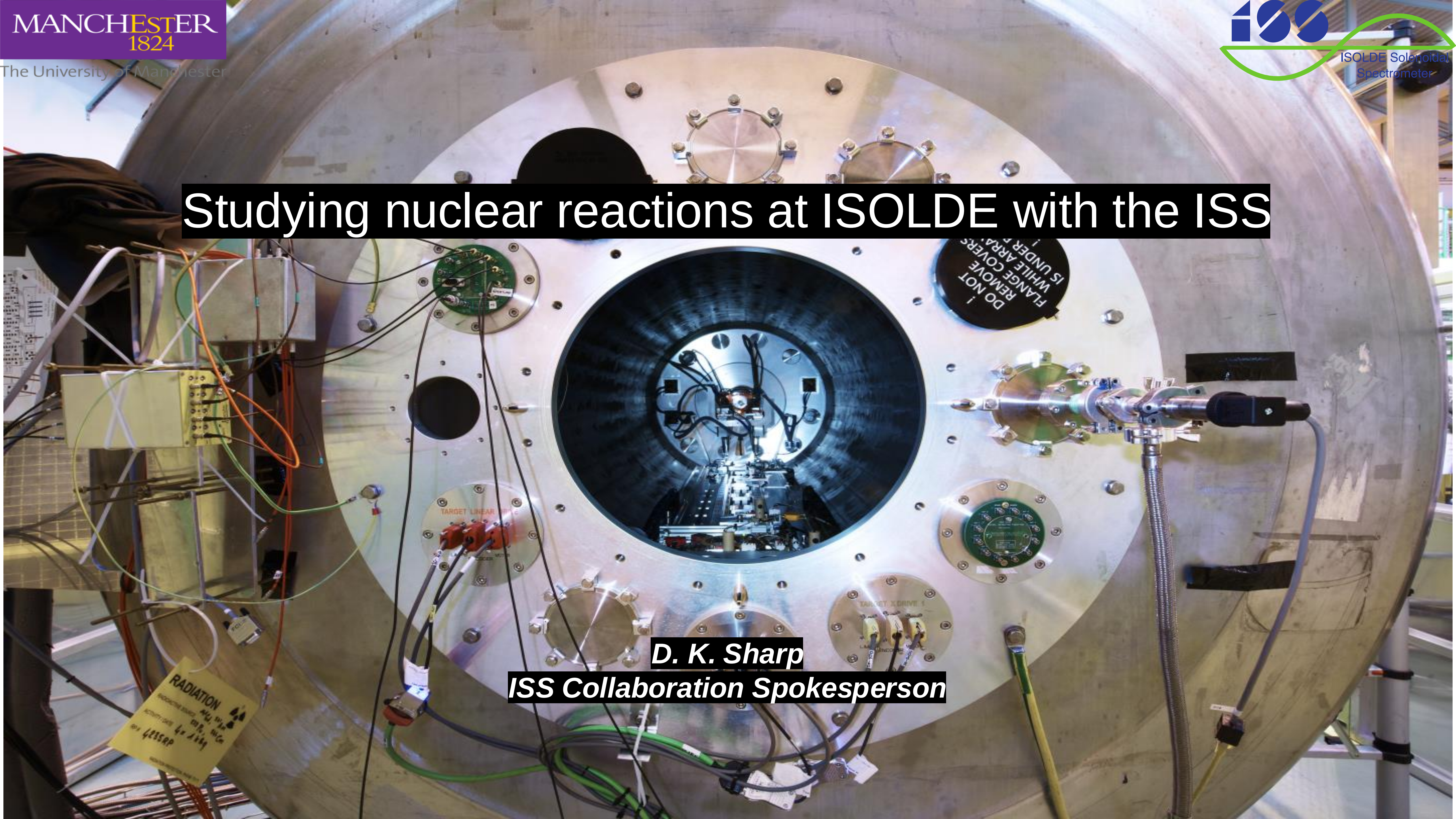


MANCHESTER 1824
The University of Manchester

ISOLDE Solenoidal Spectrometer

Studying nuclear reactions at ISOLDE with the ISS

D. K. Sharp
ISS Collaboration Spokesperson

Overview

- *Introduction to direct reactions (and in particular transfer reactions)*
- *Introduction to ISOLDE and to solenoid technique used in ISS for measuring direct reactions in inverse kinematics.*
- *Examples of measurements at ISOLDE.*
- *Proof-of-principle measurements at HELIOS.*

Direct reactions

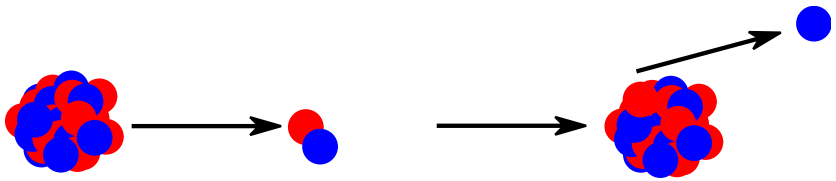
Access to variety of nuclear structure information

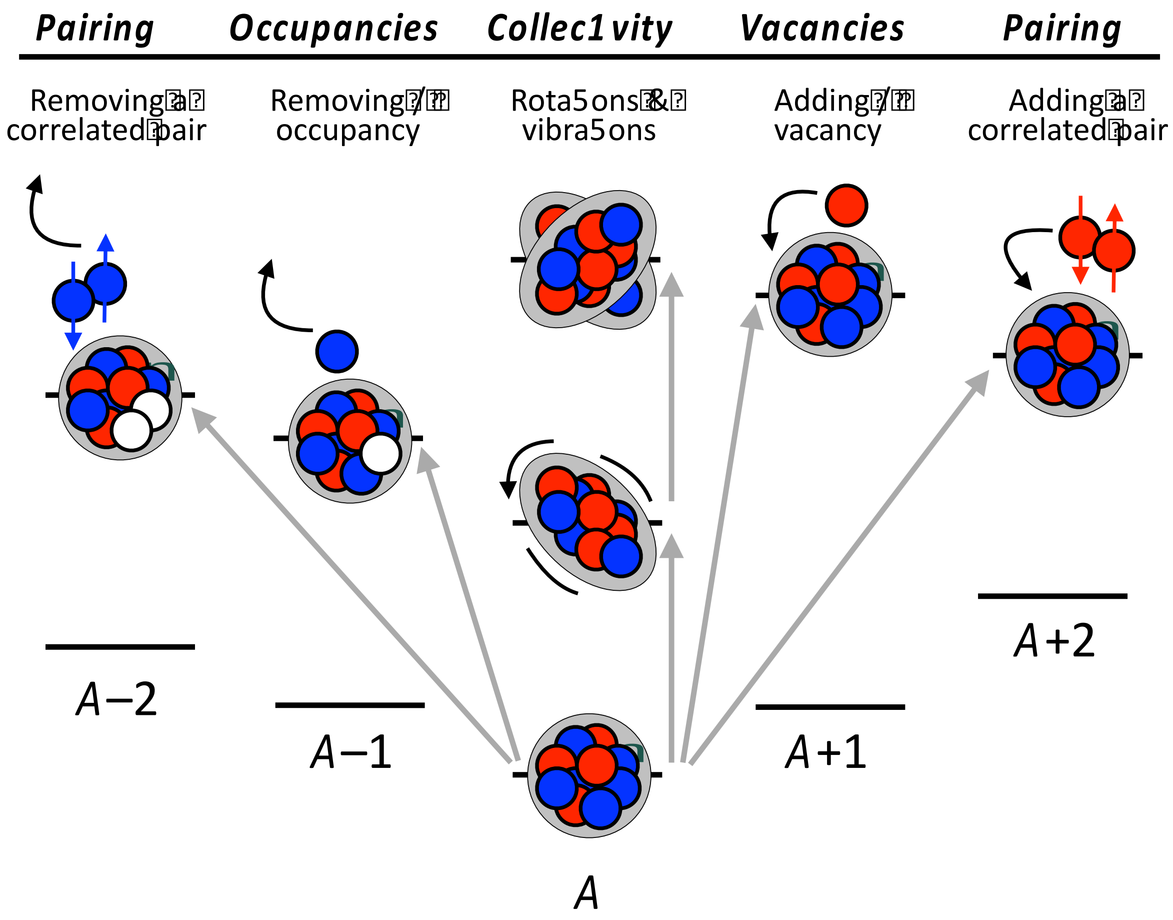
Single-particle states, *$E_{(Ex,SP)}$, l, spectroscopic factors, e.g. (d,p), (p,d)…*

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

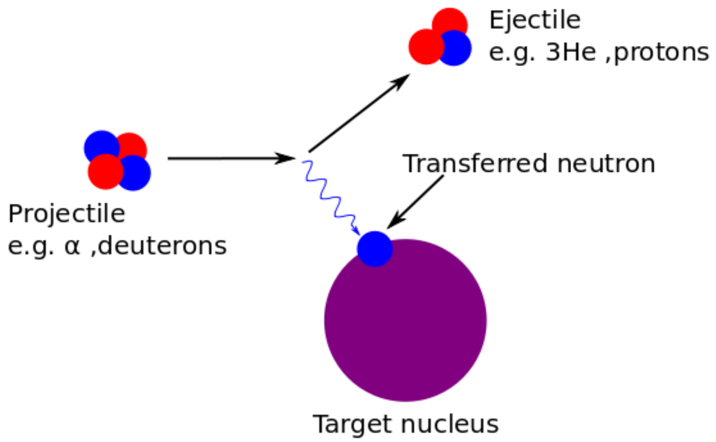
***Collective properties** via e.g. (p,p′), (d,d′), (α,α′)…*

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



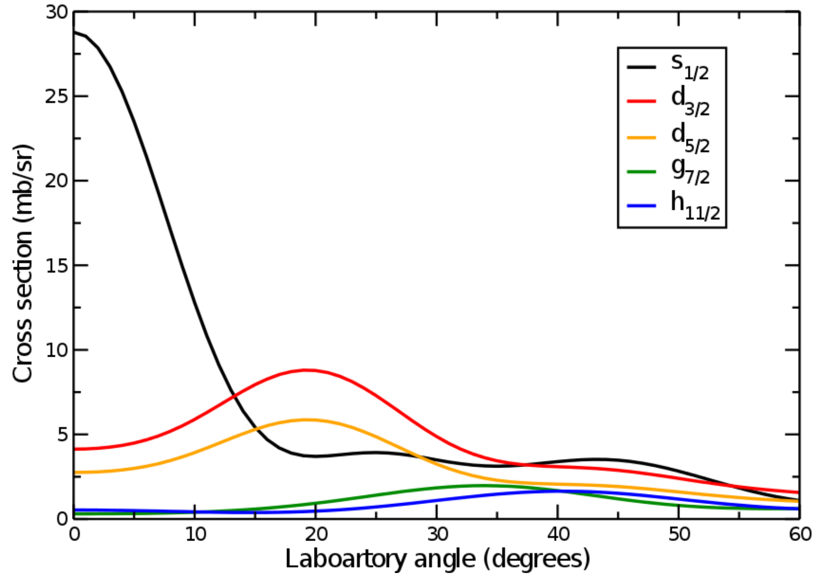


Single-nucleon transfer reactions



Measure:
Yield -> Cross section
Momentum -> Energy

Angular momentum from angular distributions



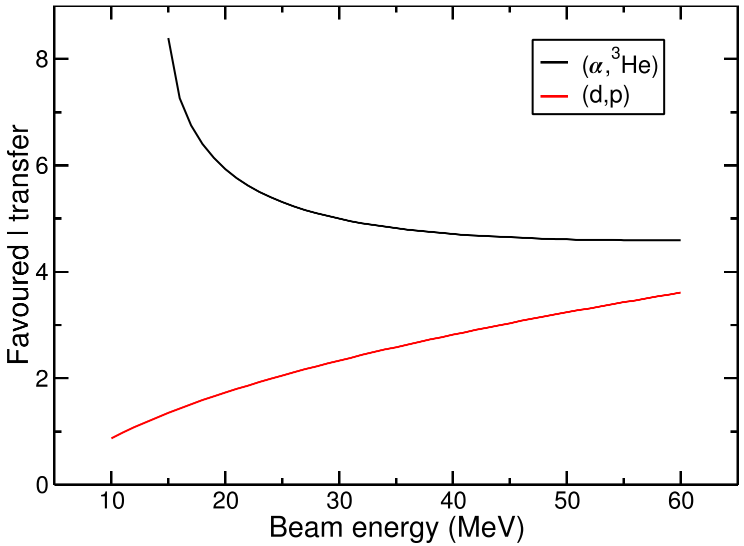
Peripheral nature of the transfer reaction means that the **linear momentum transfer** q is related to the **angular momentum transfer** ℓ via the nuclear radius in a semi-classical model.

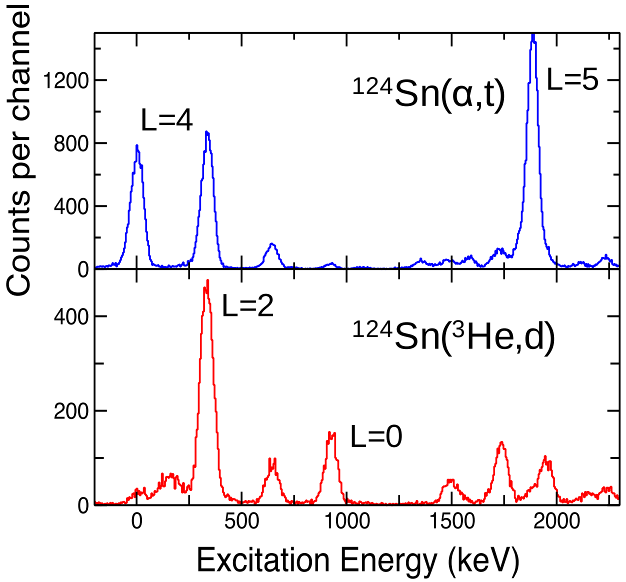
$$\ell = r \times q$$

Larger angular momentum transfer typically favours larger angles.

Large reaction Q-values naturally leads to large q. Leading to **enhanced population** of higher ℓ states.

Next step is to take measured quantities and extract information on the single-particle properties (ESPEs and occupancies).





