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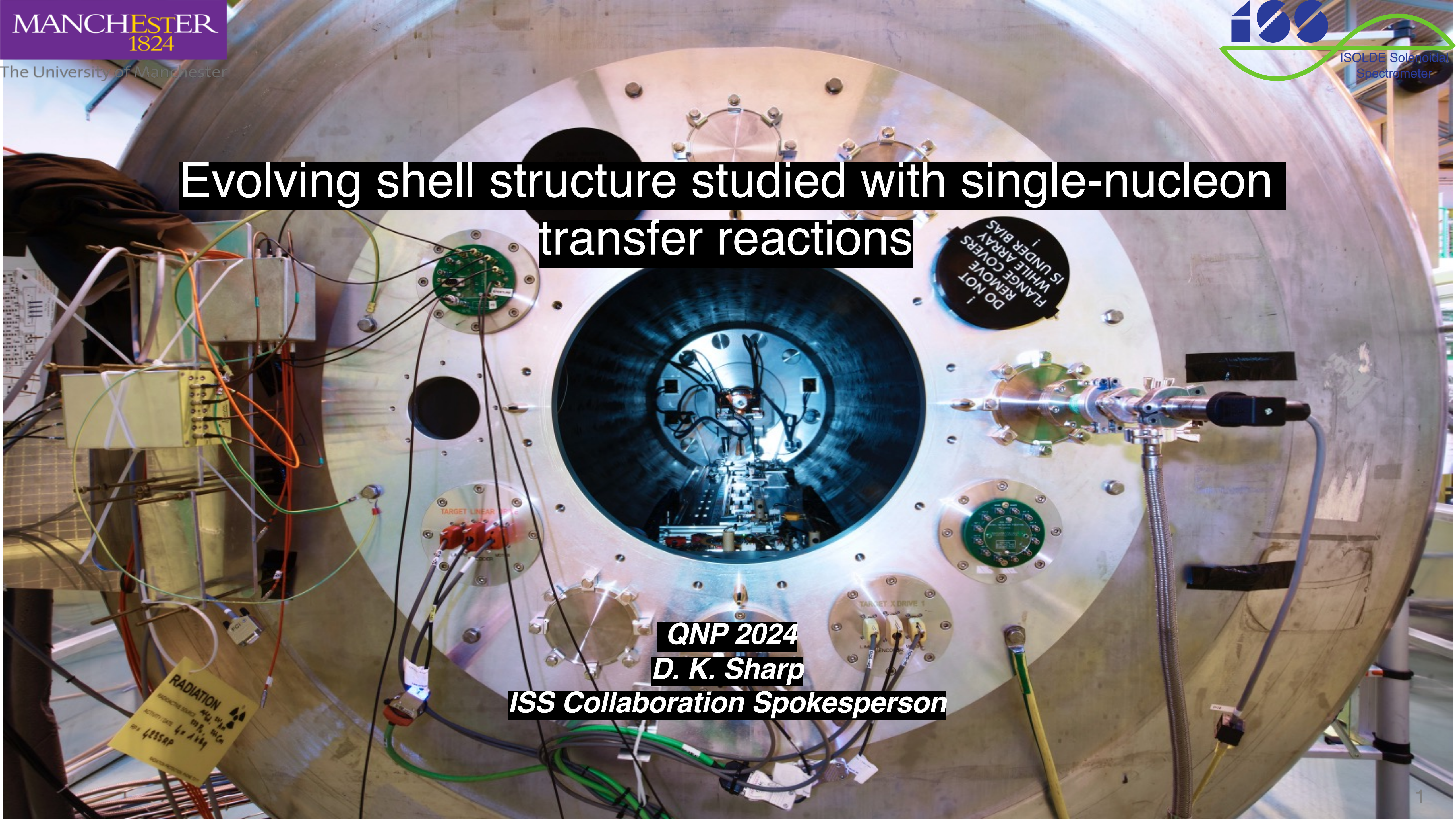
ISOLDE Solenoidal Spectrometer

Evolving shell structure studied with single-nucleon transfer reactions

QNP 2024

D. K. Sharp

ISS Collaboration Spokesperson



Overview

- *Brief introduction to solenoid technique for direct reactions*

- *Single-particle properties of nuclei*
  - *Along N=17*
    - *Description of negative-parity states*
    - *Evolution along N=17*

  - *Along N=127*
    - *Description of SP fragmentation*
    - *Monopole shifts*

Direct reactions

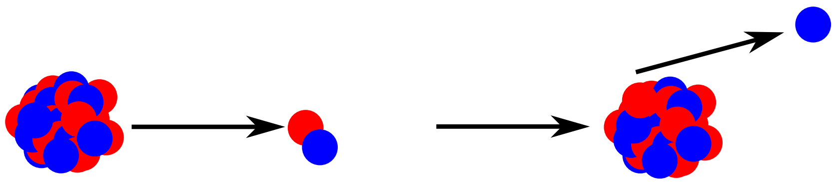
Access to variety of nuclear structure information

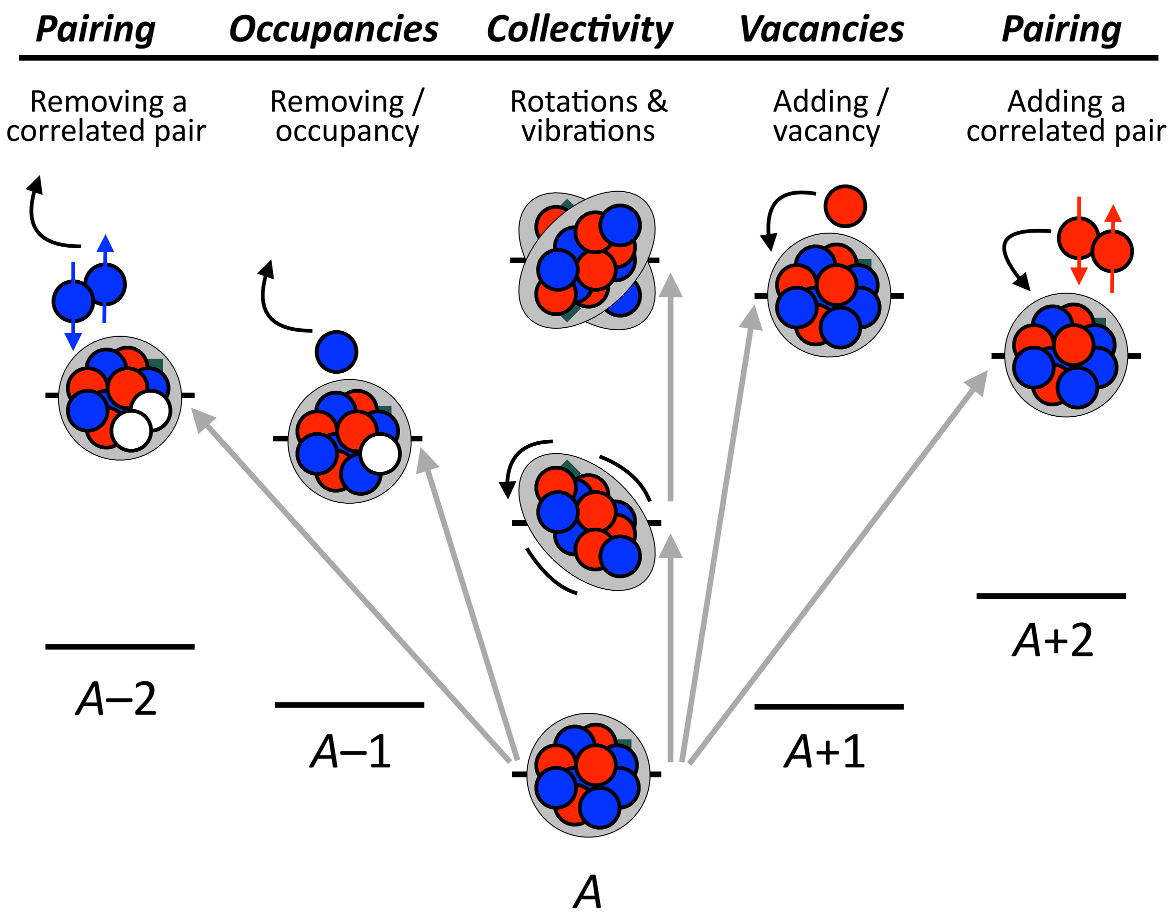
***Single-particle states**, $E_{(Ex,SP)}$, l, spectroscopic factors, e.g. (d,p), (p,d)…*

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

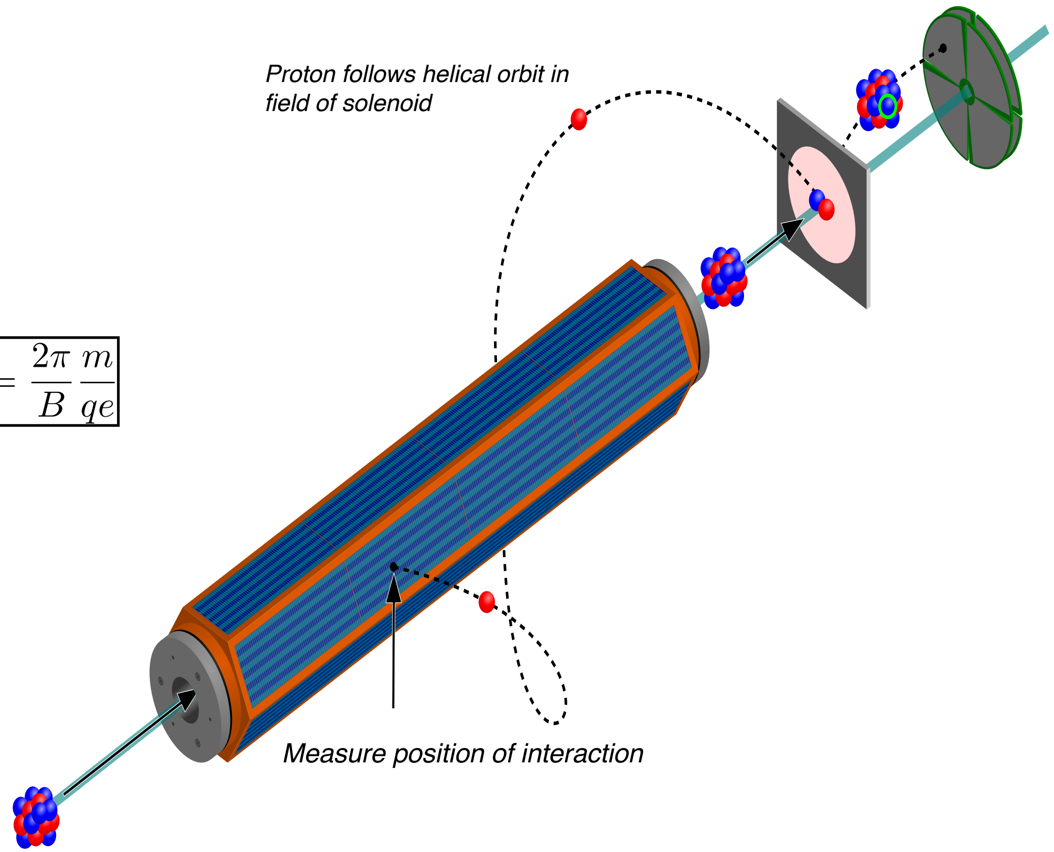
***Collective properties** via e.g. (p,p′), (d,d′), (α,α′)…*

