

Evolution of single-particle structure probed with the ISOLDE Solenoidal Spectrometer

ARIS 2023
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ISS Collaboration Spokesperson

Overview

- Brief introduction to solenoid technique
- Overview of ISS operation.
- Summary of ISS physics (preliminary).
- Single-particle properties of nuclei
 - Along $N=17$
 - Along $N=127$
- Future capabilities – transfer-induced fission



Direct reactions

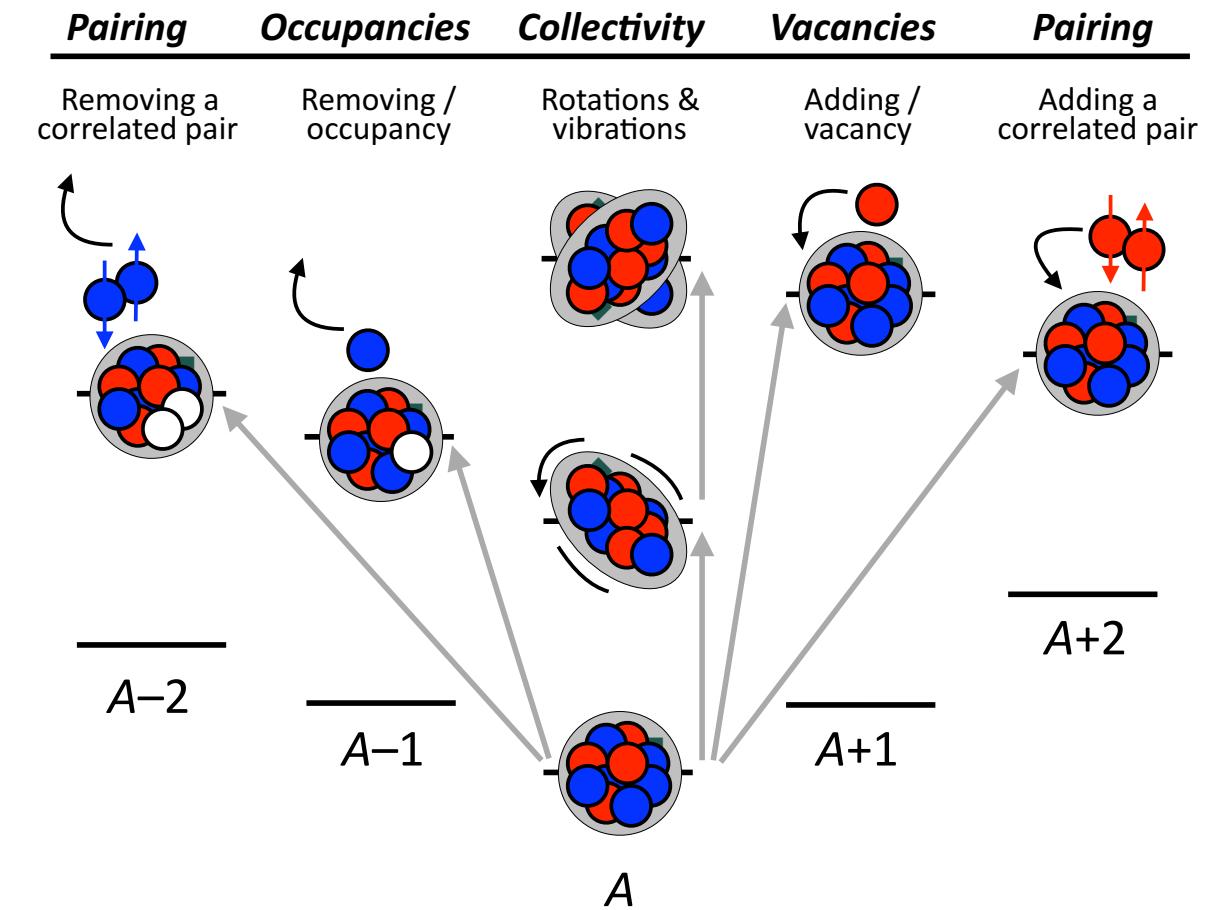
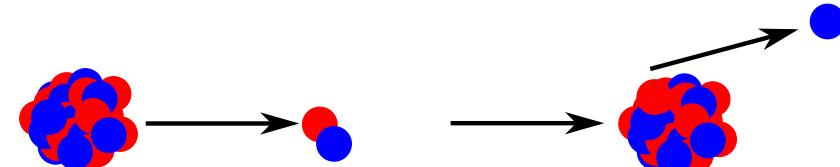
Access to variety of nuclear structure information

Single-particle states, $E_{(Ex,SP)}$, I , spectroscopic factors,
e.g. (d,p) , $(p,d)\dots$

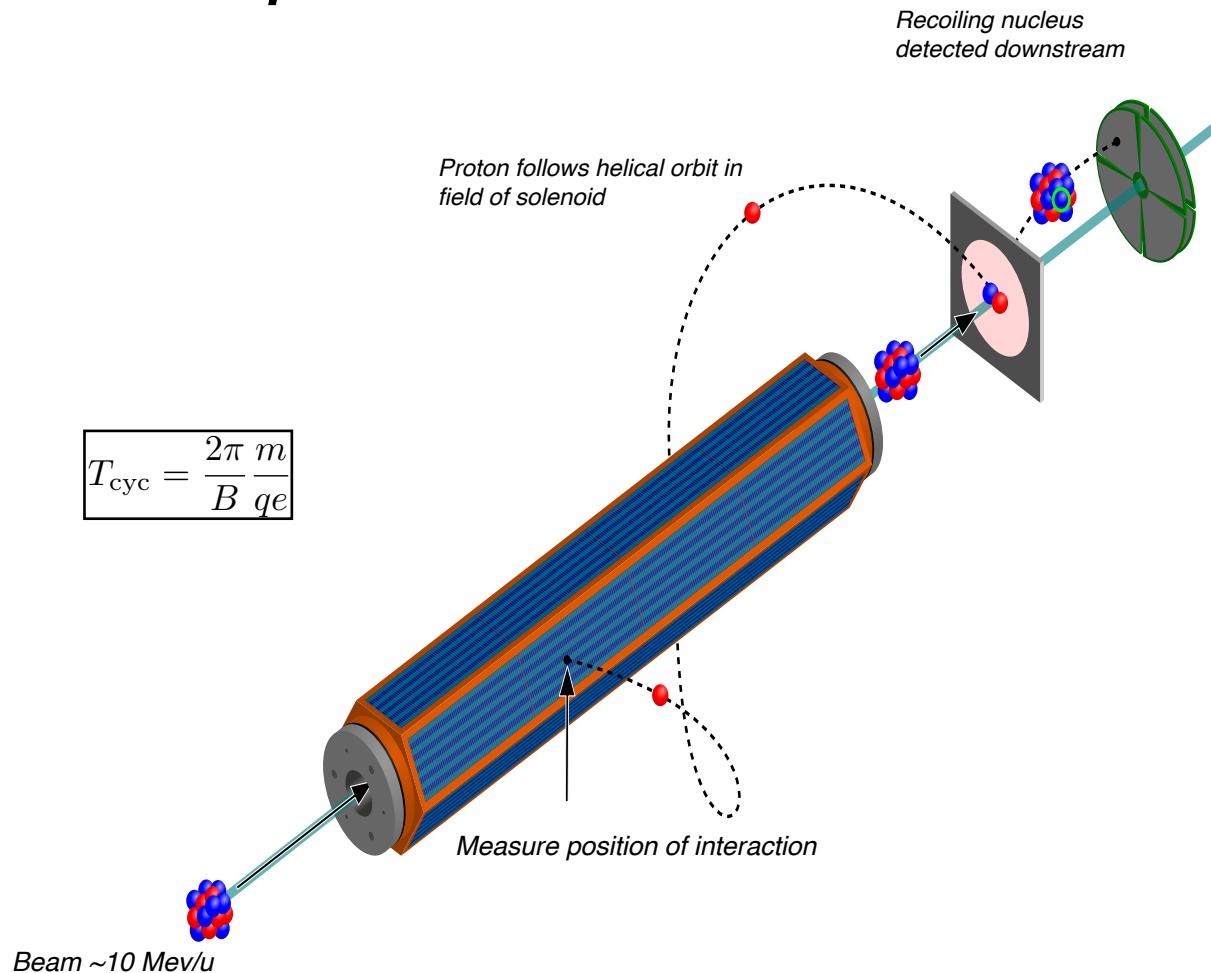
Pair-correlations, $E_{(Ex)}$, $\ell\ell$, e.g. (p,t) , $(t,p)\dots$

Collective properties via e.g. (p,p') , (d,d') , $(\alpha,\alpha')\dots$

Reactions performed ~ 10 Mev/u (few to 10s MeV/u).



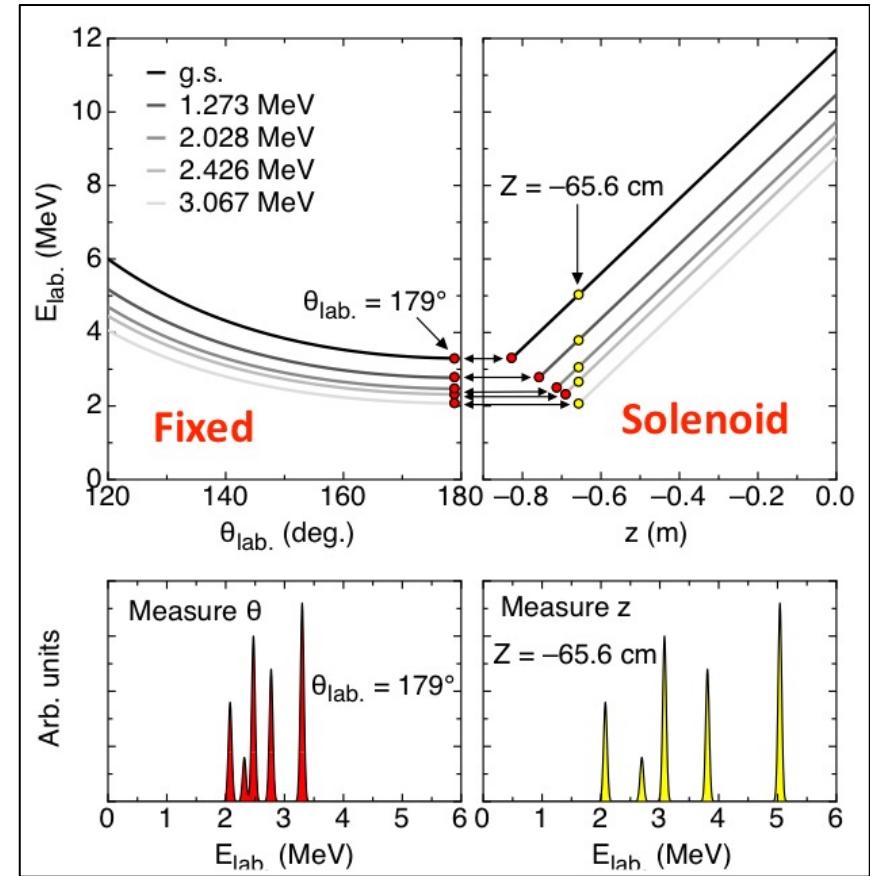
Solenoid technique



MEASURED QUANTITIES: position z , cyclotron period T_{cyc} and lab particle energy E_p .

Suffers no kinematic compression of the Q-value spectrum.

Linear relationship between E_{cm} and E_{lab} .



