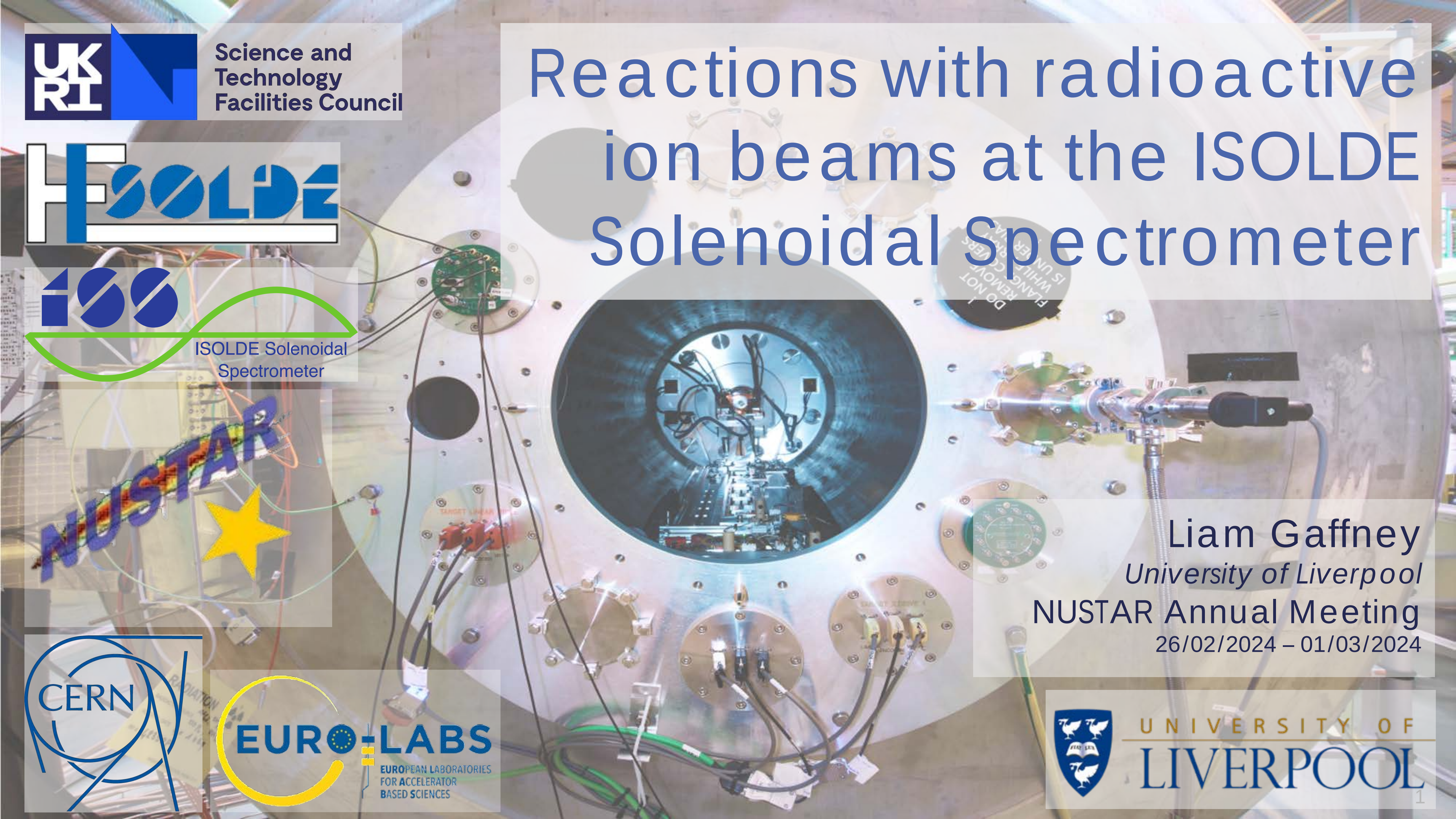
Reactions with radioactive ion beams at the ISOLDE Solenoidal Spectrometer



Liam Gaffney

University of Liverpool

NUSTAR Annual Meeting

26/02/2024 – 01/03/2024

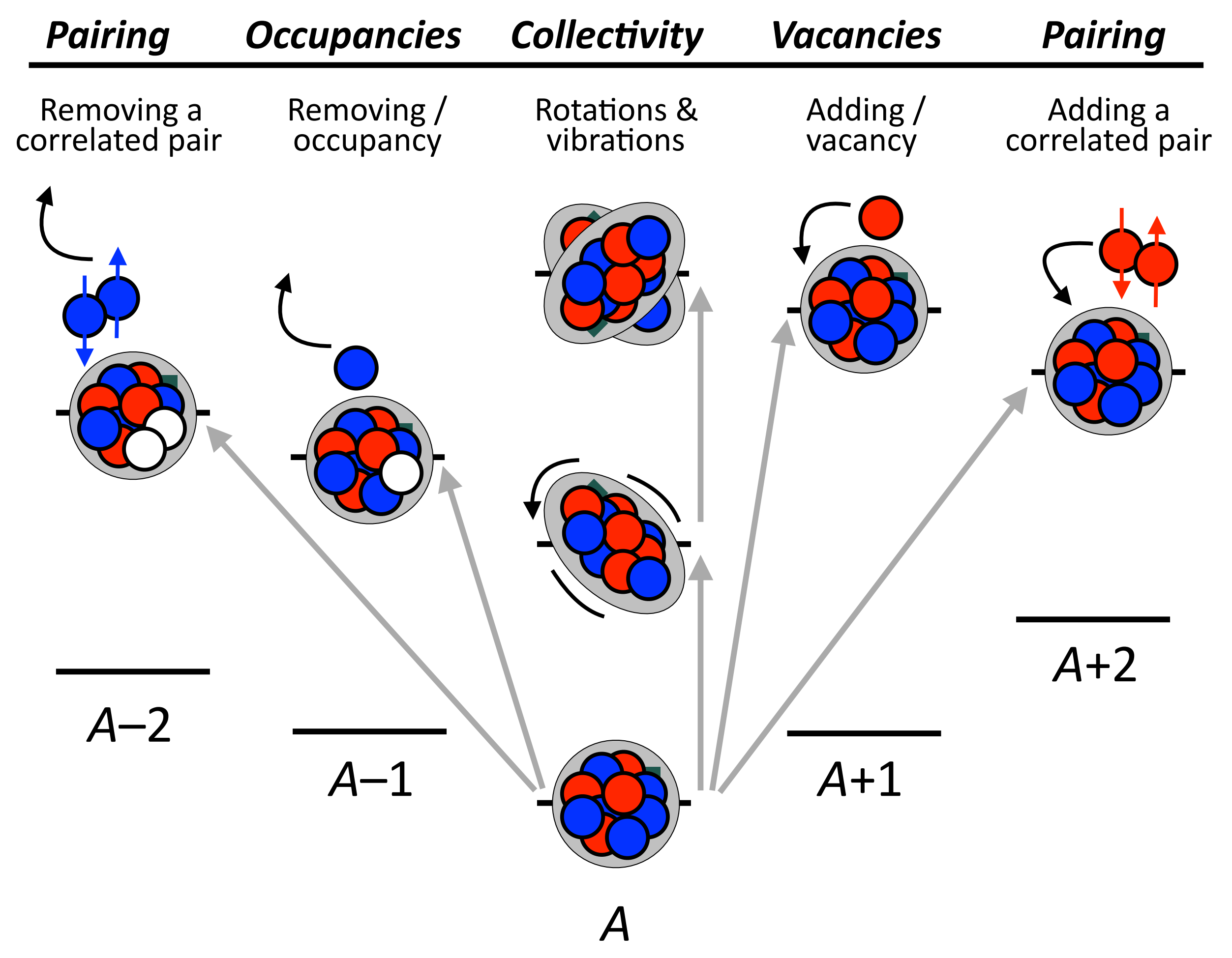
Overview

- Introduction to solenoid technique
  - ISS@HIE-ISOLDE
- Overview of ISS operation.
- Summary of ISS physics (so far).
  - Neutron states above N=126
  - Onset of deformation at N=60
  - Single-particle states around ^{68}Ni
  - Towards the (1st) island-of-inversion
- SpecMAT active target
- Future program at ISS.

ISOLDE Solenoidal Spectrometer

Direct reactions around the Coulomb barrier

- Access to variety of nuclear structure information
- Single-particle states, $E_{(Ex,SP)}$, ℓ, spectroscopic factors, e.g. (*d*,*p*), (*p*,*d*)…
- Pair-correlations, $E_{(Ex)}$, ℓ, e.g. (*p*,*t*), (*t*,*p*)…
- Collective properties via e.g. (*p*,*p*′), (*d*,*d*′), (α,α′), Coulex…
- Reactions performed ~10 MeV/*u* (few to 10s MeV/*u*).



