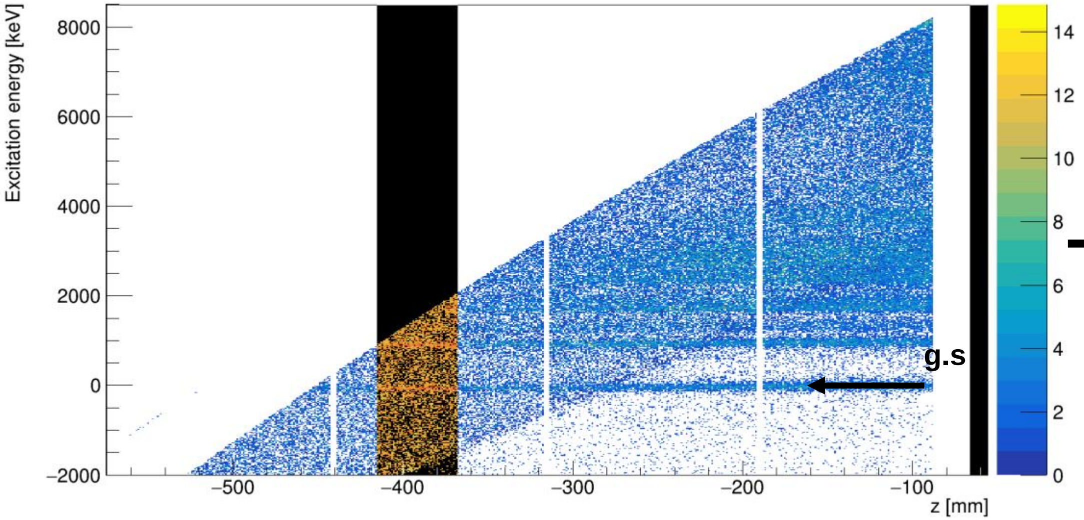
z cuts – remove double turns

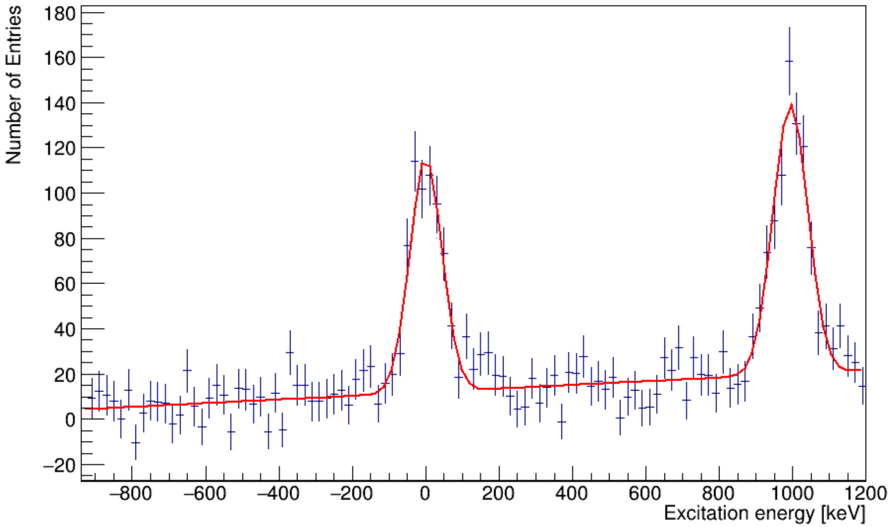


Preliminary excitation energy spectrum



- 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

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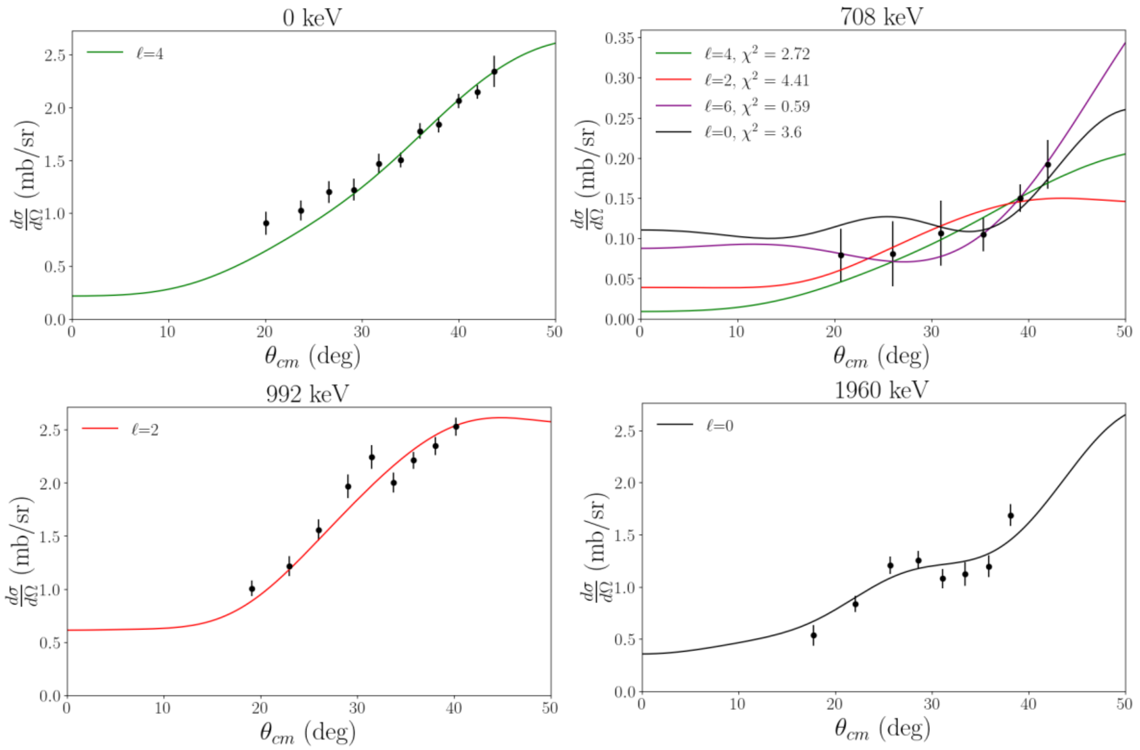
- PTOLEMY used to calculate angular distributions
- Measured angular distributions, compared to calculations and assignments made for states up to 2.1 MeV



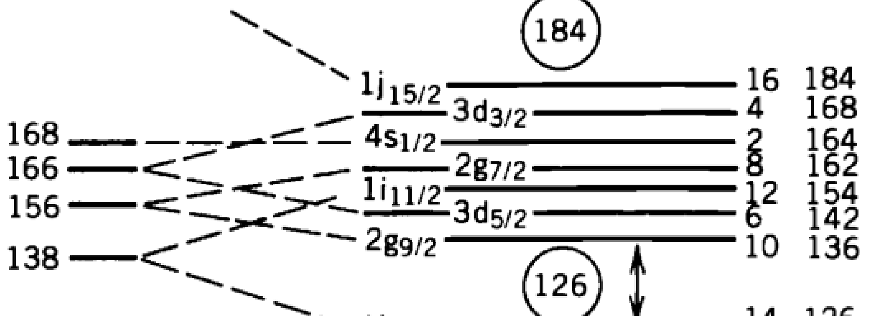
Energy / keV	L	nlj	S
0	4	$2g_{9/2}$	1.00
708(11)	6	$1i_{11/2}$	1.25
992(1)	2		0.31
1330(3)	2/0		0.12/0.22
1454(5)	2/0		0.08/0.16
1790(2)	2		0.26
1960(2)	0	$4s_{1/2}$	0.36
2139(5)	0	$4s_{1/2}$	0.21