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

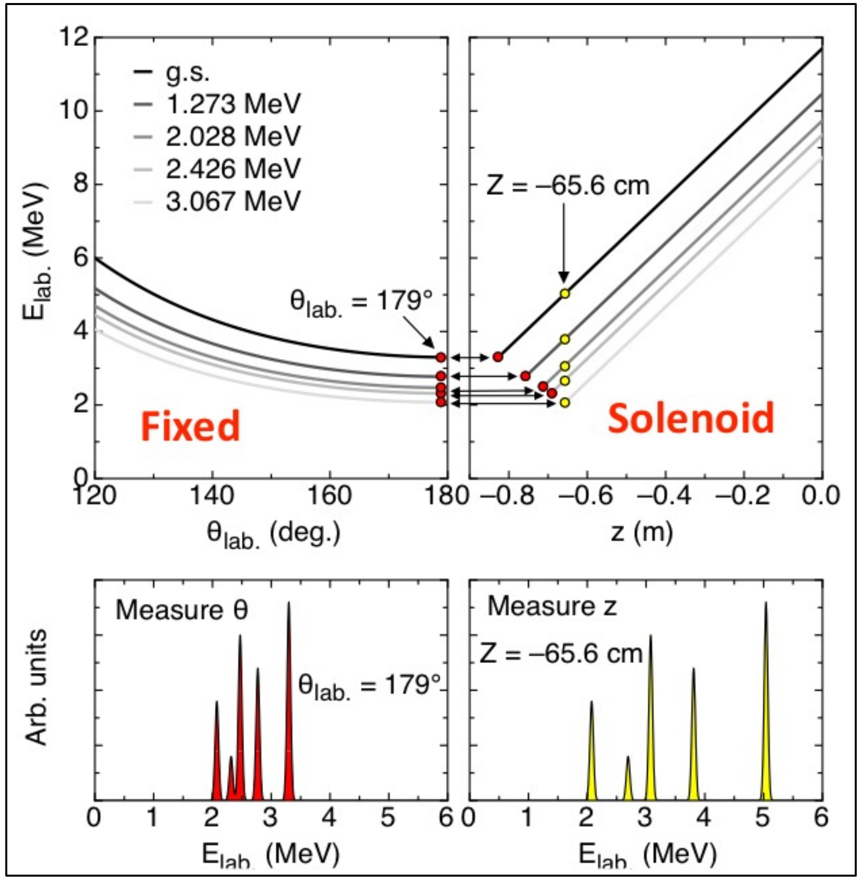




Solenoid technique



$$T_{\mathrm{cyc}} = \frac{2\pi}{B}\frac{m}{qe}$$



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

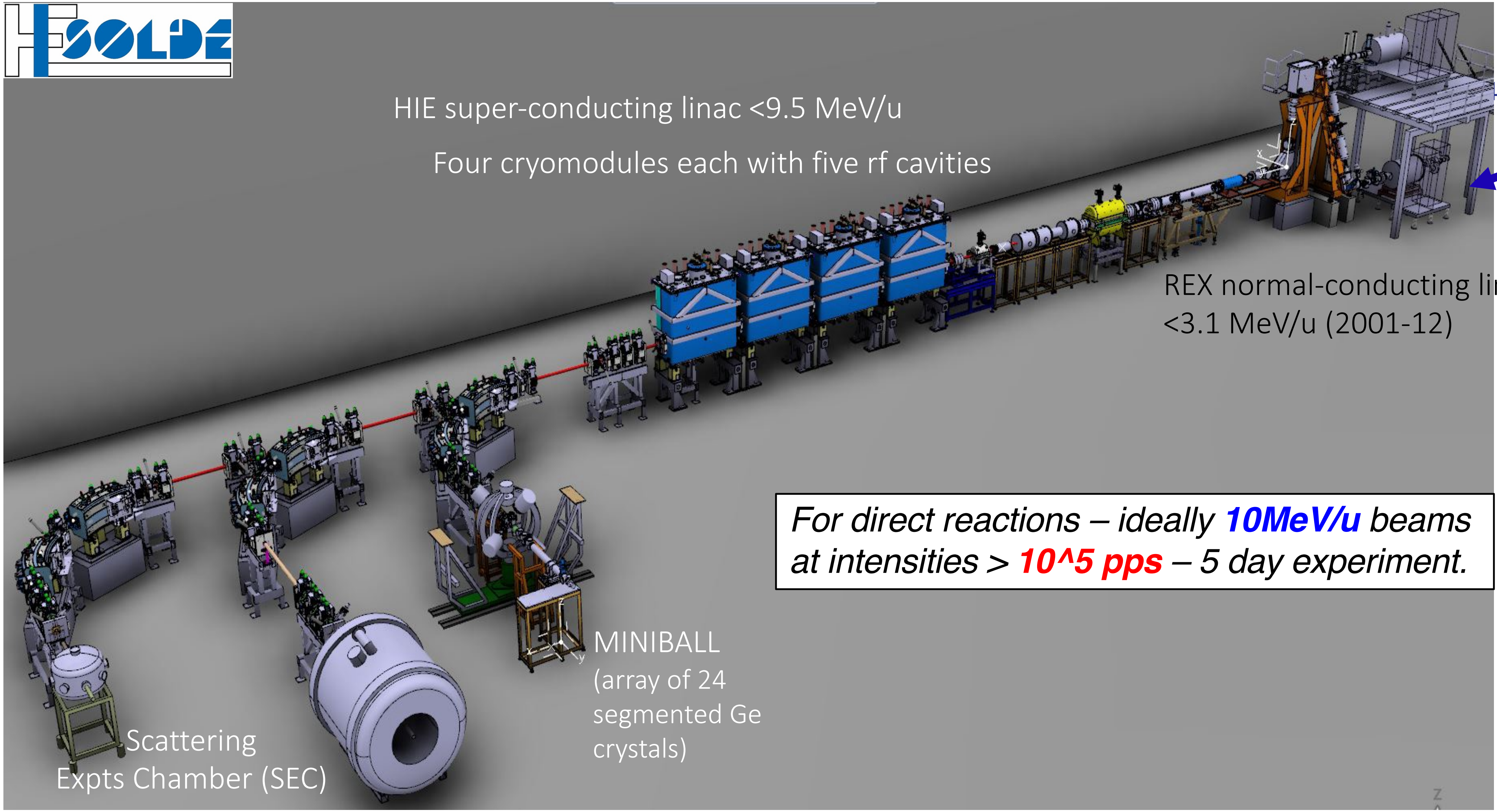
$$E_{\mathrm{cm}} = E_{\mathrm{lab}} + \frac{mV_{\mathrm{cm}}^2}{2} - \frac{mzV_{\mathrm{cm}}}{T_{\mathrm{cyc}}}$$

Suffers no kinematic compression of the Q-value spectrum – resolution 100-150 keV.

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

Physics at HIE-ISOLDE with a solenoid

ISOLDE Solenoidal Spectrometer



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

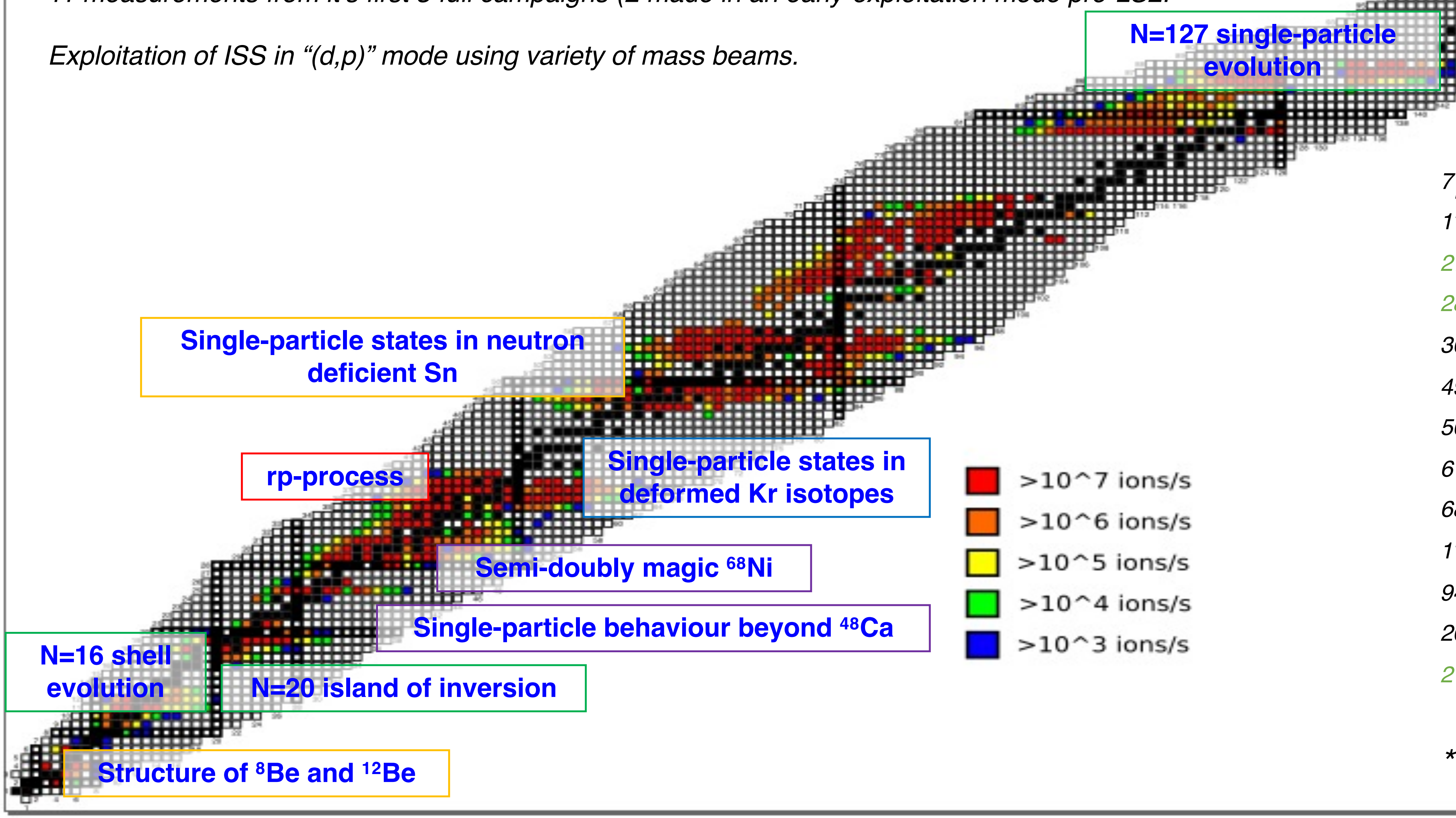
ISOLDE Solenoidal Spectrometer (ISS)

ISS summary

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

11 measurements from it's first 3 full campaigns (2 made in an early-exploitation mode pre-LS2.

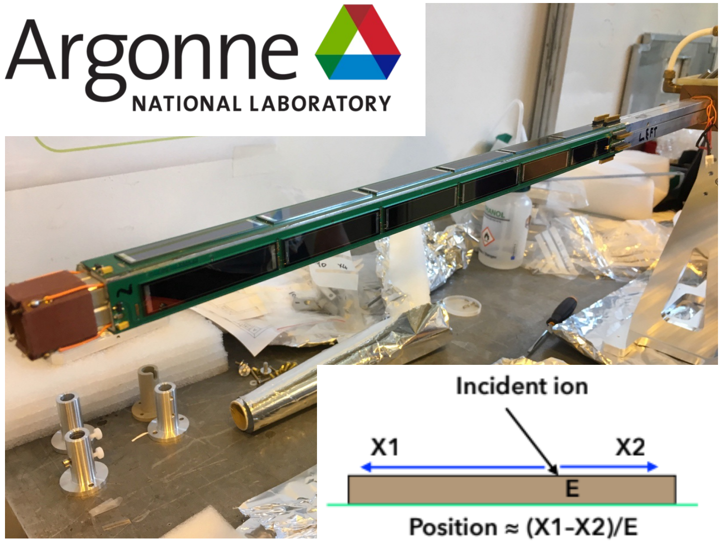
Exploitation of ISS in "(d,p)" mode using variety of mass beams.