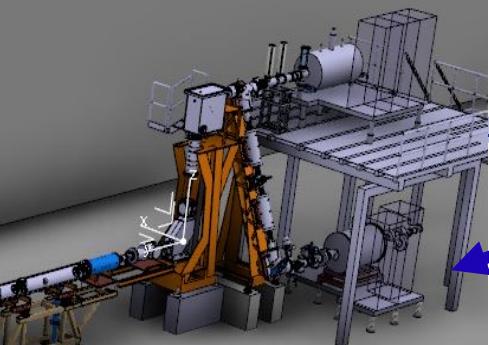
$$E_{\text{cm}} = E_{\text{lab.}} + \frac{m V_{\text{cm}}^2}{2} - \frac{m z V_{\text{cm}}}{T_{\text{cyc}}}$$

Physics at HIE-ISOLDE with a solenoid

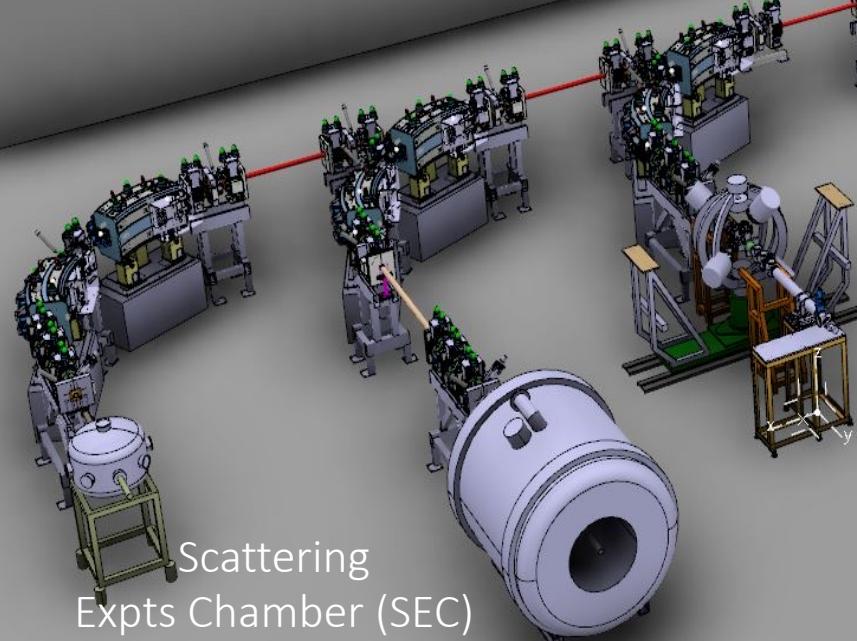


HIE super-conducting linac <9.5 MeV/u

Four cryomodules each with five rf cavities



REX normal-conducting linac
<3.1 MeV/u (2001-12)



MINIBALL
(array of 24
segmented Ge
crystals)

*For direct reactions – ideally **10MeV/u** beams
at intensities > **10^5 pps** – 5 day experiment.*

Scattering
Expts Chamber (SEC)

ISOLDE Solenoidal Spectrometer (ISS)

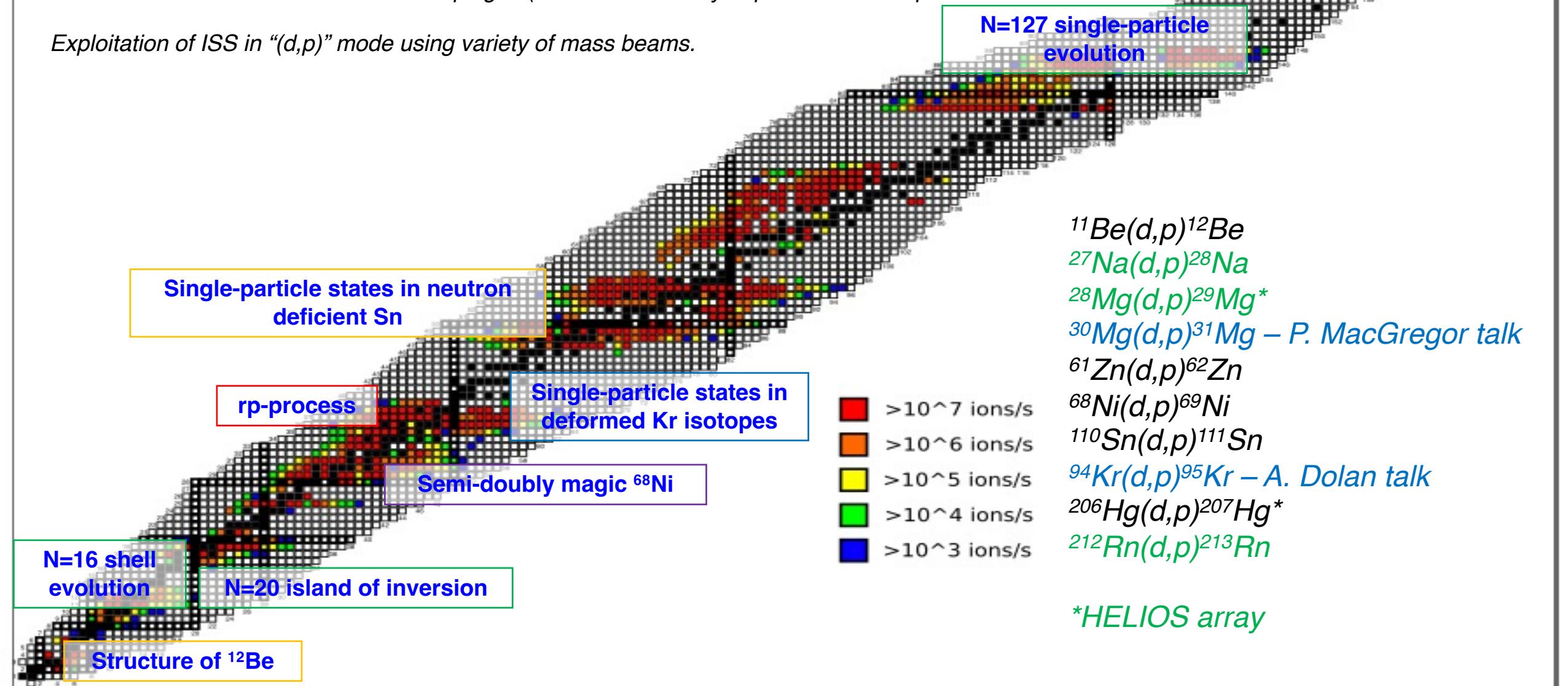


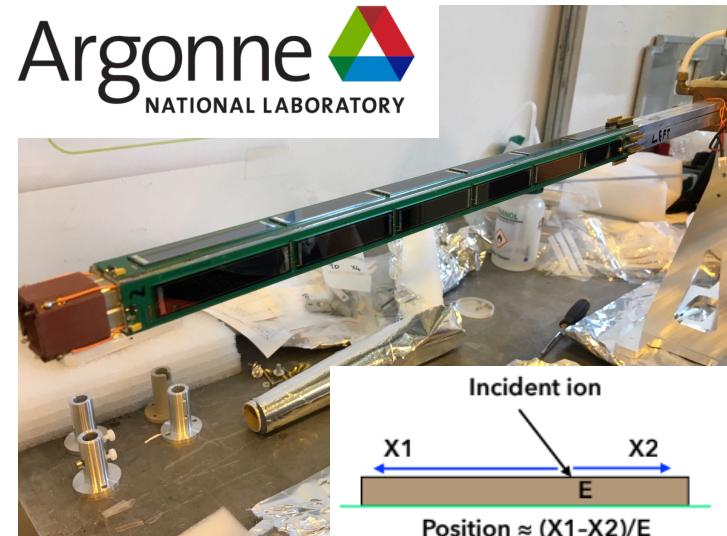
ISS summary

ISS fully commissioned June 2021 (early exploitation campaign 2018).

8 measurements from it's first 2 full campaigns (2 made in an early-exploitation mode pre-LS2).

Exploitation of ISS in “(d,p)” mode using variety of mass beams.





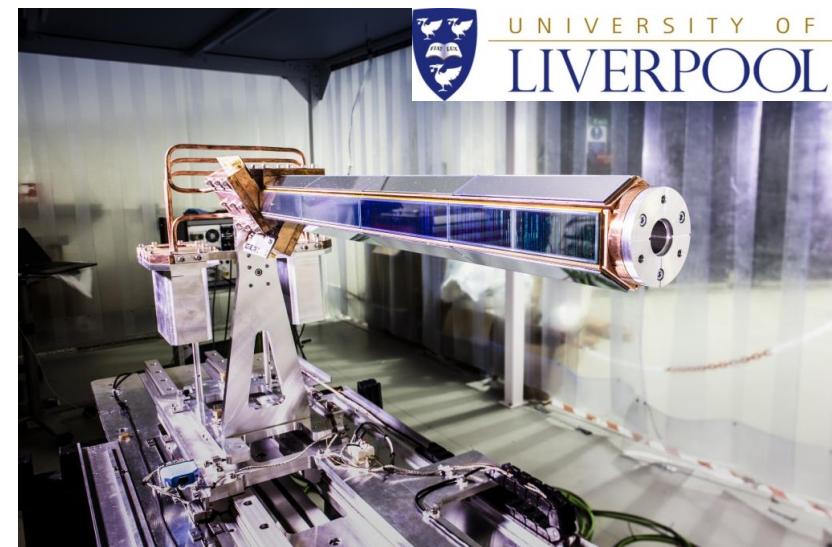
HELIOS silicon array

Used for early-exploitation before LS2.

Four-sided array consisting of six resistive-strip silicon detectors.

Total silicon length $\sim 300\text{mm}$.

42% solid angle coverage.



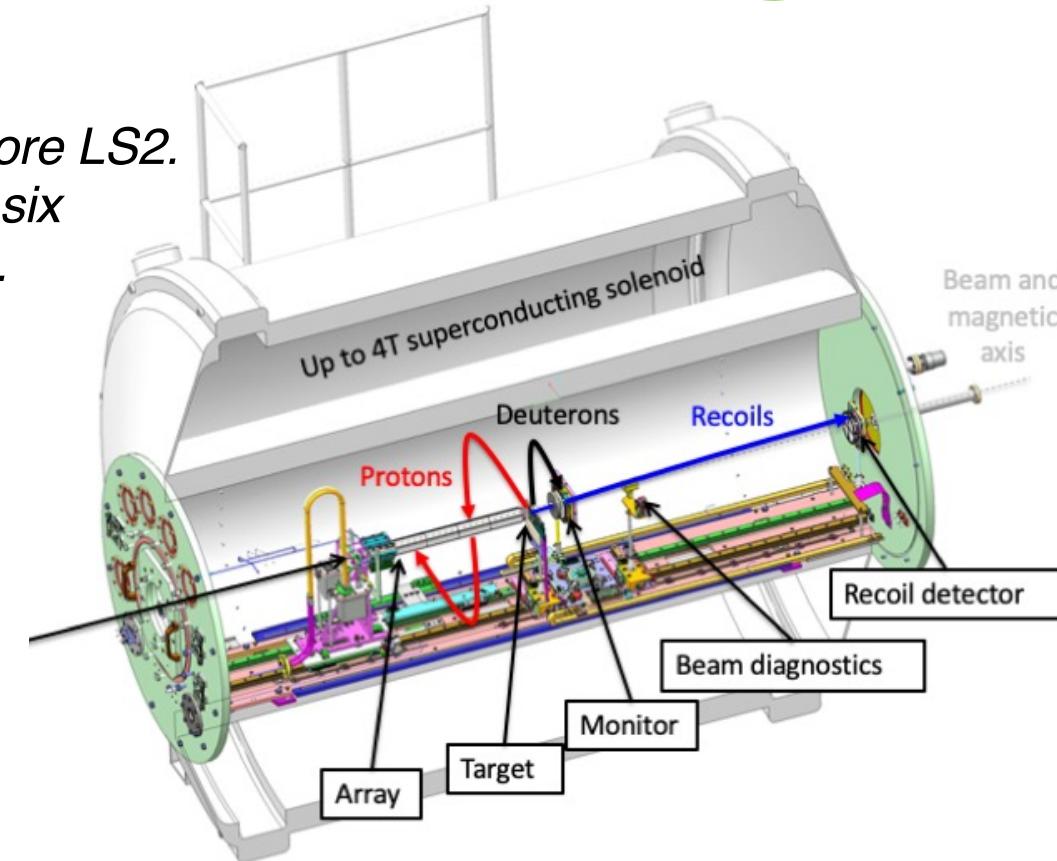
New silicon array

Six-sided array consisting of four DSSSDs with ASICs readout (R^3B) on each side.