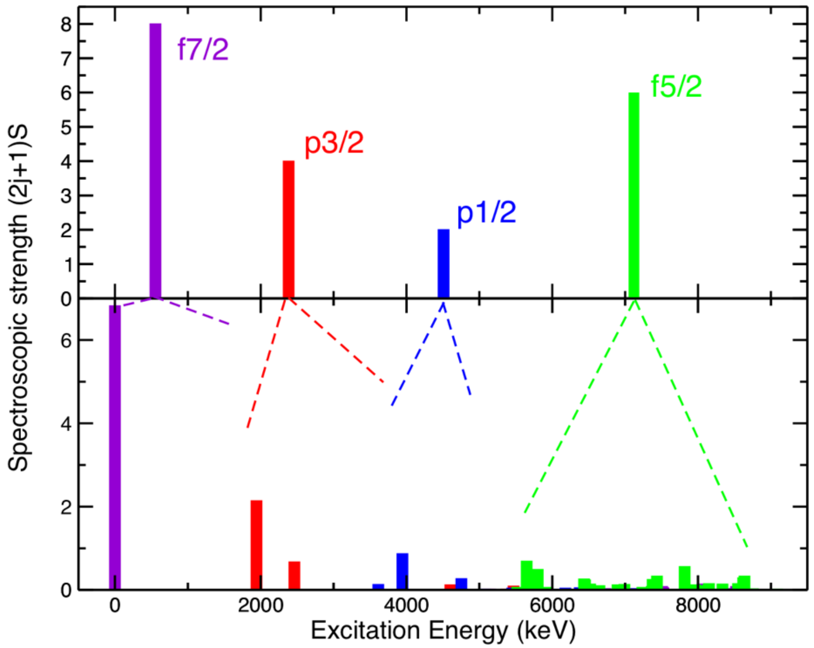
Single-nucleon transfer reactions

*Single-particle energies and occupancies are **not directly observable**, but a framework exists in which we can discuss them.*

*Important as transfer is one of a few **direct probes** of the single-particle content of a state.*

*Spectroscopic overlap functions can be recast as **spectroscopic factors** (SF); requires faith in the reaction model to extract structural information from a **single** experimental observable.*

Allows a measure of the single-particle content of each state.



One may naively say:

- ***Identify** the j,l associated with the populated states*
- ***Measure** the cross section*
- ***Compare** to FR-DWBA (or ADWA) and infer SF.*
- ***Calculate** the centroid of the strength distribution to estimate the SPE or sum the SFs to get the occupancy/vacancy.*

$$\frac{ds}{dW}_{Measured} = gS_{lj}\,\frac{ds}{dW}_{DWBA}$$

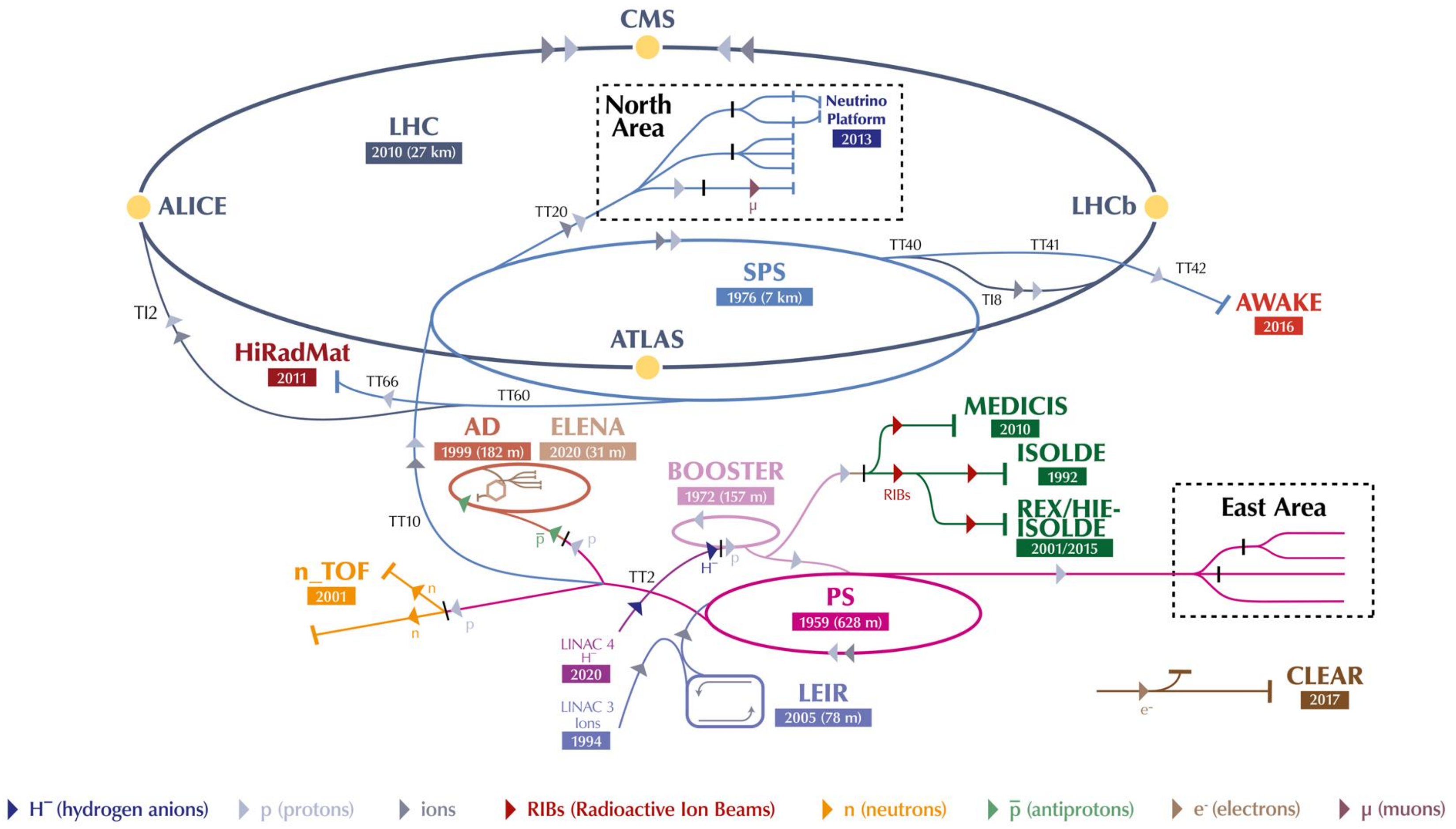
$$E_{\text{centroid}} = \frac{\sum_i E_i S_i}{\sum_i S_i}$$

$$\sum_i (2j+1)\,S_{j\ell} = (2j+1) - n_j(A)$$

$$\sum_{J_A} S_{j\ell} = n_j(B)$$

Radioactive beams at CERN

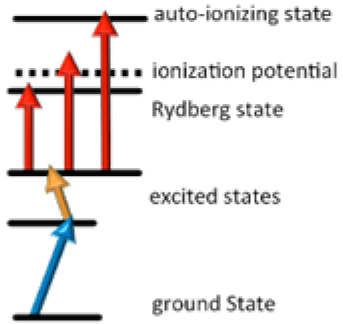
The CERN accelerator complex
Complexe des accélérateurs du CERN

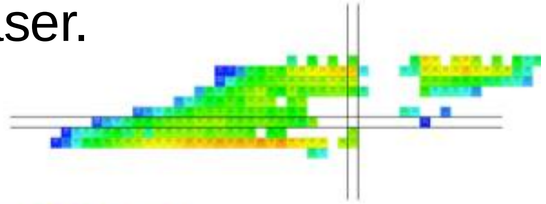


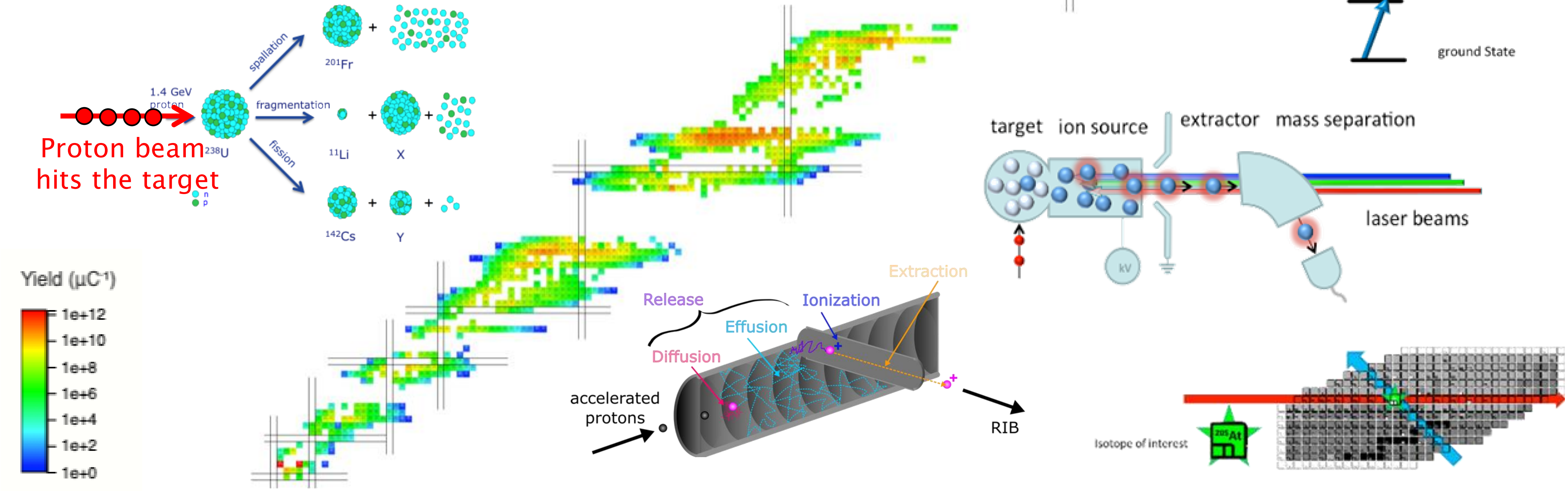
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

Radioactive beams at CERN

- High-energy protons are impacted onto a thick target, e.g. ^{238}U.
- The reactions produce a wide variety of nuclei simultaneously.
- Over 20 target materials − carbides, oxides, solid metals, molten metals and molten salts − operated at high temperature.
- Three broad types of ion sources: surface, plasma, laser.
- > 1300 isotopes of 75 chemical elements.

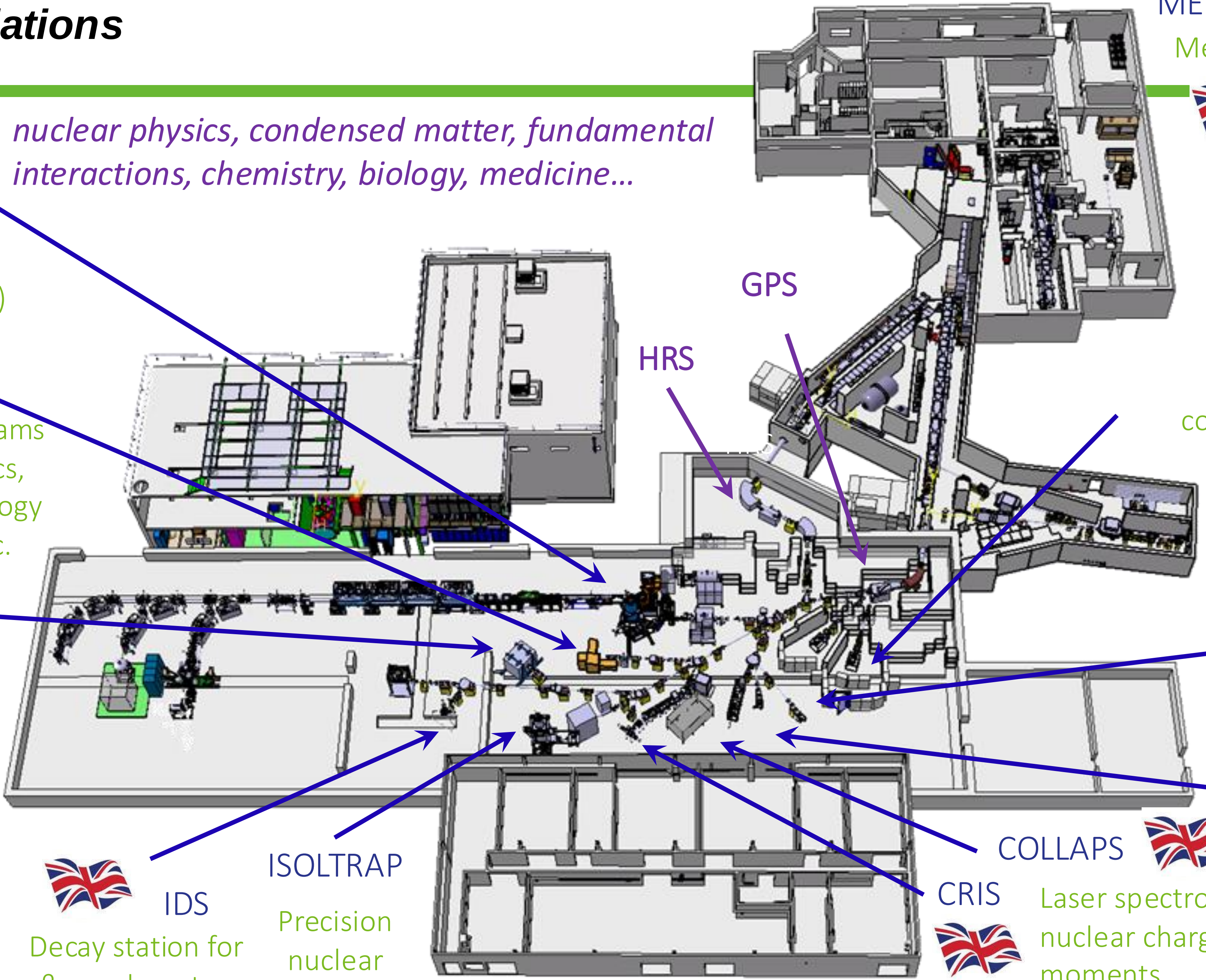






Low-energy installations

nuclear physics, condensed matter, fundamental interactions, chemistry, biology, medicine…



WISArD

Scalar and tensor currents in weak interactions: $\beta\nu(\theta)$

VITO

Laser-polarised beams for nuclear physics, chemistry and biology using β-NMR etc.

TAS

Total absorption spectrometer for β-decay feeding

IDS

Decay station for α,β,γ and neutrons

ISOLTRAP

Precision nuclear masses

HRS

GPS

MEDICIS

Medical isotopes research

Condensed-matter physics

Emission channeling, perturbed angular correlations, Mössbauer, isotope collections….

.