$^{7}Be(d,p)^{8}Be$
$^{11}Be(d,p)^{12}Be$
$^{27}Na(d,p)^{28}Na$
*$^{28}Mg(d,p)^{29}Mg$**
$^{30}Mg(d,p)^{31}Mg$
$^{49}Ca(d,p)^{50}Ca$
$^{50}Ca(d,p)^{51}Ca$
$^{61}Zn(d,p)^{62}Zn$
$^{68}Ni(d,p)^{69}Ni$
$^{110}Sn(d,p)^{111}Sn$
$^{94}Kr(d,p)^{95}Kr$
*$^{206}Hg(d,p)^{207}Hg$**
$^{212}Rn(d,p)^{213}Rn$

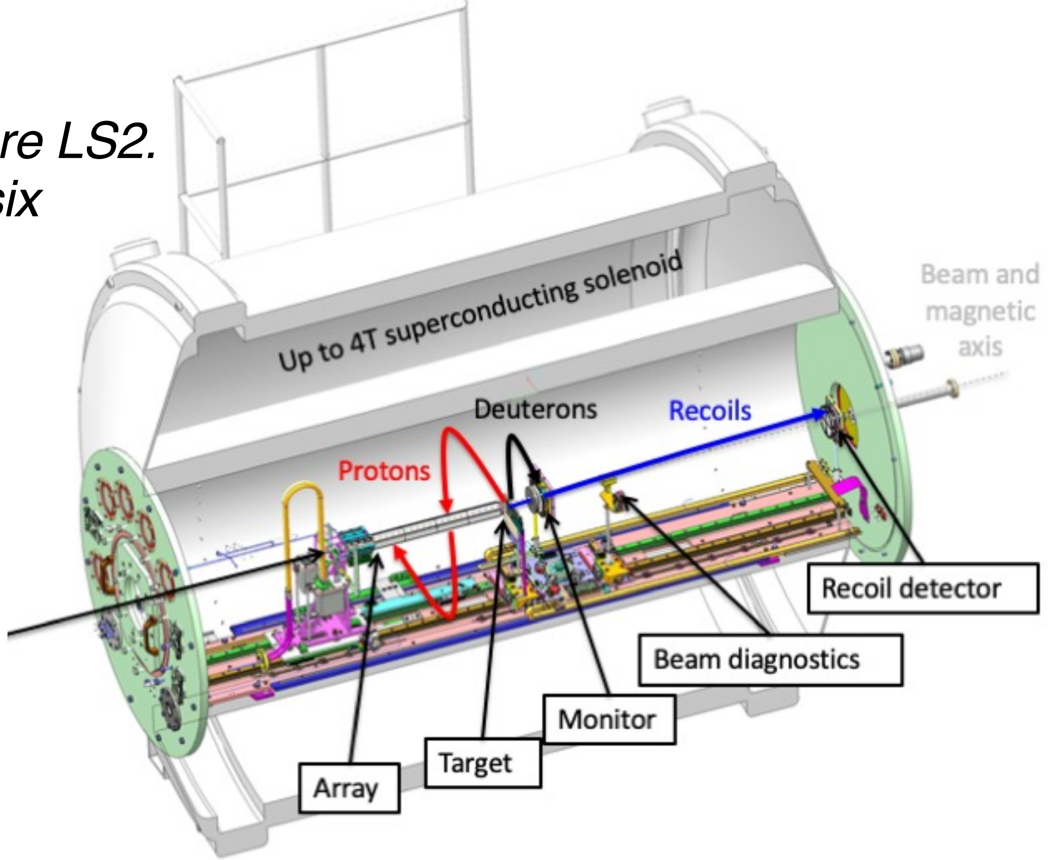
**HELIOS array*

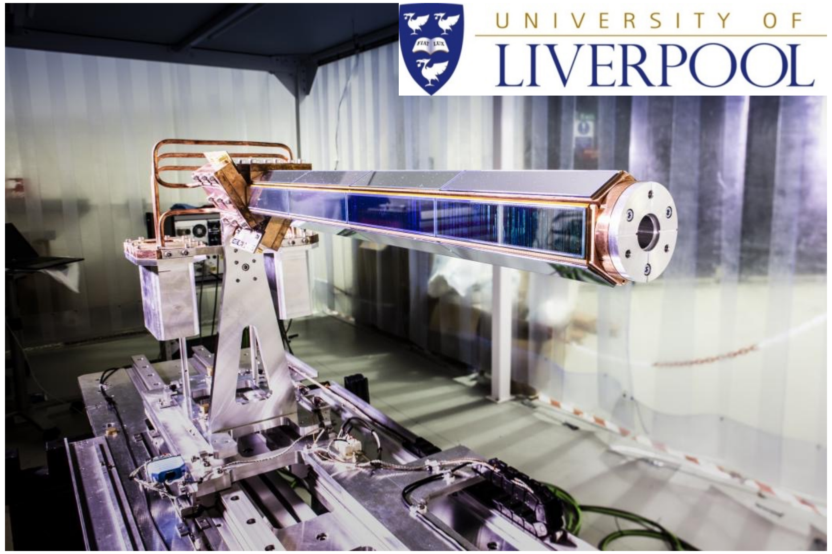
ISOLDE Solenoidal Spectrometer



HELIOS silicon array

Used for early-exploitation before LS2.
Four-sided array consisting of six resistive-strip silicon detectors.
Total silicon length ~300mm.
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

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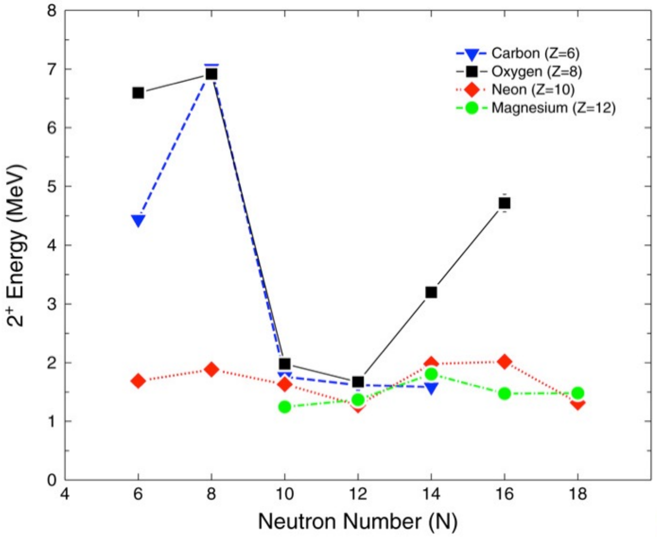
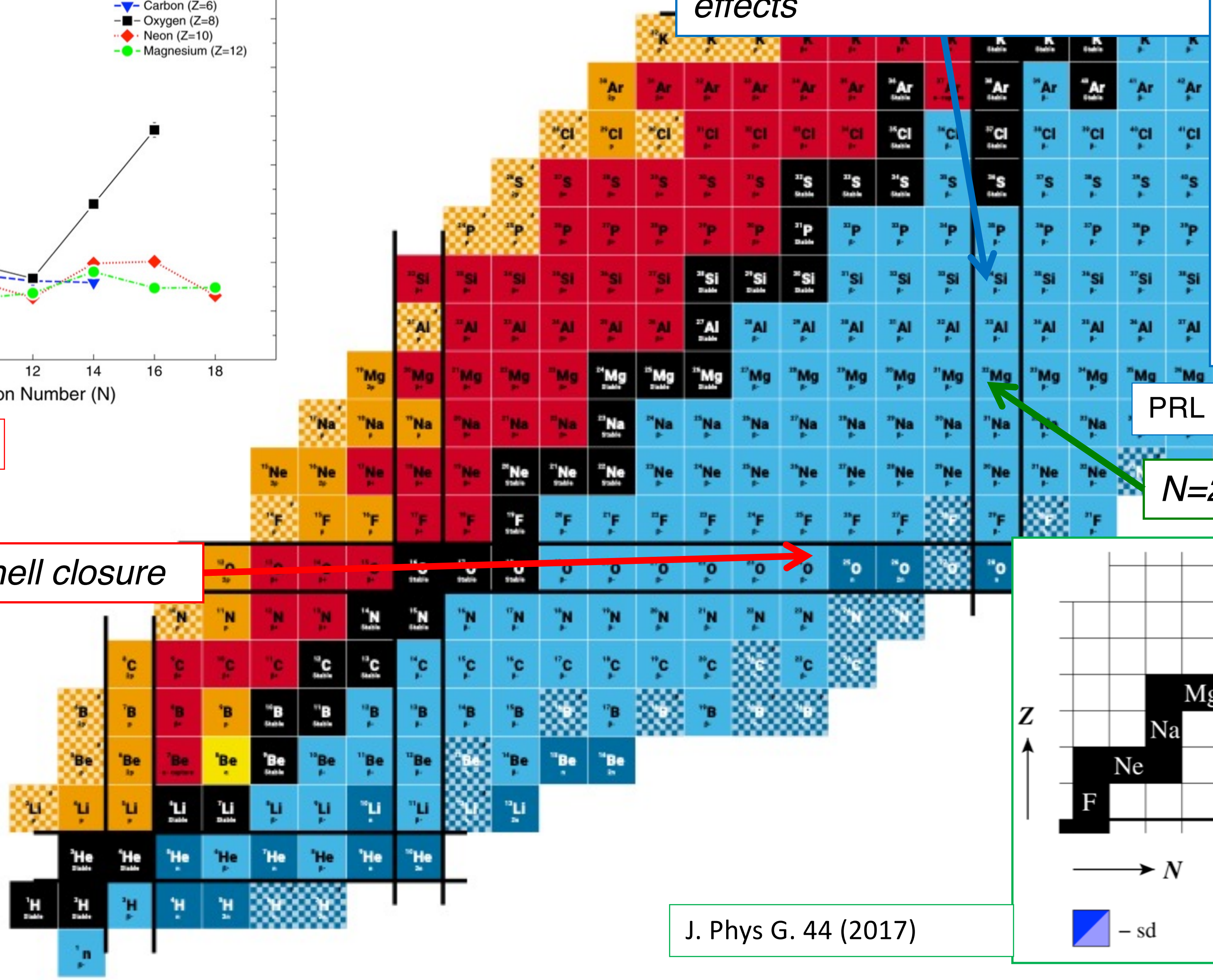


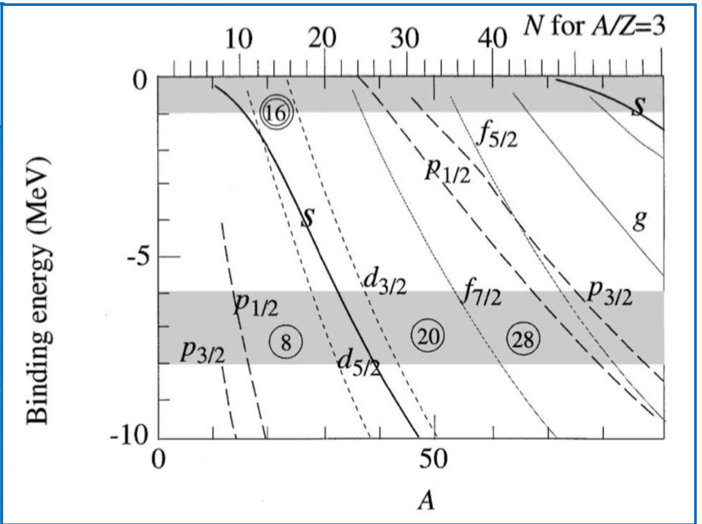
PLB **672** 17 (2009)