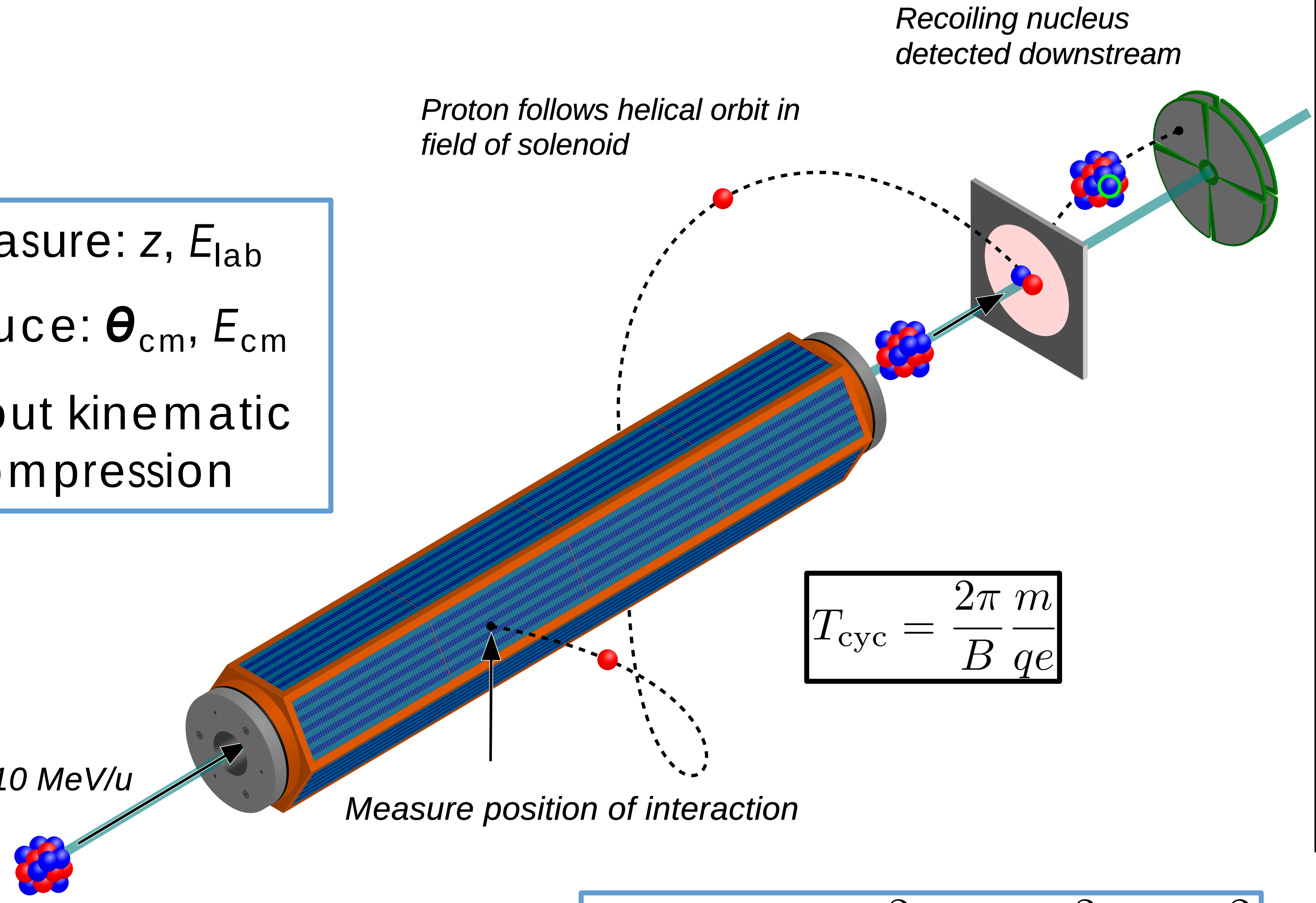
ISOLDE Solenoidal Spectrometer

Solenoidal spectrometer technique

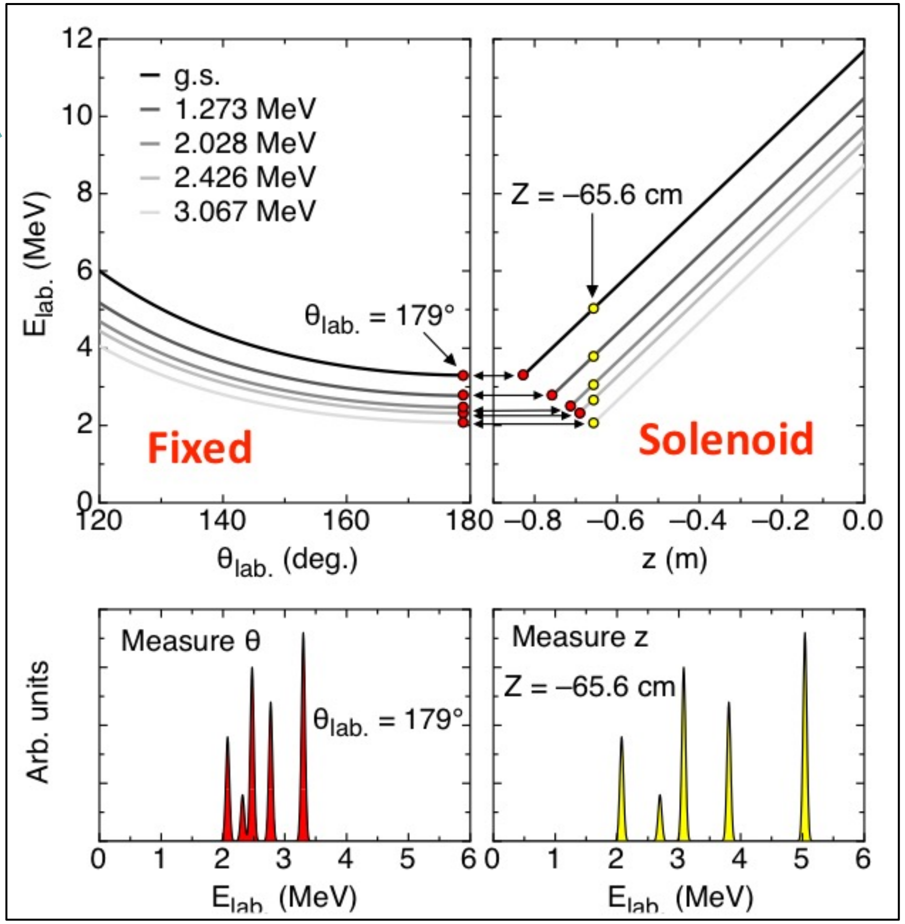
Measure: z, E_{lab}

Deduce: $\boldsymbol{\theta}_{cm}$, E_{cm}

without kinematic compression



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



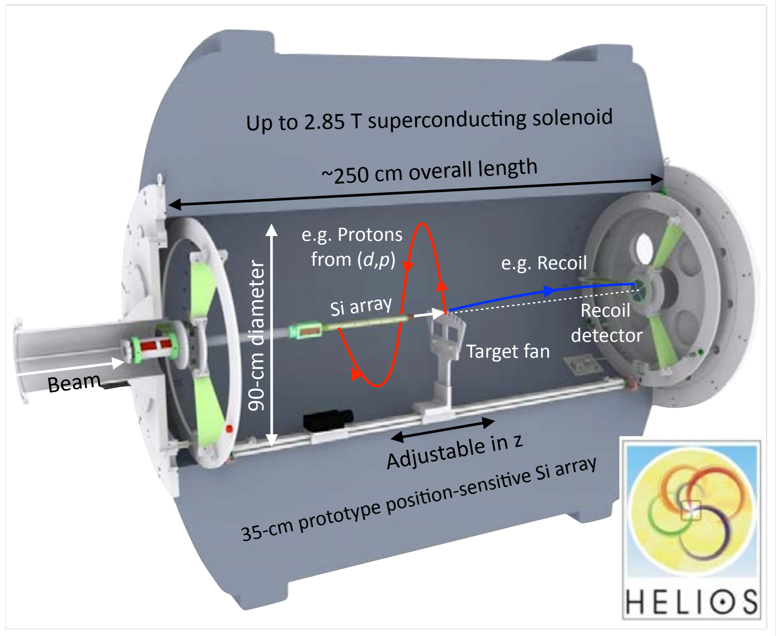
$$\cos\theta_{cm} = \frac{v_{lab}^2 - V_{cm}^2 - v_0^2}{2v_0 V_{cm}}$$

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

ISOLDE Solenoidal Spectrometer

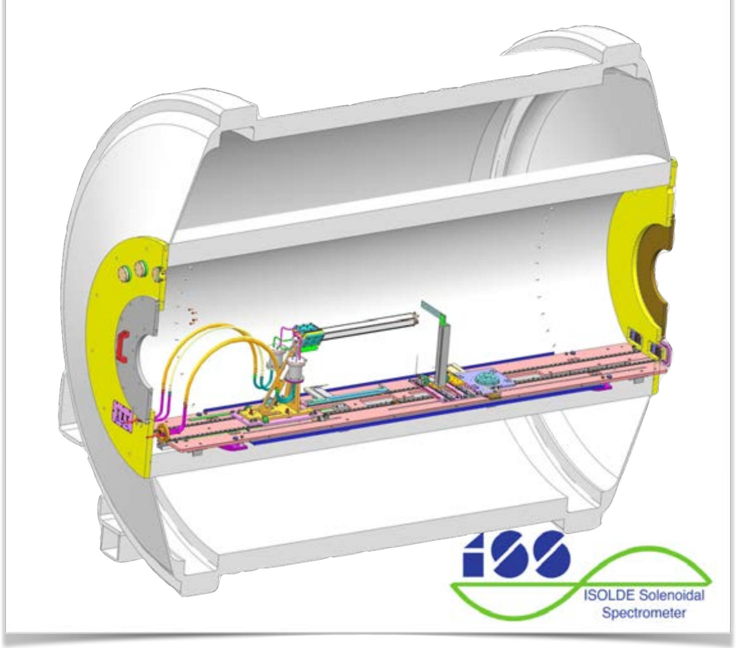
Solenoidal spectrometers around the world

HELIOS@Argonne



- "The pioneer" from 2008.
- Stable beams, RAISOR and CARIBU.
- 3T MRI magnet.
- Resistive-division Si array.

ISS@ISOLDE



- Since 2018 (LS2 2019-2021).
- Post-accelerated ISOL beams.
- Energies up to ~10 MeV/*u*.
- Pre-LS2 with HELIOS on-axis array.
- Post-LS2 double-sided Si strip array.
- 4T MRI magnet – clearance for 2.5 T.
- Solenoidal spectrometer & SpecMAT.

SOLARIS@FRIB

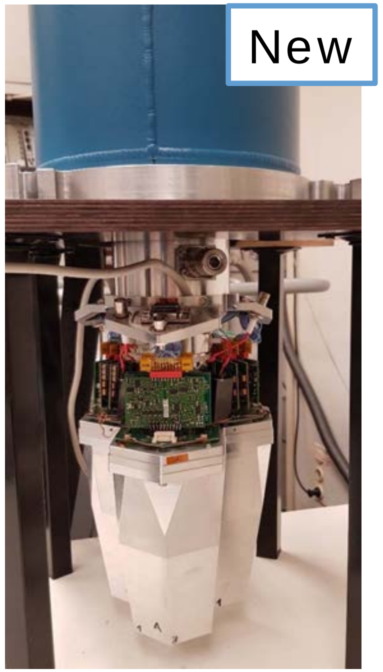
- From 2021 with initial configuration.
- ReA6 beam line.
- Early implementation using HELIOS array.
- Building forward/backward dual array.
- 4T MRI magnet.
- Solenoidal spectrometer & AT-TPC.

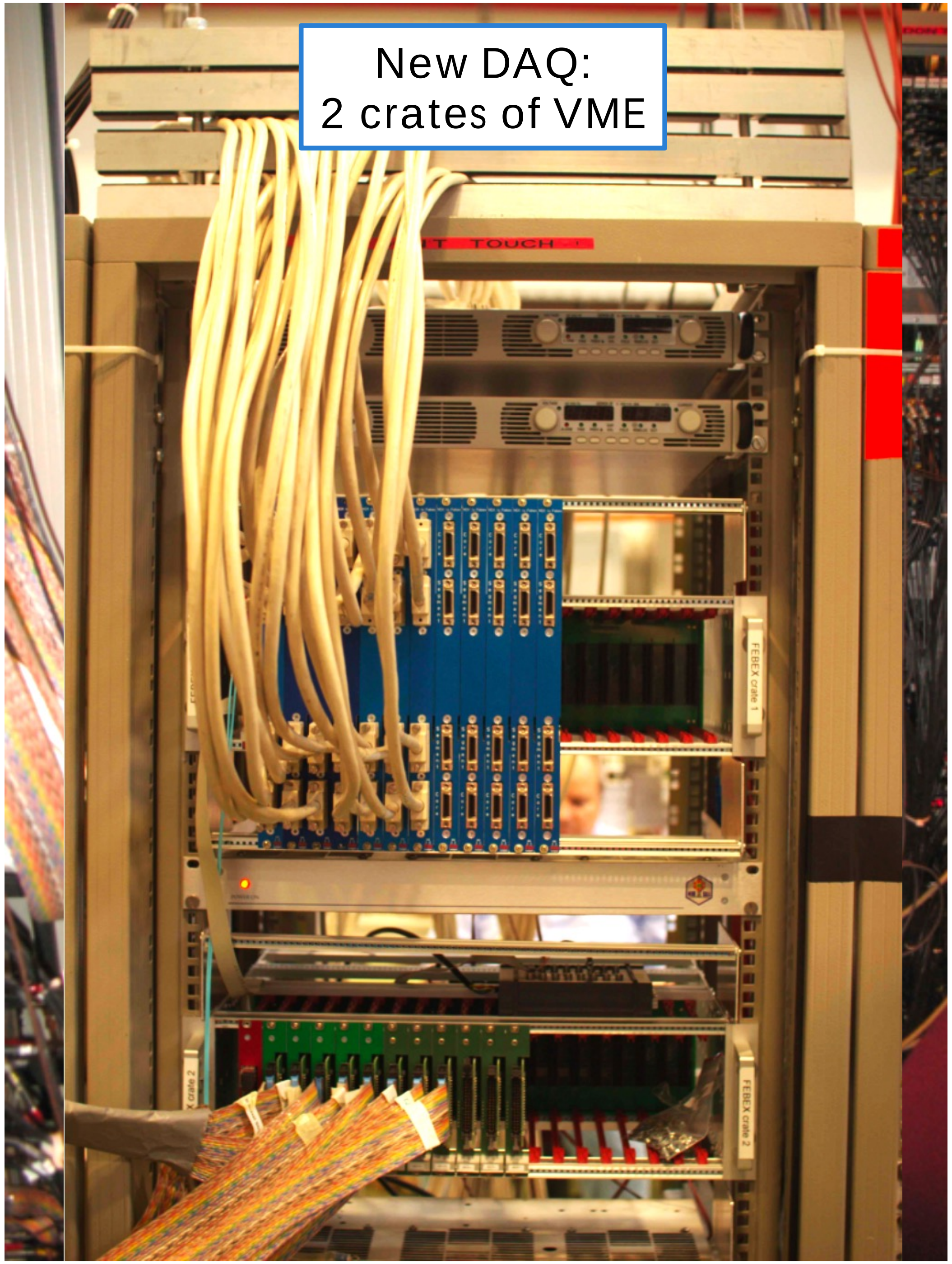
ISOLDE Solenoidal
Spectrometer

HIE-ISOLDE Phase 2 (2018)

Brief aside – new-Miniball

- New DAQ based on FEBEX4 from GSI
  - 16 channel, differential input, plus SE adaptor boards
  - Big thanks to Nik Kurz and Shizu Minami for help and guidance
- Bespoke firmware developed at STFC Daresbury
  - Free-running triggerless readout, cross-channel triggering
  - CFD, MWD, pileup flagging, trace mode, etc…
- New cryostats and new encapsulation of the crystals.
- New preamps based on the AGATA design.