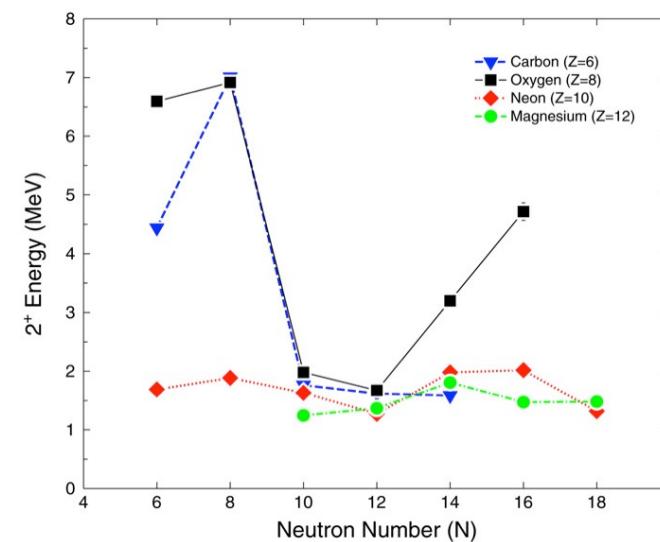
Each detector consists of **128 x 0.95mm strips** along the length of the detector **11 x 2mm** along the width. **1668 channels of readout**.

Total length of silicon is 510.4mm (486.4mm active).

66% solid angle coverage.

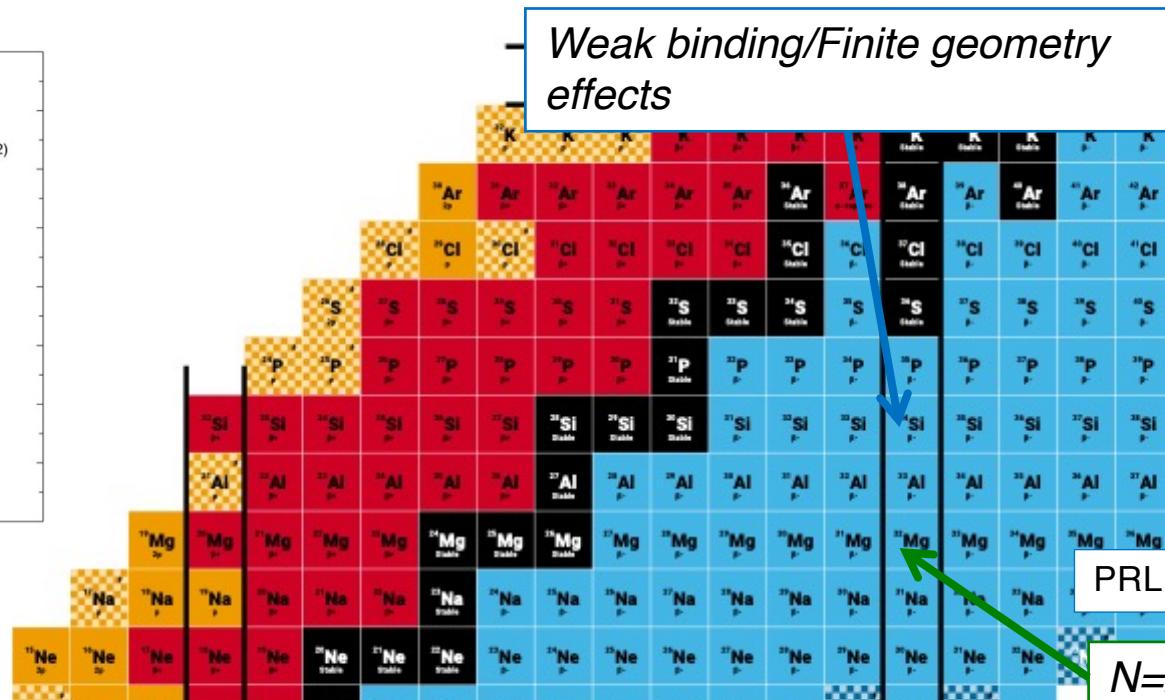


Evolving nuclear structure in n -rich nuclei



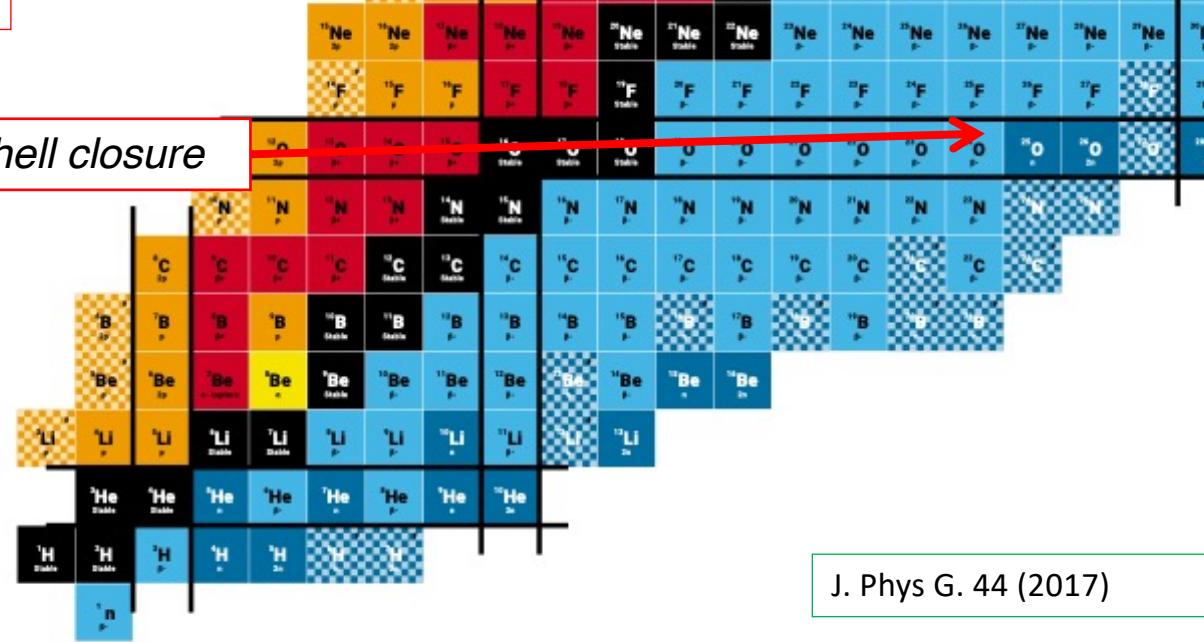
PLB 672 17 (2009)

- Weak binding/Finite geometry effects

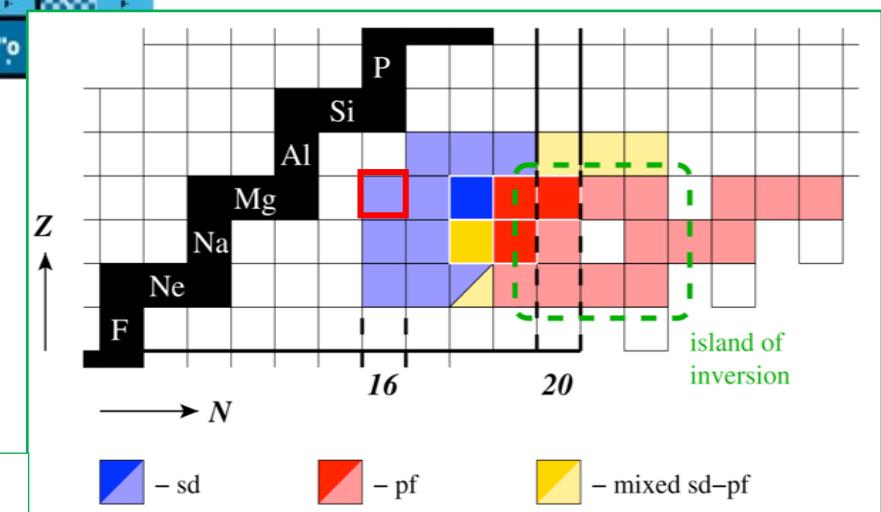


PRL 119, 182502 (2017); PRL 84, 5493 (2000).

$N=20$ Island of Inversion



J. Phys G. 44 (2017)



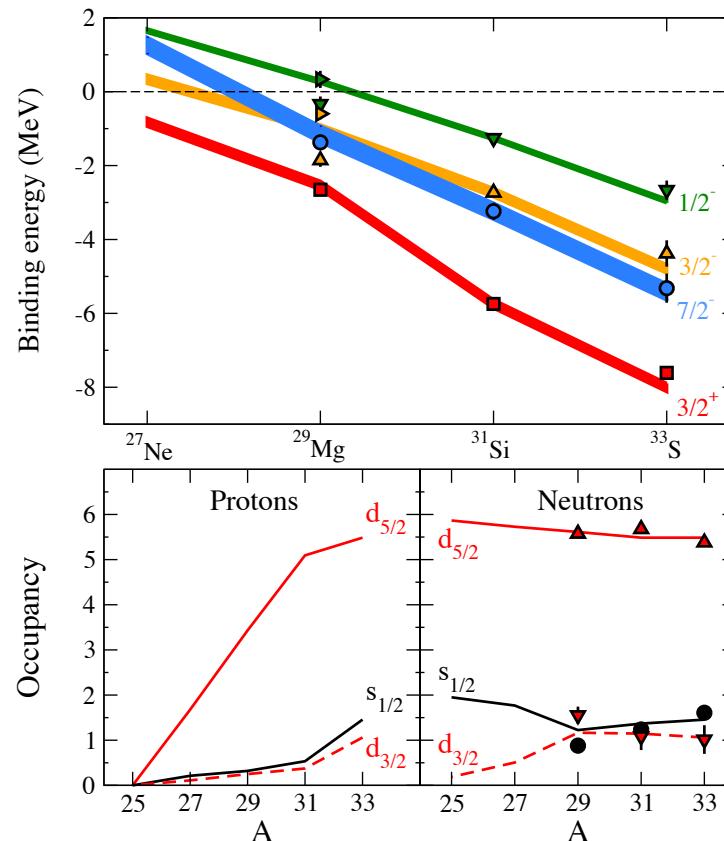
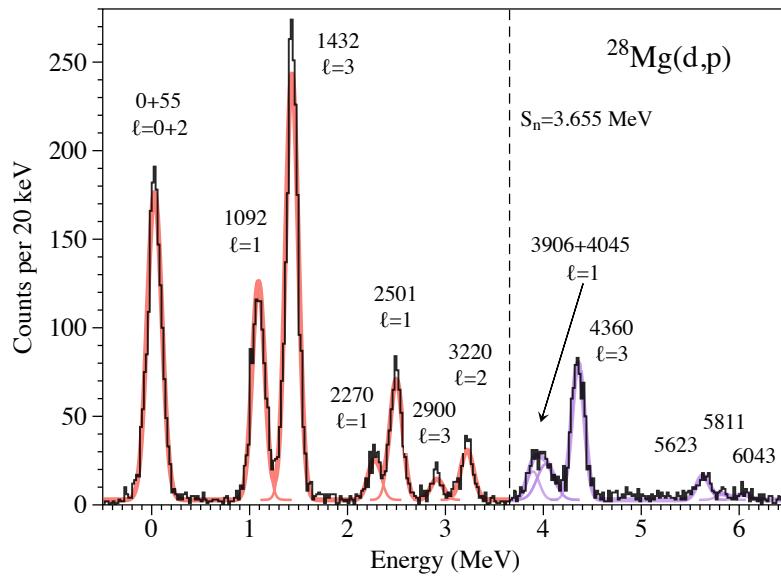
Trends in $N=17$ isotones

$^{28}\text{Mg}(d,p)^{29}\text{Mg}$ reaction measured before LS2 and data combined with existing stable systems.