Weak binding/Finite geometry effects

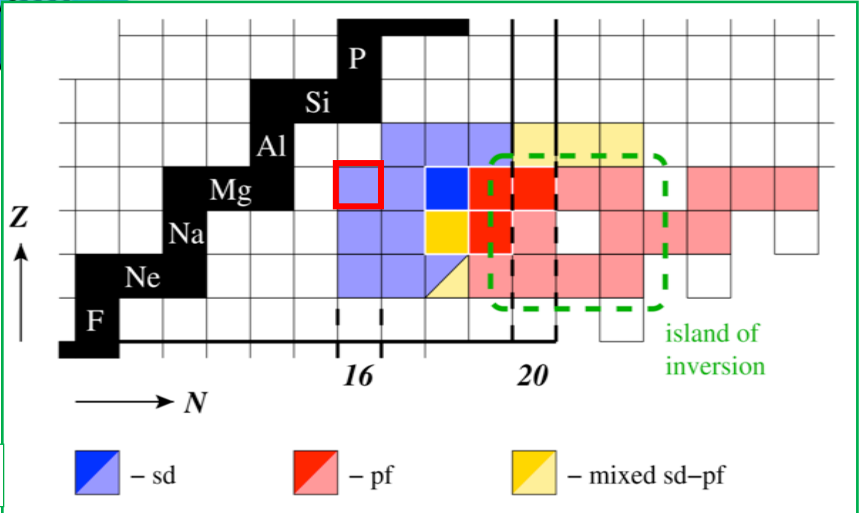


N=16 shell closure

N=20 Island of Inversion



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



J. Phys G. 44 (2017)

Trends in N=17 isotones – odd Z systems

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

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

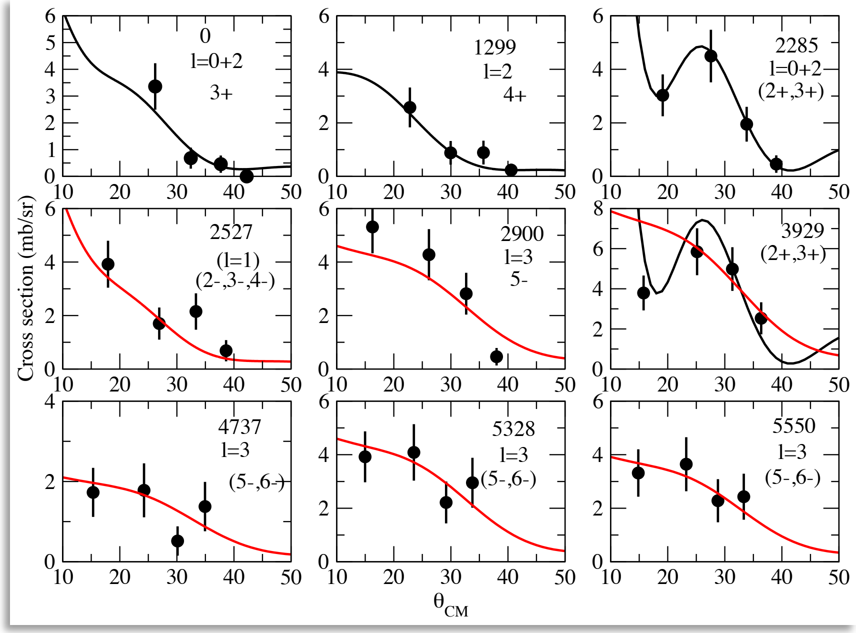
1x10^{4}pps @ 10.5 MeV/u ^{29}Al

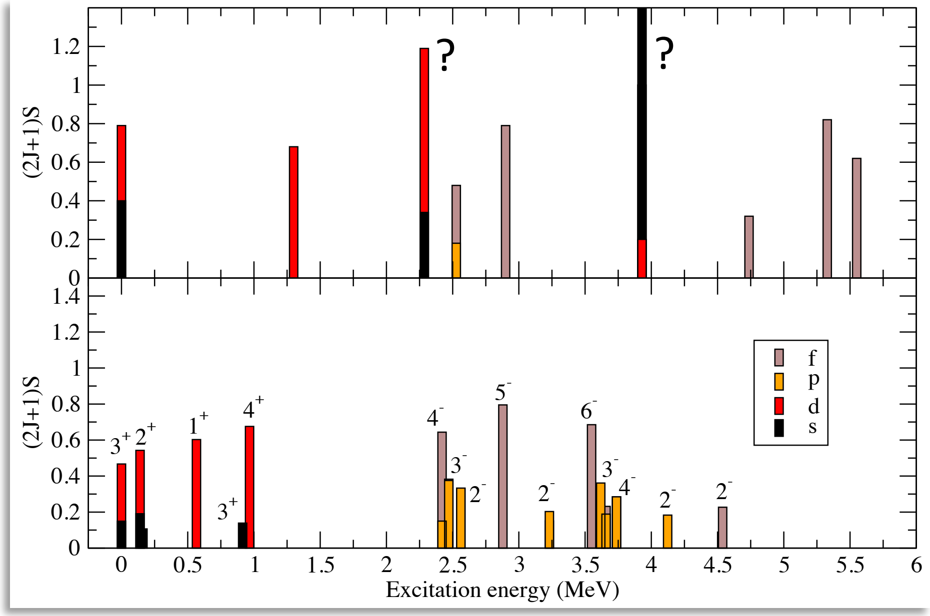
Aim to identify the negative-parity states in these systems and their relative behaviour as protons are removed and benchmark new SM interactions.

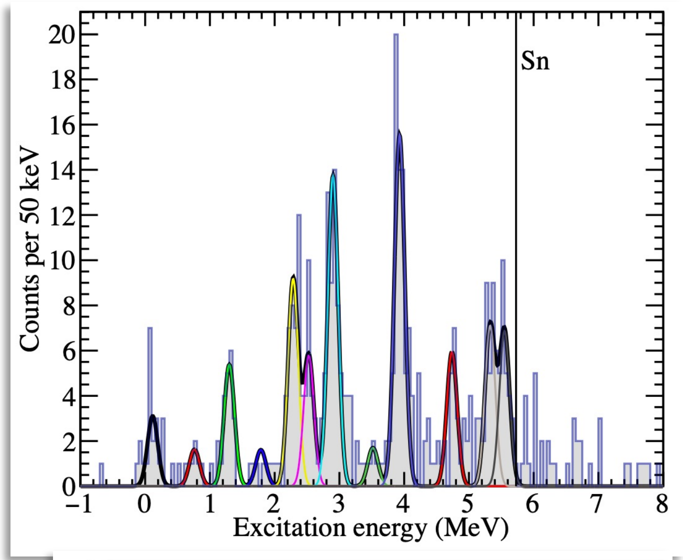
Angular distributions provide identification of parity (+ve l=0+2, -ve l=1+3) for comparison to shell model calculations (ongoing analysis).

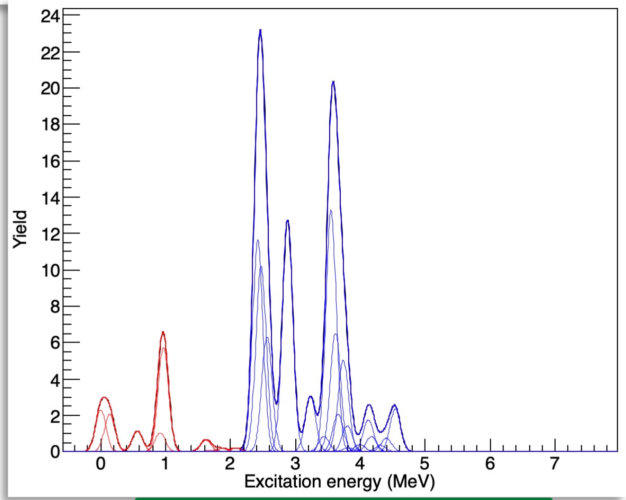
^{30}Al compares well to shell model using FSU interaction (1 or 2 discrepancies likely of exp origin).

PRELIMINARY ANALYSIS









Courtesy of S Bennett

Trends in N=17 isotones – odd Z systems

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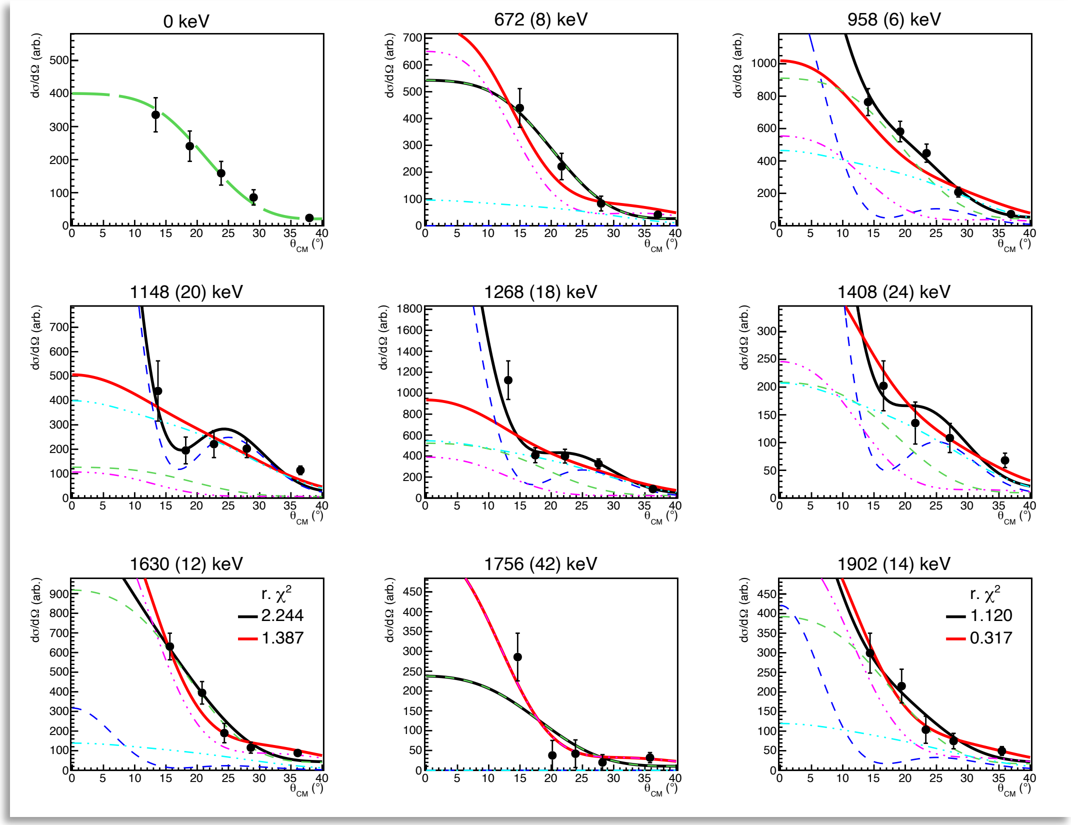
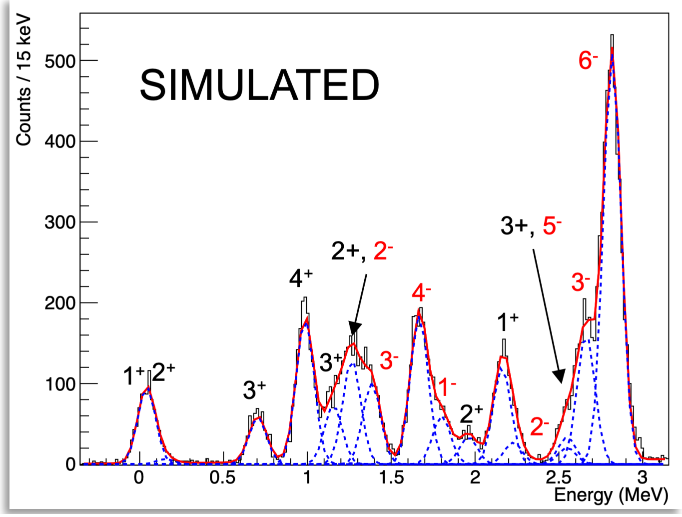
Similarly study of ^{27}Na(d,p) reaction reveals some encouraging agreement with shell model simulations– distribution of cross section compared. SF's still required.

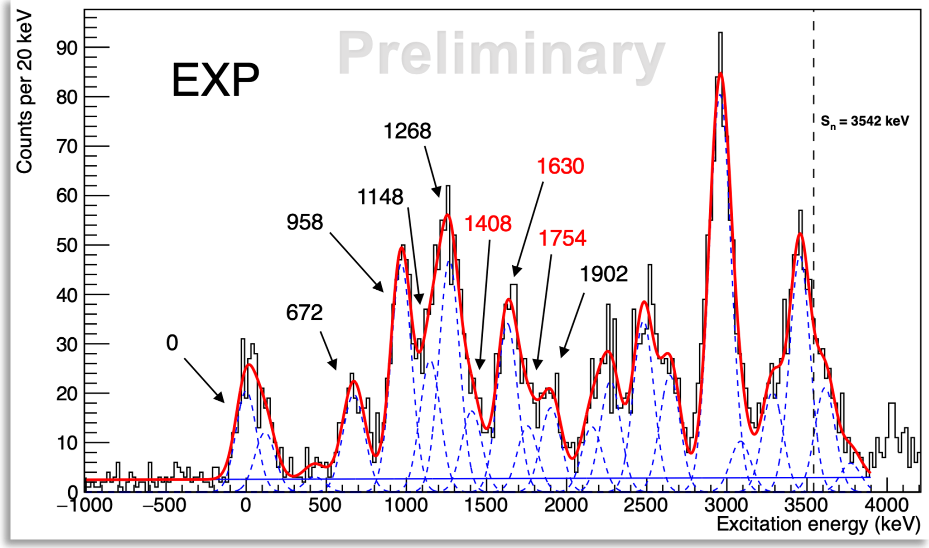
More statistics and resolution obtained should allow a more comprehensive study of fragmentation in this system.