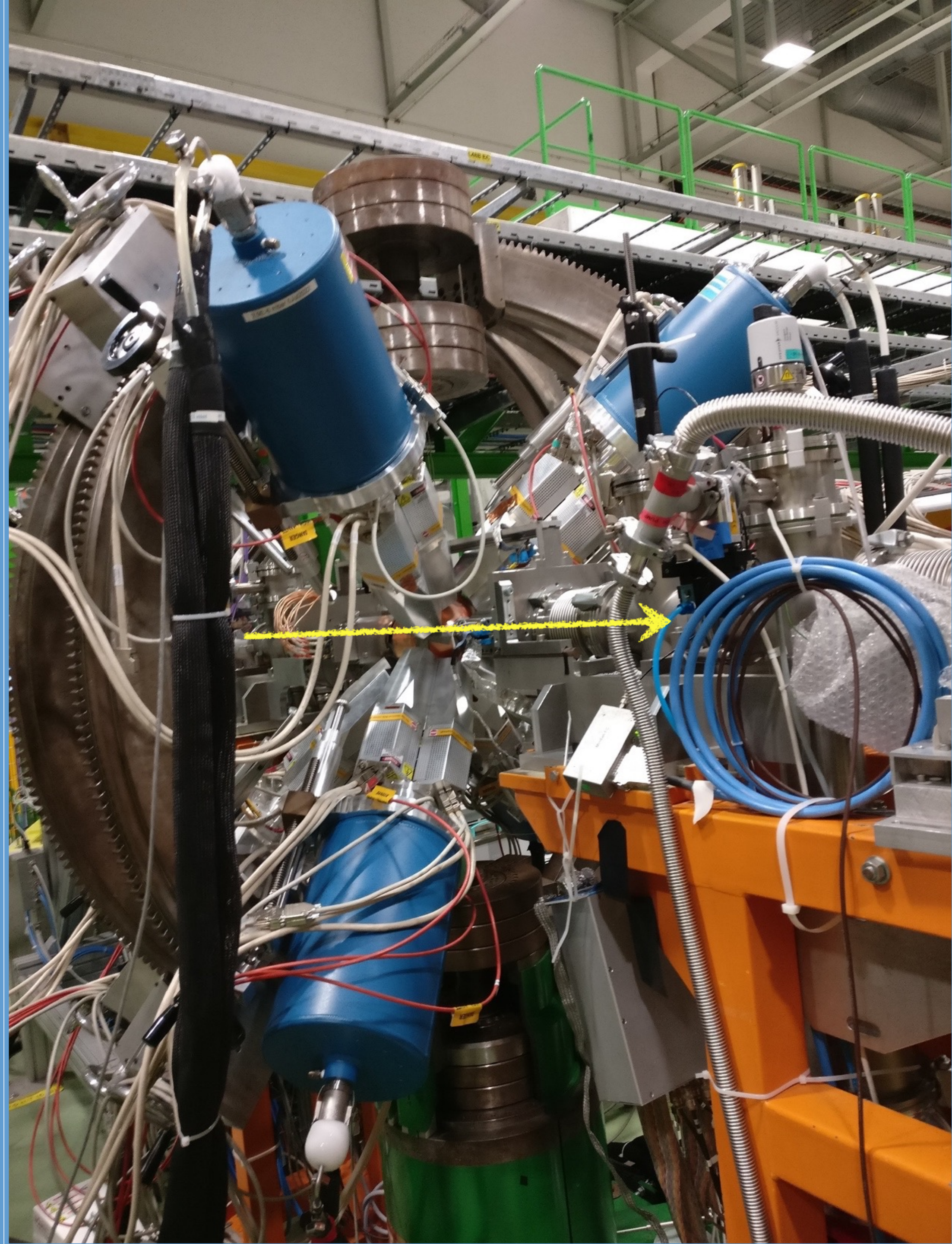




Universität zu Köln

Science and Technology Facilities Council

Miniball @ HIE-ISOLDE



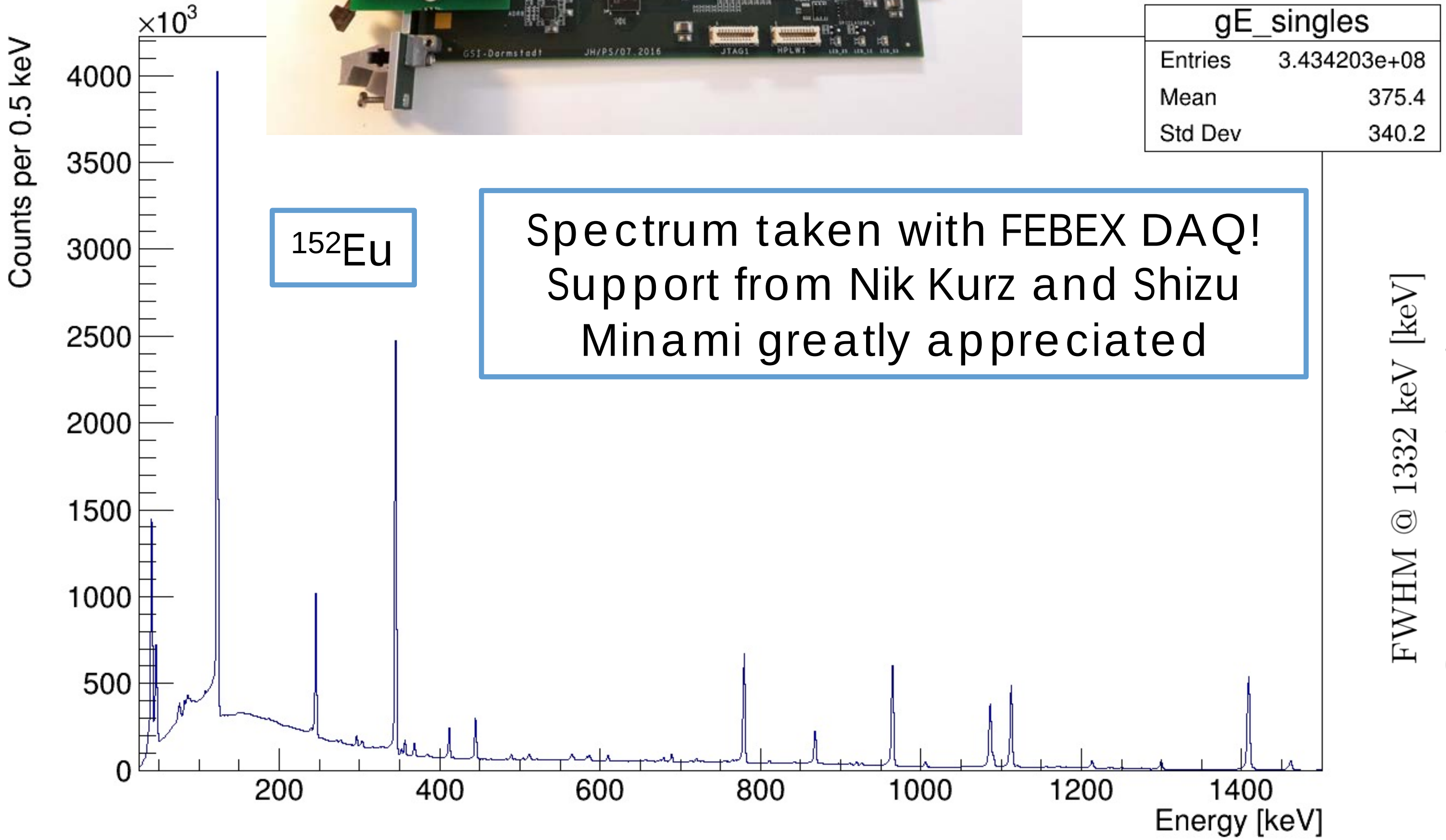
After LS2:
< 9.5 MeV/*u*
(November 2022 - …)

ISOLDE Solenc
Spectromete

Re-commissioning

- Seven new triple cryostats approved, mounted and operational in November 2022 “mini-campaign”.
- Full campaign in 2023 with 8 triples and 25 FEBEX modules with bespoke firmware

GSI

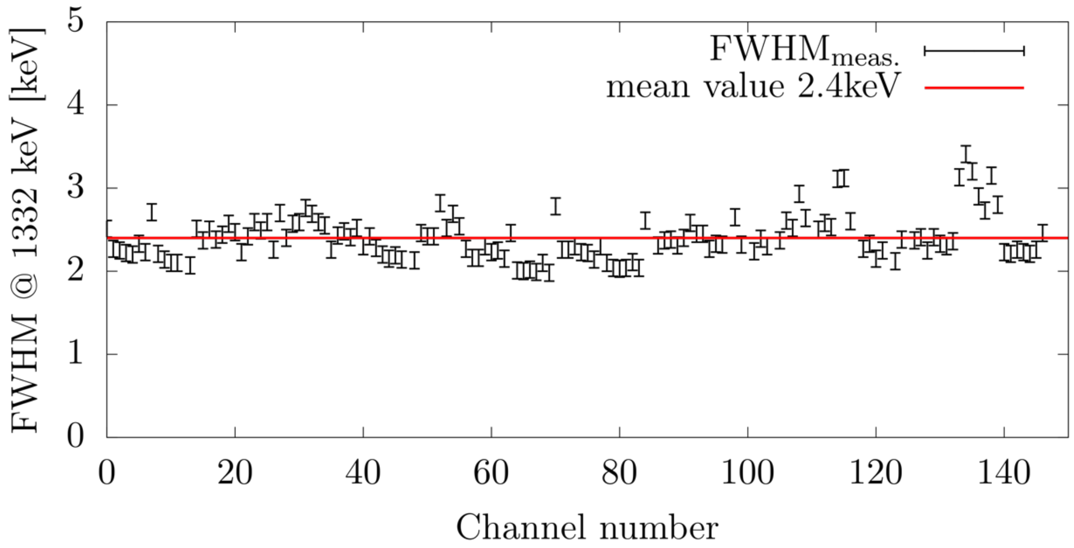


Spectrum taken with FEBEX DAQ!
Support from Nik Kurz and Shizu Minami greatly appreciated