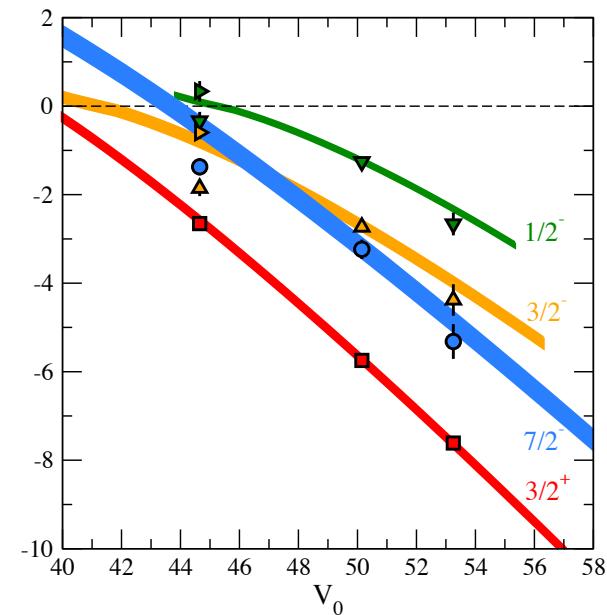
Strength distribution compares well to calculations – only $0p$ - $0h$ or $1p$ - $1h$ needed.

Energy centroids are well reproduced by SM calculations.

Extracted neutron occupancies also compare well.



Woods-Saxon calculations also reproduce changes in BE. Smooth reduction in SO separation by ~ 500 keV from stability.
Effect of finite geometry of potential well.



Trends in $N=17$ isotones – odd Z systems

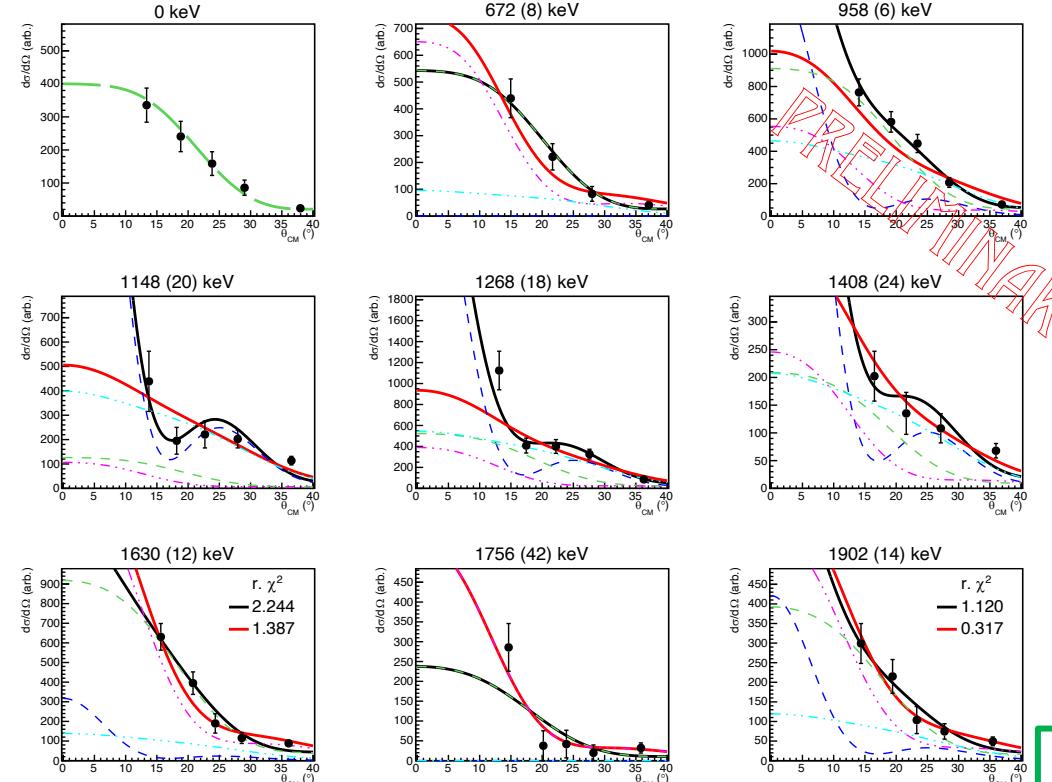
Study of single neutron outside $N=16$ has been extended to look at odd- Z systems.

$^{29}\text{Al}(d,p)^{30}\text{Al}$ (HELIOS), $^{27}\text{Na}(d,p)^{28}\text{Na}$ (ISS)

Aim to identify the negative-parity states in these systems and their relative behaviour as protons are removed.

Reaction of interest identified through recoil gating.

Angular distributions provide identification of parity (+ve $I=0+2$, -ve $I=1+3$).



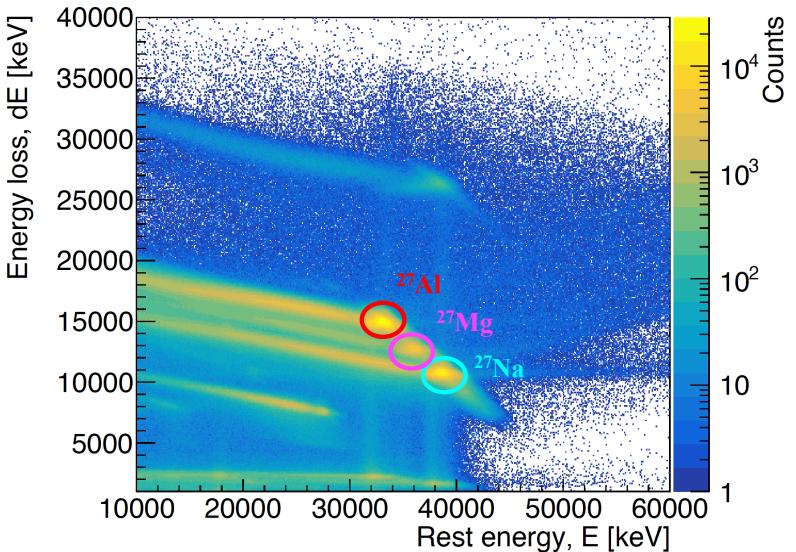
Courtesy of S Reeve

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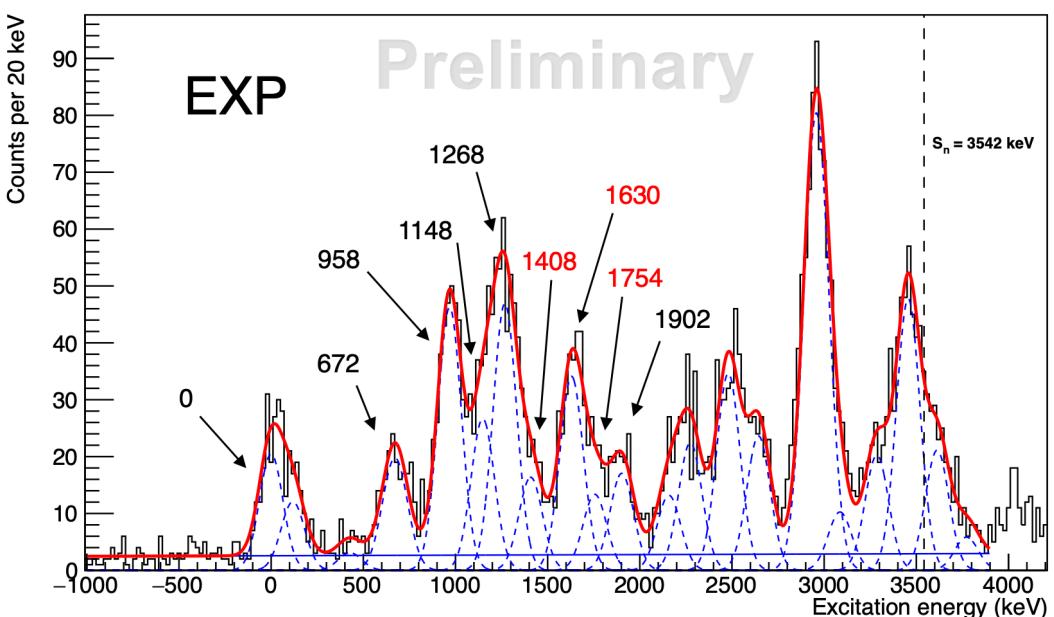
The University of Manchester



Recoil E-dE plot for sector 2



8×10^5 pps @ 9.7 MeV/u ^{27}Na



Trends in $N=17$ isotones – odd Z systems

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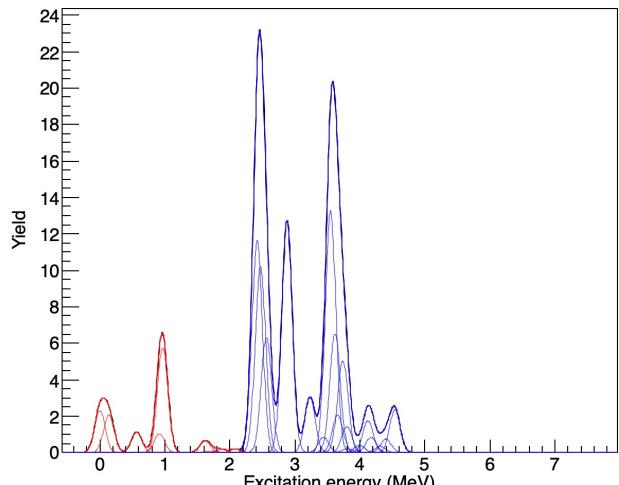
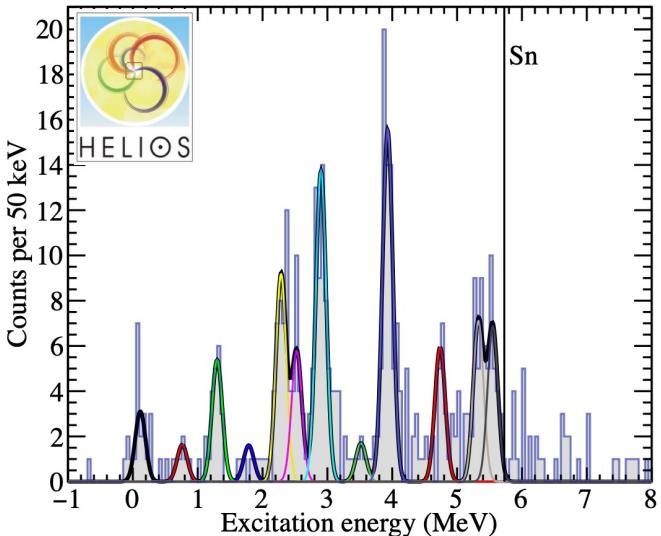
The University of Manchester