8x10^{5}pps @ 9.7 MeV/u ^{27}Na

PRELIMINARY ANALYSIS







Trends in N=17 isotones

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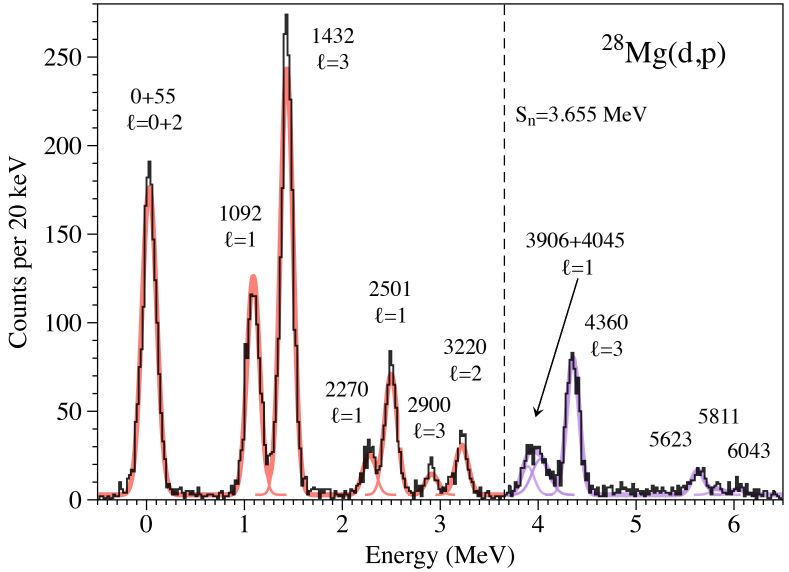
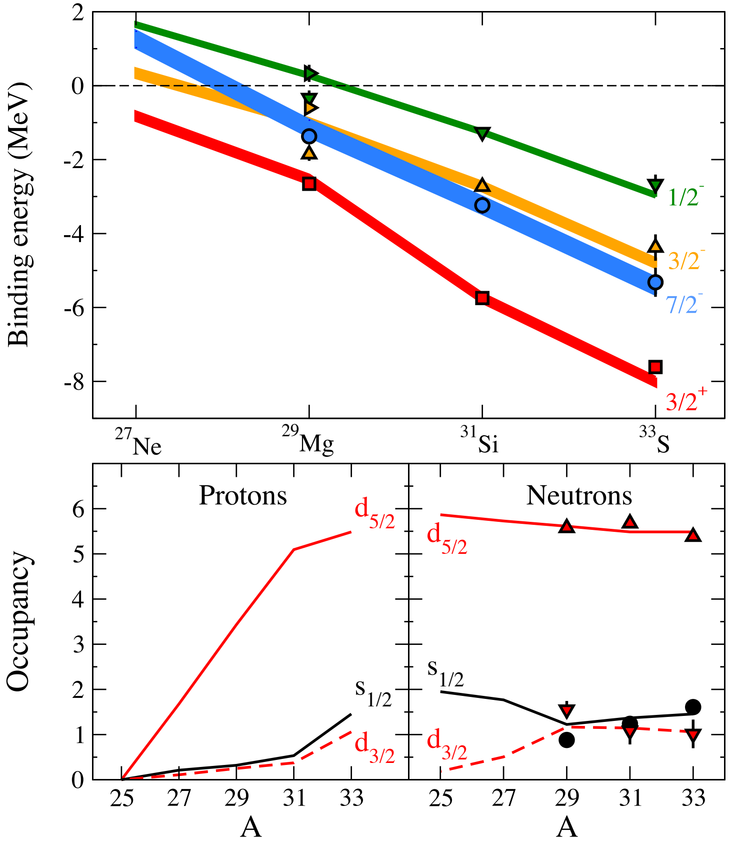
^{28}Mg(d,p)^{29}Mg reaction measured before LS2 and data combined with existing stable systems.

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.





P.T.MacGregor *et. al.*, PRC **104**, L051301 (2021).

Trends in N=17 isotones - finite binding

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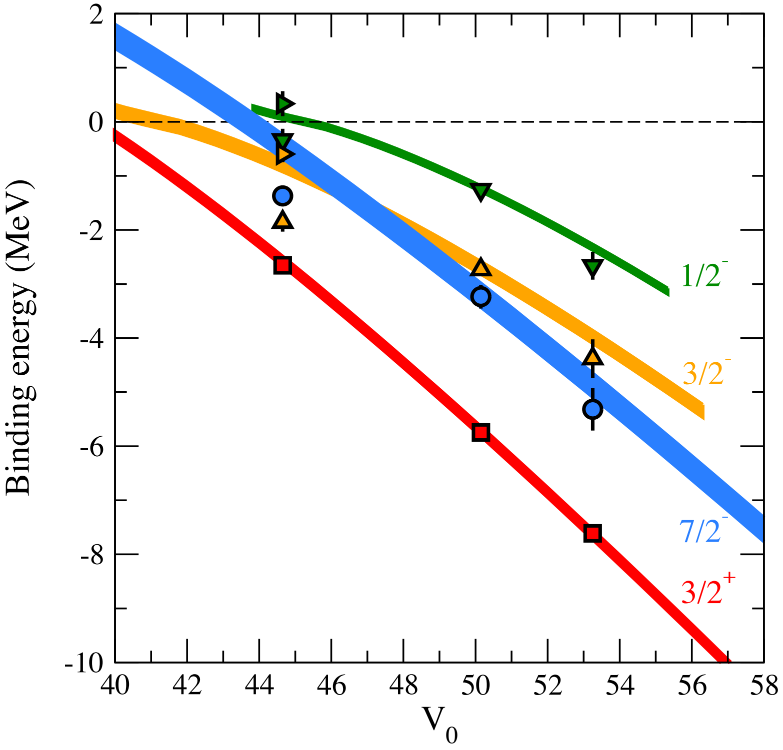
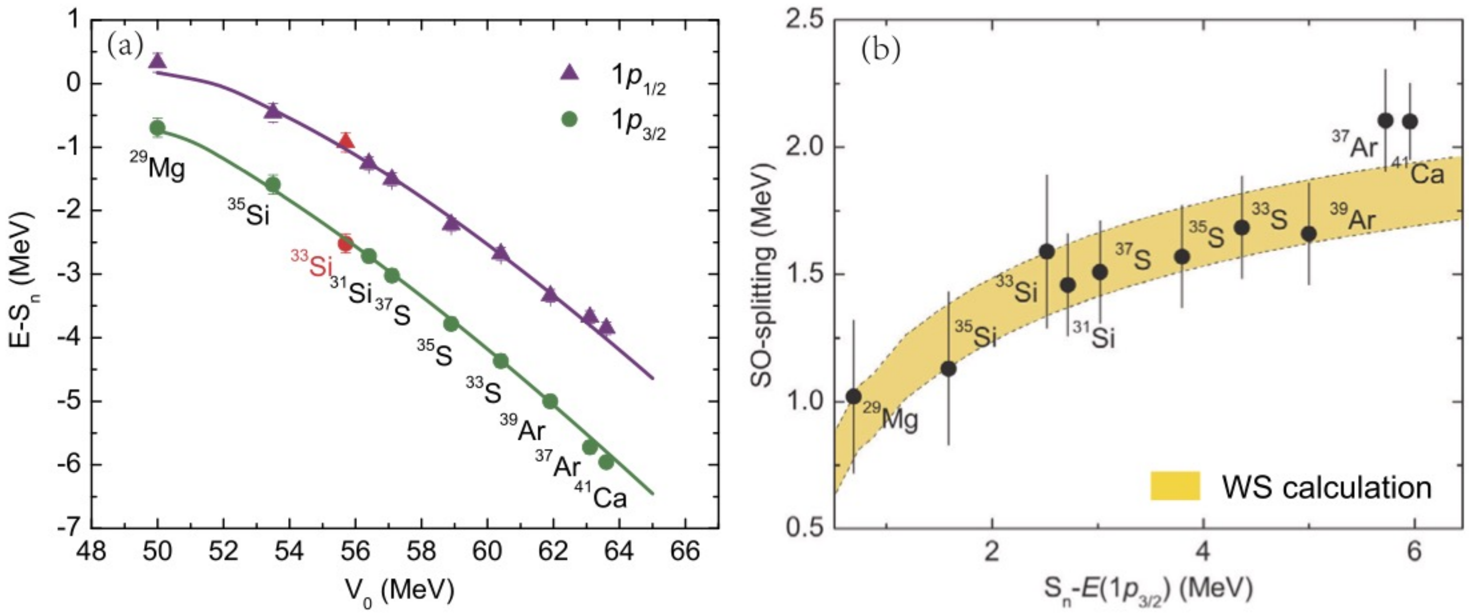
Woods-Saxon calculations also reproduce changes in BE. Smooth reduction in SO separation by ~500 keV from stability. Effect of finite geometry of potential well.



P.T.MacGregor *et. al.*, PRC **104**, L051301 (2021).

This appears to be a global trend (also explains reduction in p-orbital separation in bubble nucleus).



J. Chen *et. al.*, PLB **853** (2024).

Evolution of single-particle structure along shell-closures

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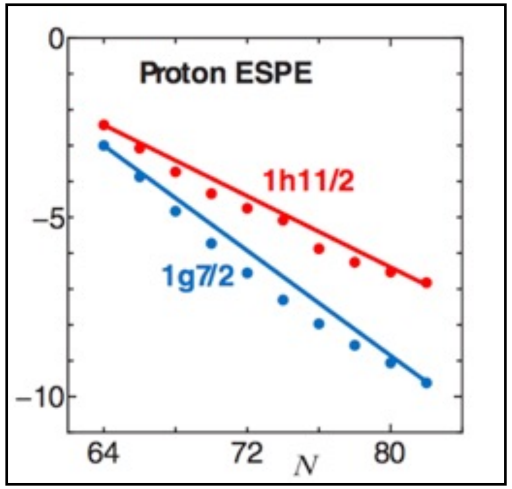
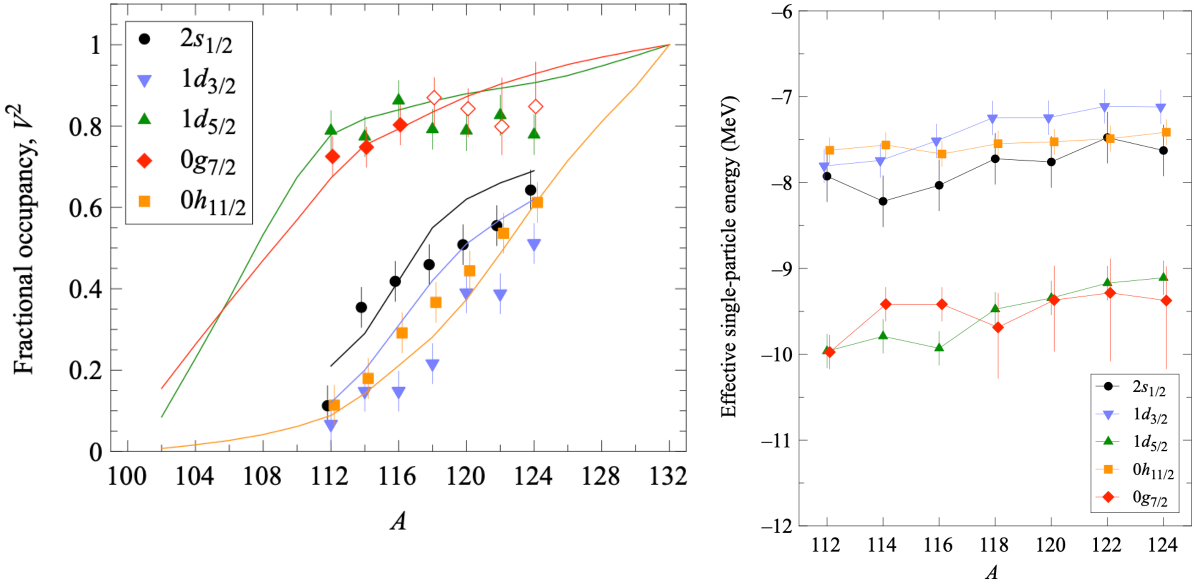
Trends observed in light nuclei have even been observed in stable heavier nuclei - Changes in high-j states as high-j orbitals are filling.

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.