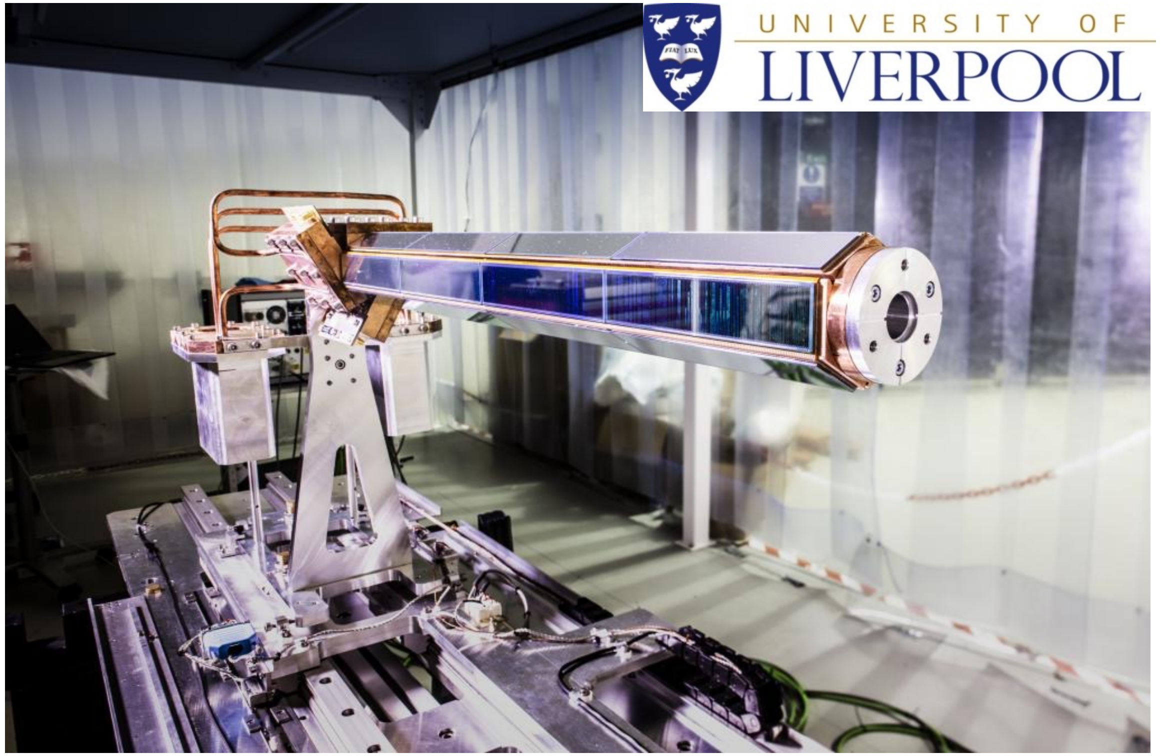
ISOLDE

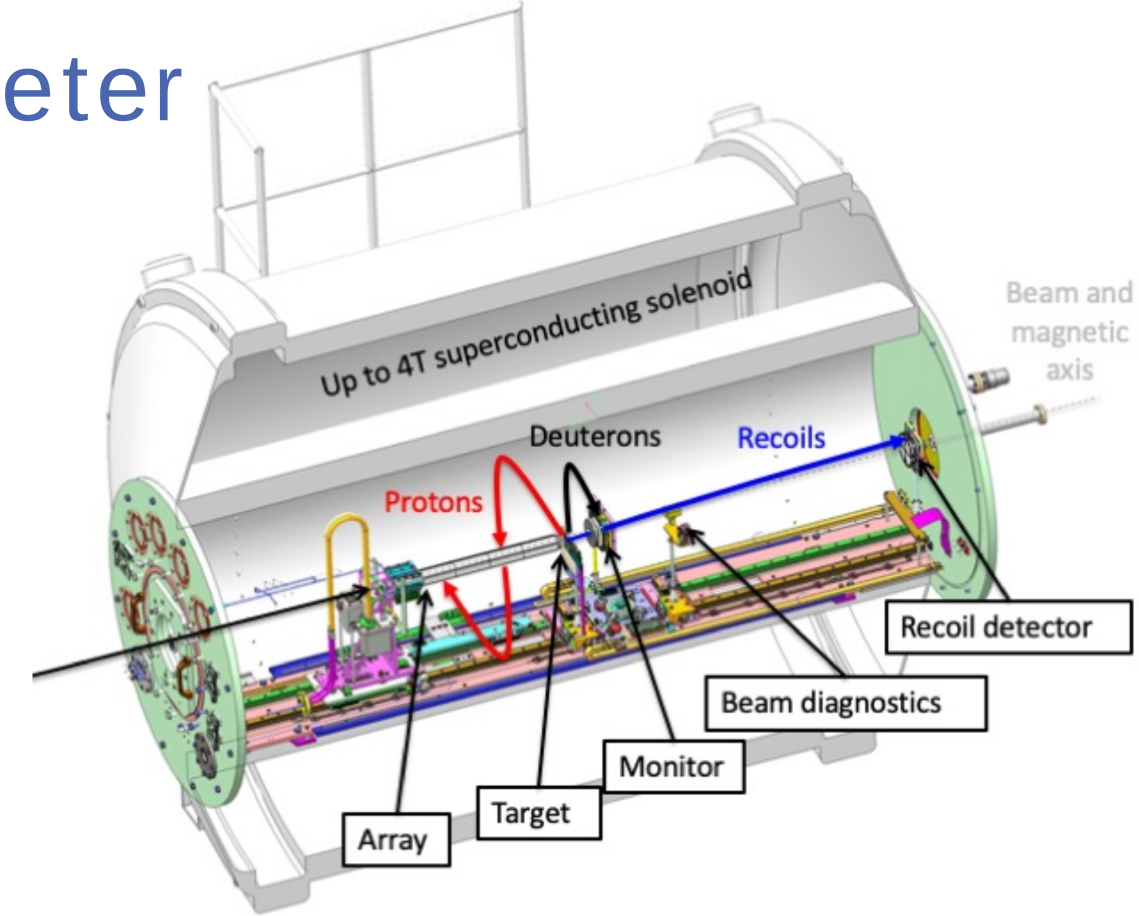
Universität zu Köln

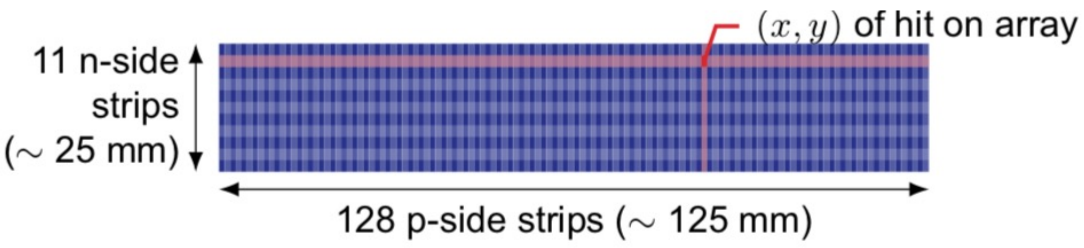
Analysis by Max Droste
Work on the ground from Herbert Hess and Frank Browne



ISOLDE Solenoidal Spectrometer







On-axis silicon detector

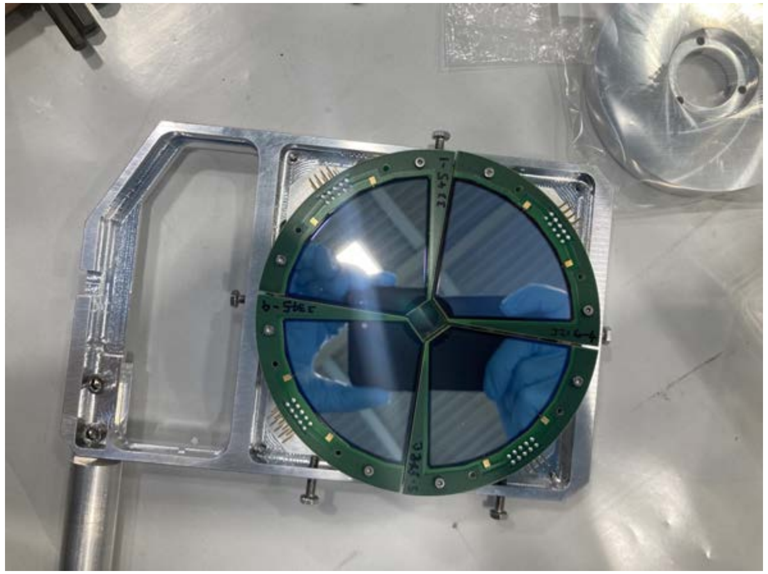
- Hexagonal array with four DSSDs on each side.
  - 128 x 0.95 mm p-side strips along the length.
  - 11 x 2 mm n-side strips along the width
  - 1800 channels → R^3B ASICs for readout!
- Total length of silicon = 510.4 mm.
  - 66% solid angle coverage.

ISOLDE Solenoidal Spectrometer

ISS modes of operation

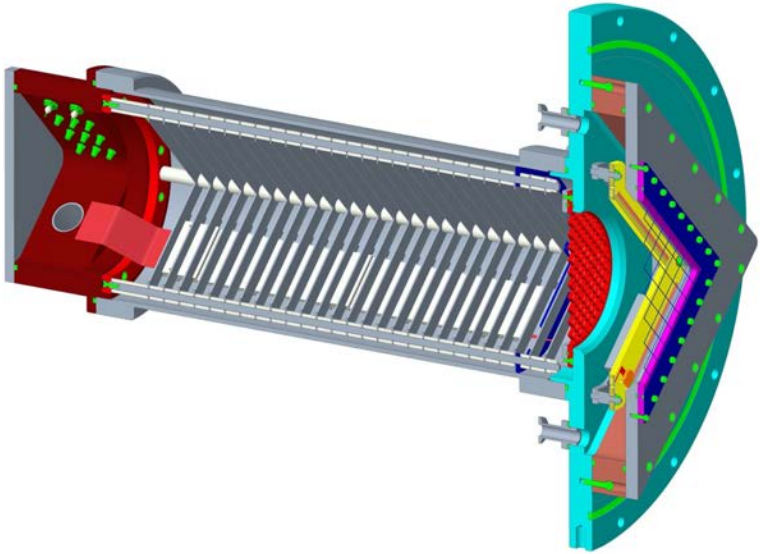
Si-recoil mode

- Silicon ΔE-E for beam-like reaction partner; used for $A < 50$.
- Clean selection of reaction channel; removes fusion on carbon and isobars in beam.



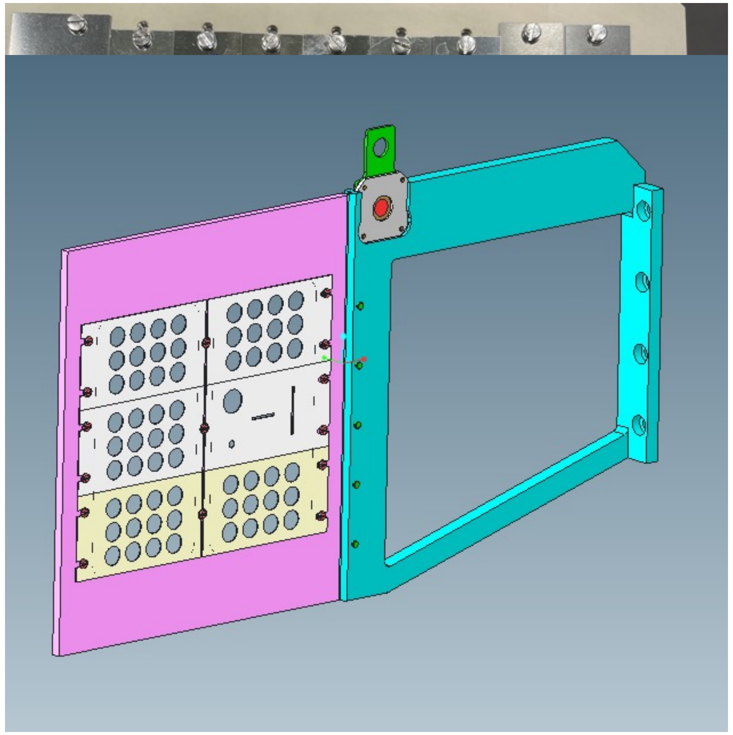
Gas-recoil mode

- Fast-counting Bragg chamber and MWPC for medium-mass beams.
- Used in beam just twice so far; fast pre-amps and zero-degree blocker being implemented for 2024.