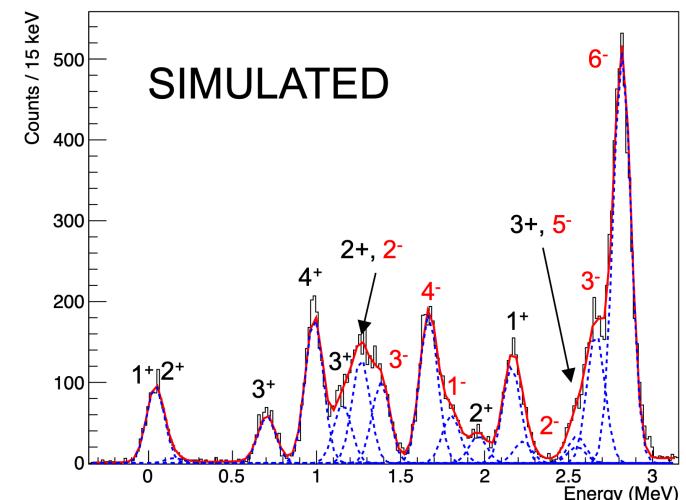
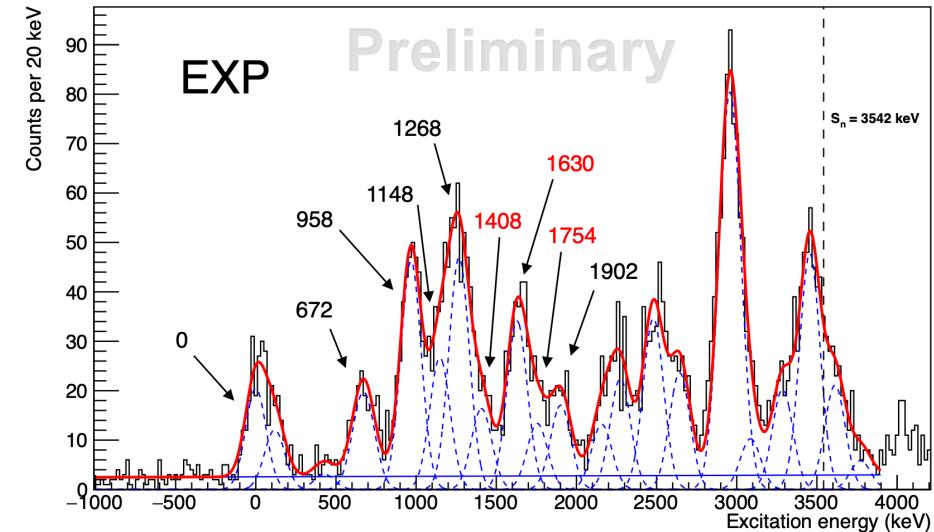
A cursory analysis of the data compares favourably to SM calculations using FSU interaction in terms of distribution of cross section.

Comparison to SFs needed still.

4x10⁴pps @ 10.5 MeV/u ^{29}Al



8x10⁵pps @ 9.7 MeV/u ^{27}Na



Courtesy of S Bennett and S Reeve

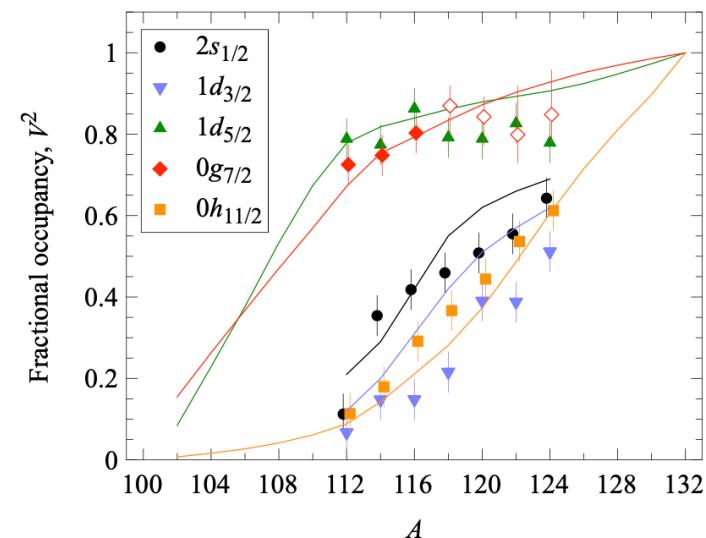
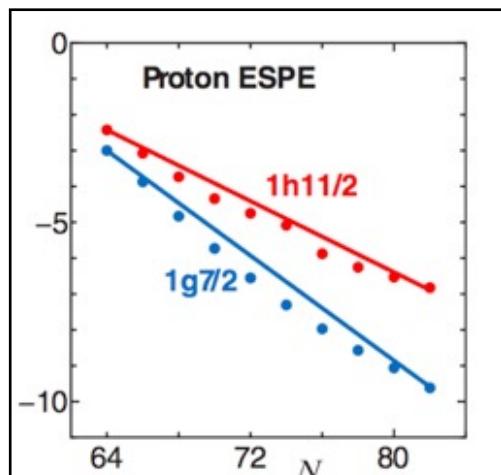
Evolution of single-particle structure along shell-closures



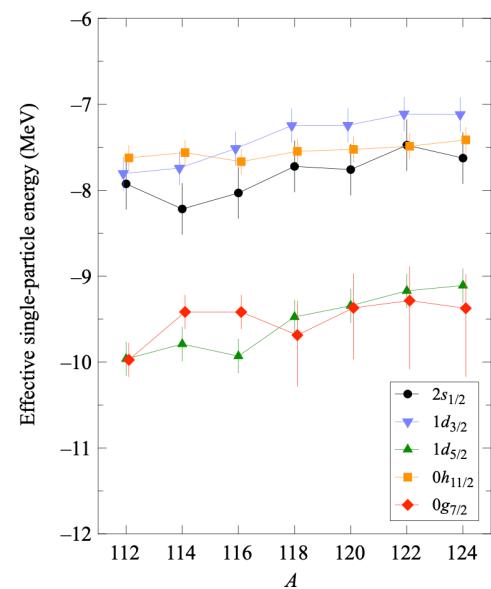
Trends observed in light nuclei have even been observed in stable heavier nuclei - Changes in high- j states as high- j orbitals are filling.

Studies of chains of isotopes/isotones have pointed to fairly robust mechanisms for these changes such as the requirement to include a tensor interaction ($N=51$, $Z=51$, $N=83$). ESPE's and occupancies mapped out in stable systems.

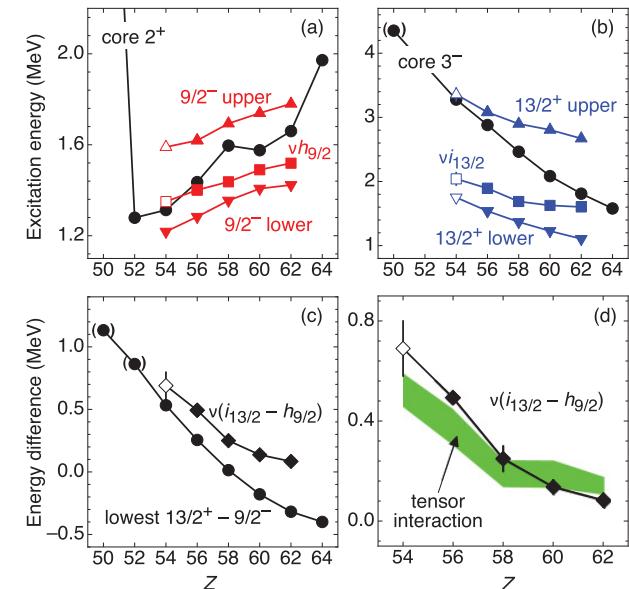
Access to RIBs at HIE-ISOLDE allows access to measurements across large chains of isotopes/isotones probing the interactions further from stability (Sn isotopes) and in new regions such as $N=127$.



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



S. Szwec et al., Phys. Rev. C **94**, 054314 (2016)

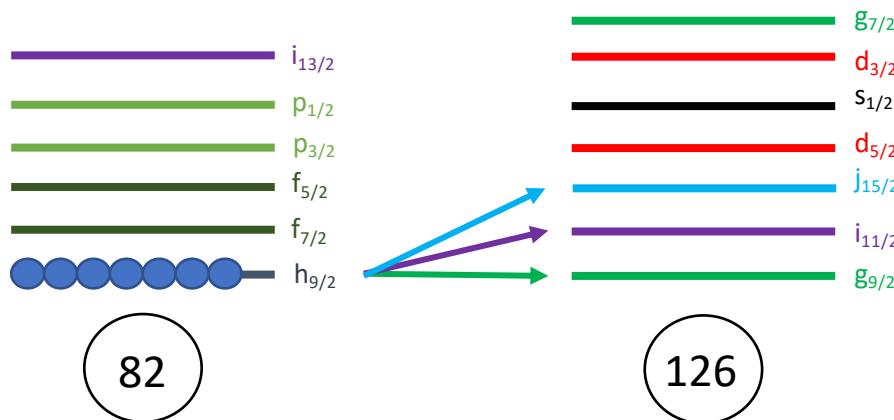


B. P. Kay et al, Phys.Lett.B **658** 216 (2008)
B. P. Kay et al, Phys.Rev.C **84** 024325 (2011)

IS689 - Single-particle structure along N=127 - $^{212}\text{Rn}(d,p)^{213}\text{Rn}$

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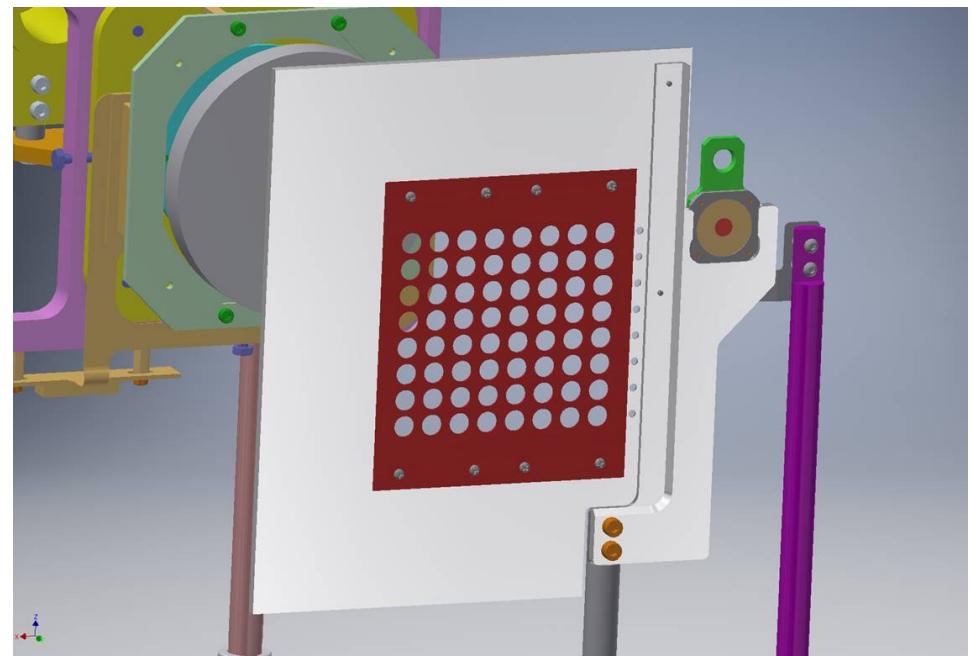
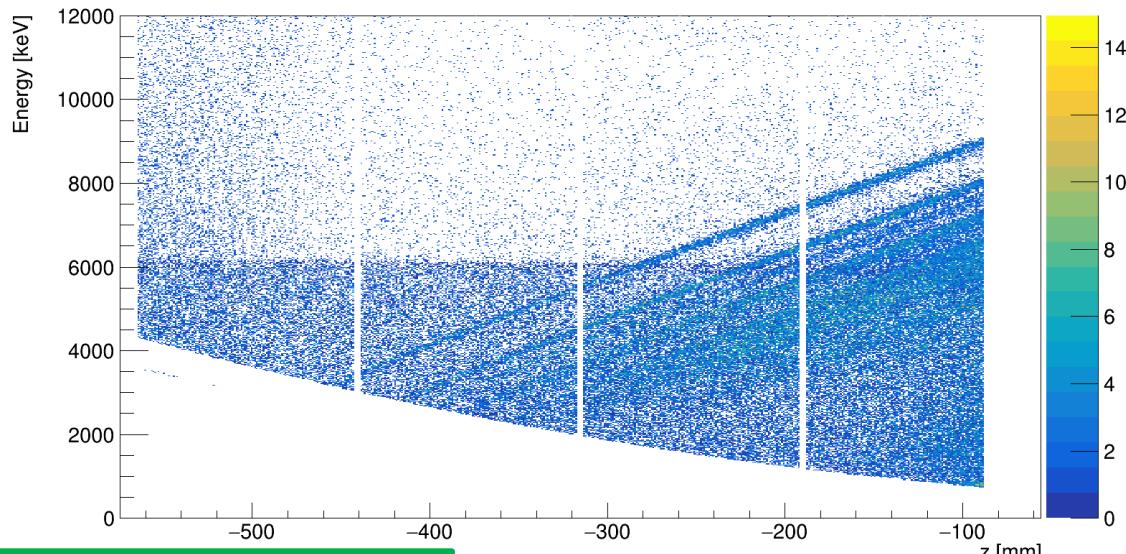
First probe of low-lying levels in ^{213}Rn (17 new states identified).