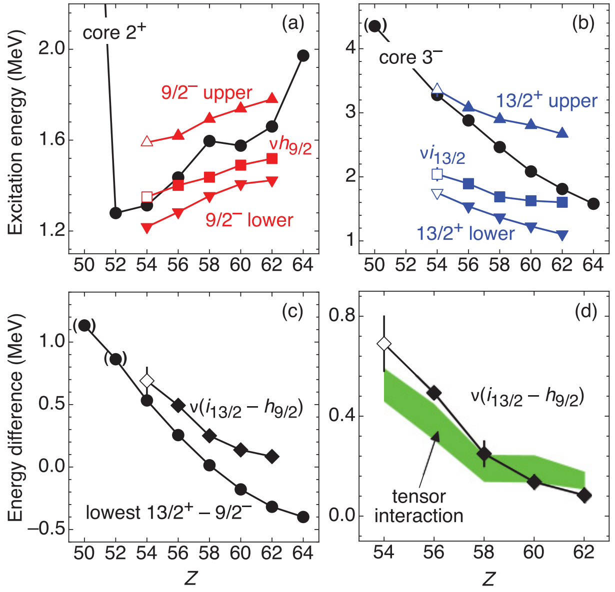
Access to RIBs at HIE-ISOLDE allows access to measurements across large chains of isotopes/isotones probing the interactions further from stability (Sn isotopes) and in new regions such as N=127 .



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

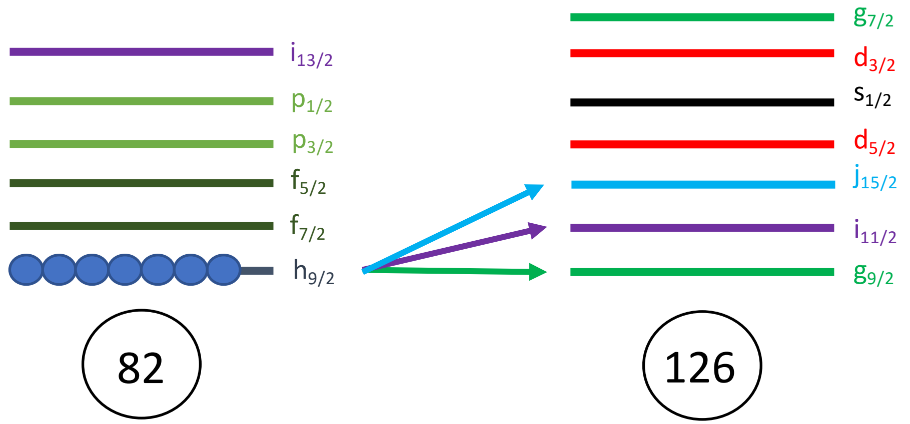


S. Szwec et al.,Phys. Rev. C **94**, 054314 (2016)



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 - $^{212}Rn(d,p)^{213}Rn$



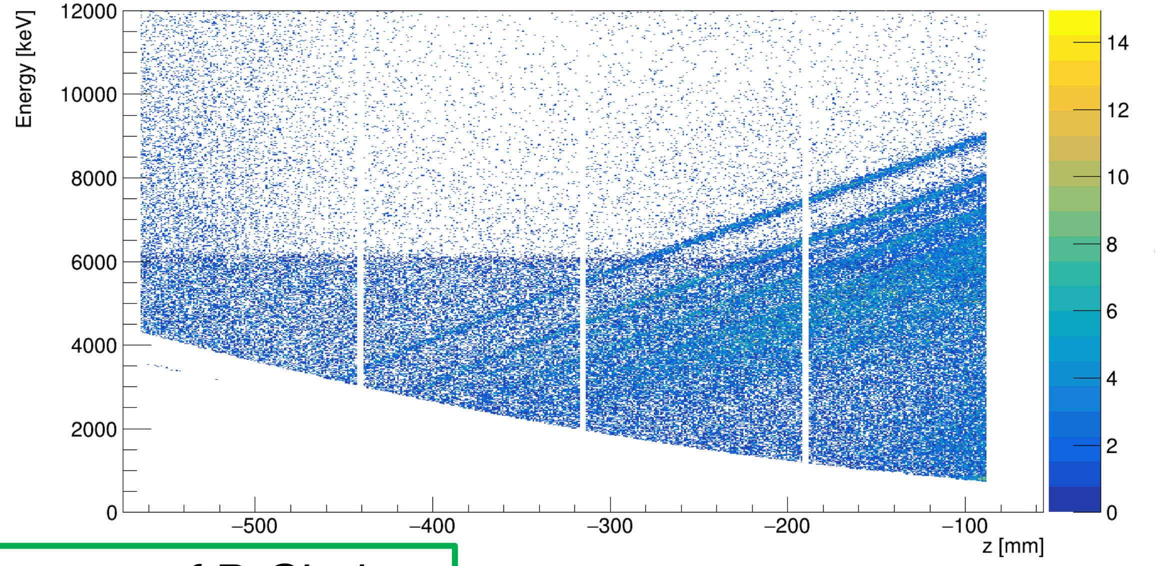
First probe of low-lying levels in ^{213}Rn (17 new states identified).

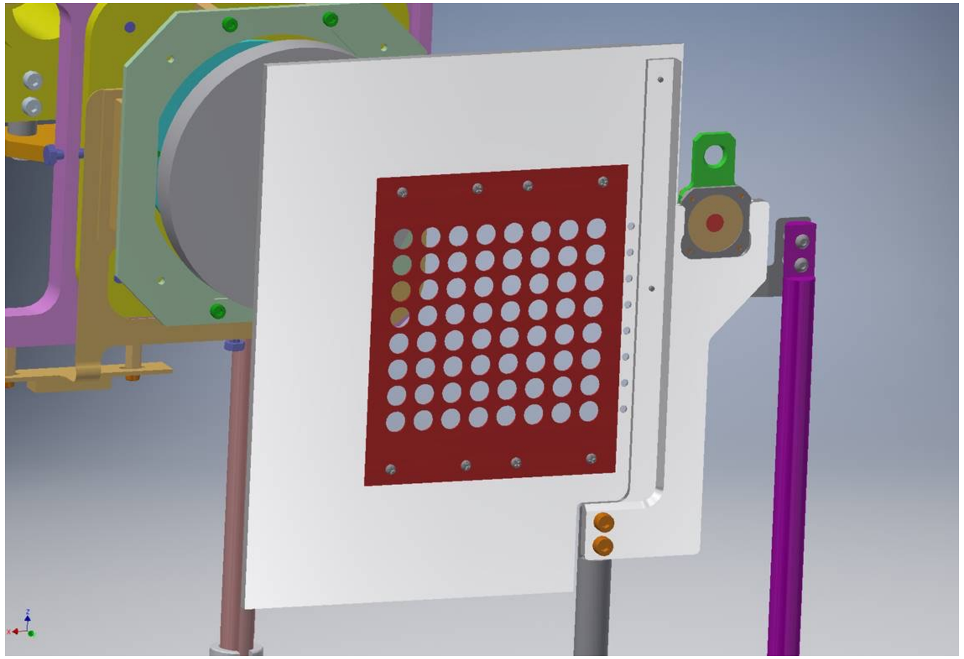
Investigating monopole shifts and role of particle-vibration coupling on fragmentation of strength north of ^{208}Pb.

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

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

~5x10^6 pps 7.6 MeV/u ^{212}Rn, 125µg/cm^2, 120-keV FWHM.





Courtesy of D Clarke

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

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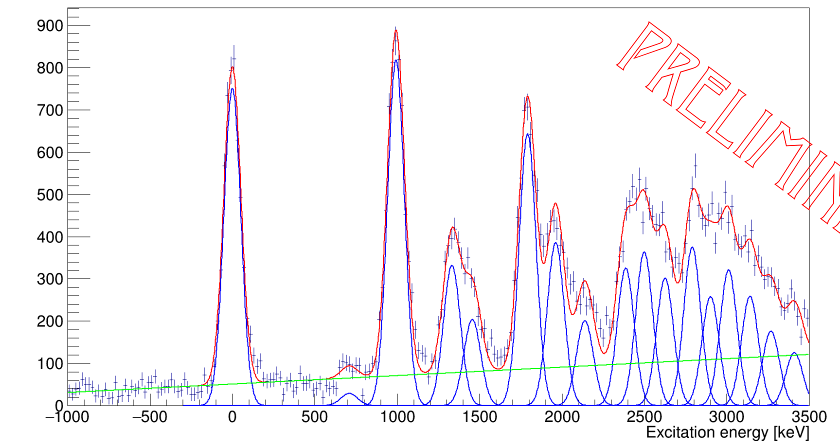
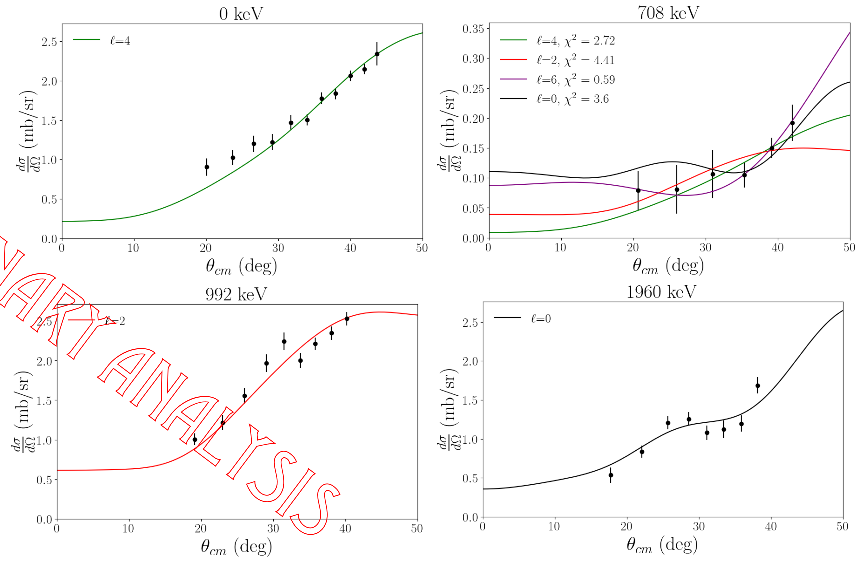
ISOLDE Solenoidal Spectrometer

Courtesy of D Clarke (EXP), G Colo (DFT)

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

Assignments made up to 2.5 MeV.





Preliminary data shown compared to systemics for N=127.

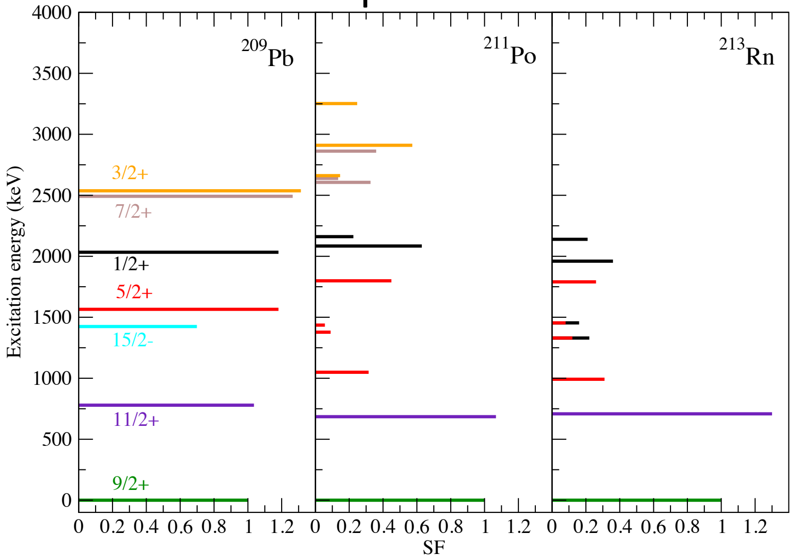
^{213}Rn strength distribution similar to ^{211}Po.

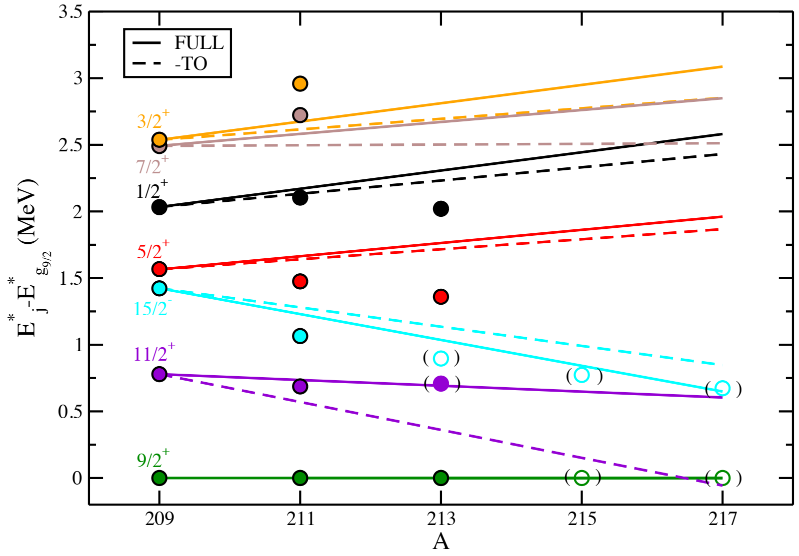
Early comparison to DFT calculations.