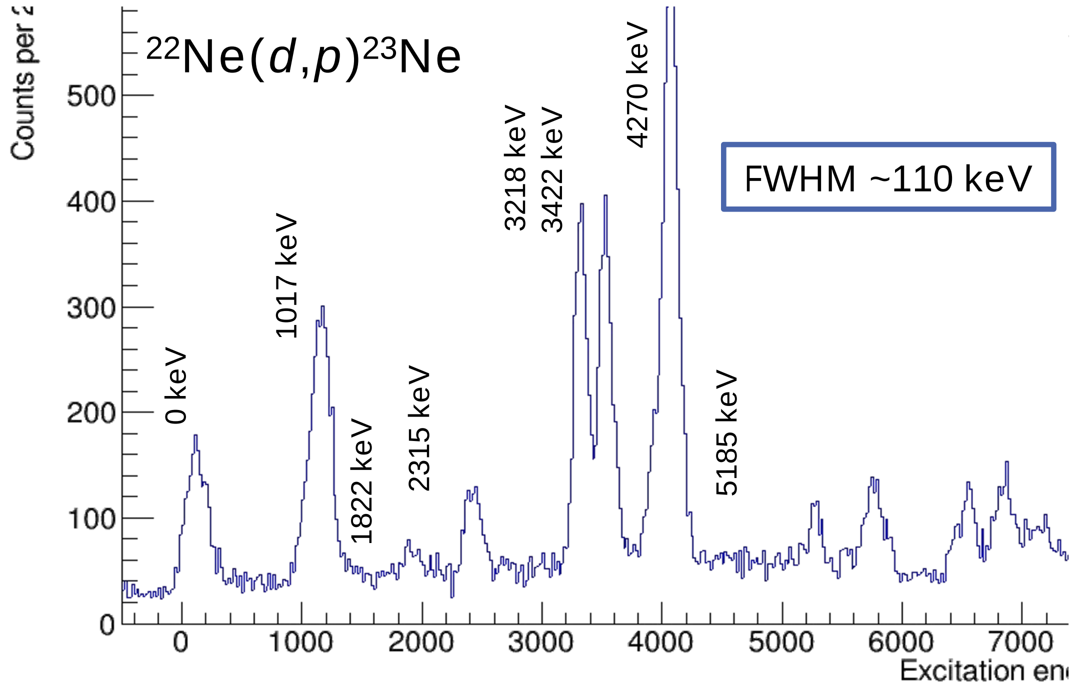
Singles mode

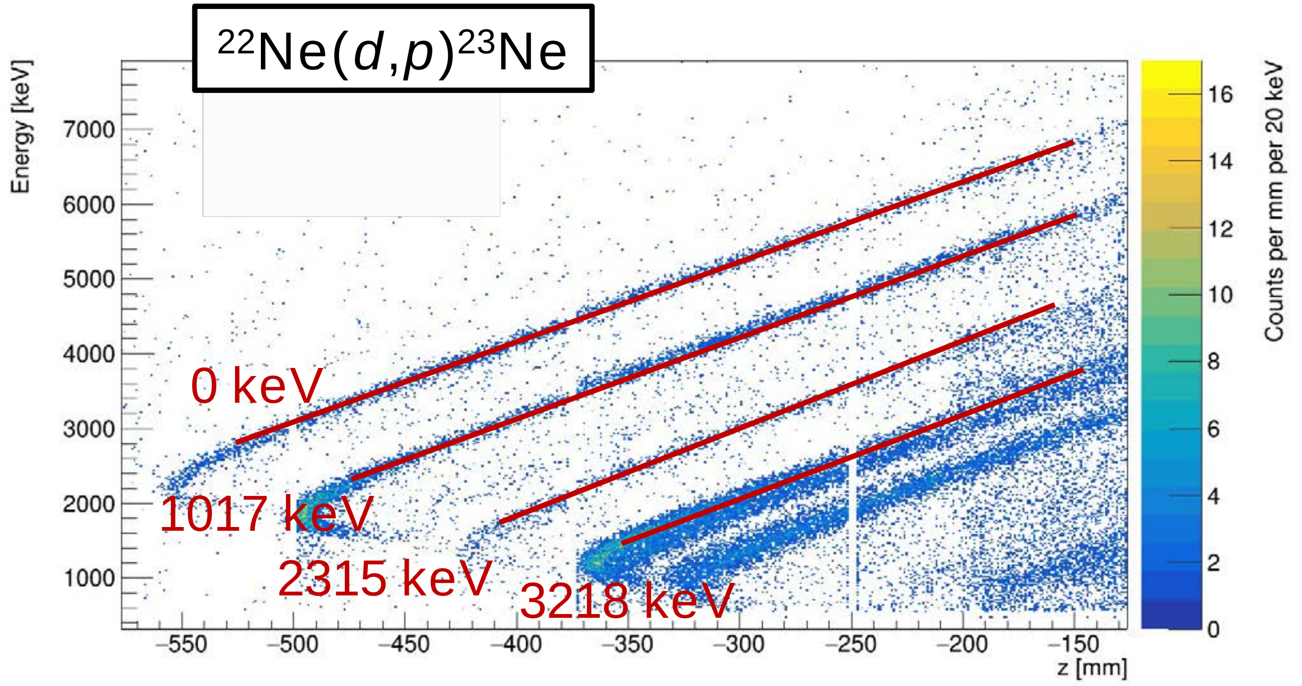
- High intensity or heavy beams.
- FC at zero degrees, EBIS time structure to remove decay background.



Proof-of-principle experiment at ISS

- Stable beam following CERN's LS2 in 2021… ^{22}Ne at 6.05 MeV/*u.*
  - Matching normal kinematics study with gas target! [H.F. Lutz et al. NPA 95 (1967) 591]
  - Implementation of precise energy calibration, pulse-height corrections, energy loss corrections, kinematic reconstruction





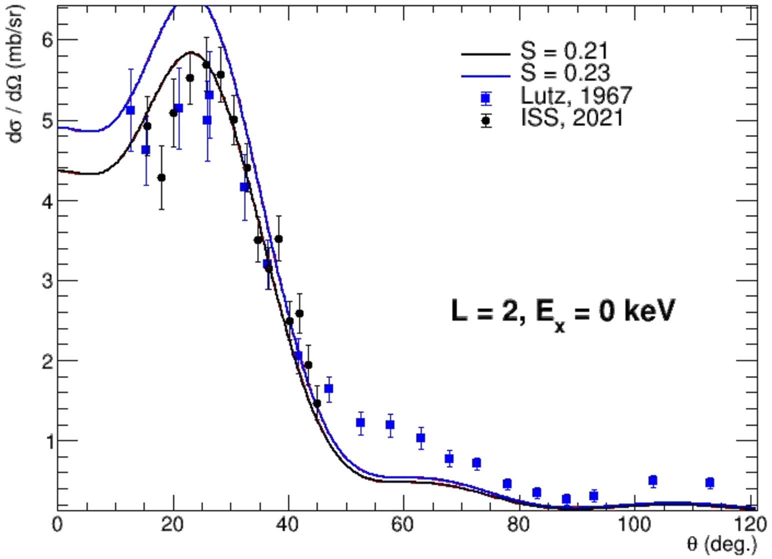
Full code available: https://github.com/ISOLDESolenoidalSpectrometer/ISSSort

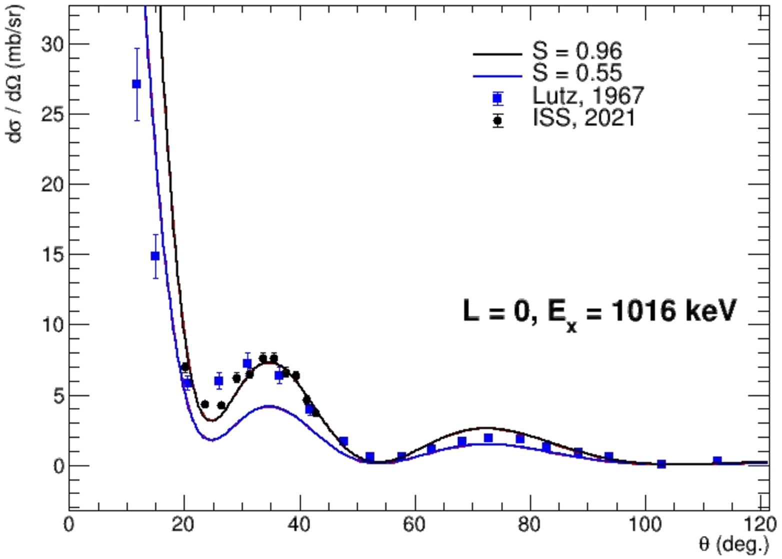
ISOLDE Solenoidal Spectrometer

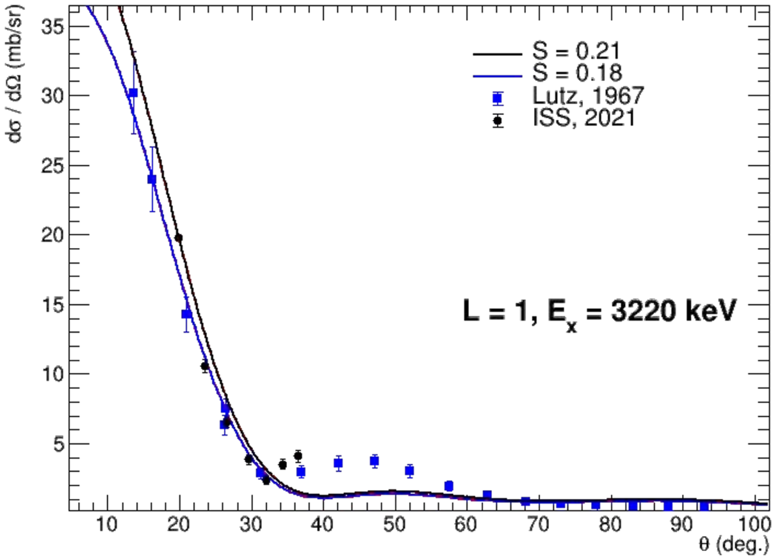
Proof-of-principle experiment at ISS

- Stable beam following CERN's LS2 in 2021… ^{22}Ne at 6.05 MeV/*u.*
  - Matching normal kinematics study with gas target! [H.F. Lutz et al. NPA 95 (1967) 591]
  - Implementation of precise energy calibration, pulse-height corrections, energy loss corrections, kinematic reconstruction