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

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



Preliminary spectroscopic factors

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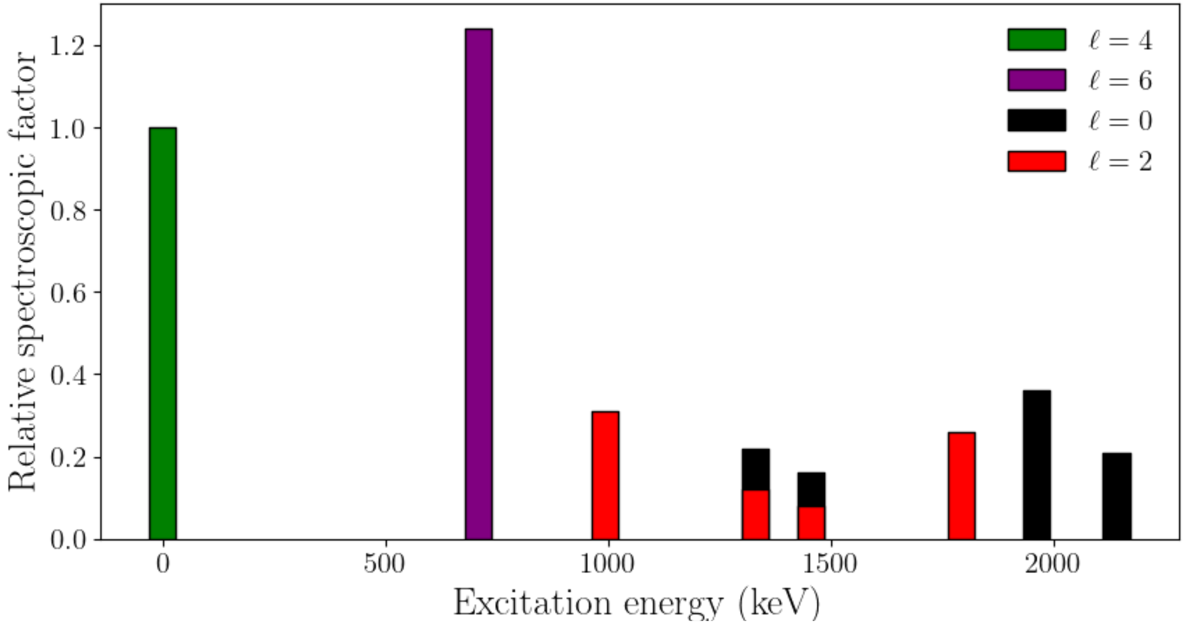
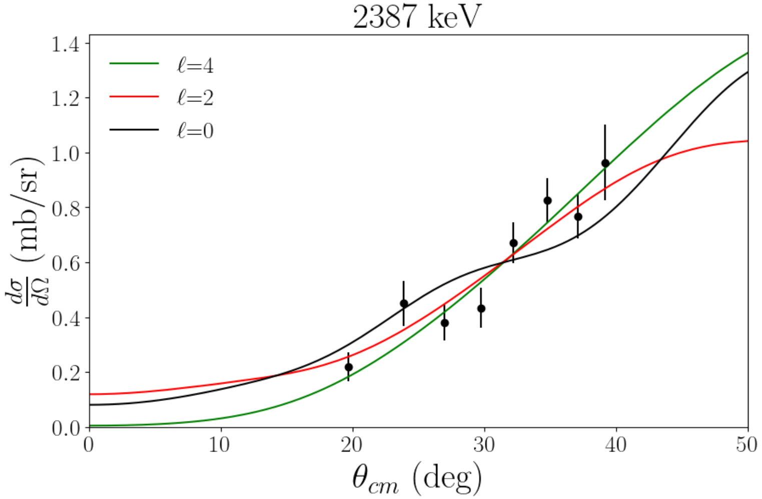
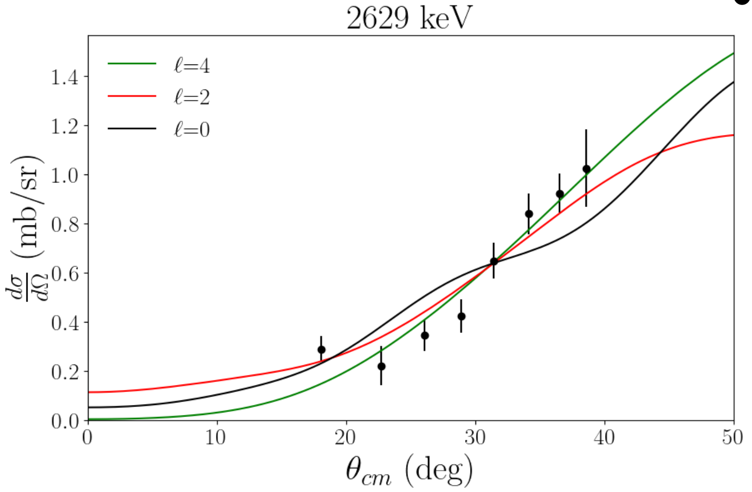
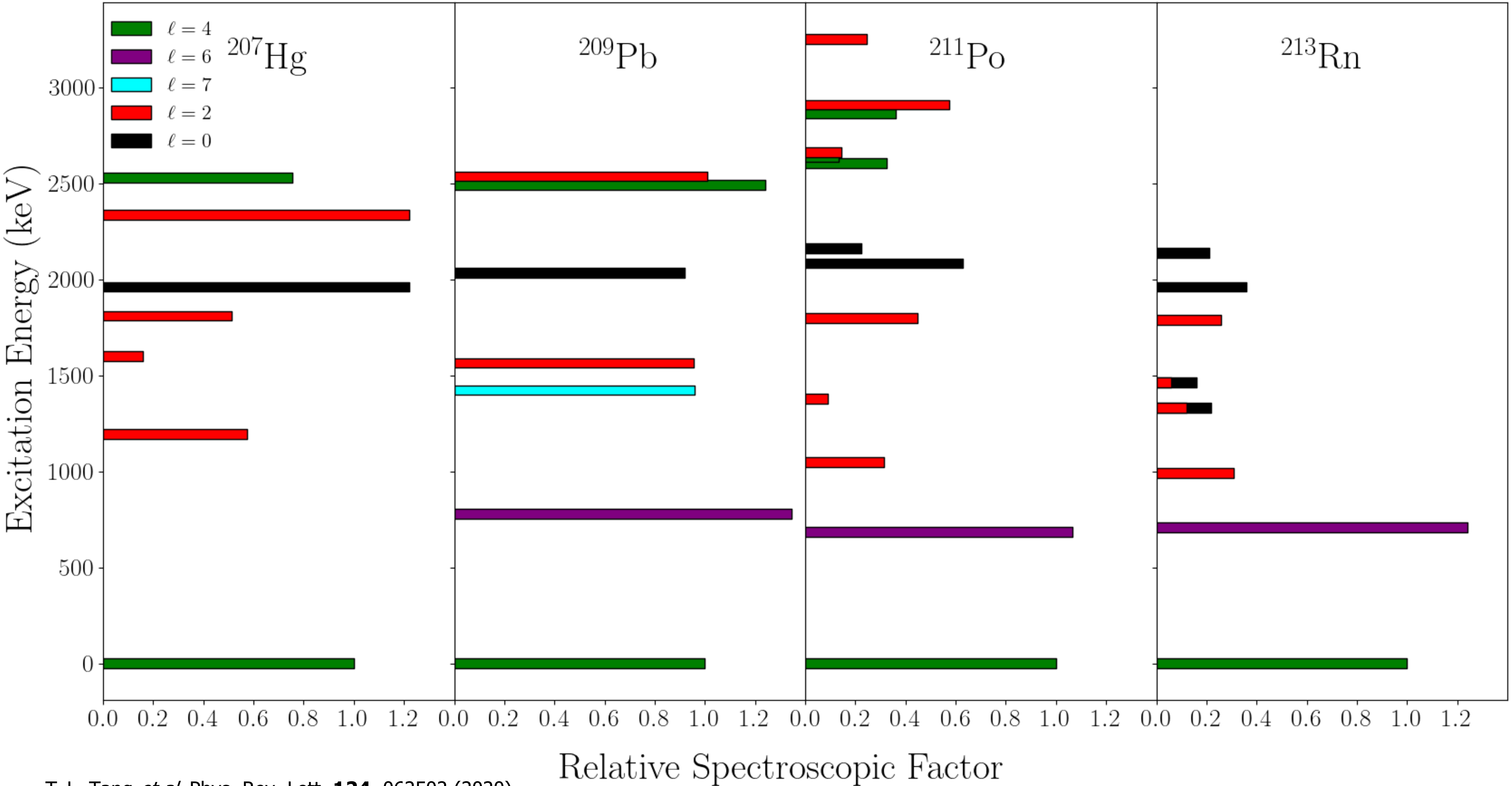