Monopole shifts from TBME calculation

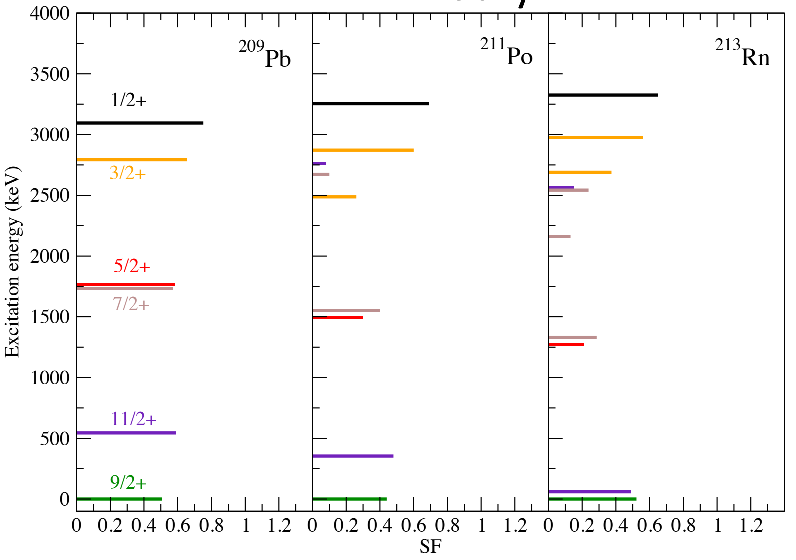
Centroids **very preliminary – full consideration of assignments required**

Experiment





Theory



Summary

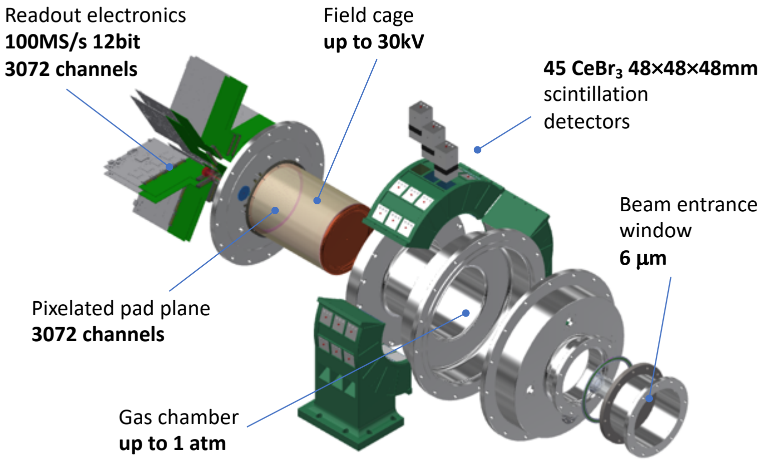
ISOLDE Solenoidal Spectrometer

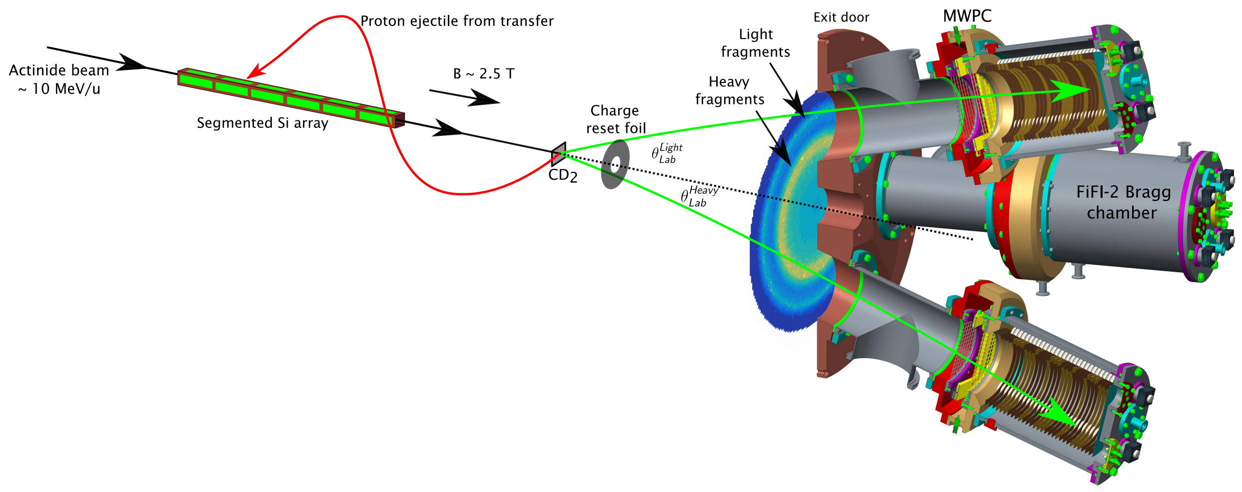
Lots of physics from first ISS runs – only a snapshot here

Focus has been on single-neutron adding – evolution of SP properties.

Not limited to (d,p). Accepted proposals for (d,d'), (t,p), transfer-induced fission.

TPC mode of operation being developed.





Thanks to collaboration and funders

ISOLDE Solenoidal Spectrometer

UKRI Science and Technology Facilities Council

erc

THE ROYAL SOCIETY

ISOLDE

EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

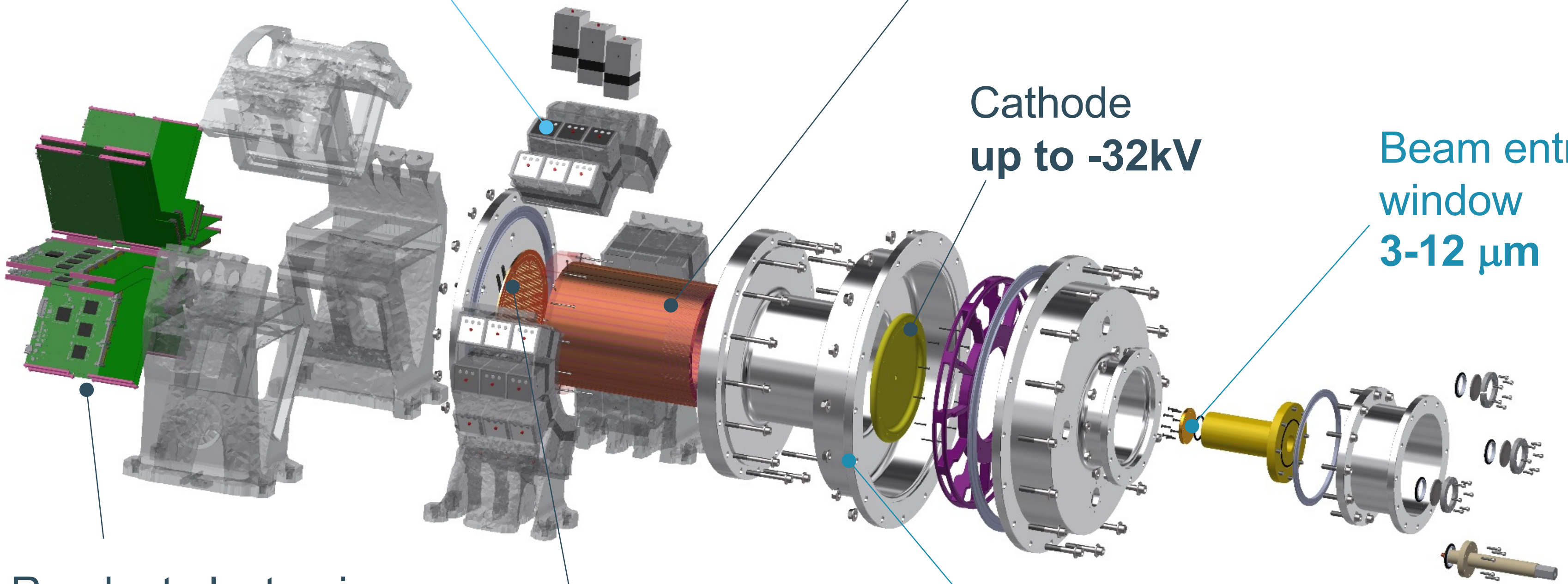
Argonne NATIONAL LABORATORY

45 $CeBr_3$
48×48×48mm
scintillation detectors

Field cage
homogeneous electric field ~2%

Cathode
up to -32kV

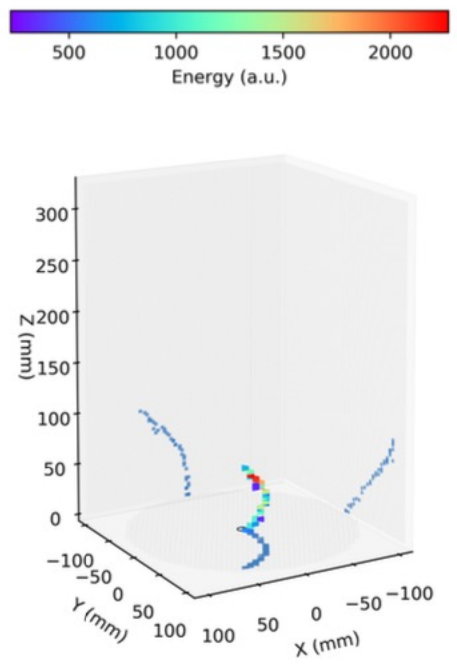
Beam entrance window
3-12 μm

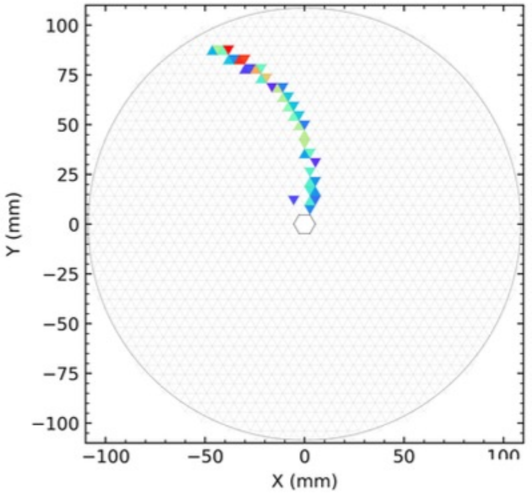


Readout electronics
1-100MS/s 12bit
3072+256 channels

MICROMEGAS detector
2916 channels

Gas chamber
up to 1 atm
min wall thickness 3mm





Measured α-particle track in B=2.5T

Fast-counting ionization chamber

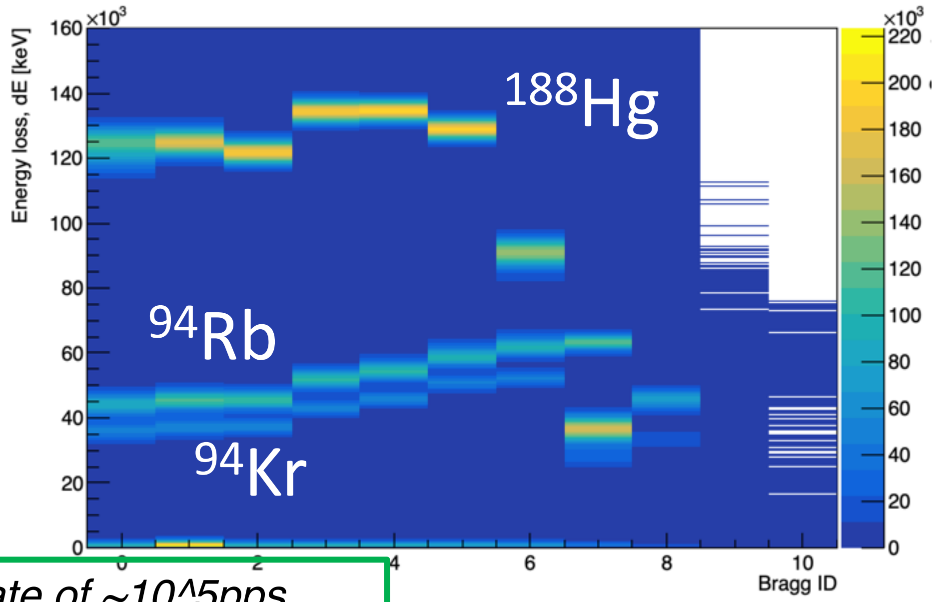
ISOLDE Solenoidal Spectrometer

Used to determine beam composition.