Protons

Travelling setups

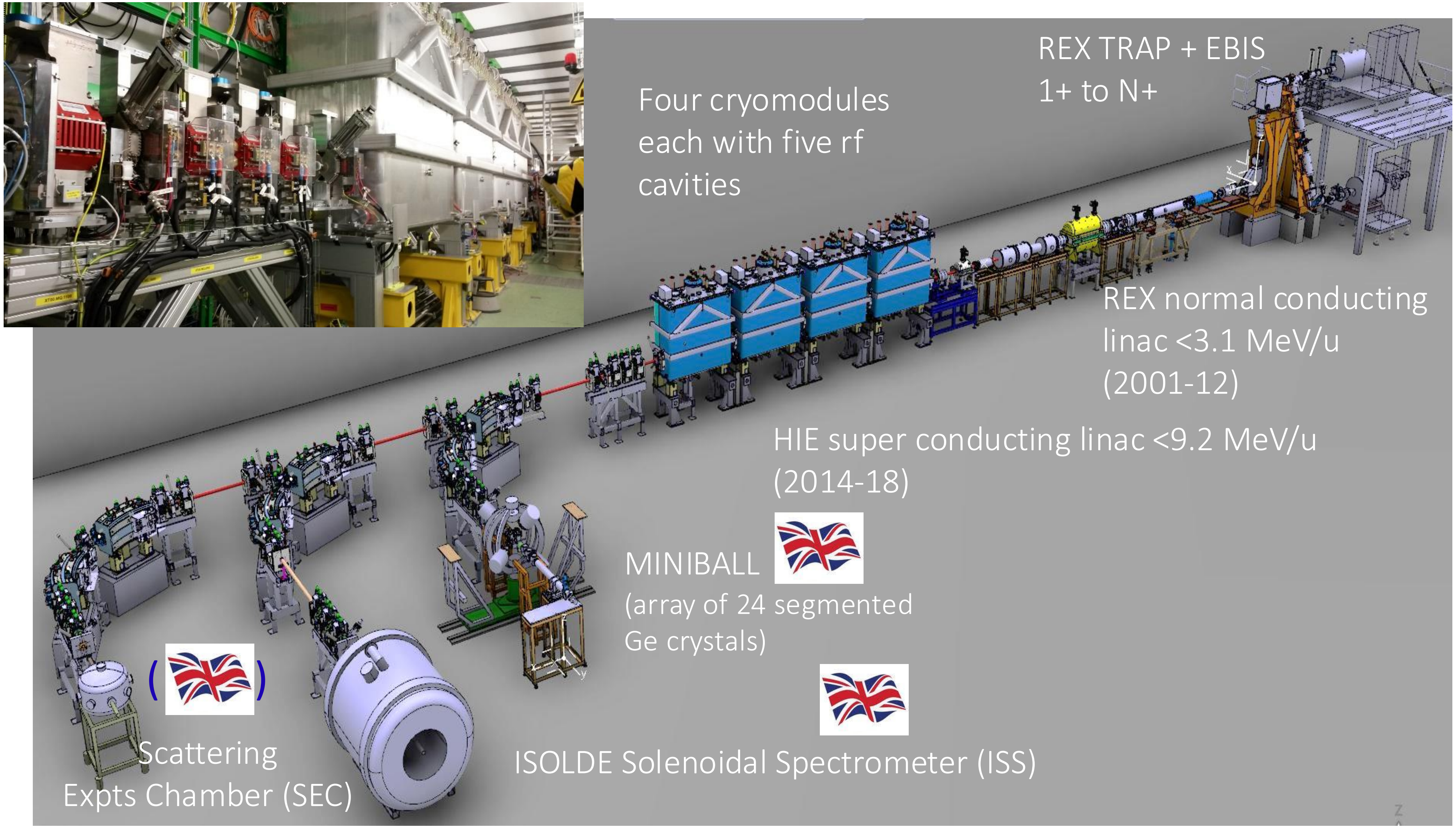
MIRACLS MR-TOF

COLLAPS

CRIS

Laser spectroscopy: nuclear charge radii and moments.

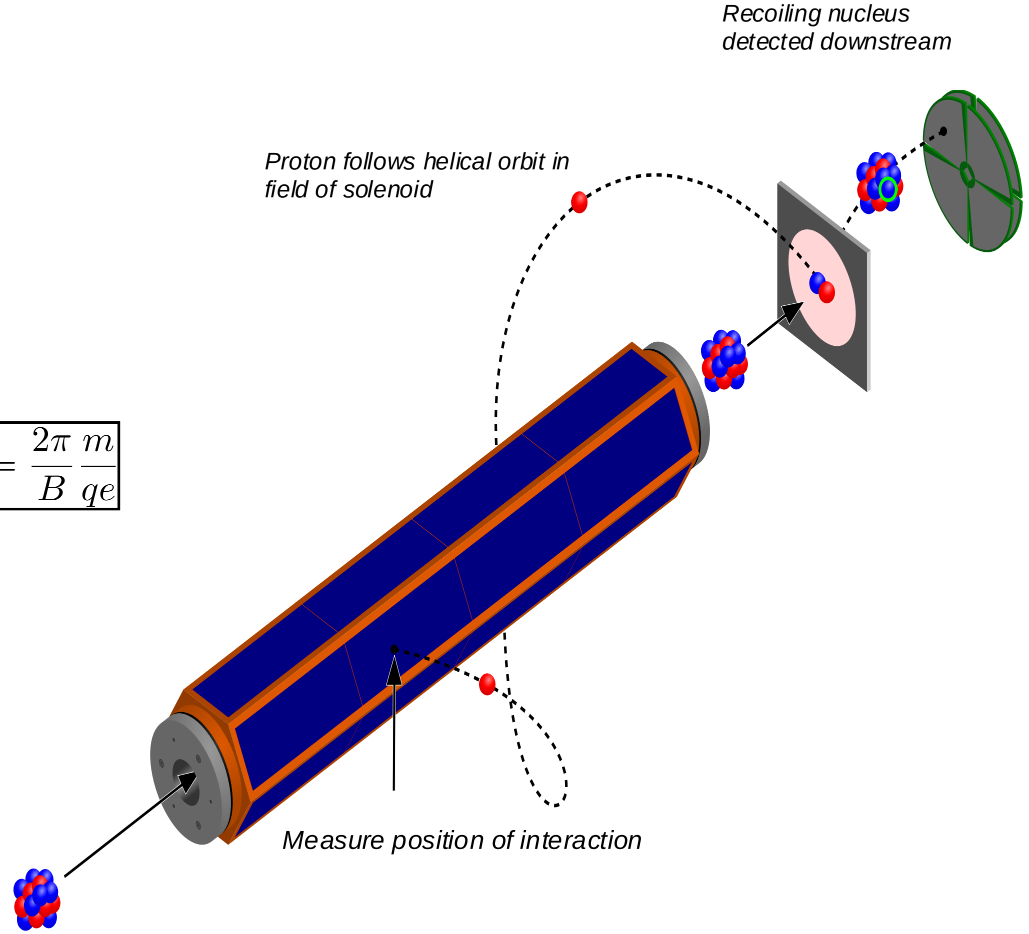
Reaccelerated beams for reactions



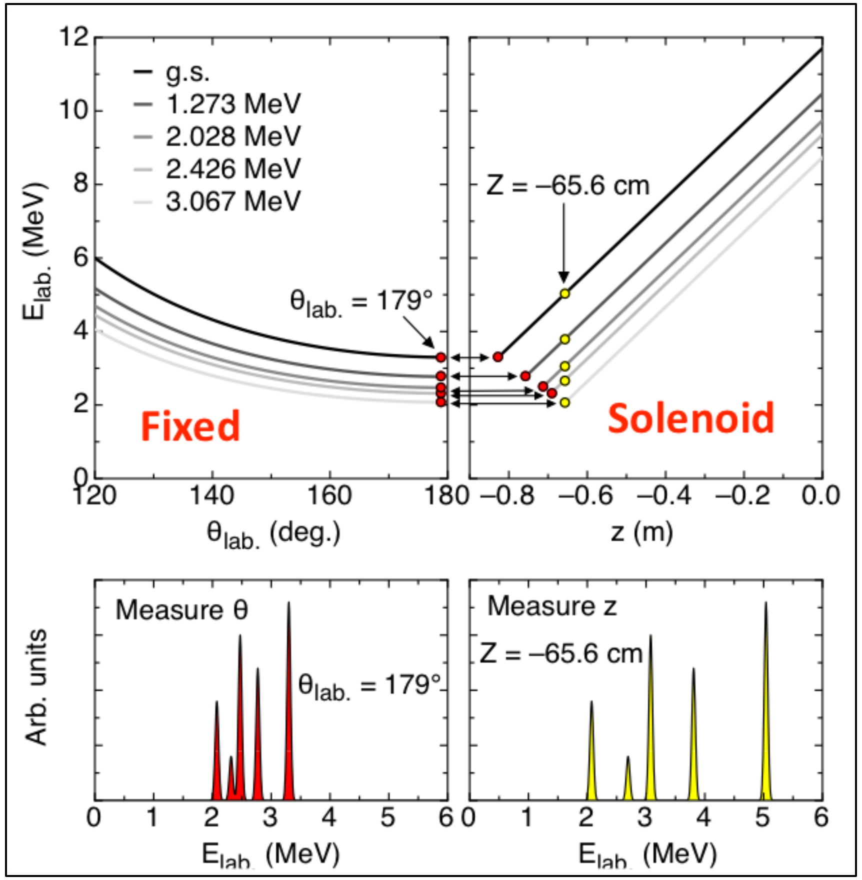
40-60 keV 1+ ions

nuclear structure, reactions and astrophysics

Solenoid technique – transfer in inverse kinematics



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



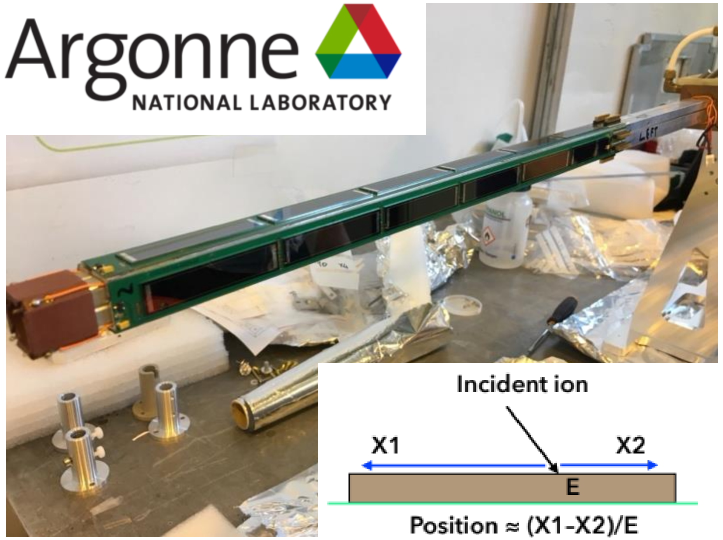
MEASURED QUANTITIES: position z, cyclotron period T_{cyc} and lab particle energy E_{p}.

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

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

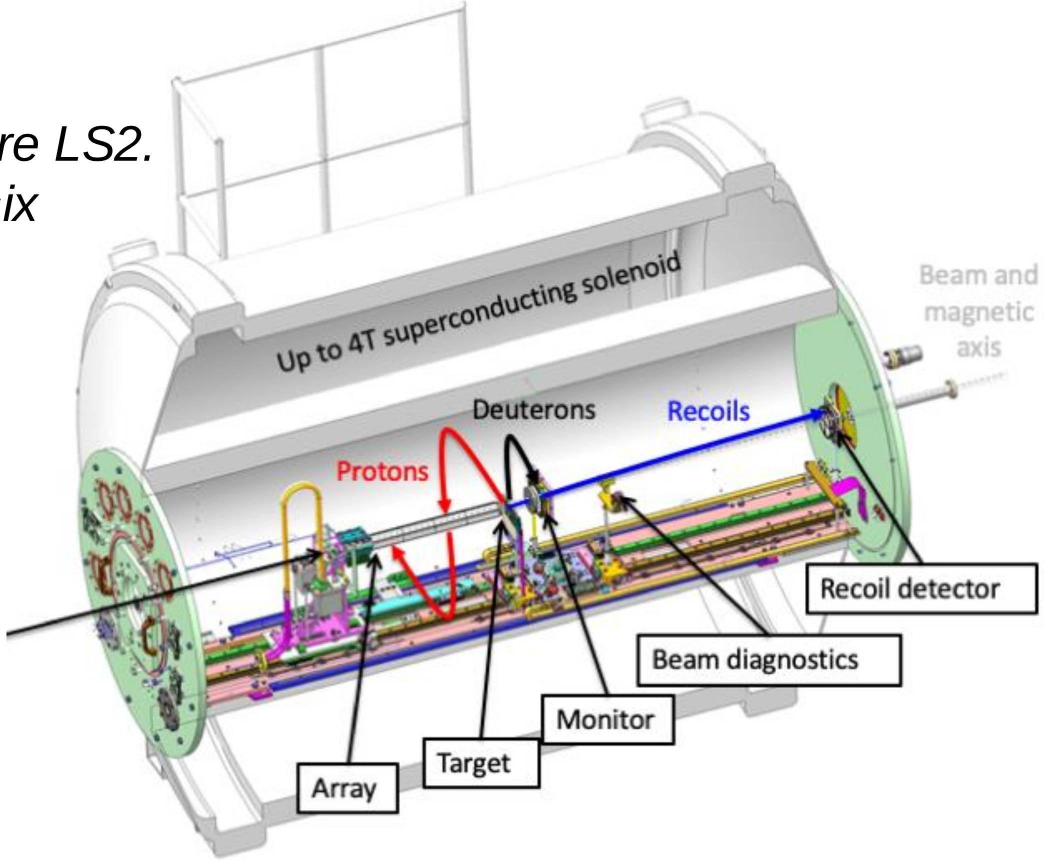
Linear relationship between E_{cm} and E_{lab}.