- Normalized to the $2g_{9/2}$ ground state
- If doublet states are both L=0, all $4s_{1/2}$ strength is here (Sum SF = 0.95)
- If doublet states are both L=2 and $3d_{5/2}$, most of the strength is here (Sum SF = 0.77)
- Challenging to assign states above 2.1 MeV
  - Larger uncertainties for cross sections
  - θ angle coverage decreases with excitation energy
  - PTOLEMY calculations become more similar

Systematics in this region



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

- 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
- Going forward:
  - Compare to modern shell-model DFT calculations (Gianluca Colò, Università degli Studi di Milano)

ISOLDE Solenoidal Spectrometer

Science and Technology Facilities Council

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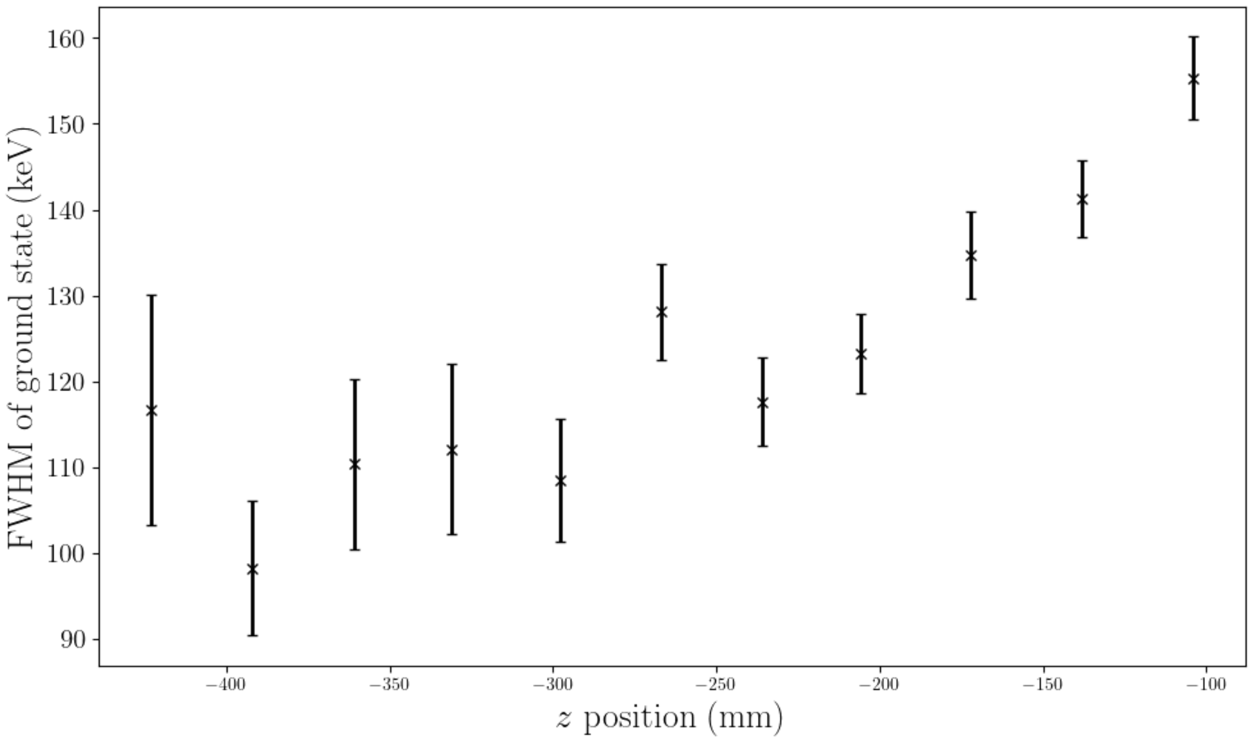
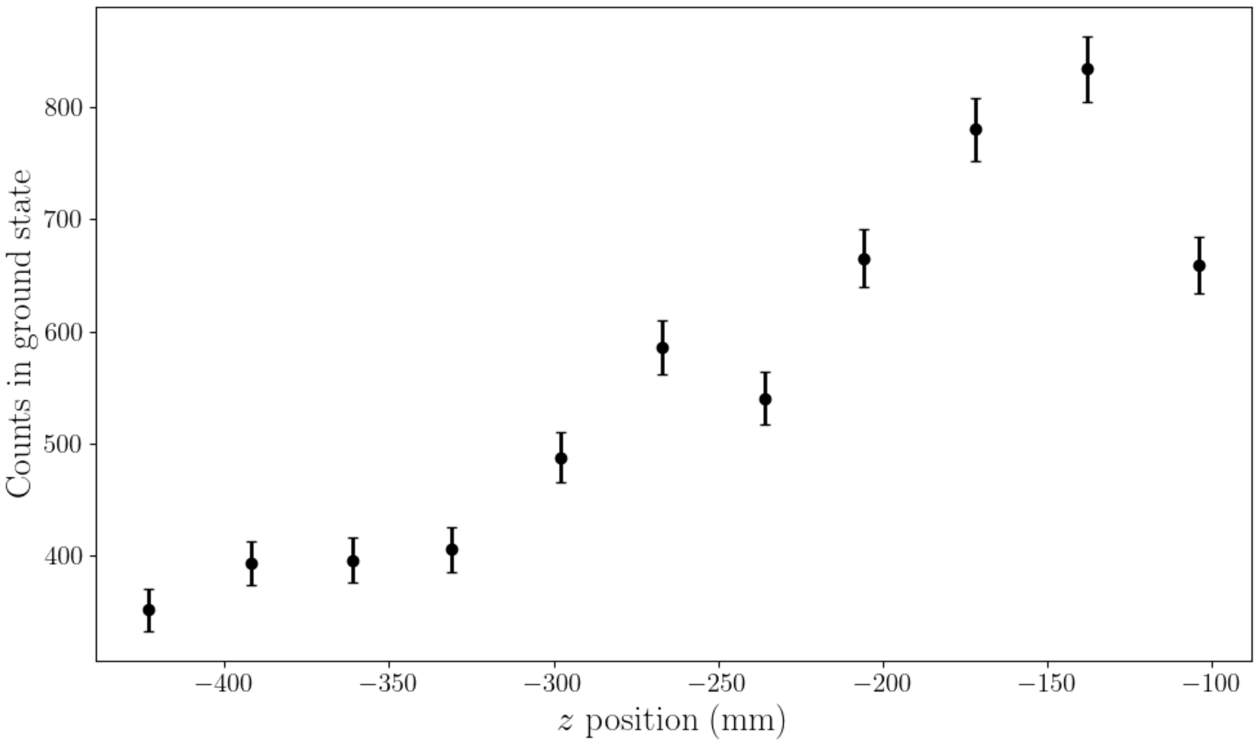
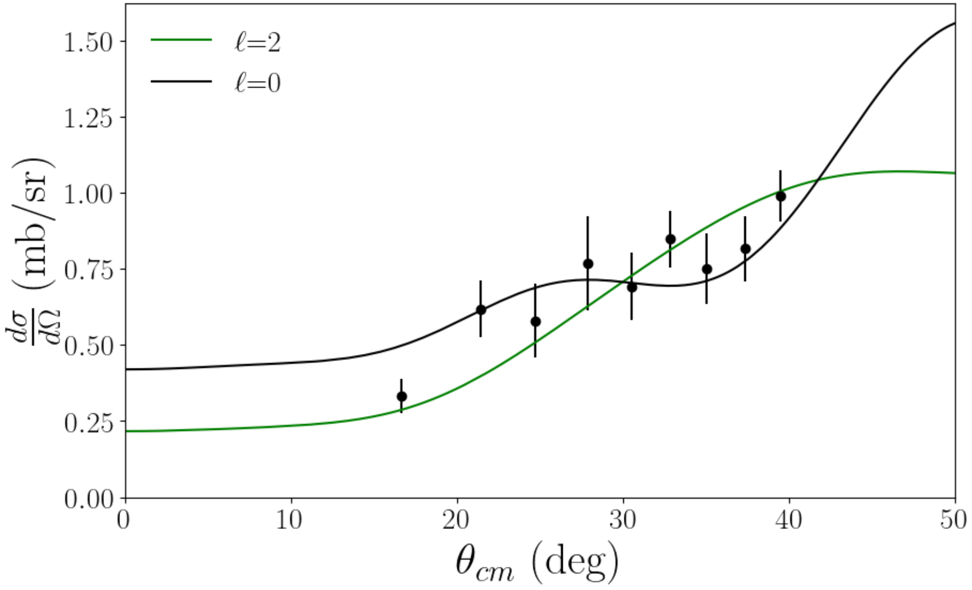
Resolution of the ground state