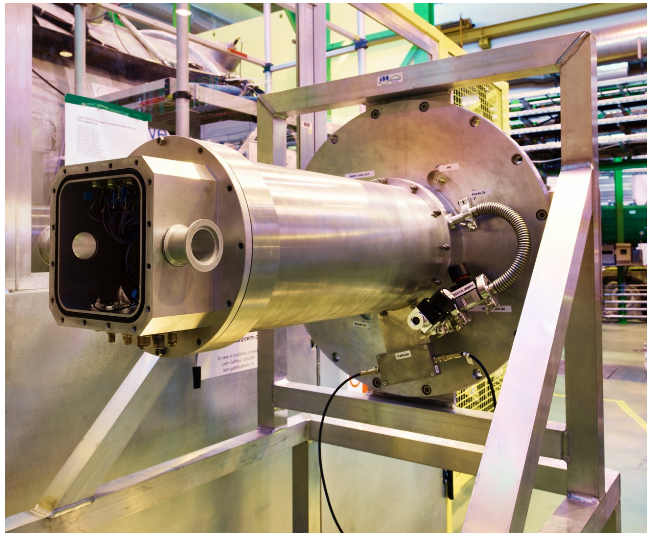
Based on modification of previous designs that operate up to 100 kHz.

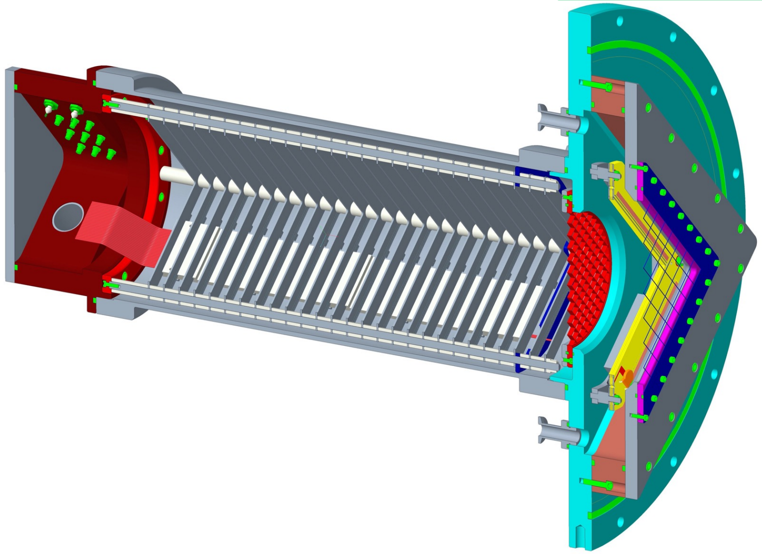
Essentially a stack of 13 PPAC's with short drift lengths to reduce pulse risetime.

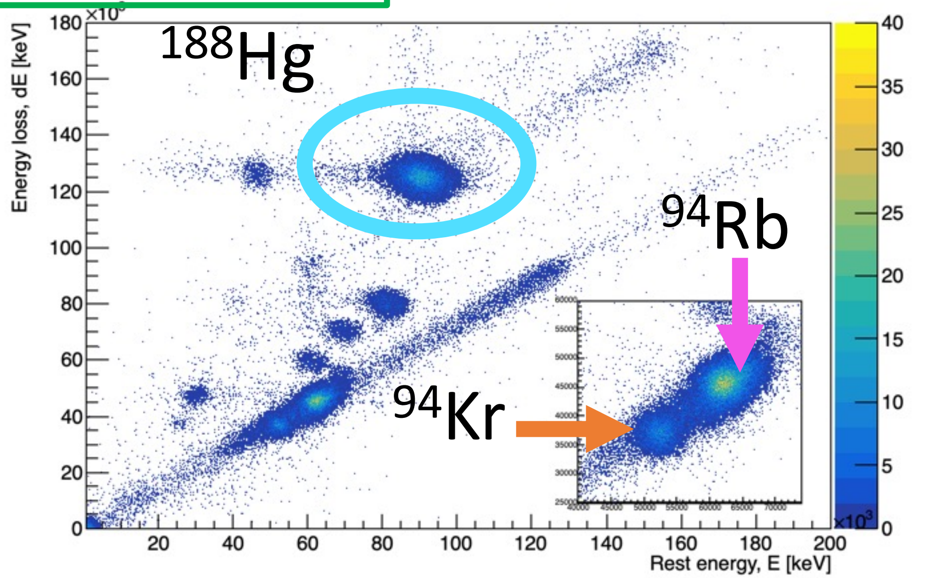
Constructed and tested – identified improvements to preamplifiers and zero-degree blocker design.



Total beam rate of ~10^5pps







Evolving nuclear structure in n-rich nuclei

ISOLDE Solenoidal Spectrometer

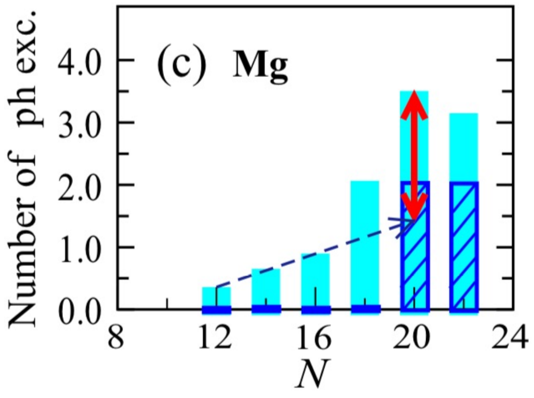
Shell-model calculations have in the past had difficulties reproducing behaviour of negative-parity states inside the Island of Inversion (or even approaching it) – without ad hoc changes.

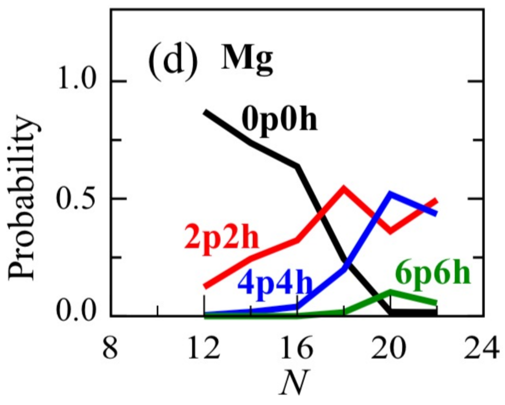
Has instigated the development of new interactions.

FSU – Configuration interaction, derived using fitting method including more SPE's and TBMEs for pf shell.

[Phys. Rev. C. 100, 034308 (2019).]

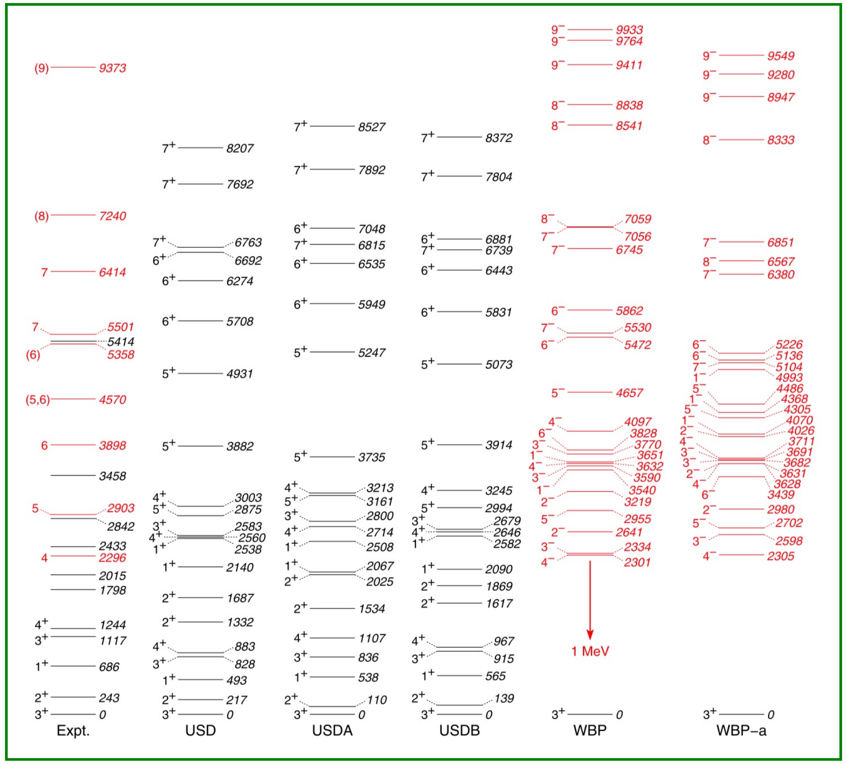
EEfd1 – New interaction derived using EKK method and Chiral EFT – no fitting of TBMEs. This interaction describes a smother transition of p-h excitations than previously thought.





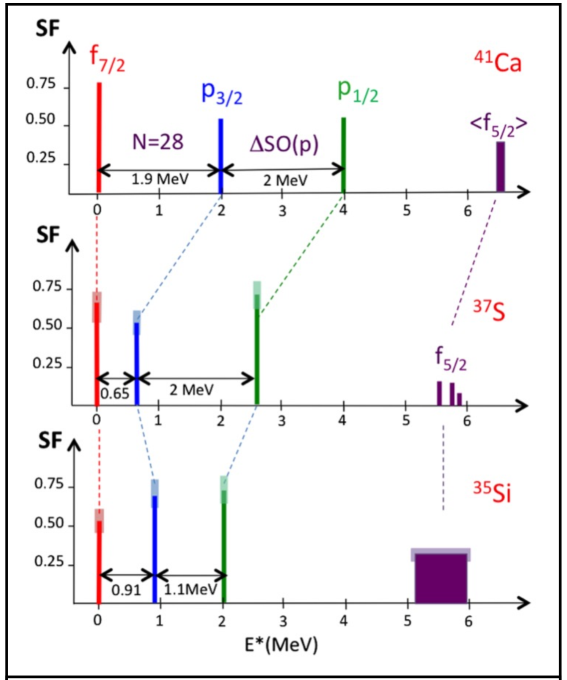
N. Tsunoda *et. al.,* Phys. Rev. C **95**, 021304(R) (2017)

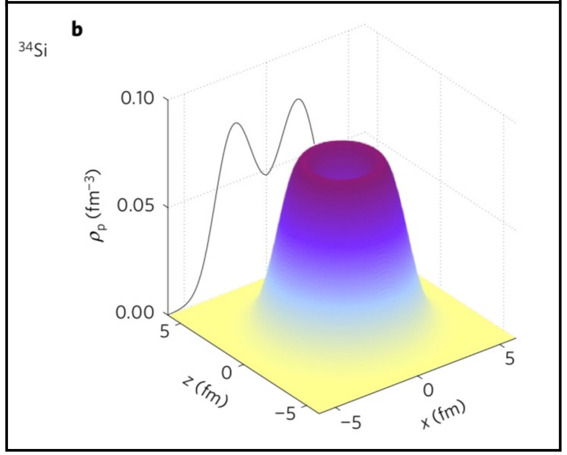
^{30}Al



D. Steppenbeck *et. al.,* Nucl. Phys. A **847**, 149 (2010)

Spin-orbit weakening Bubble or Weak-binding





^{34}Si – Bubble nucleus.

Removal of pair of s1/2 protons.

Component of SO of opposite sign (proportional to derivative of density distribution) – reduction in splitting due to internal component.

PRL **112**, 042502 (2014);
Nature Physics **13**, 152-156 (2017).

Weak-binding/finite geometry

Near threshold low-ℓ orbits experience a smaller (or no) centrifugal barrier – more extended wavefunction – lowers energy.

S-states linger – halo-formation

Also apparent in p-states - as p1/2 approaches threshold before p3/2 then reduction in splitting.

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