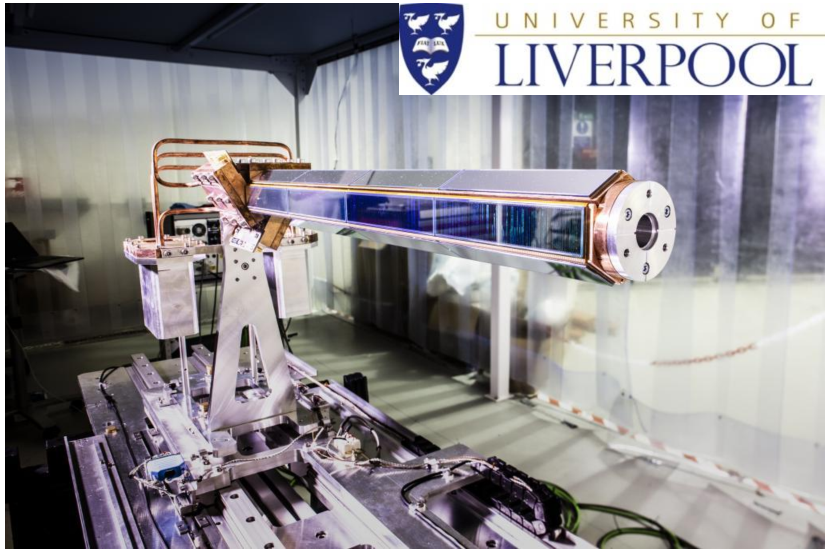
ISOLDE Solenoidal Spectrometer



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

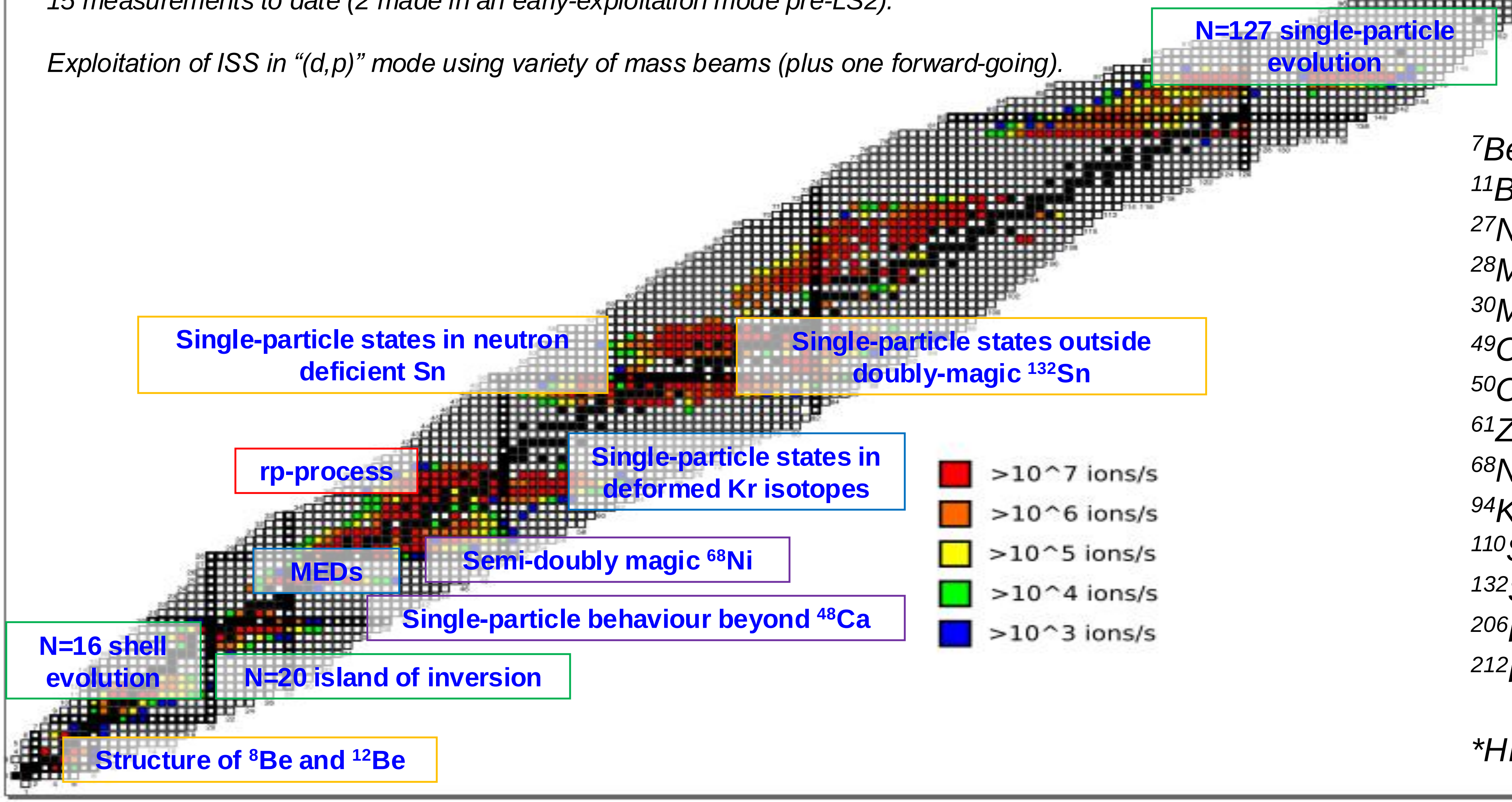
Six-sided array consisting of four DSSSDs with ASICs readout (R^3B) on each side.
Each detector consists of ***128 x 0.95mm strips*** *along the length of the detector* ***11 x 2mm*** *along the width.* ***1800*** *channels of readout.*
Total length of silicon is 510.4mm (486.4mm active).
66% solid angle coverage.

ISS summary

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

15 measurements to date (2 made in an early-exploitation mode pre-LS2).

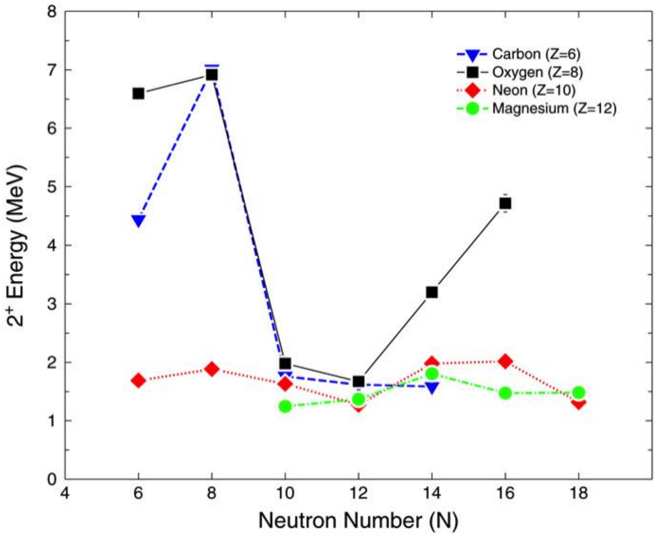
Exploitation of ISS in "(d,p)" mode using variety of mass beams (plus one forward-going).



^{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
^{94}Kr(d,p)^{95}Kr
^{110}Sn(d,p)^{111}Sn
^{132}Sn(d,p)^{133}Sn
*^{206}Hg(d,p)^{207}Hg**
^{212}Rn(d,p)^{213}Rn

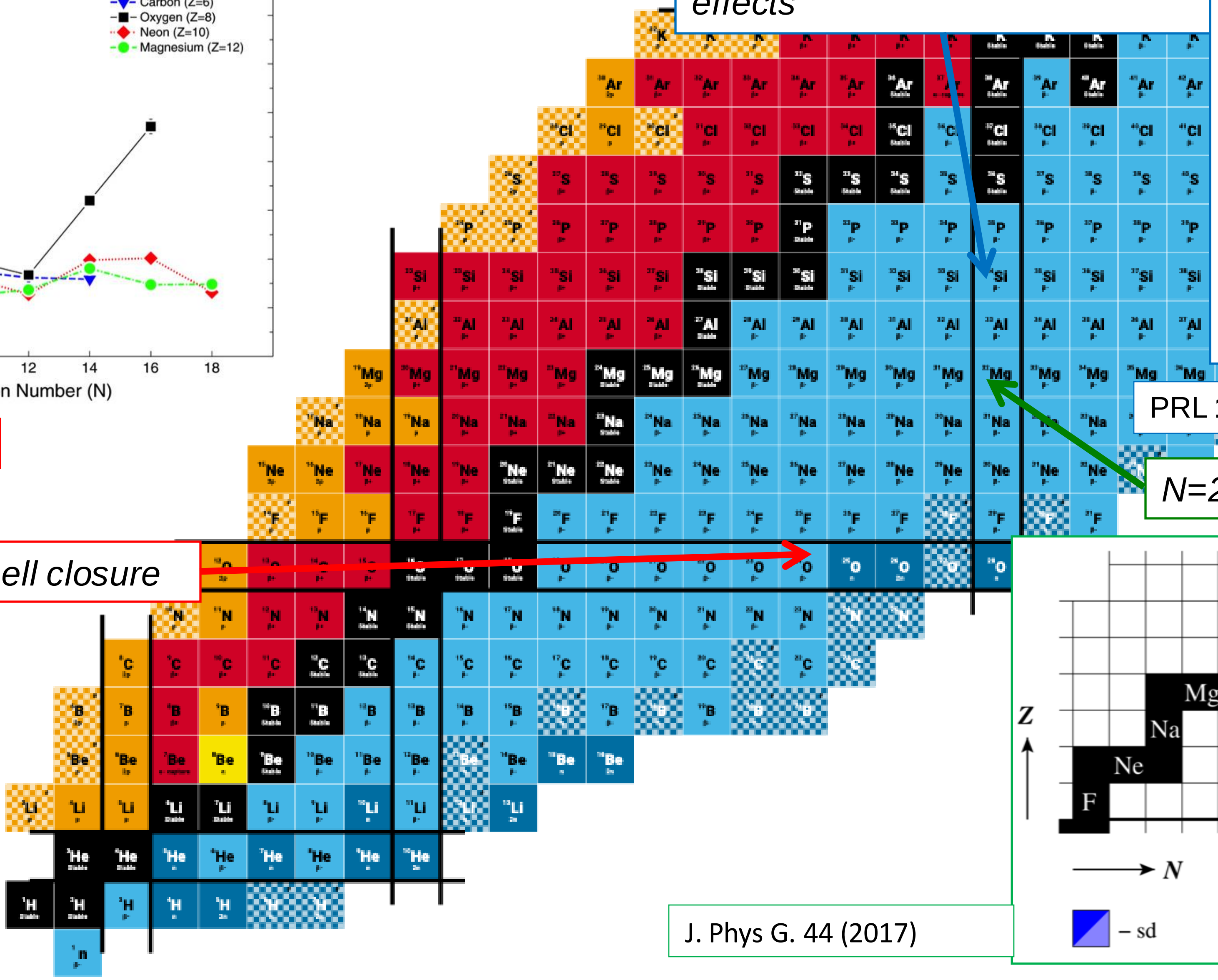
**HELIOS array*

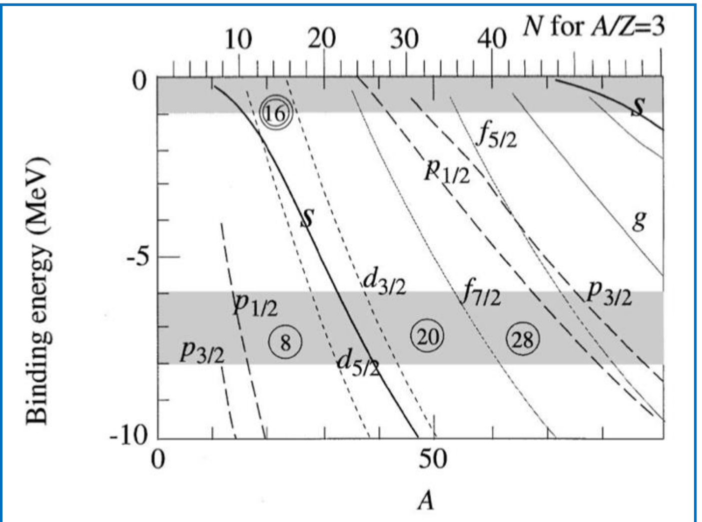
Evolving nuclear structure in n-rich nuclei



PLB **672** 17 (2009)

Weak binding/Finite geometry effects

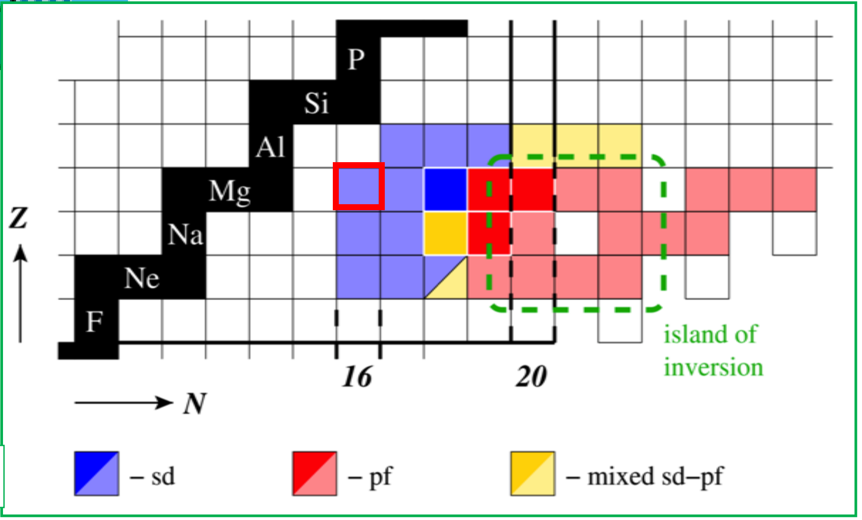




PRL **119**, 182502 (2017); PRL **84**, 5493 (2000).

N=20 Island of Inversion

N=16 shell closure



J. Phys G. 44 (2017)

Trends in N=17 isotones

MANCHESTER 1824 The University of Manchester

ISOLDE Solenoidal Spectrometer

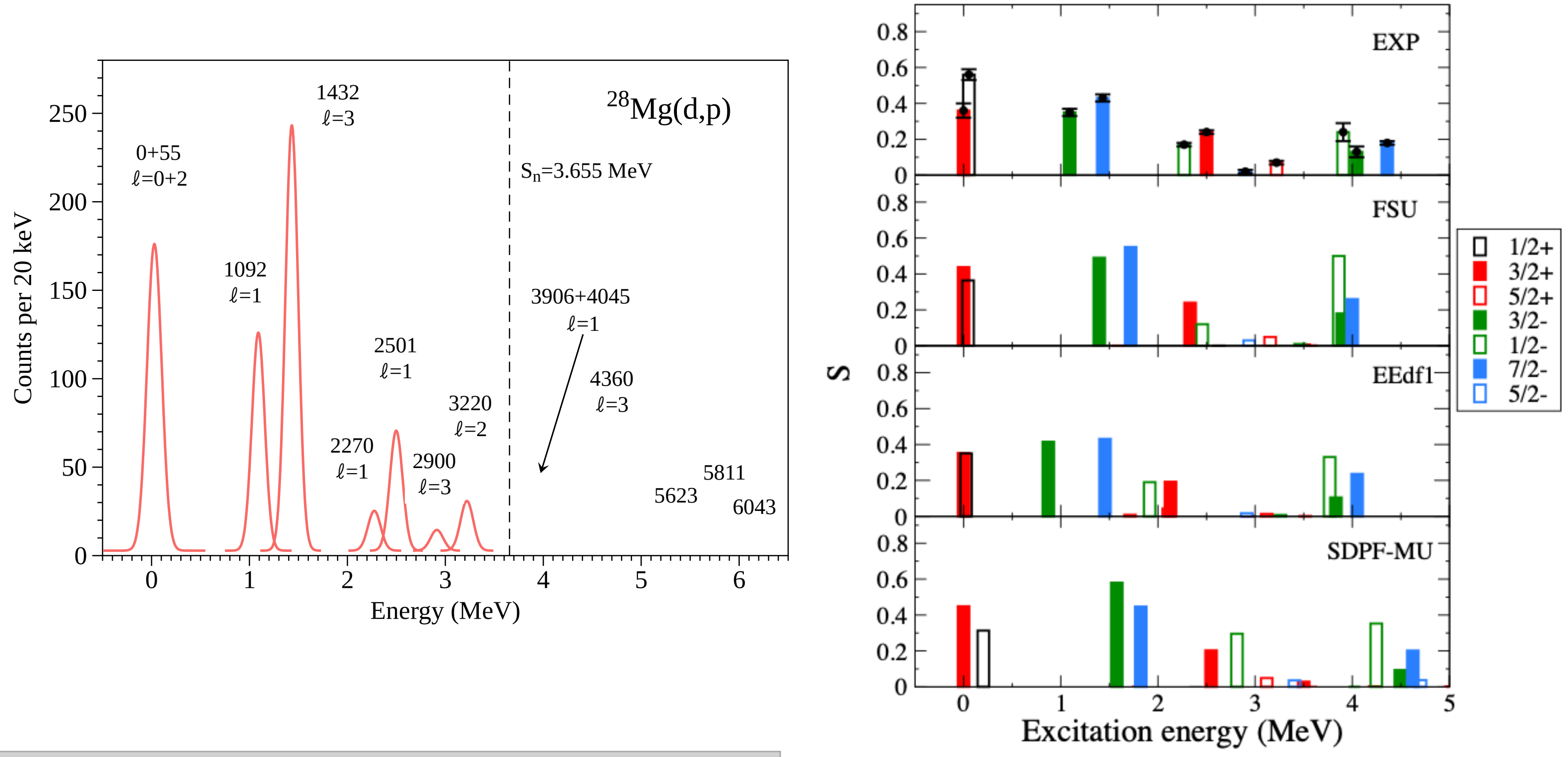
^{28}Mg(d,p)^{29}Mg reaction measured before LS2 and data combined with existing stable systems.