^{22}Ne(d,p)^{23}Ne







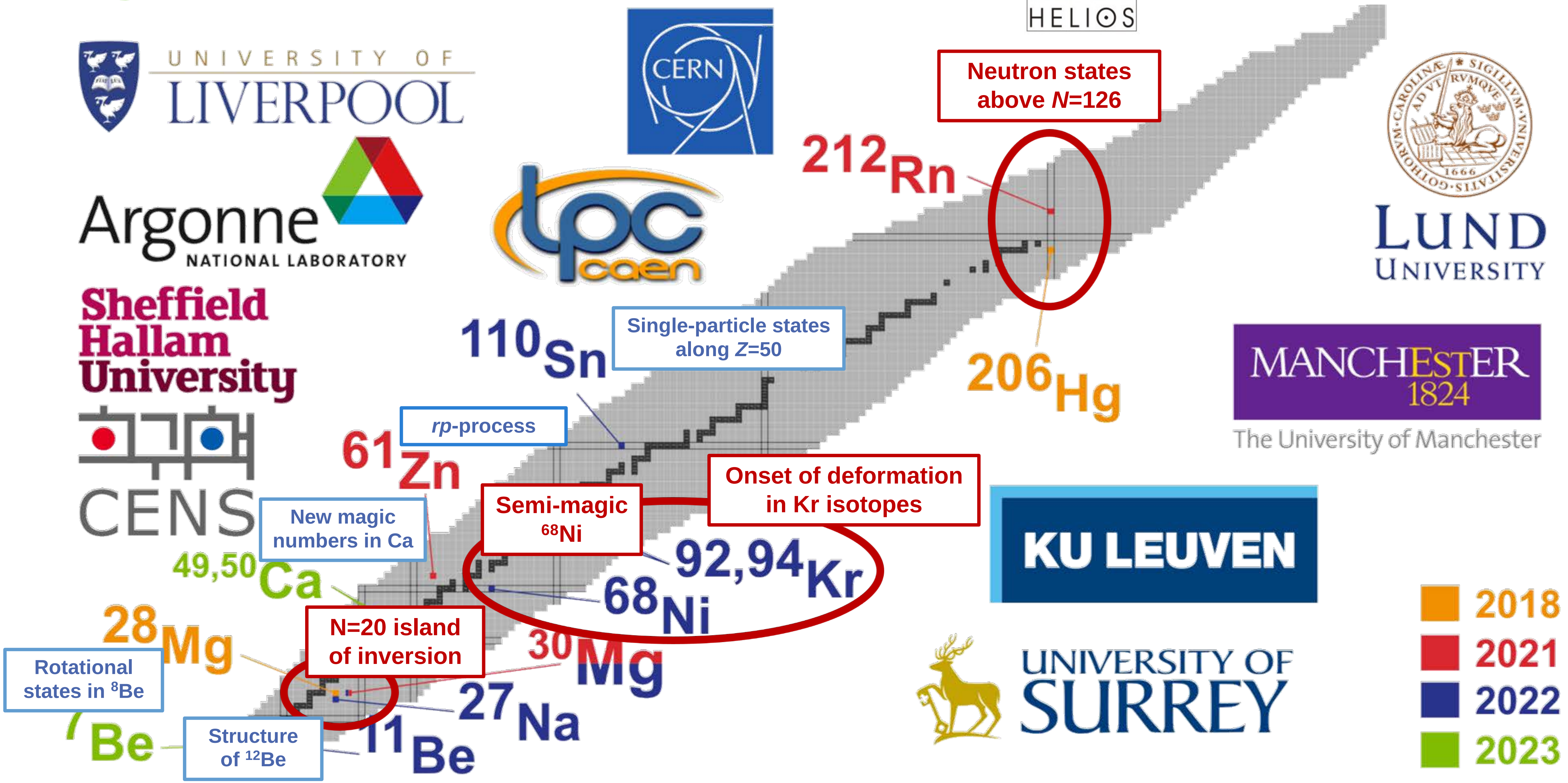
ISOLDE Solenoidal Spectrometer

Full code available: https://github.com/ISOLDESolenoidalSpectrometer/ISSSort

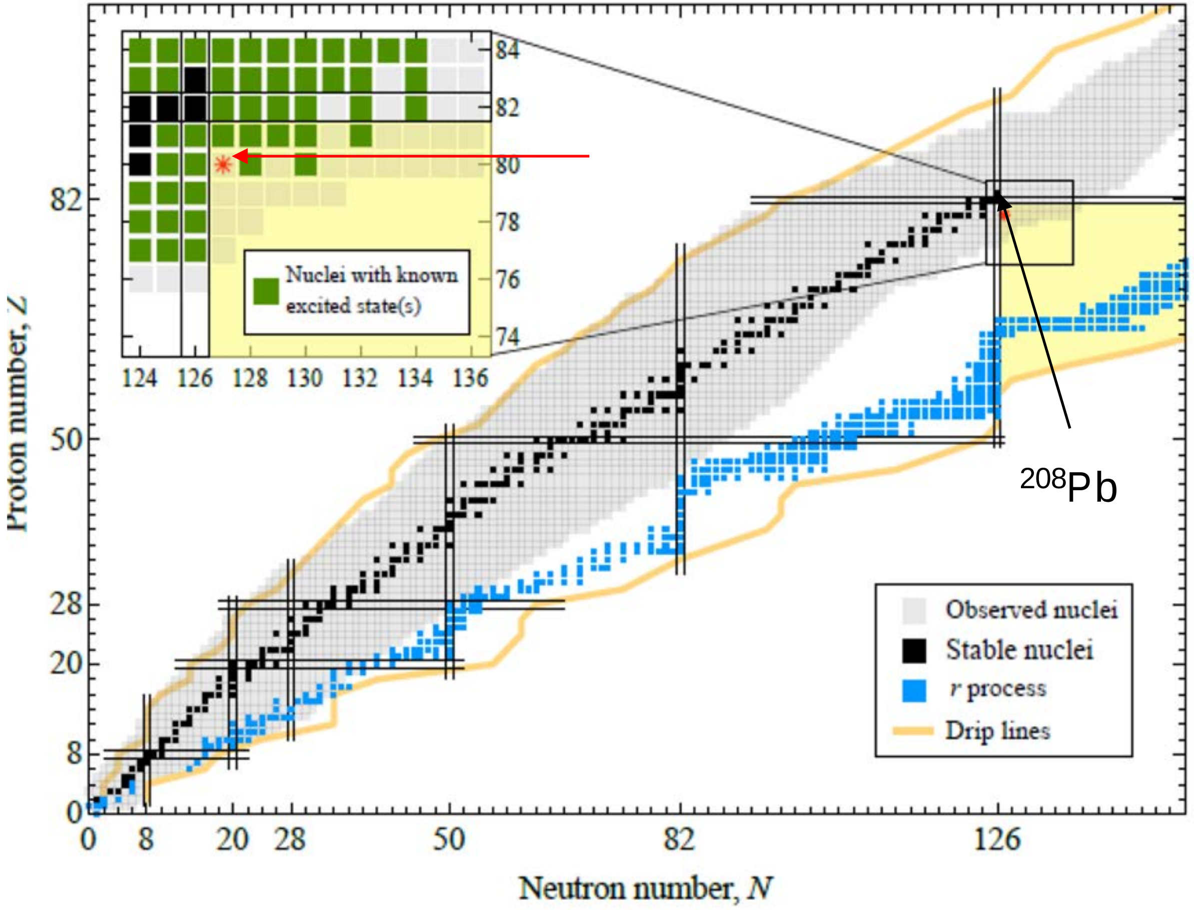
ISOLDE Solenoidal Spectrometer

Physics so far

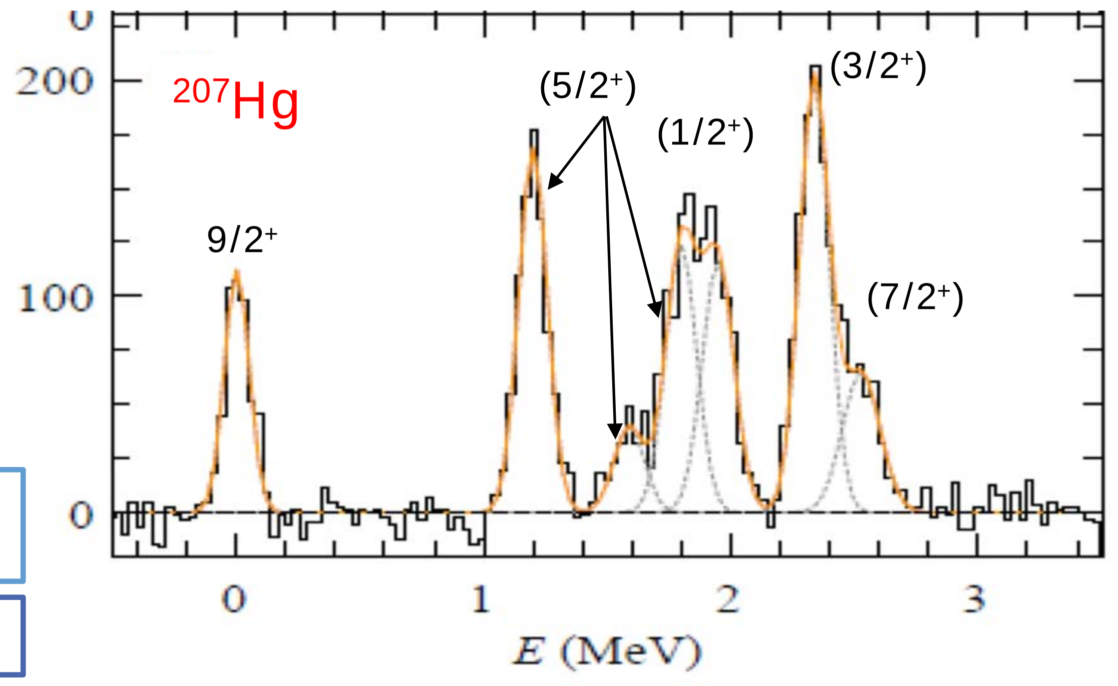
2018 Campaign achieved with HELIOS array + DAQ



Neutron states above *N*=126 – ^{206}Hg(*d*,*p*)^{207}Hg



- Terra incognita for excited states south-east of ^{208}Pb… New Hg beam development.
- First probe of neutron single-particle states above *N*=126 in elements below Pb.
  - Important for evolution towards the *r*-process.

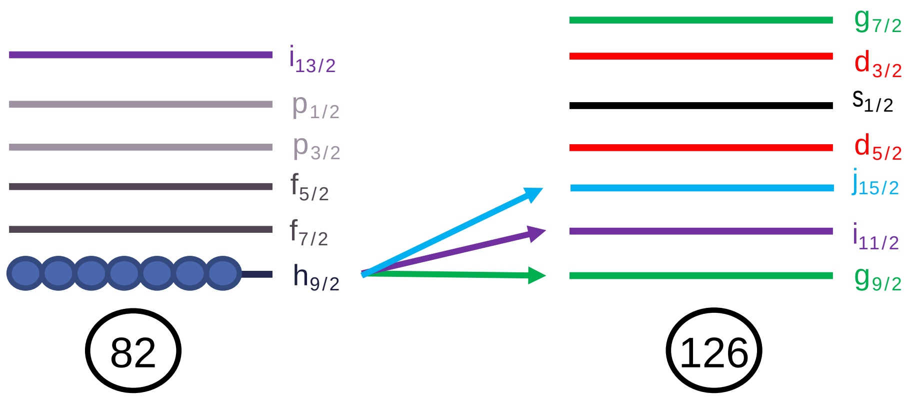


First result from ISS; early exploitation mode before CERN's LS2 using HELIOS array + DAQ

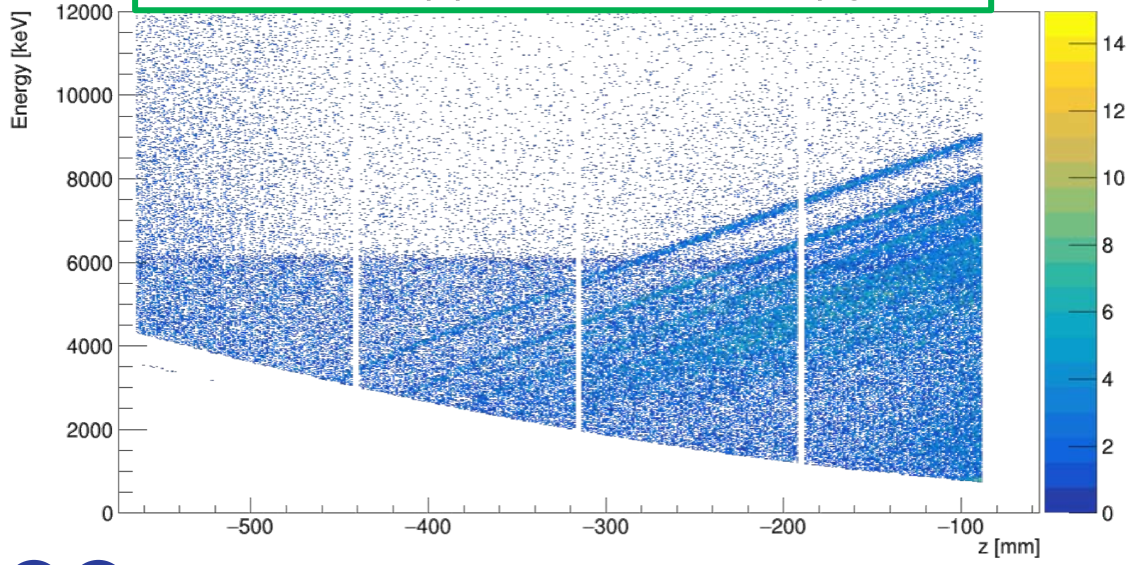
Tang et al. PRL 124, 062502 (2020)

ISOLDE Solenoidal Spectrometer

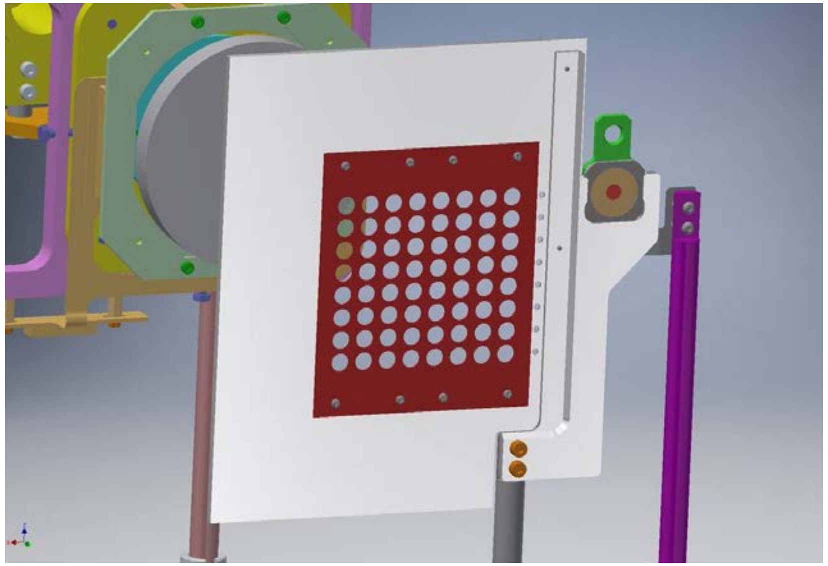
Neutron states above N=126 - ^{212}Rn(d,p)^{213}Rn



^{212}Rn ~5x10^6 pps 7.6 MeV/u, 125µg/cm^2



- 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 we have access to in nuclear chart.
  - Benchmark calculations by studying single-particle behaviour.
- Background from alpha decay of beam
  - EBIS on/EBIS off subtraction removes almost all background.