Investigating monopole shifts and role of particle-vibration coupling on fragmentation of strength north of ^{208}Pb .

Heaviest shell closure outside which to benchmark calculations using single-particle behaviour.

Background mainly from a decay of beam – EBIS on/EBIS off subtraction.

$\sim 5 \times 10^6$ pps 7.6 MeV/u ^{212}Rn , 125 $\mu\text{g}/\text{cm}^2$, 120-keV FWHM.



Courtesy of D Clarke

IS689 - Single-particle structure along N=127 - $^{212}\text{Rn}(d,p)^{213}\text{Rn}$

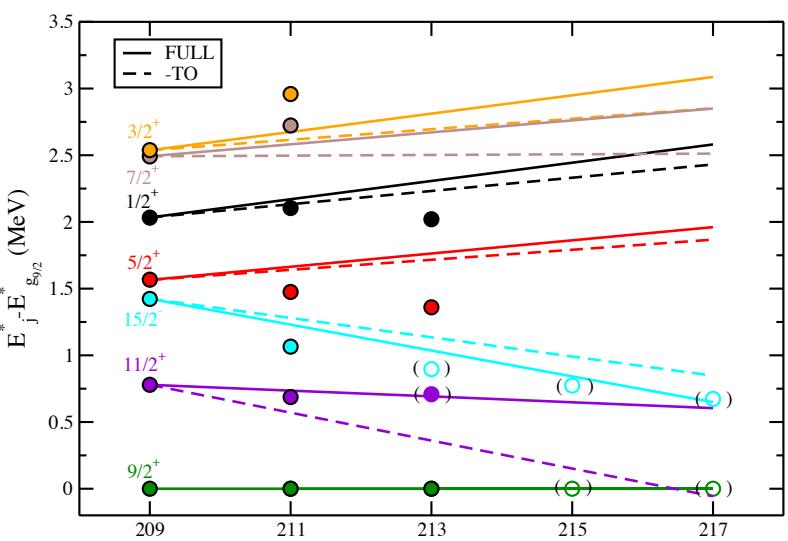
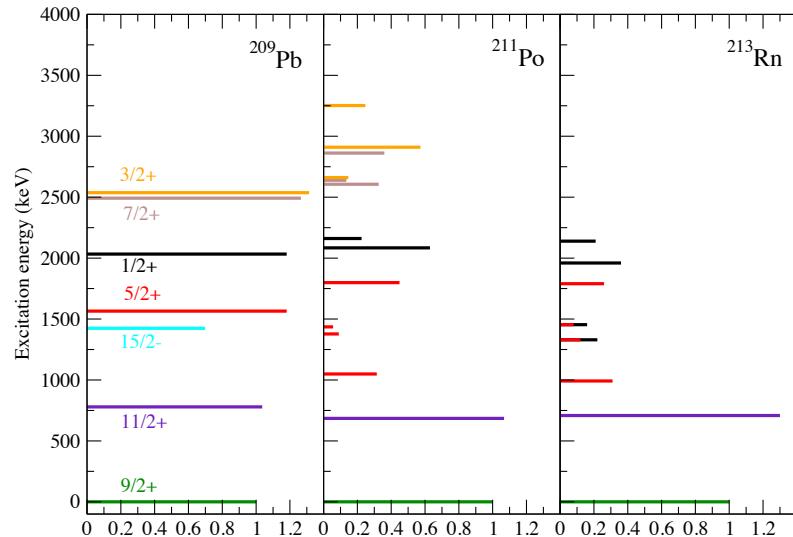
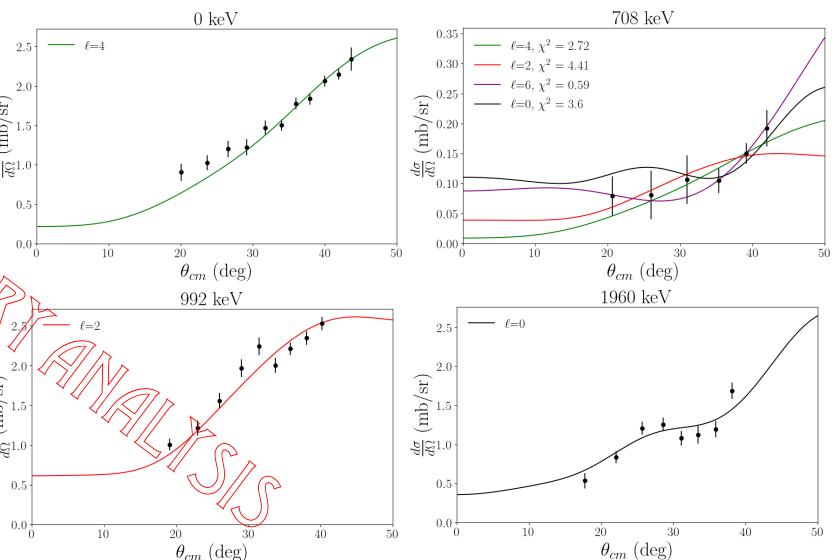
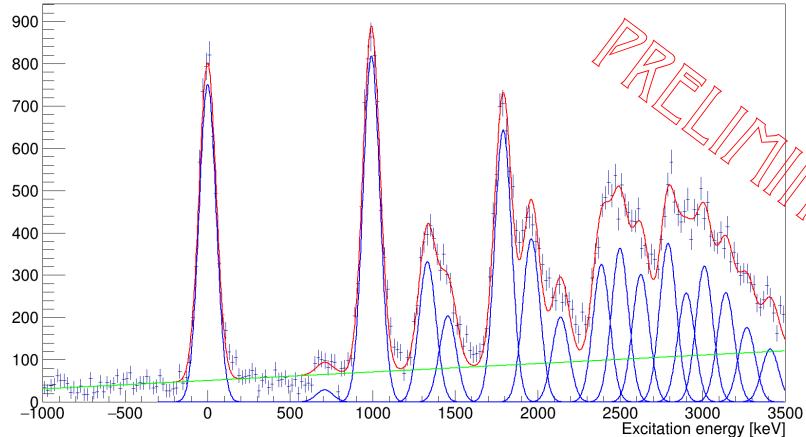
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17 new states identified up to 4 MeV, predominately $I=0, 2$ and 4 strength and low-lying $i_{11/2}$.

Assignments made up to 2.5 MeV.



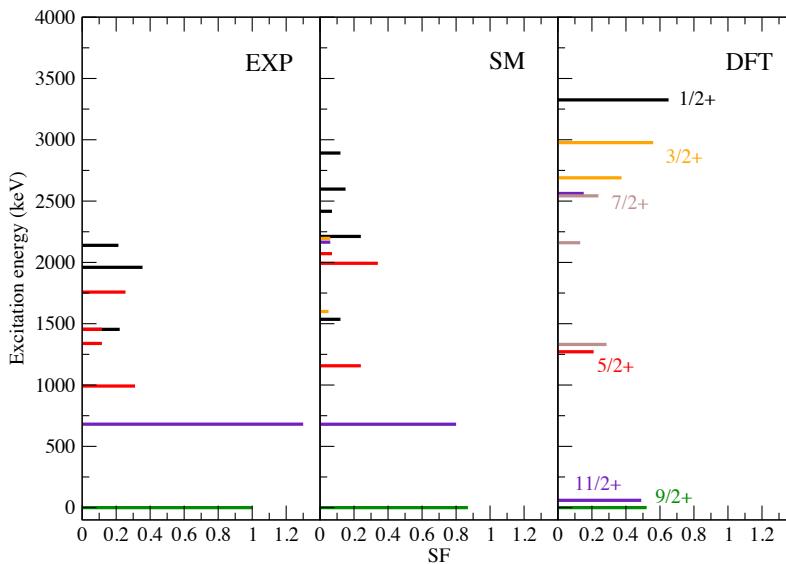
Courtesy of D Clarke (EXP), G Colo (DFT),
A Brown (SM)

Preliminary data shown compared to systemsics for N=127.

^{213}Rn strength distribution similar to ^{211}Po .

Early comparison to SM and DFT calculations.

Monopole shifts from TBME calculation



Developments for 2023 – transfer-induced fission

Argonne NATIONAL LABORATORY

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ISOLDE Solenoidal Spectrometer

Actinide beam $\sim 10 \text{ MeV/u}$

Segmented Si array

Proton ejectile from transfer

$B \sim 2.5 \text{ T}$

Charge reset foil

CD2

$\theta_{\text{Lab}}^{\text{Light}}$

$\theta_{\text{Lab}}^{\text{Heavy}}$

Exit door

MWPC

Light fragments

Heavy fragments

FiFI-2 Bragg chamber

Data on neutron-induced fission is difficult to access

Terrestrial interest – reactor design and waste management.
Fundamental data on fission process.
Fission-recycling in the r process..

Advantages of (d,pF) to probe fissioning systems

Direct measurement of fission barriers. Simultaneously probing above and below Sn.

Fragments are boosted into a small solid angle in inverse kinematics. Full Bragg peak spectroscopy possible due to energy of fragments.