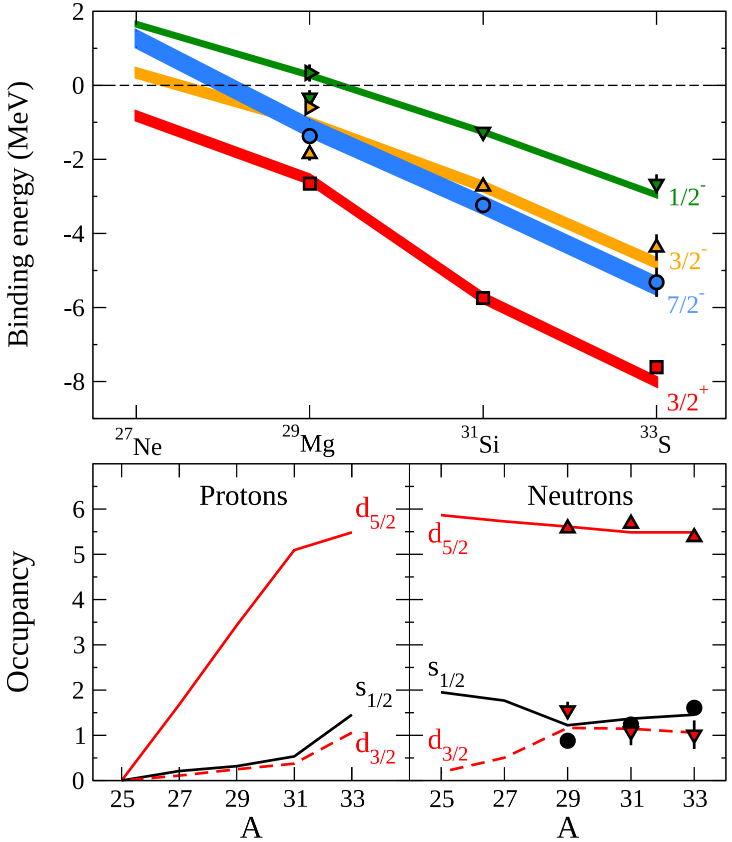
1x10^{6}pps @ 9.7 MeV/u ^{28}Mg

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.



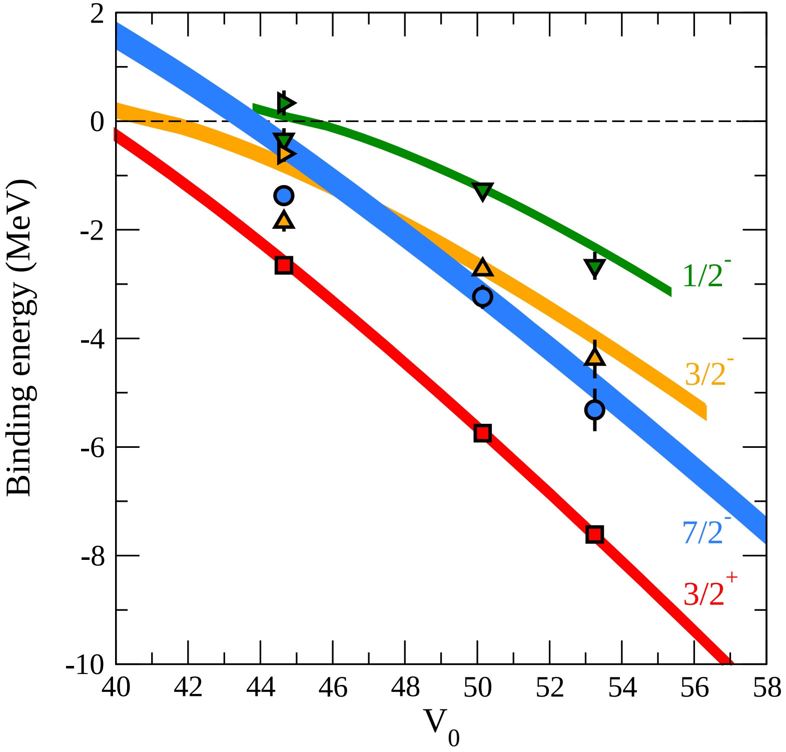


P.T.MacGregor *et. al.*, PRC **104**, L051301 (2021).

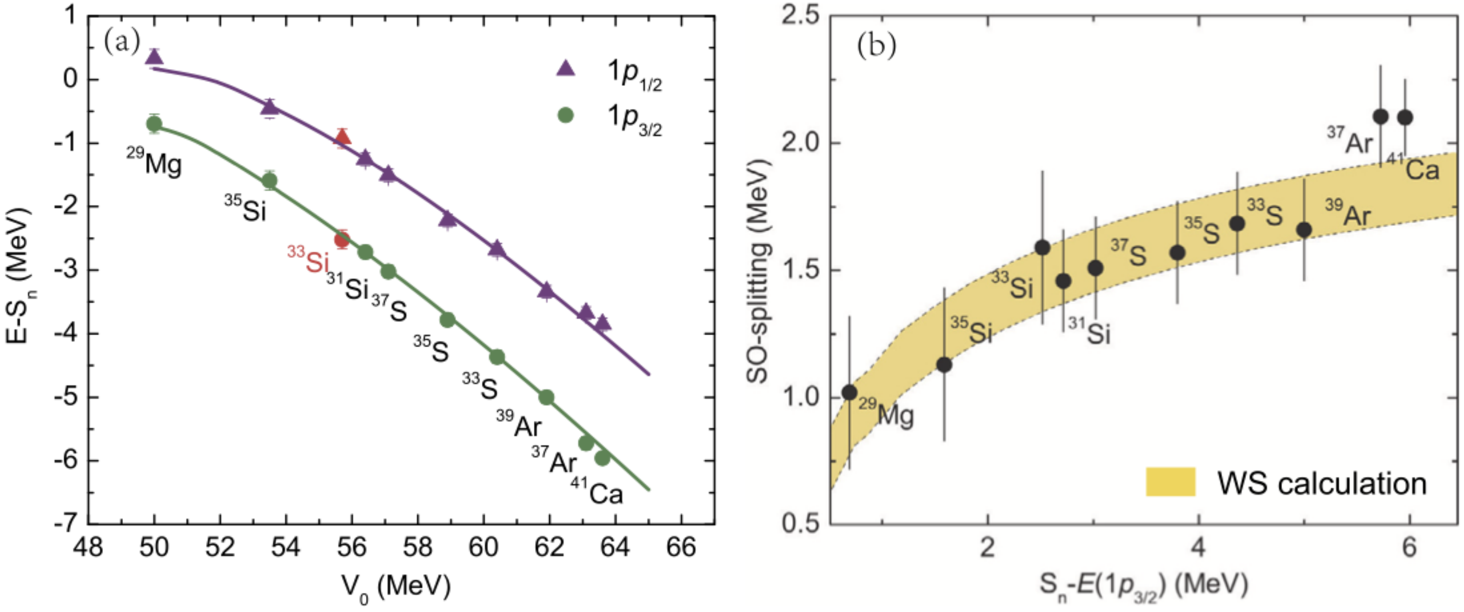
Trends in N=17 isotones - finite binding

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.

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



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



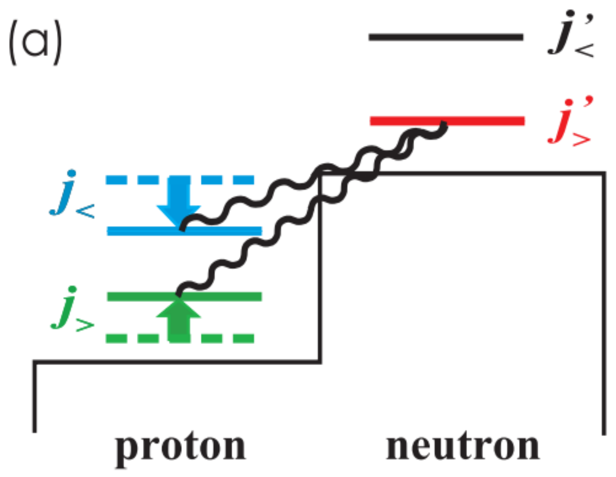
J. Chen *et. al.*, PLB **853** (2024).

Evolution of single-particle structure along shell-closures

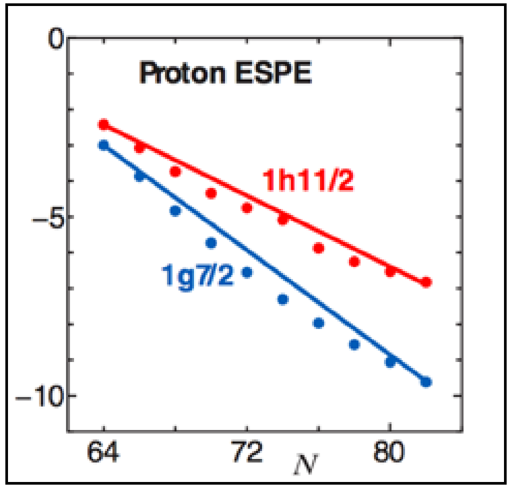
Trends observed in light nuclei have even been observed in stable heavier nuclei - Changes in high-j states as high-j orbitals are filling.

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.*

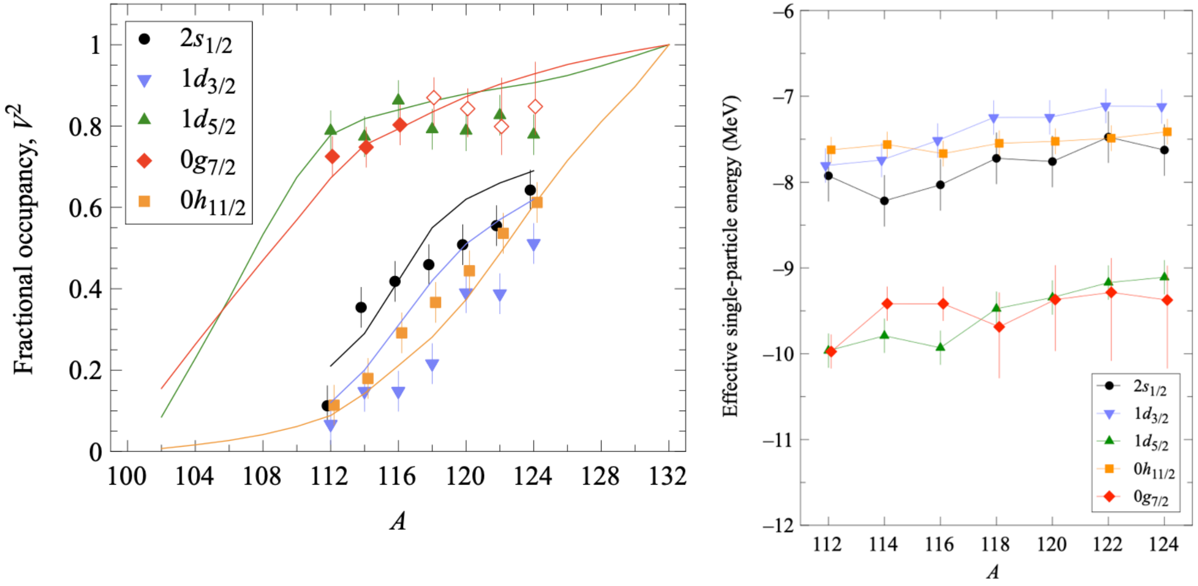
Access to RIBs at HIE-ISOLDE allows access to measurements across large chains of isotopes/isotones probing the interactions further from stability (Sn isotopes) and in new regions such as N=127 .