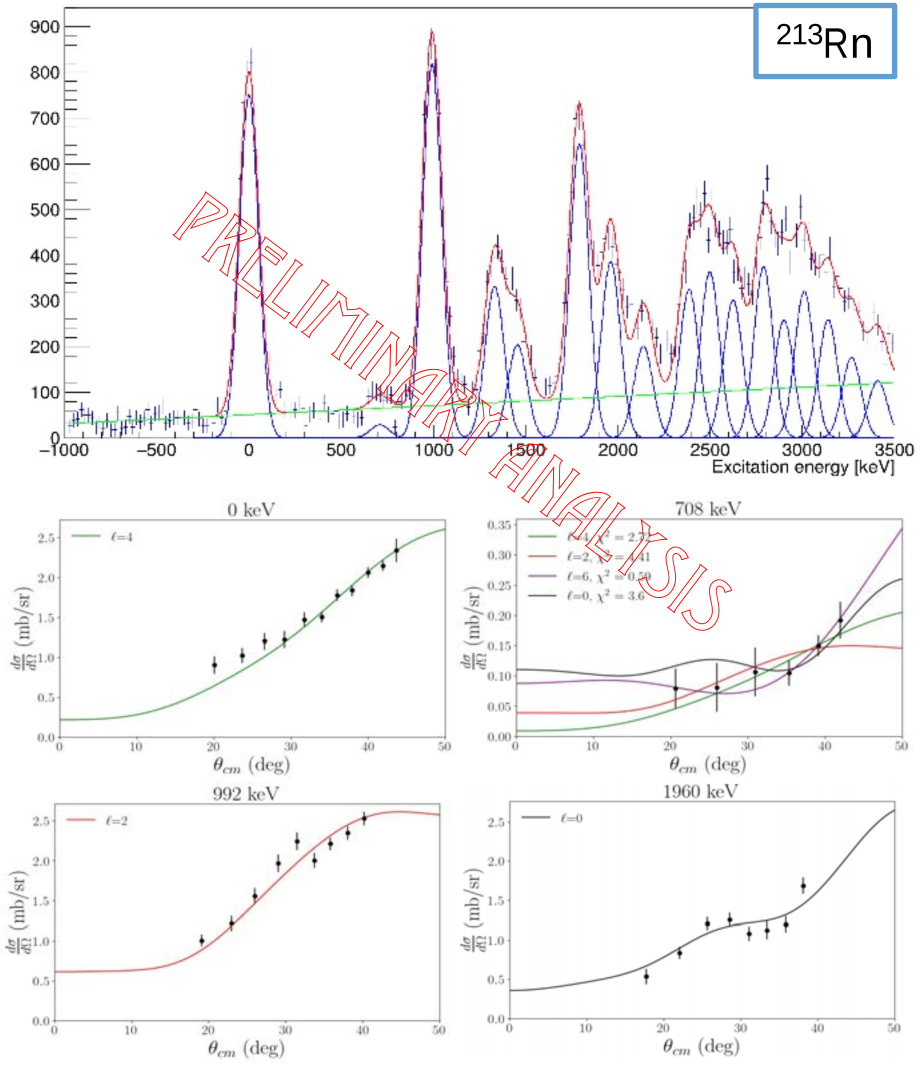


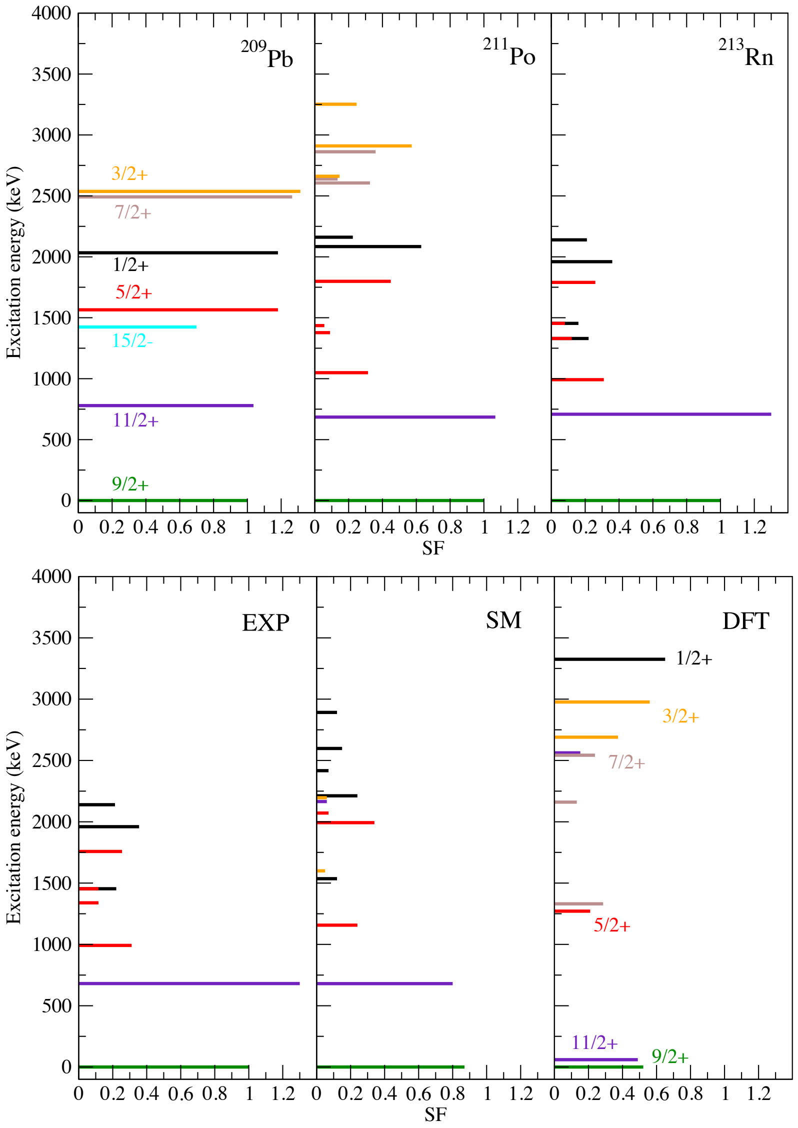
ISOLDE Solenoidal Spectrometer

Courtesy of D Clarke (Manchester)

MANCHESTER 1824 The University of Manchester

Neutron states above N=126 - ^{212}Rn(d,p)^{213}Rn





- Angular distributions and absolute cross-sections obtained for 17 states in ^{213}Rn.
  - Mainly ℓ = 2, 4 plus $i_{11/2}$ at 708 keV
- Preliminary data compared to systemics for N=127.
- ^{213}Rn strength distribution similar to ^{211}Po, up to 2 MeV (so far).
- Early comparison to SM (B. A. Brown) and DFT (G. Colo).
- Analysis to be completed this spring…

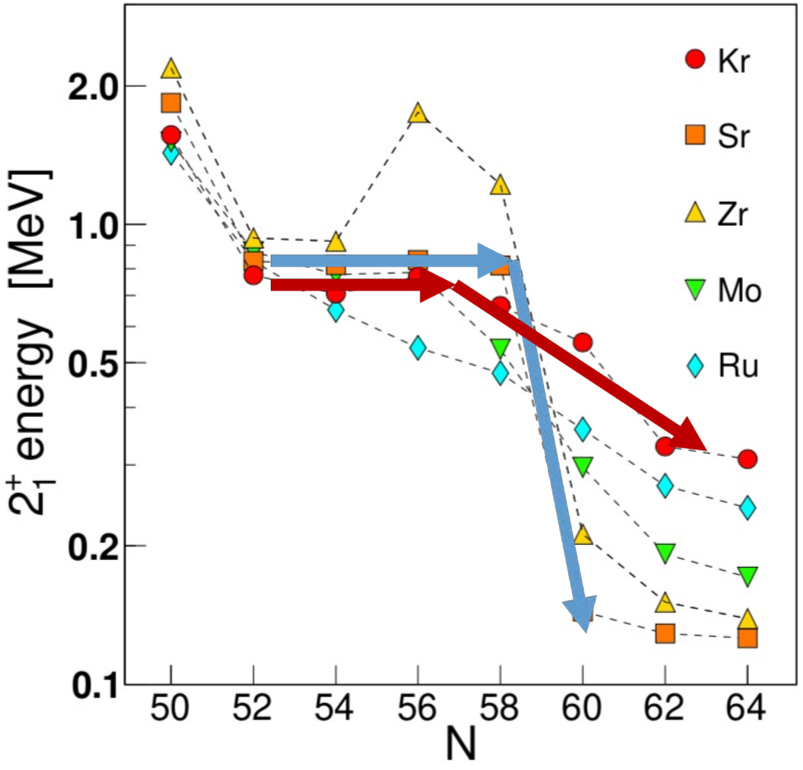
ISOLDE Solenoidal Spectrometer

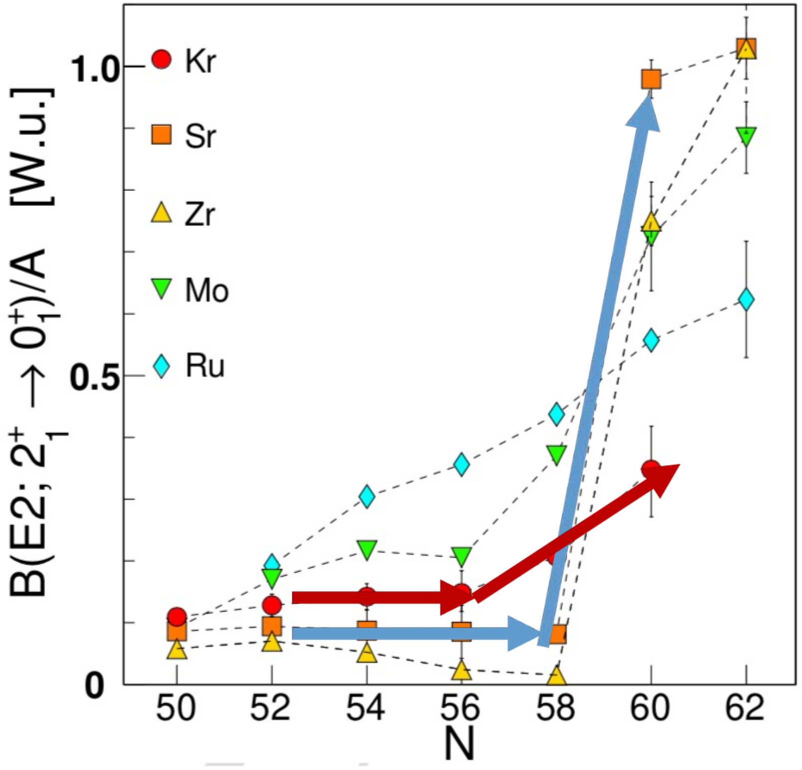
Analysis by Daniel Clarke (Manchester)

MANCHESTER 1824 The University of Manchester

Onset of deformation at N=60 – $^{92}Kr(d,p)^{93}Kr$

- Sr and Zr show rapid and dramatic onset of deformation at N=60.
- Smooth increase for the Kr isotopic chain[1].
- Low-lying intruder configurations → shape coexistence[2,3]
- Proton excitations across Z = 40 to $\pi g_{9/2}$.
  - Ground-state configuration at N = 60.
  - Filling neutron orbitals lowers energy of $\pi g_{9/2}$.
  - Large overlap of $\pi g_{9/2}$ and $\nu g_{7/2}$...
  - Tensor force[4] → Type-II shell evolution[5]
- Close proximity of $\nu s_{1/2}$, $\nu d_{3/2}$, $\nu g_{7/2}$, $\nu h_{11/2}$ orbitals.
  - Enhanced quadrupole interaction from coherent contributions → deformation