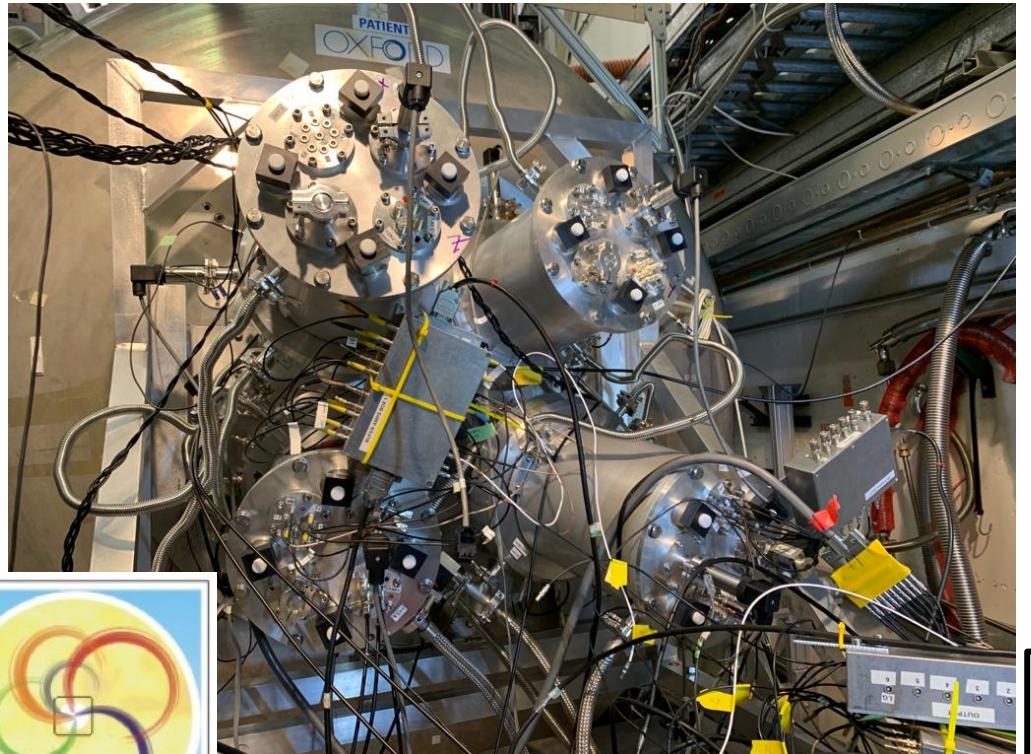
Detection of proton in coincidence with fission fragments provides clean event selection.

Access to short-lived actinides at ISOLDE.

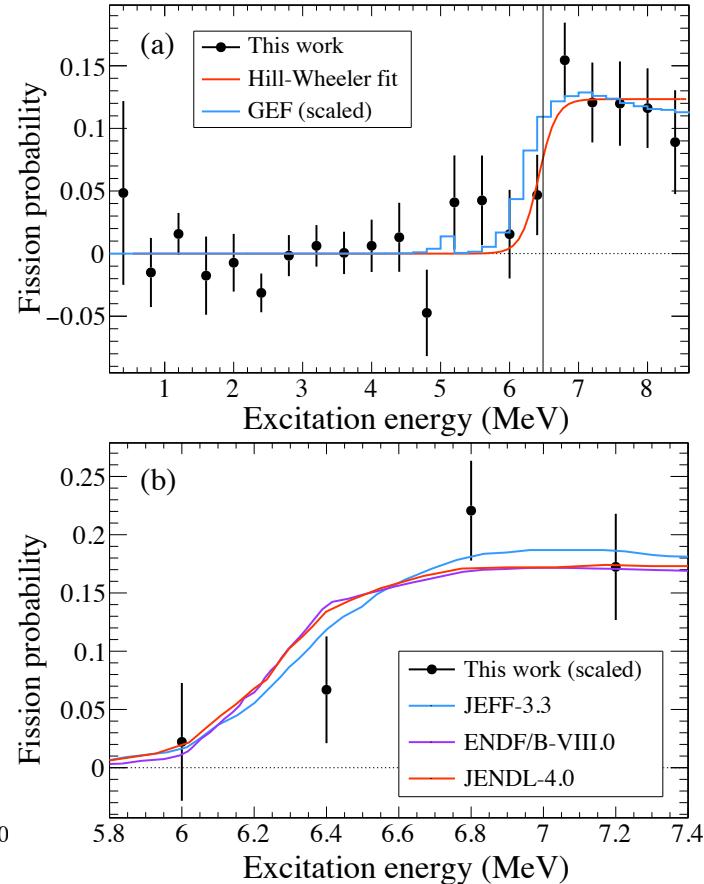
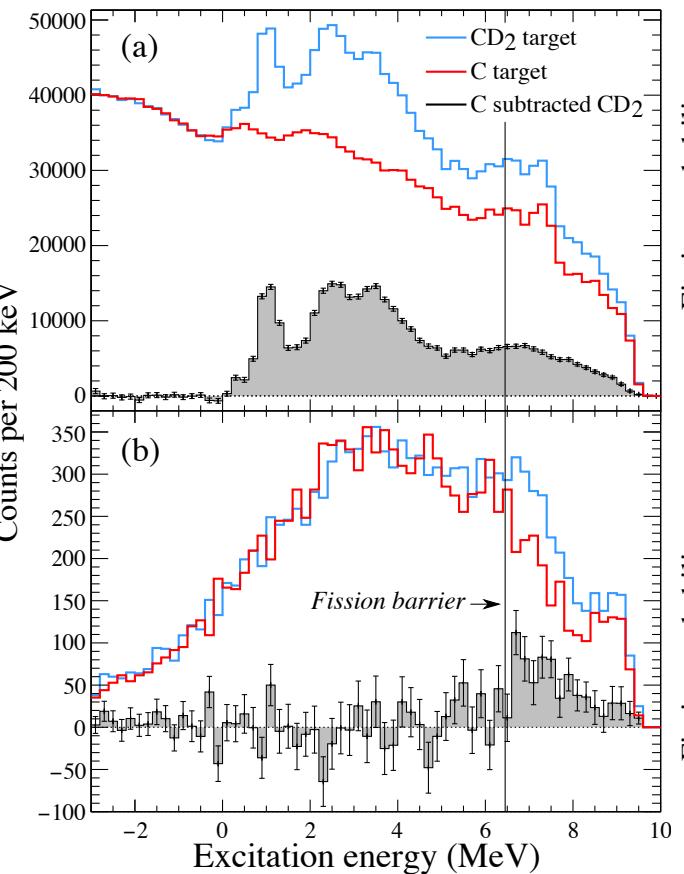
Proof-of-principle

Measurement performed at HELIOS in 2021.

4 Bragg detectors assembled on rear door of magnet.



HELIOS



Background from reactions on C in CD_2 target, subtraction using C target.

$$B_f = 6.42(12) \text{ MeV} [\text{Lit. Val. } 6.46 \text{ MeV Rev. Mod. Phys. 52, 725 (1980)]$$

Thanks to collaboration and funders

Lots of physics from ISS from it's first 2 campaigns.

Baffin Bay

Exploitation of ISS in "(d,p)" mode using variety of mass beams.

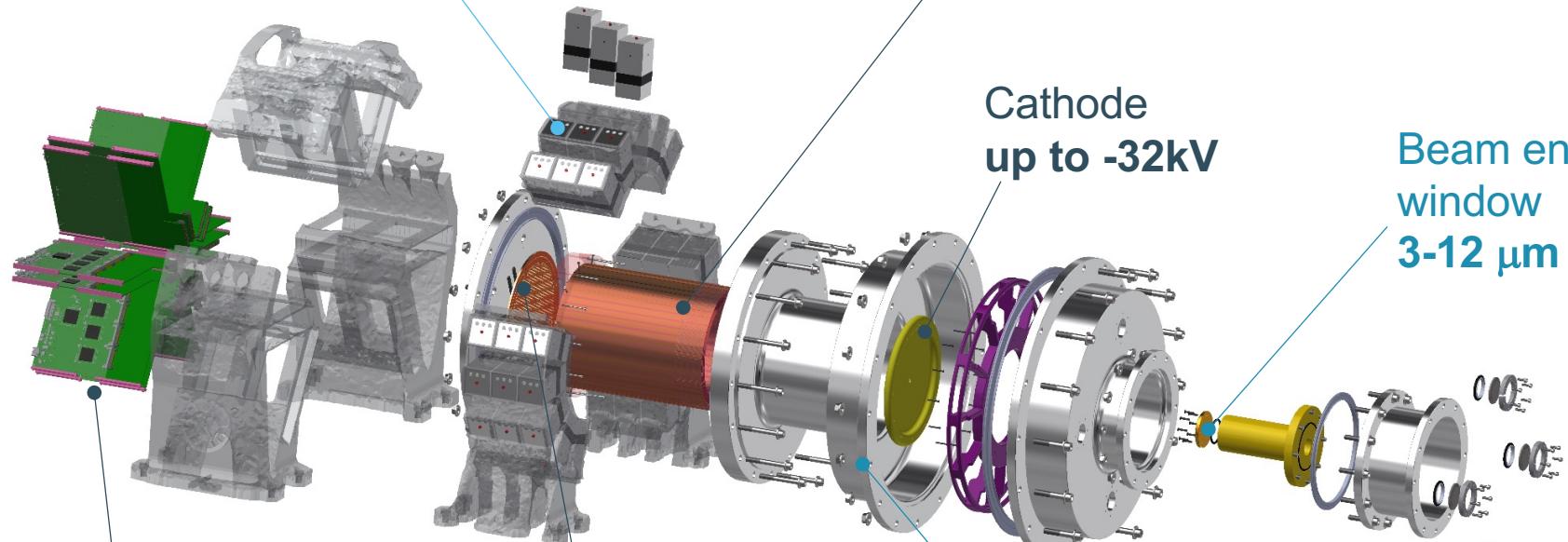
Plans for forward-going reactions in the future. – (d,d')

Tritium induced reactions – (t,p), (t,a) reactions.

Transfer-induced fission with short-lived beams



45 CeBr₃
48×48×48mm
scintillation
detectors



Readout electronics
1-100MS/s 12bit
3072+256 channels

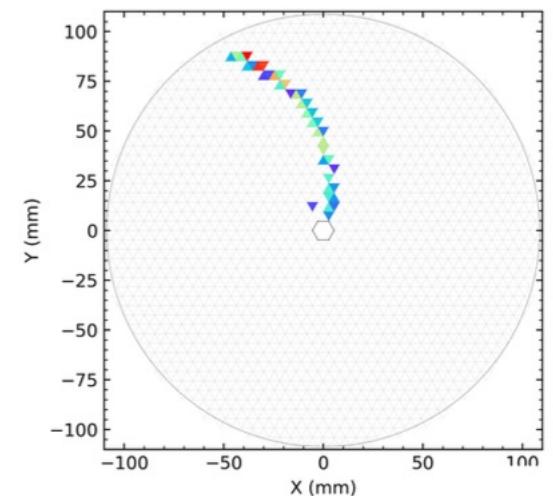
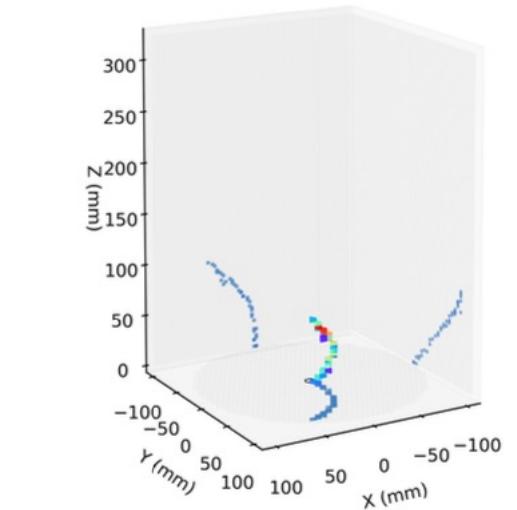
MICROMEGAS detector
2916 channels