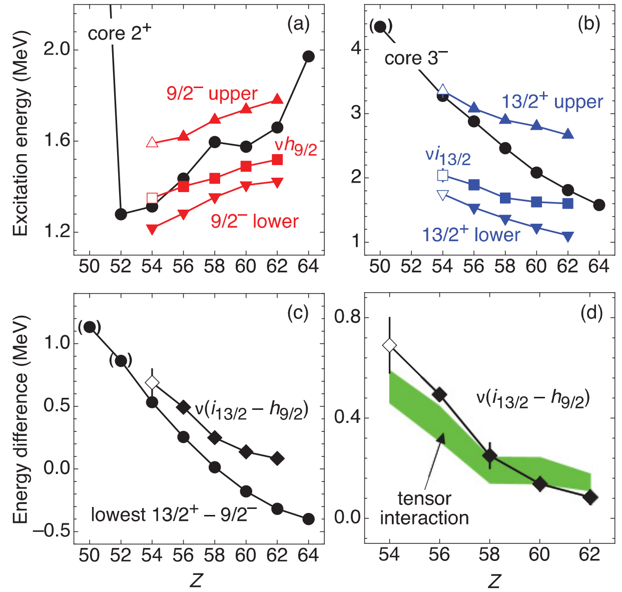
T. Otsuka et al, PRL 104, 012501 (2010)



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)

Single-particle states outside doubly-magic ^{132}Sn

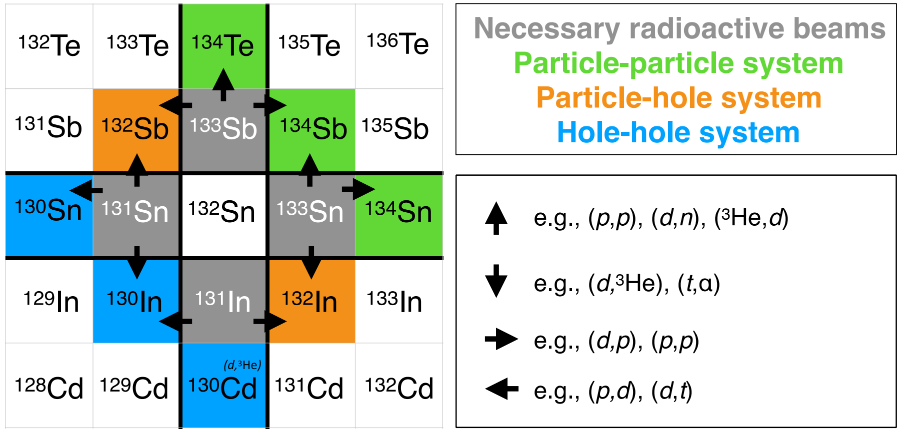
ISOLDE Solenoidal Spectrometer

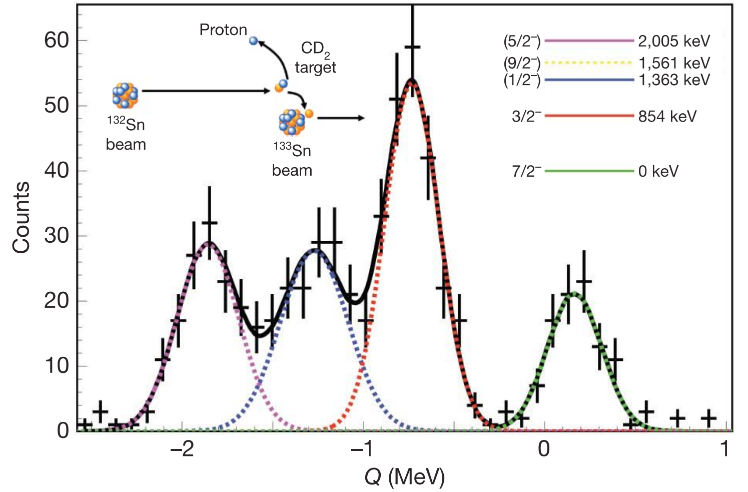
Studying single particle outside doubly magic nuclei provide robust tests of theoretical frameworks and directly provide information on single-particle energies and matrix elements.

^{132}Sn(d,p) has been a reaction of interest for many years. Excellent measurement made at ORNL with Orruba.

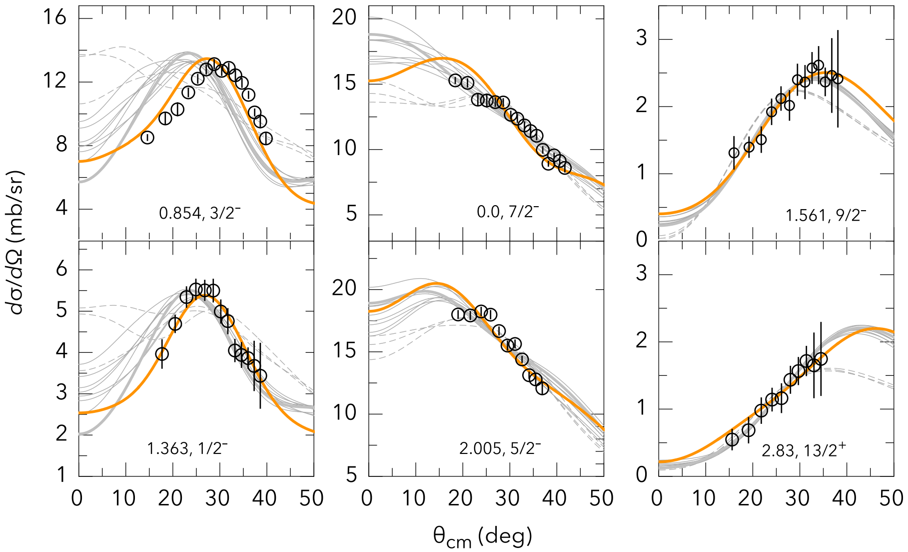
ISS able to identify all single-particle states in this system.

^{132}Sn looks like a near perfect doubly magic system

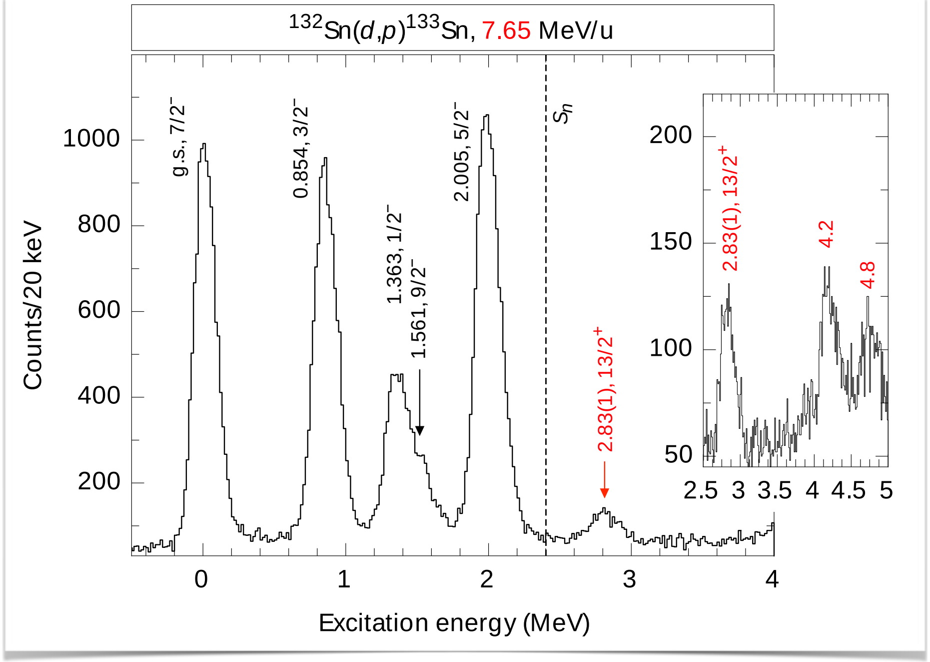




KL. Jones Nature **465**, pages 454–457 (2010)



Level	j^{π}	l	S
0	7/2⁻	3	1.00(7)
0.854	3/2⁻	1	0.9(1)
1.363	1/2⁻	1	0.79(10)
1.561	9/2⁻	5	0.80(8)
2.005	5/2⁻	3	0.97(6)
2.83(1)	13/2⁺	6	1.10(22)

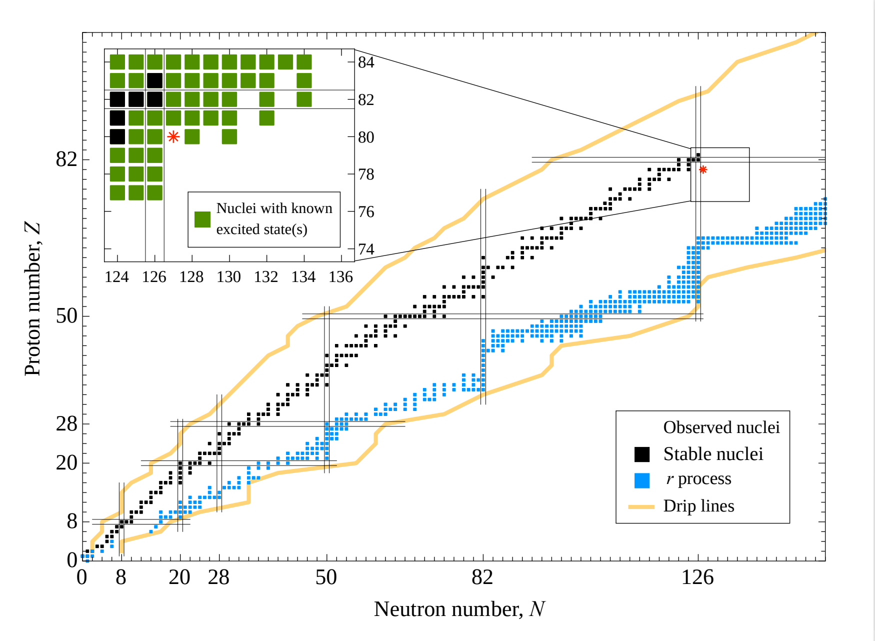


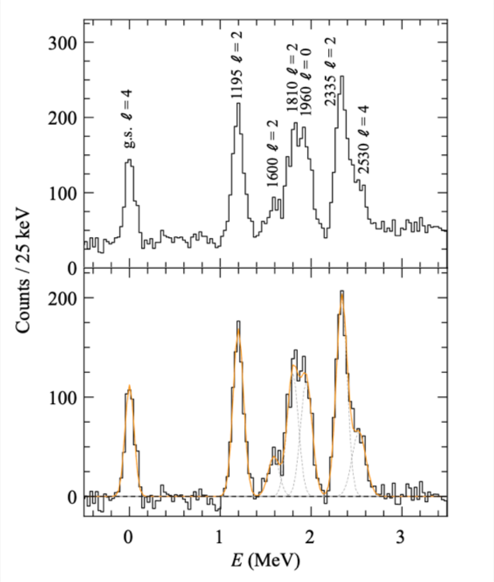
Slide courtesy of B Kay

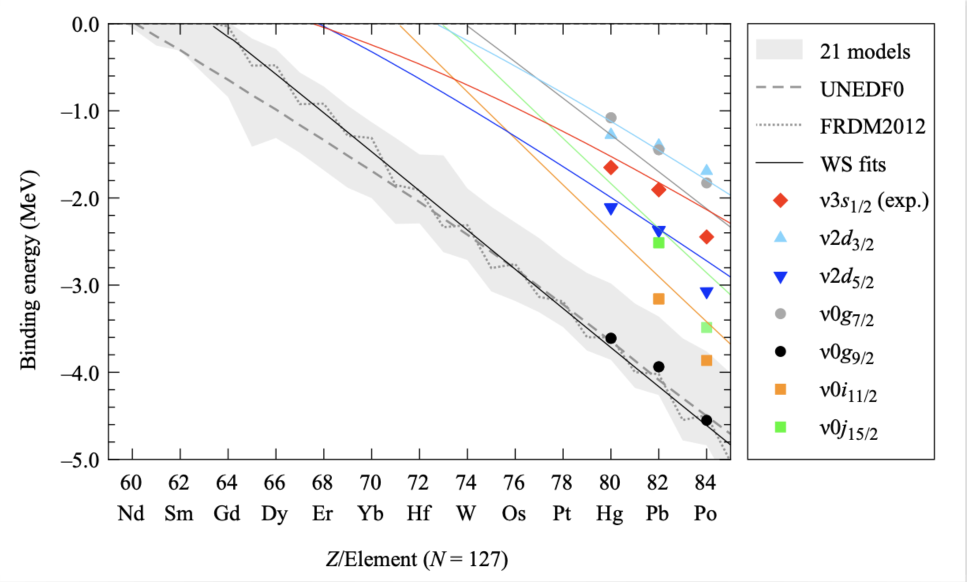
ISOLDE Solenoidal Spectrometer

Probing single-particle states in ^{207}Hg with ISS

A study of the hitherto unknown single-neutron structure of ^{207}Hg was carried out using a ***7.4 MeV/u ^{206}Hg beam*** and the ***ISOLDE Solenoidal Spectrometer*** to momentum analyze the protons following the neutron-adding (*d*,*p*) reaction







First exploration of single-particle states outside *N* = 126, south of Pb, ***made possible by ISS and HIE-ISOLDE***.

New data ***provides additional handle/constraint on the location of zero binding at N = 127*** and raises questions about how neutron-capture advances beyond *N* = 126.

T. L. Tang *et al*. Phys. Rev. Lett. **124**. 062502 (2020).

Studying the ^{62}Ge mirror nucleus via the ^{61}Zn(d,p)^{62}Zn reaction

ISOLDE Solenoidal Spectrometer

Breakout from CNO cycle to rp-process during type I XRB

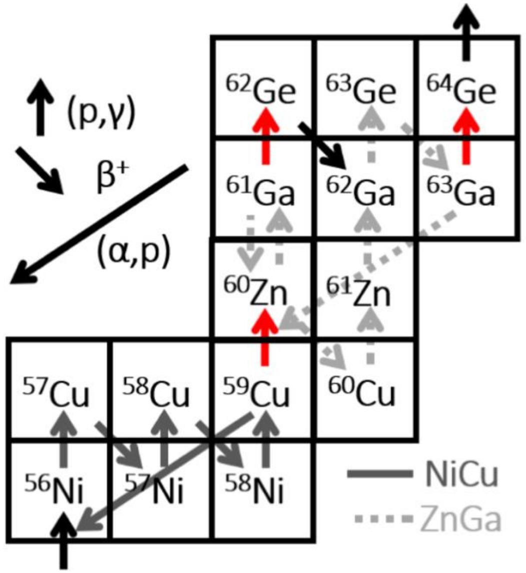
^{61}Ga(p,γ) identified as having a significant impact on light curves and abundances.

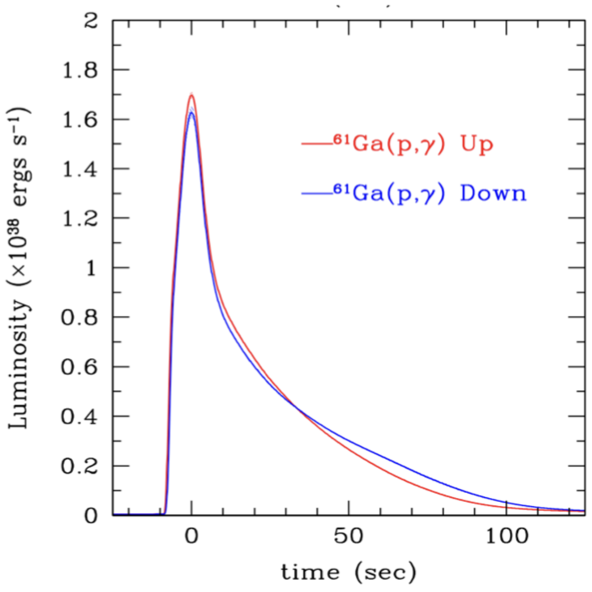
^{61}Ga(p,γ) rate expected to be dominated by resonant capture in ^{62}Ge above Sp = 2290(15) [keV]

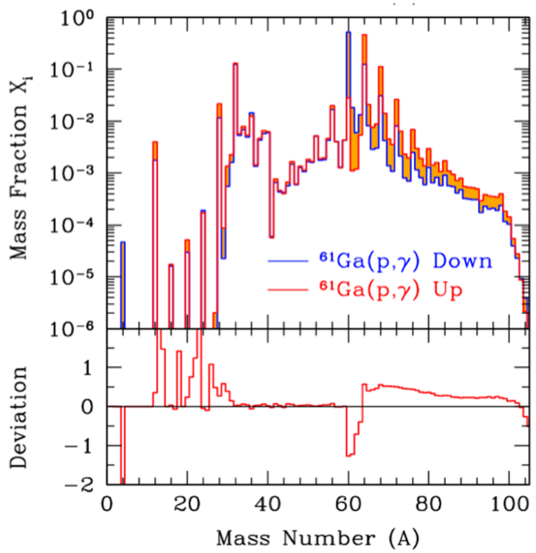
Hard to study ^{62}Ge → study mirror nucleus ^{62}Zn instead via ^{61}Zn(d,p)^{62}Zn reaction.