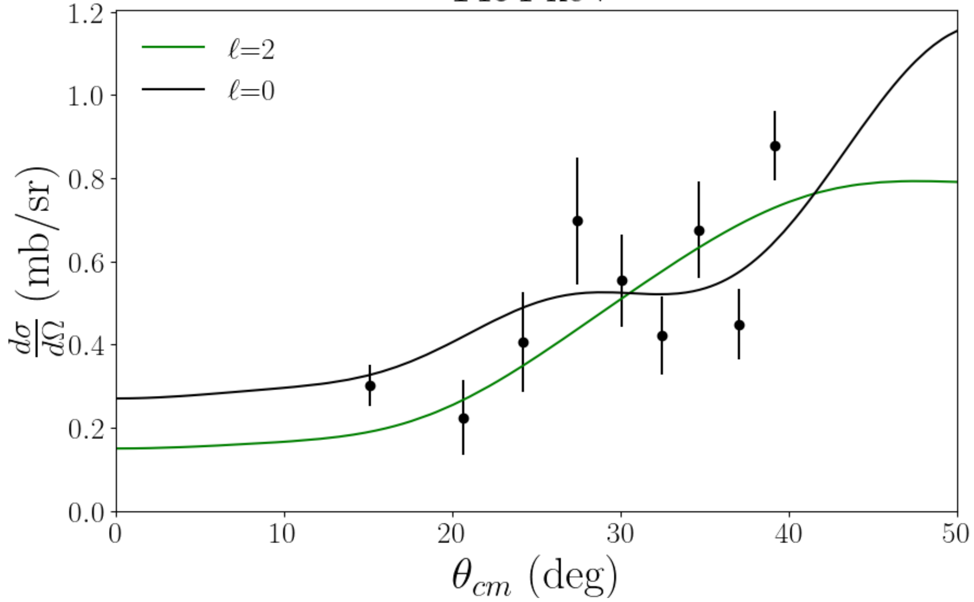




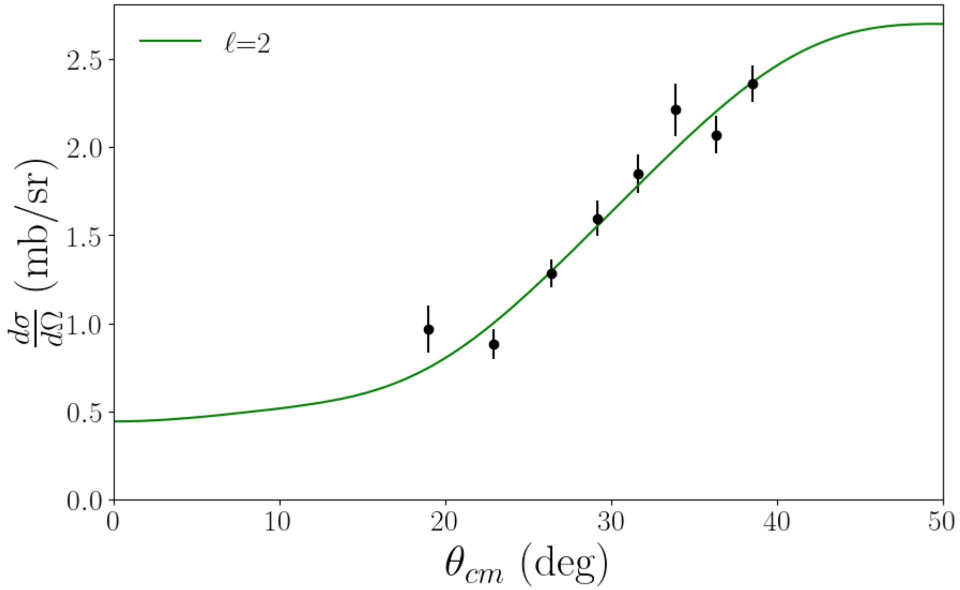
1330 keV



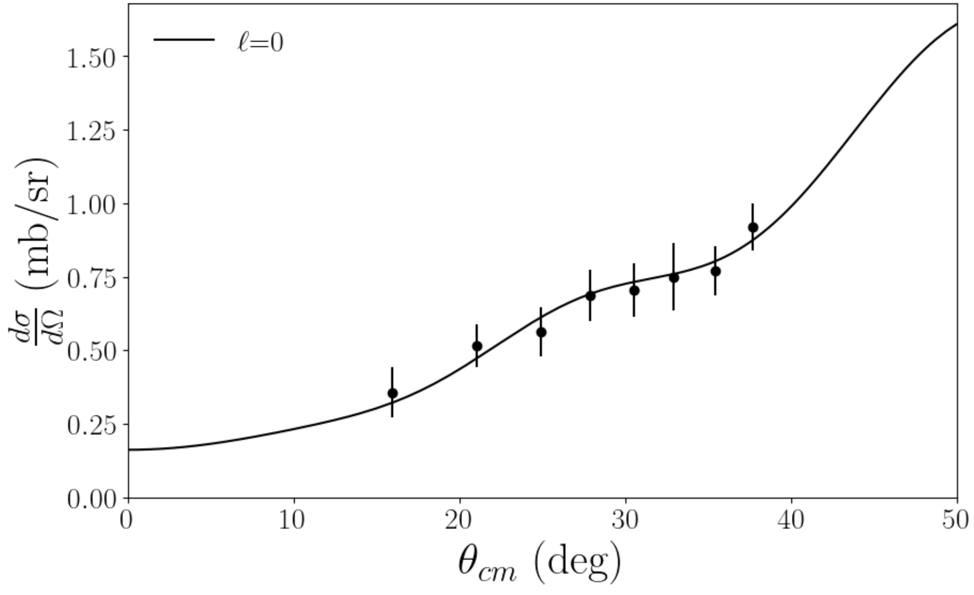
1454 keV



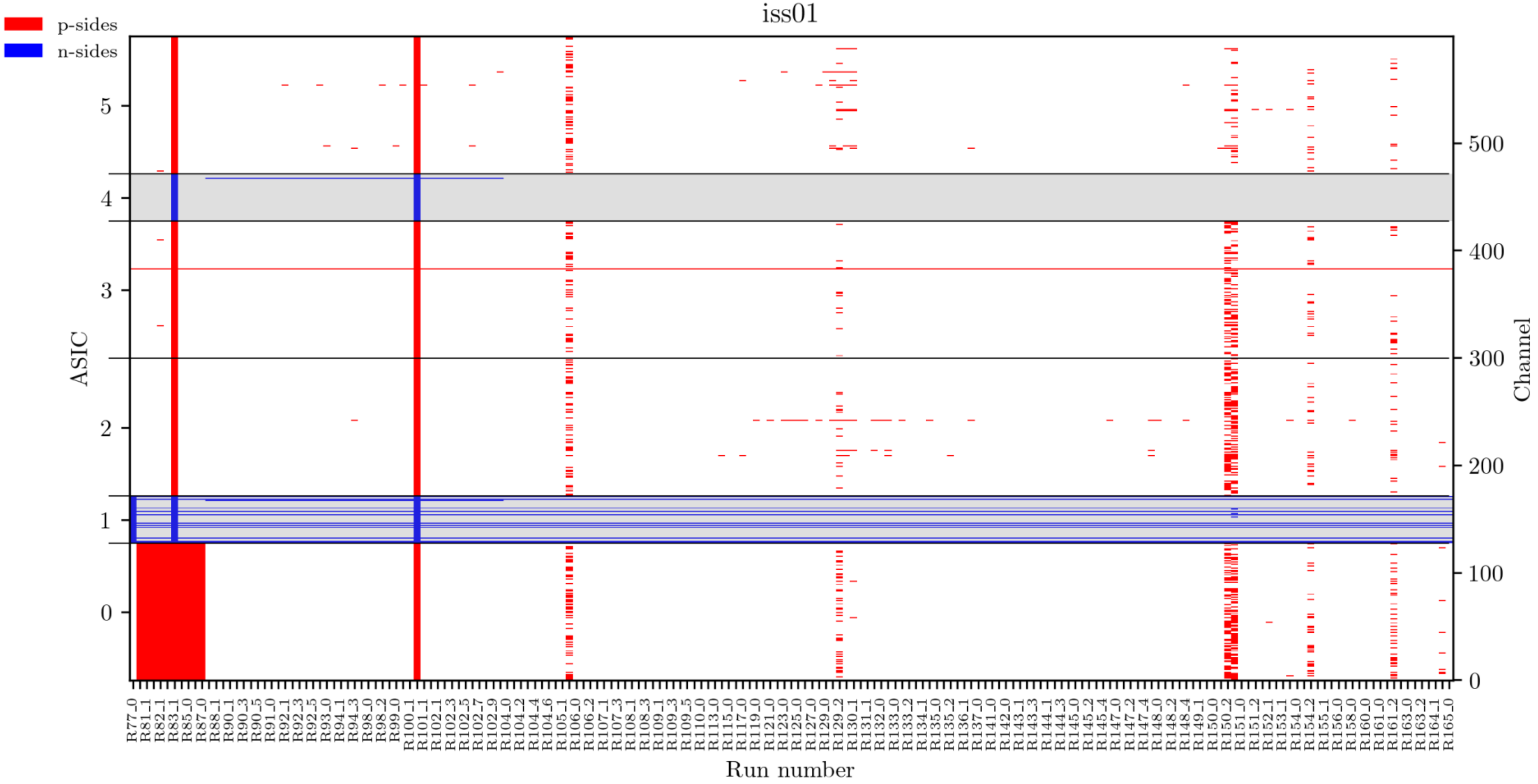
1790 keV



2139 keV

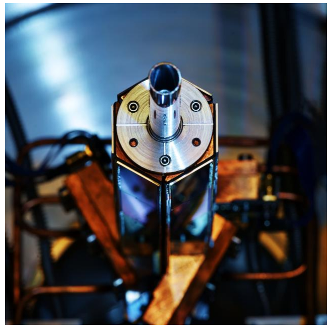