Field cage
homogeneous
electric field ~2%

Cathode
up to -32kV

Beam entrance
window
3-12 μm

Gas chamber
up to 1 atm
min wall thickness 3mm



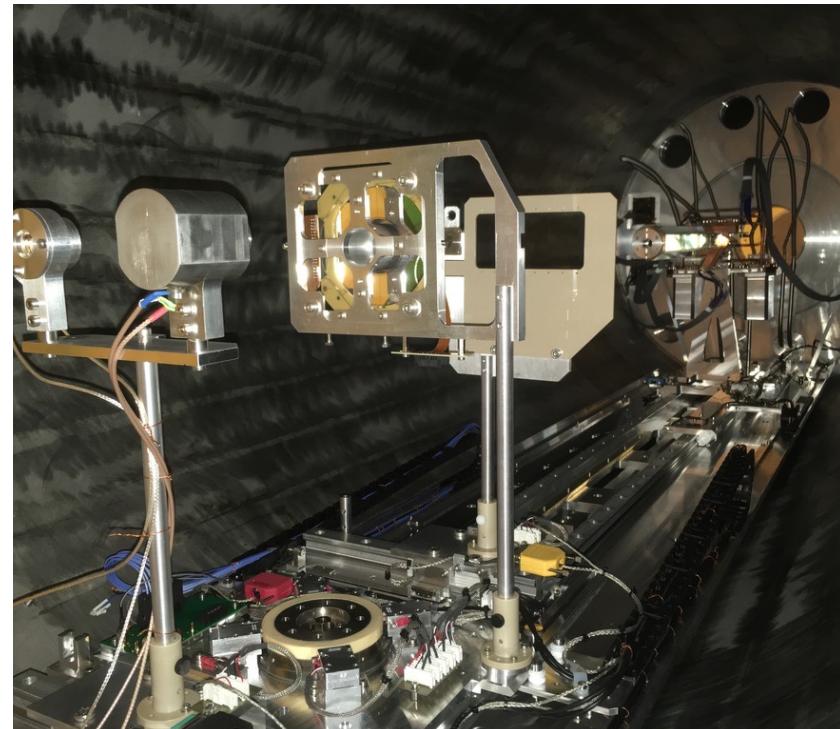
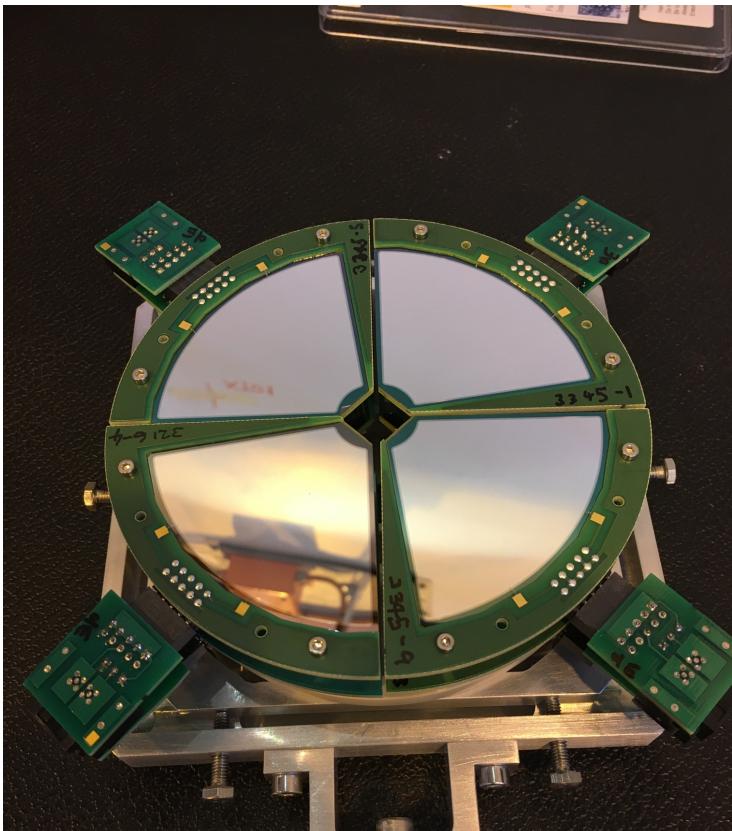
Measured α-particle
track in B=2.5T

ISS modes of operation

Si-recoil mode

Silicon $dE-E$ annular detector position at rear of magnet to identify residual nucleus.

Remove reactions on contaminants.



Singles mode

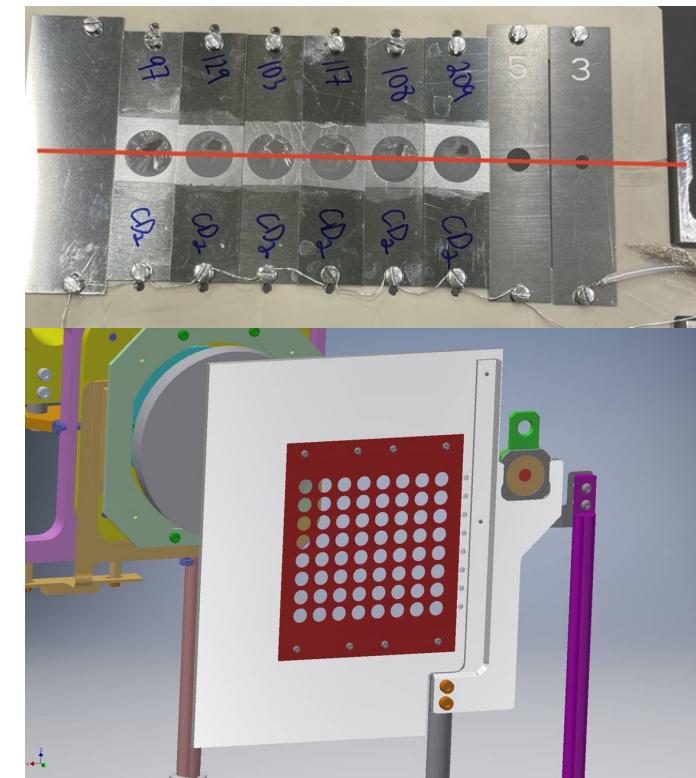
High-intensity beams led to pile-up/saturation issues with recoil detectors.

Ability to identify high-mass beams challenging.

Necessitates running in “singles” mode – only the array.
Consideration of backgrounds (FE or decay of beam).

Best with clean beams.

Lots of targets needed.



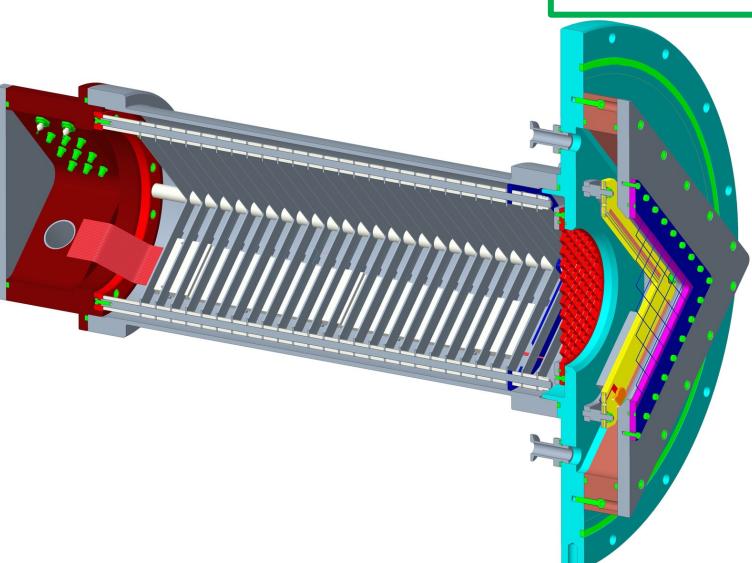
Fast-counting ionization chamber

Used to determine beam composition.

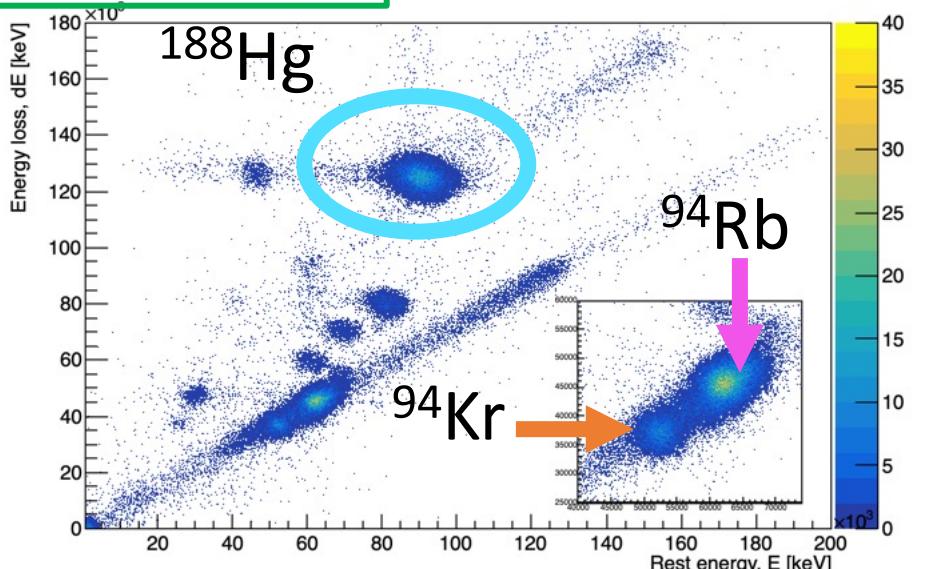
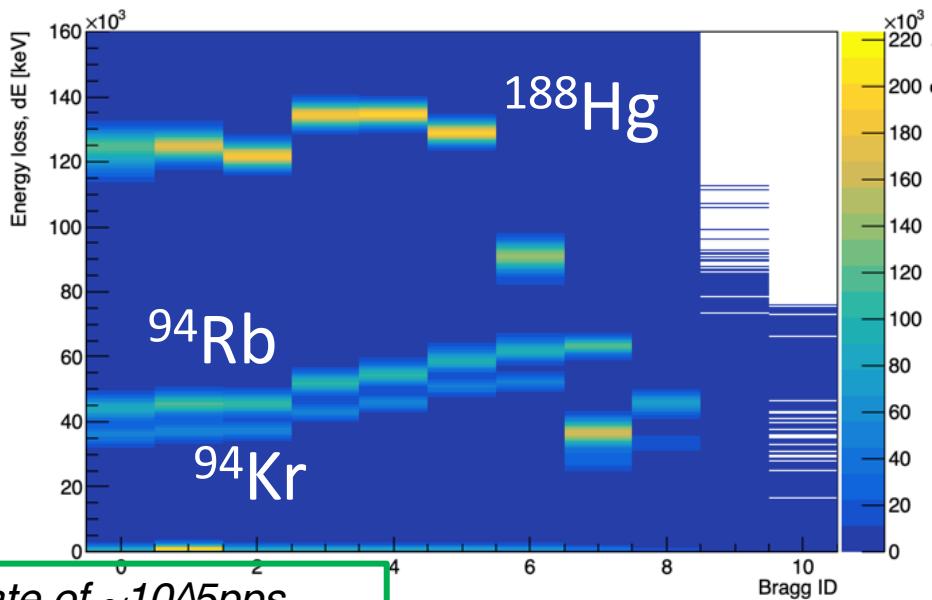
Based on modification of previous designs that operate up to 100 kHz.

Essentially a stack of 13 PPAC's with short drift lengths to reduce pulse risetime.

Constructed and tested – identified improvements to preamplifiers and zero-degree blocker design.



Total beam rate of $\sim 10^{15}$ pps



IS689 - Single-particle structure along $N=127$ - $^{212}\text{Rn}(d,p)^{213}\text{Rn}$

Courtesy of G Colo (DFT), A Brown (SM)