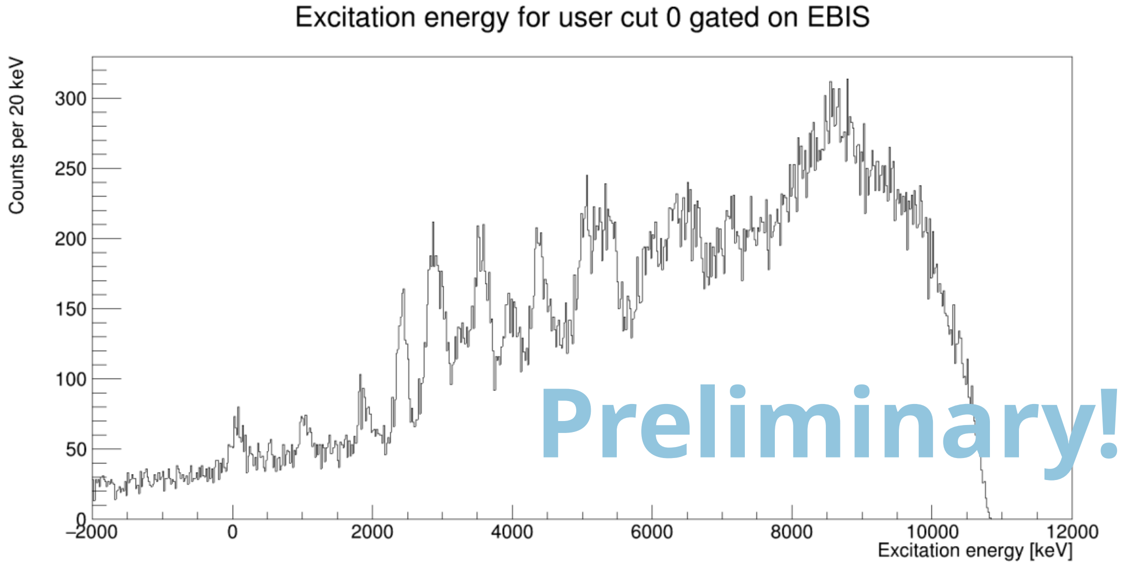
From ^{62}Zn:

- *Mirror energy differences → location of resonant states Er*
- *Spectroscopic factors C^2S → proton partial widths Γp of unbound states ∴ apply constraints to associated resonance strengths ωγ*





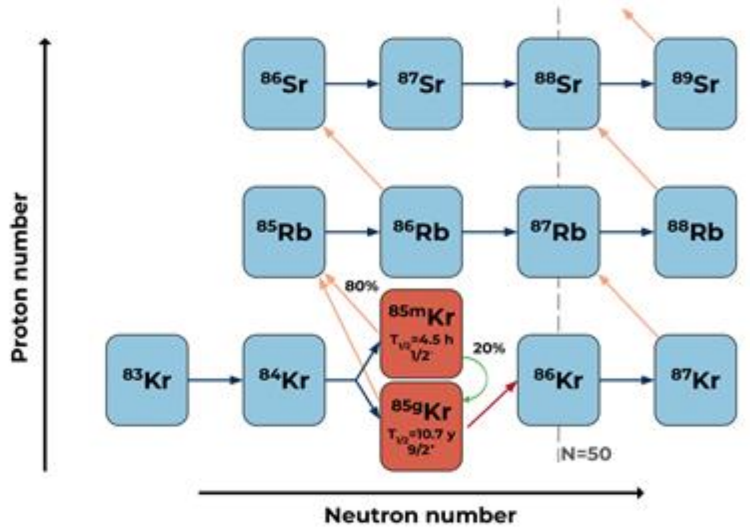




Slide courtesy of D Doherty

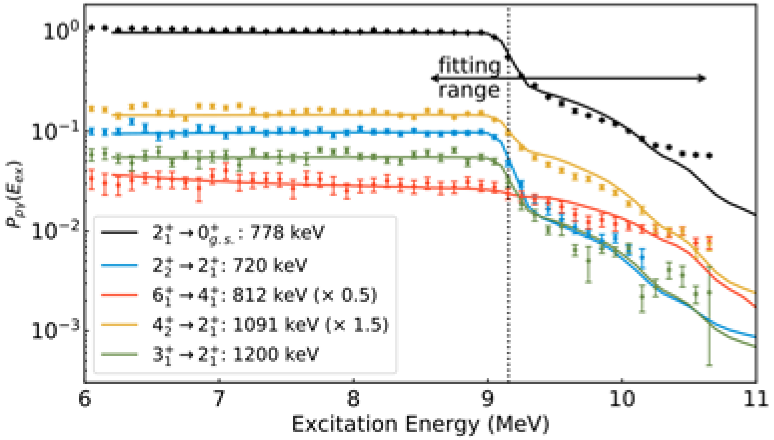
Surrogate reactions with solenoids

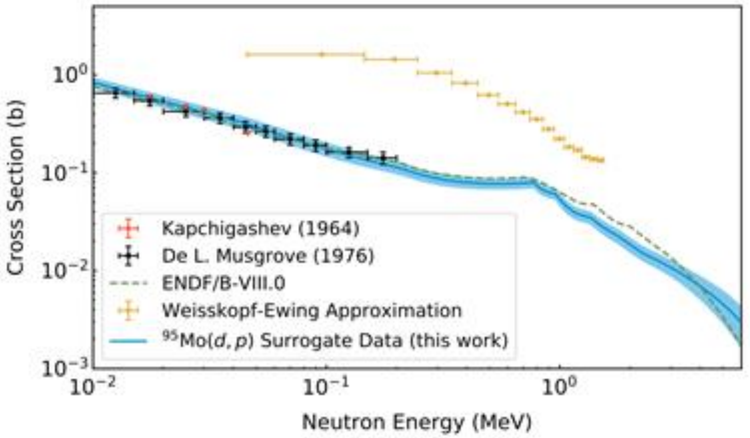
- 50% of elements heavier than Fe are produced by the s-process: $\tau_\beta \lesssim \tau_n$
- Great uncertainty derives from the competition between n-capture and β-decay in some isotopes called **branching points**
- **^{85}Kr** is an important branching point of the s-process, that influences:
  - ^{86}Kr/^{82}Kr ratio in **presolar grains**
  - Abundances of heavy **Sr isotopes** that are produced also by r-process (lines in kilonova)



^{85}Kr activity is too high to perform activation or ToF measurement → Surrogate reaction method

(d,pγ) can be performed in inverse kinematics → ^{85}Kr as beam → ≳99% purity!

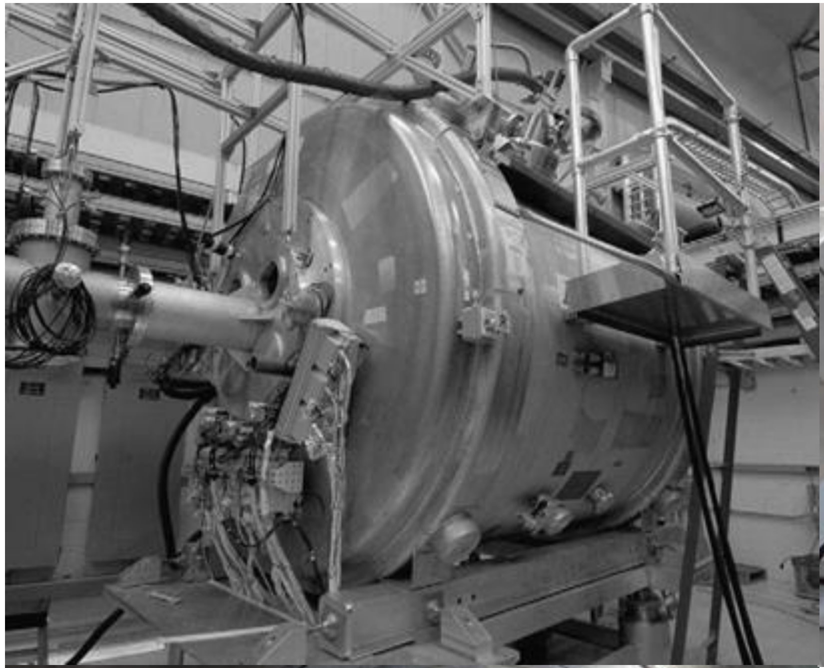


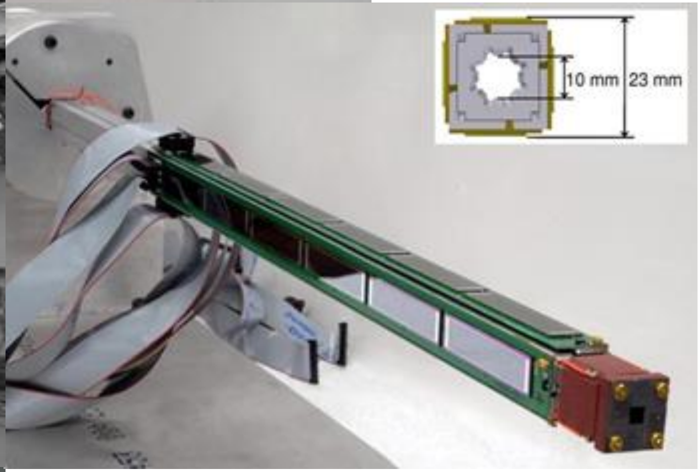


J. E. Escher et al., Phys. Rev. Lett. 121, 052501 (2018)
A. Ratkiewicz et al. Phys. Rev. Lett. 122, 052502 (2019)

Slide courtesy of S Carollo

(n,γ) set up in HELIOS





Reaction: ^{85}Kr(d,pγ)

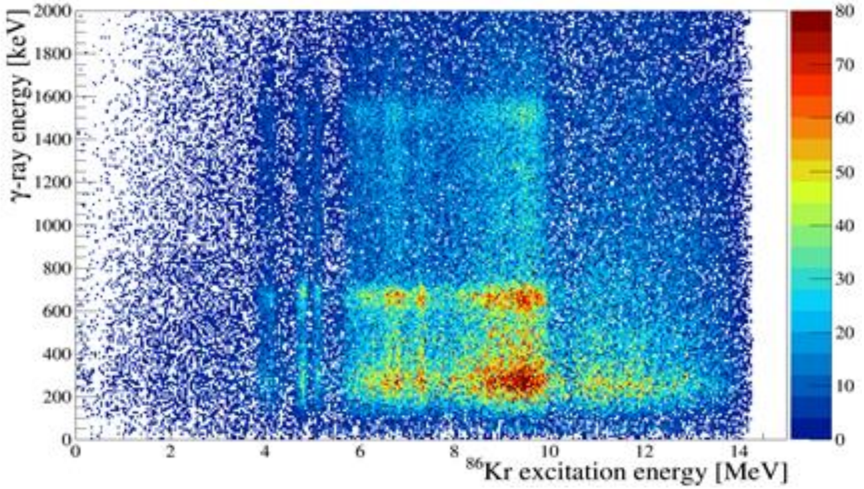
Beam: ^{85}Kr 10 MeV/u, 10^7 pps

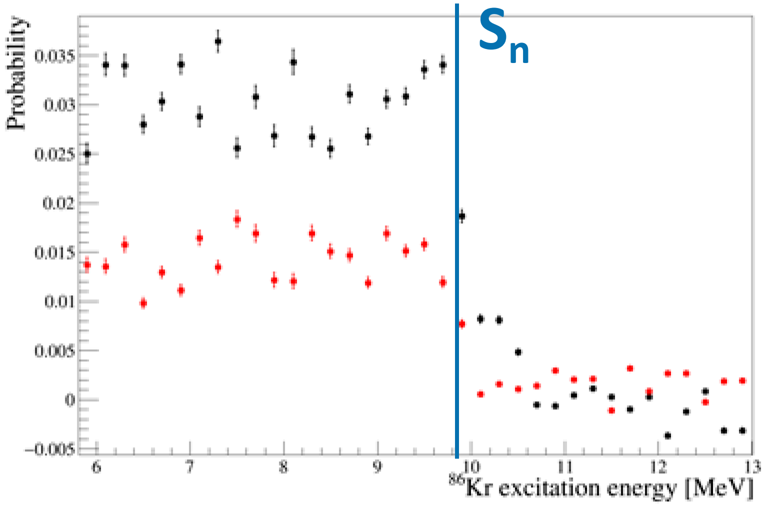
Targets: CD_2

HELIOS: Solenoidal magnetic spectrometer with B=2.0 T

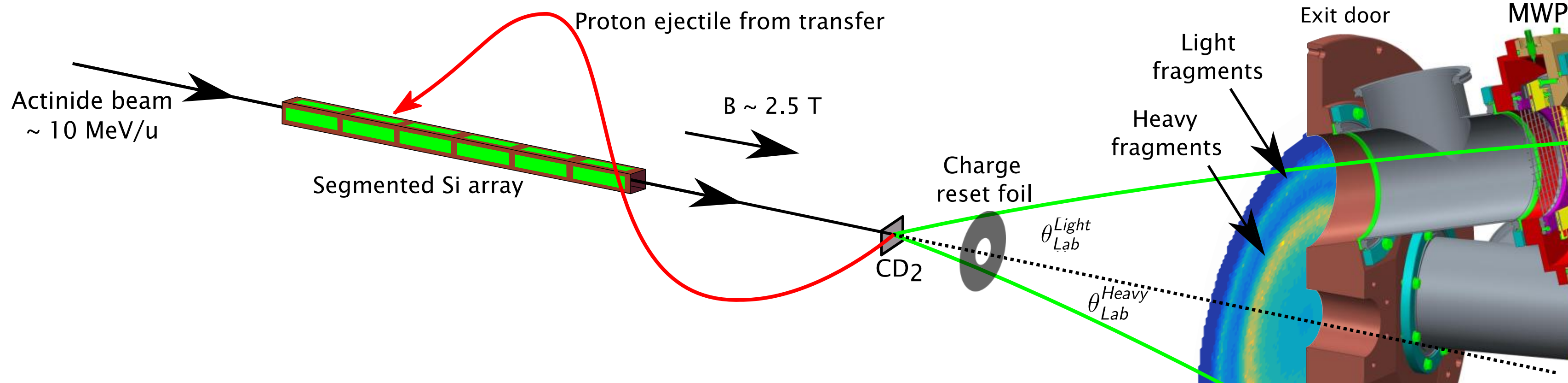
For **γ-rays**: Apollo scintillator array, 5 LaBr + 15 CsI