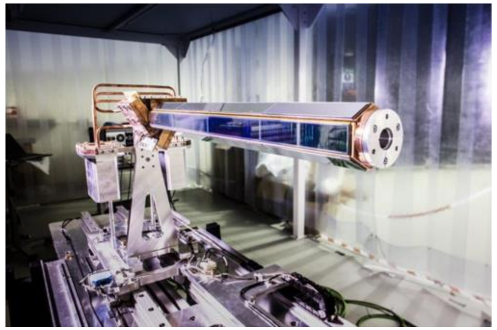
Solid angle corrections



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

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





Inverse kinematics

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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.

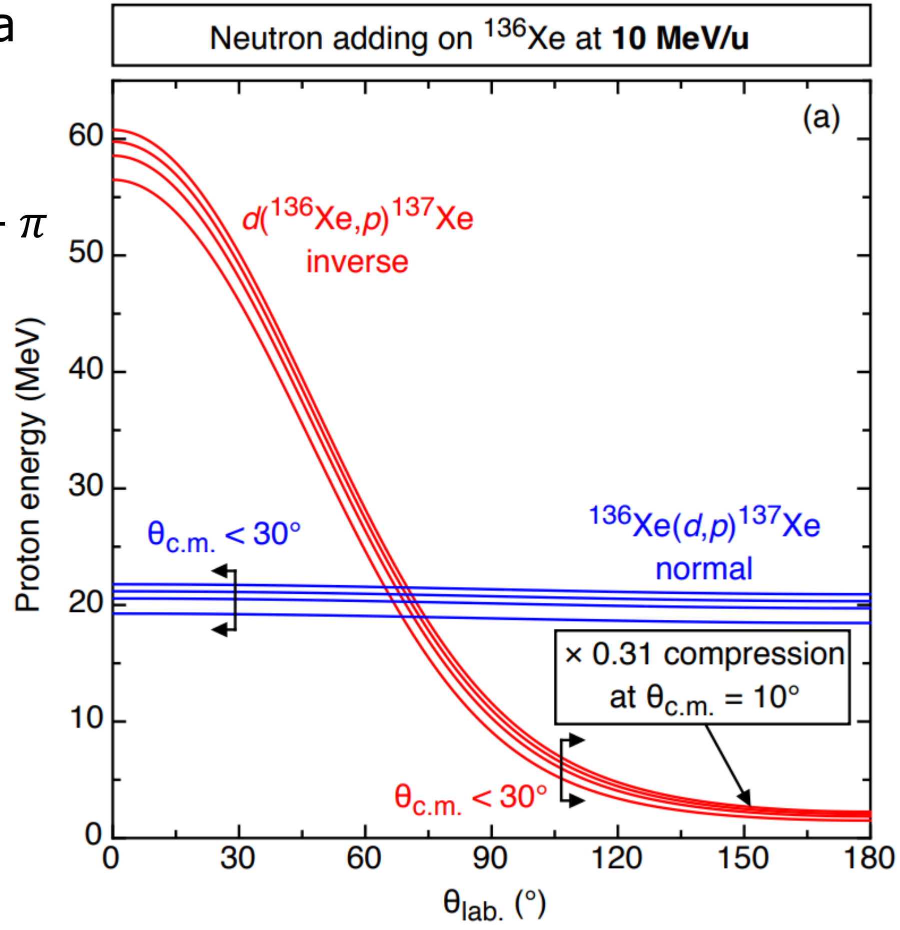
$$\Delta T_3 = A + B\sqrt{\frac{m_1}{m_2}}\cos\theta_{cm} = A - B\sqrt{\frac{m_1}{m_2}}\cos\eta_{cm}$$

$$\eta_{cm} = \theta_{cm} - \pi$$

- 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