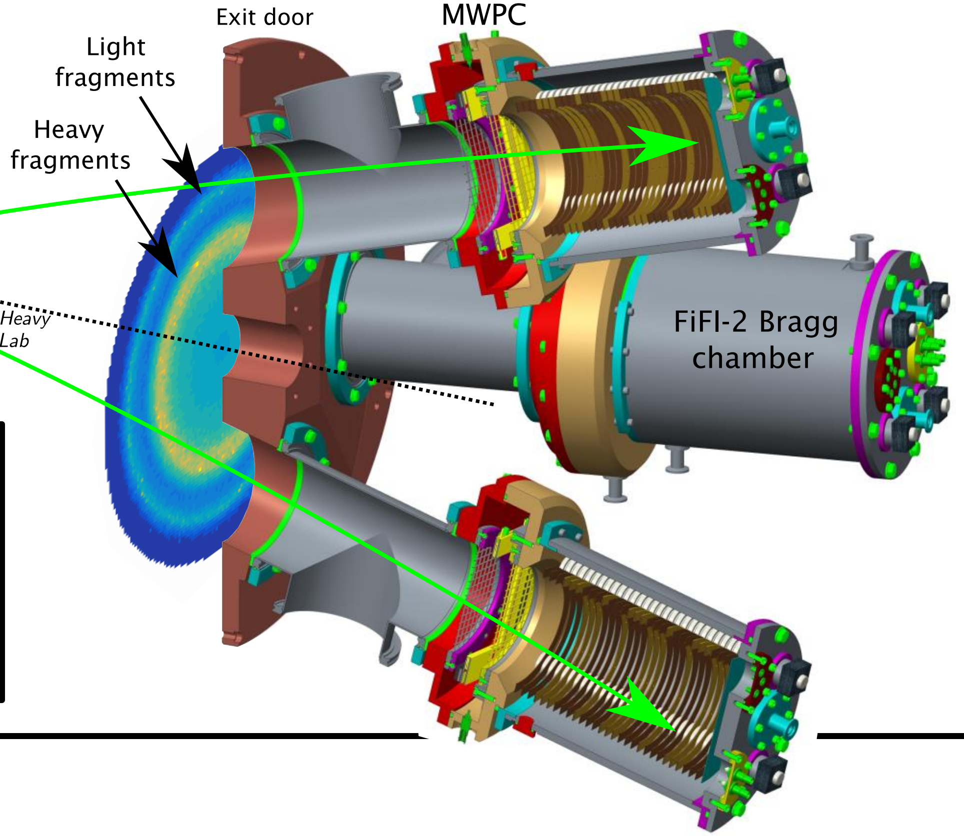
Preliminary!





Transfer-induced fission





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 in to 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.

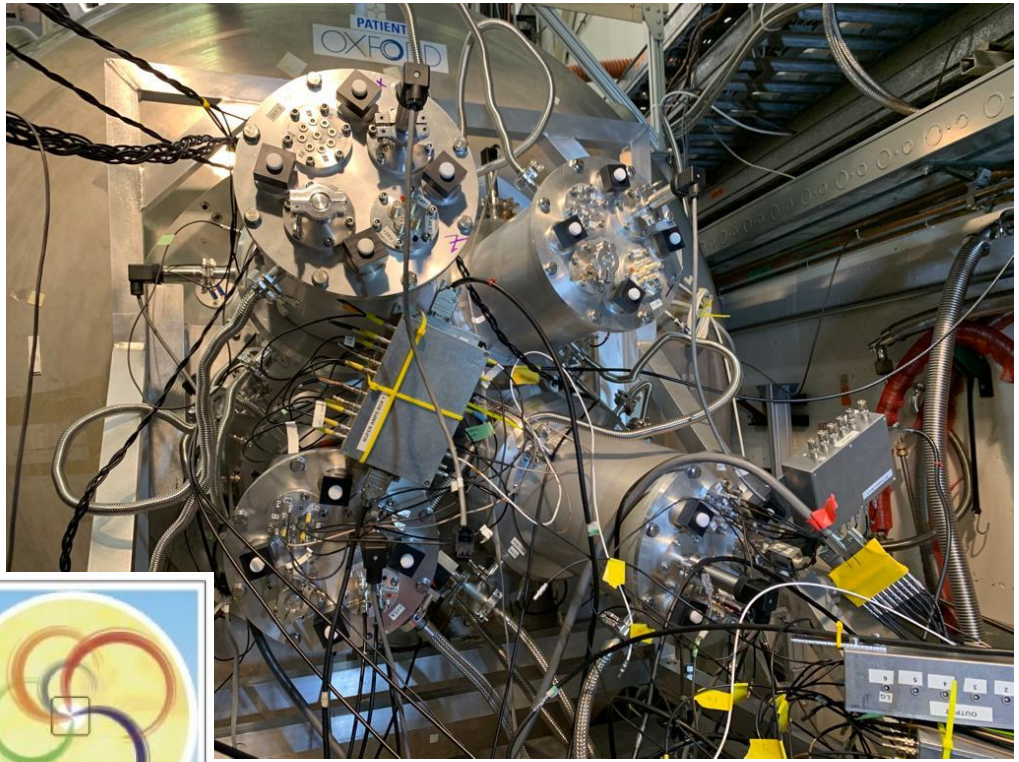
Access to short-lived actinides at ISOLDE.

Developments for 2023 – transfer-induced fission

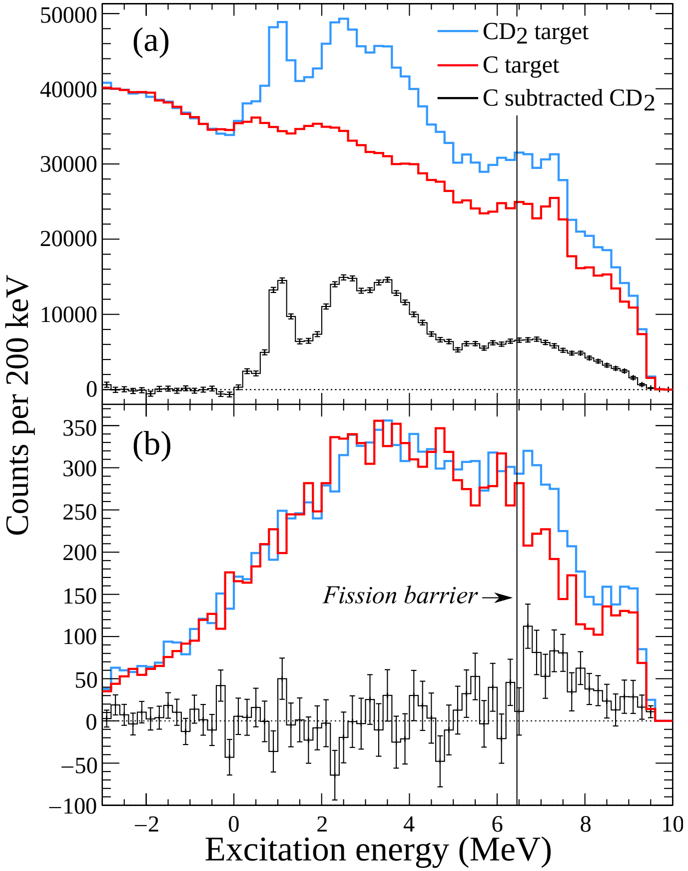
Proof-of-principle

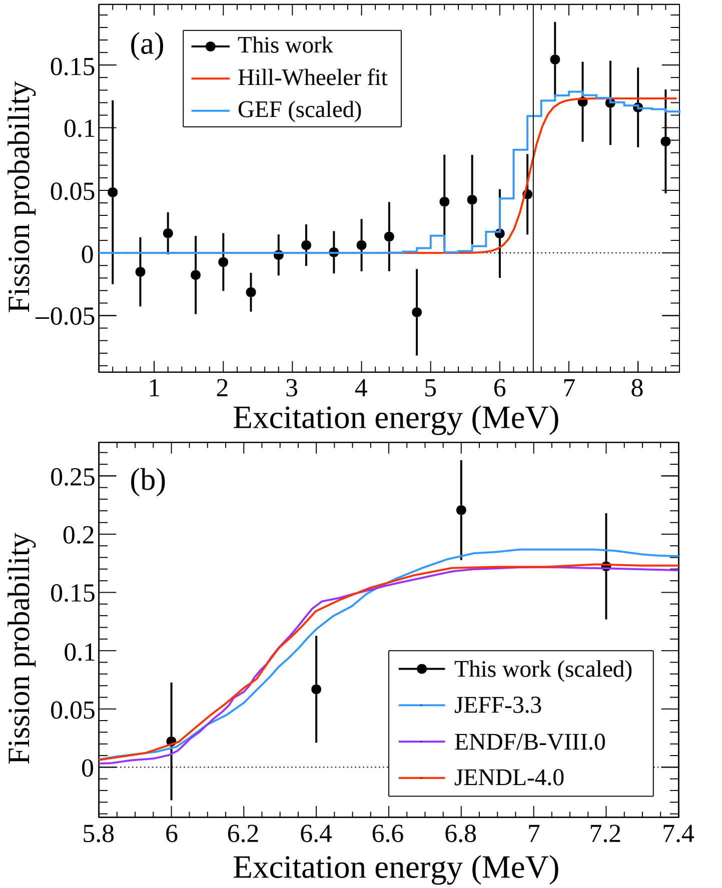
Measurement performed at HELIOS in 2021.

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) MeV [Lit. Val. 6.46 MeV Rev. Mod. Phys. **52**, 725 (1980)*]*

SA. Bennett et al., Phys. Rev. Lett. **130**, 202501 (2023).

Summary

ISOLDE Solenoidal Spectrometer

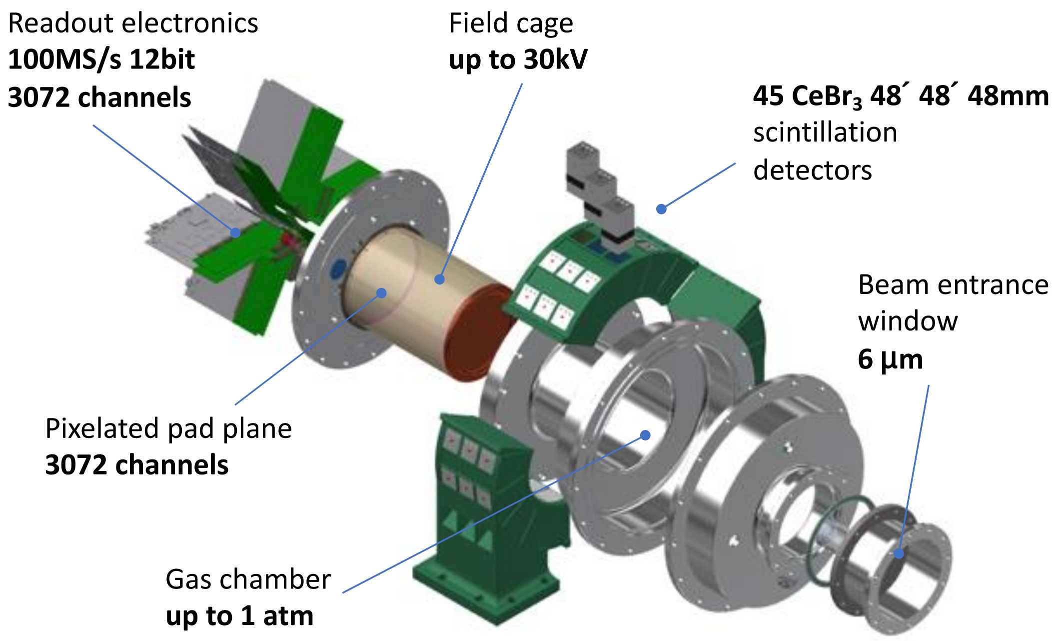
Lots of physics from first ISS runs – only a snapshot here

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

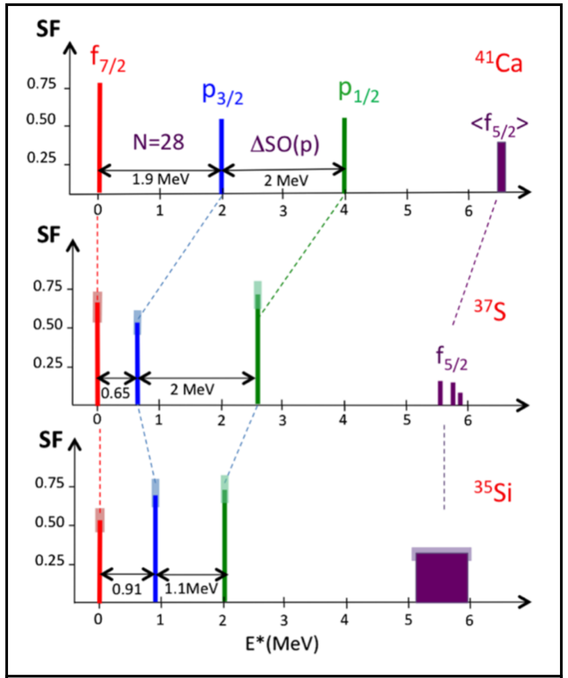
Not limited to (d,p). Accepted proposals for (d,d'), (t,p), transfer-induced fission and (d,pγ).

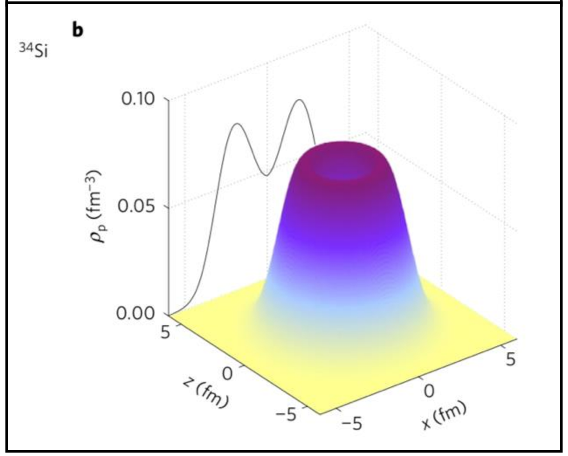
TPC mode of operation being developed.

Versatile devices that can be coupled with a variety of detection solutions.



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).