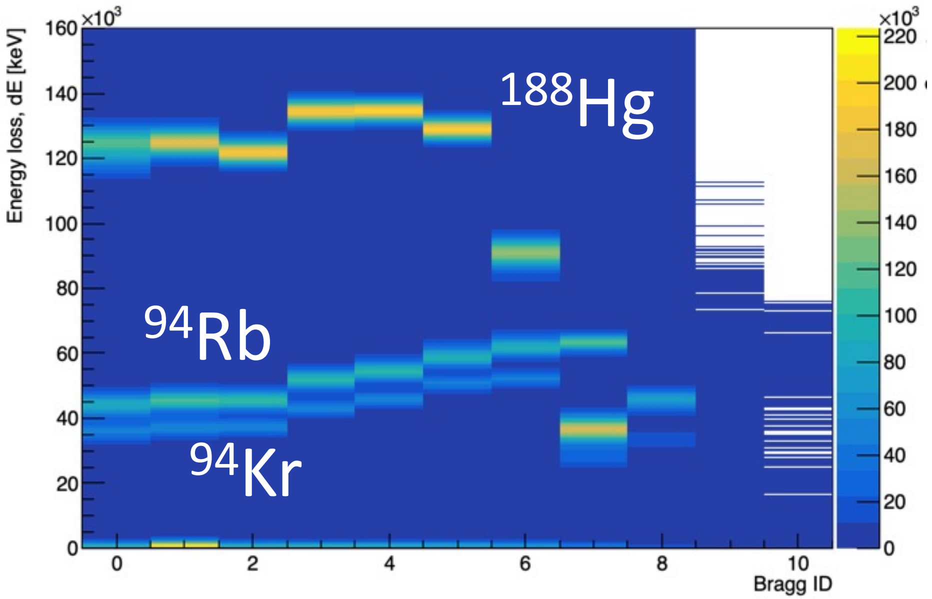


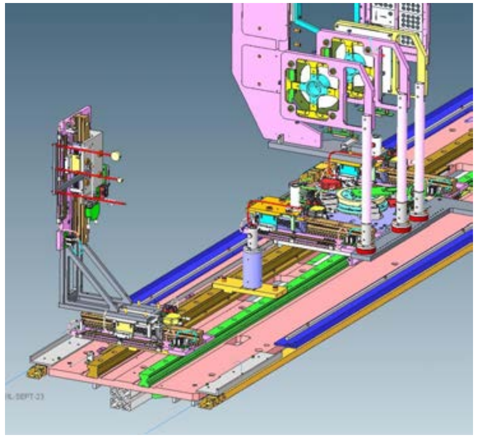
[1] M. Albers, et al., Phys. Rev. Lett. 108, 062701 (2012).
[2] J.E. García-Ramos and K. Heyde, Phys. Rev. C 100, 044315 (2019).
[3] P.E. Garrett, M. Zielińska, and E. Clément, Prog. Part. Nucl. Phys. 163, 103931 (2021).
[4] P. Federman and S. Pittel, Phys. Lett. B 69, 385 (1977).
[5] T. Togashi, Y. Tsunoda, T. Otsuka, and N. Shimizu, Phys. Rev. Lett. 117, 172502 (2016).

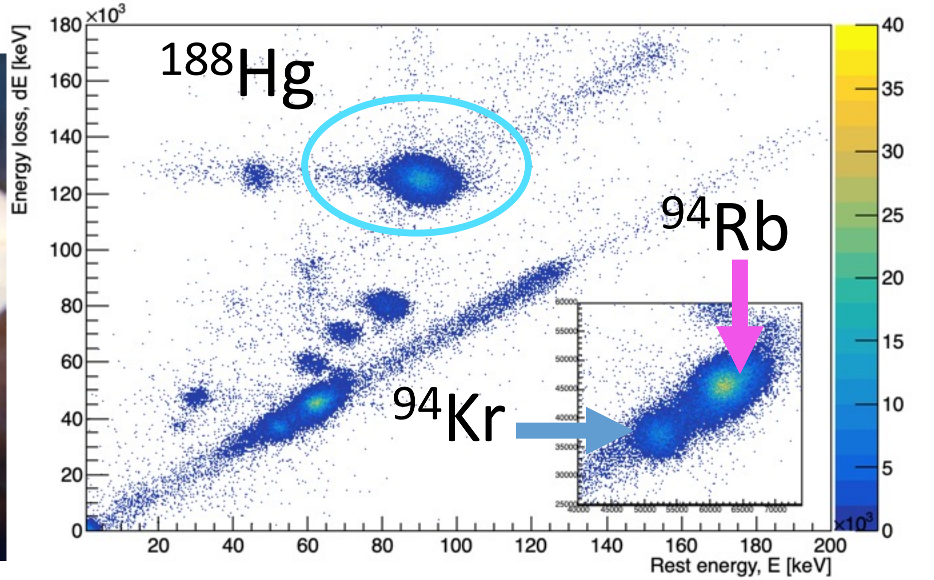
ISOLDE Solenoidal Spectrometer

Onset of deformation at N=60 – ^{92}Kr(d,p)^{93}Kr

- Fast-counting ionisation chamber used to diagnose beam composition
  - Short $T_{1/2}$ + charge breeding = in-trap decay (Rb daughter)
- Event-by-event selection wasn't possible due to pileup.
  - High instantaneous rates from EBIS + insufficient blocking of direct beam
  - Faster preamps installed for 2024
  - New beam blocker mechanism

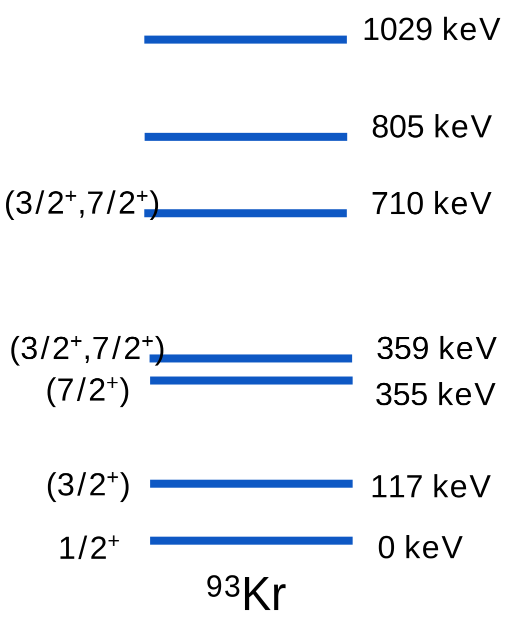


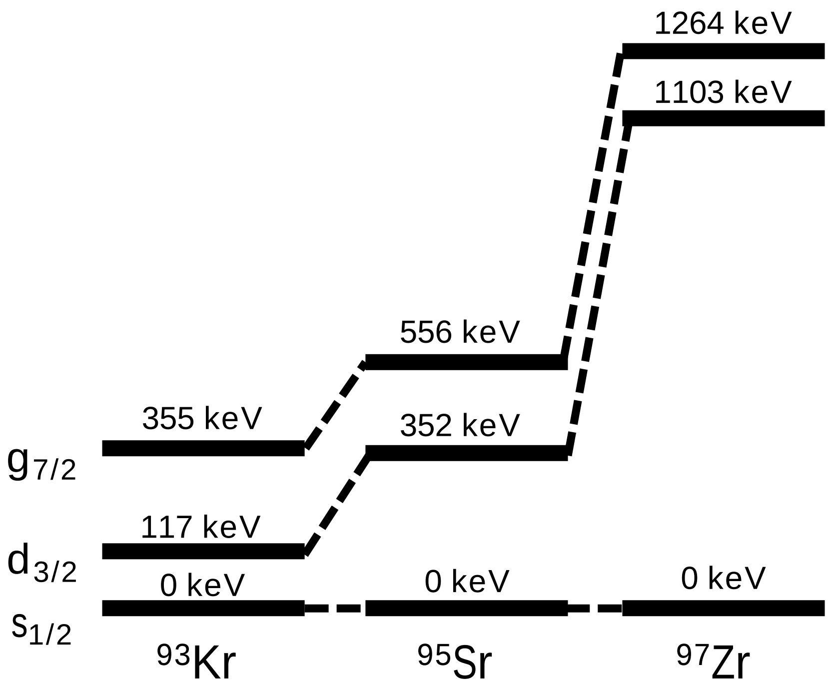




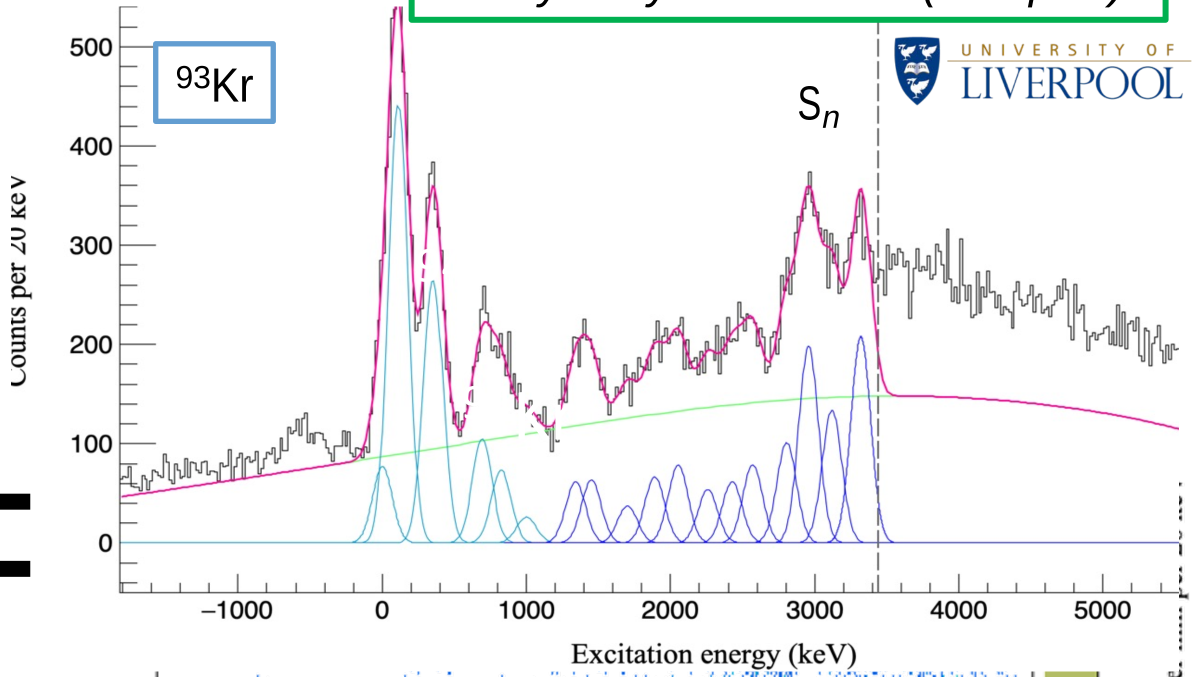
Onset of deformation at *N*=60 – ^{92}Kr(*d*,*p*)^{93}Kr

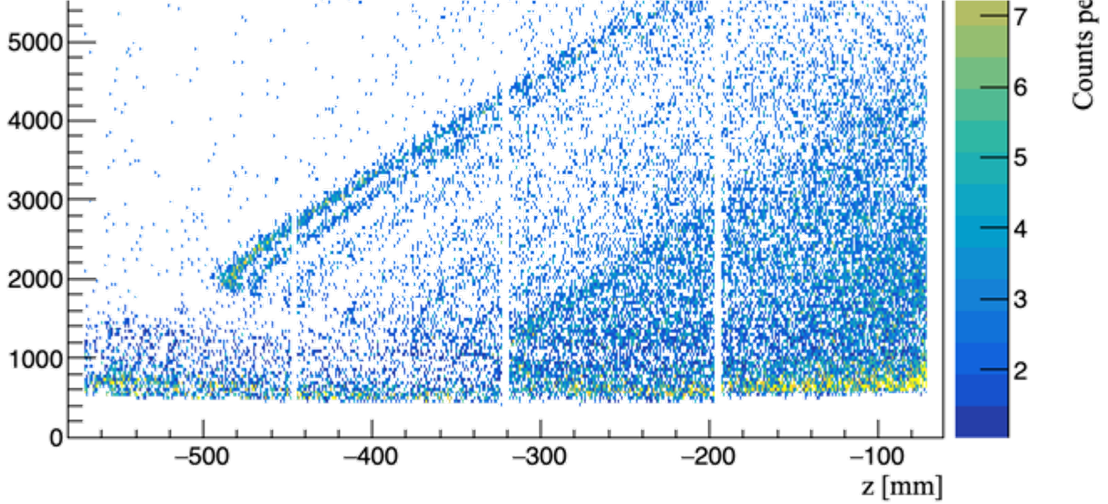
- 7 states populated up to ~1 MeV; known energy from β-decay studies.
  - 12 new states populated up to S_n.
- Angular distributions give definitive ℓ assignments.
  - Locate ℓ=4 strength to observe $g_{7/2}$ evolution





Analysis by Annie Dolan (Liverpool)





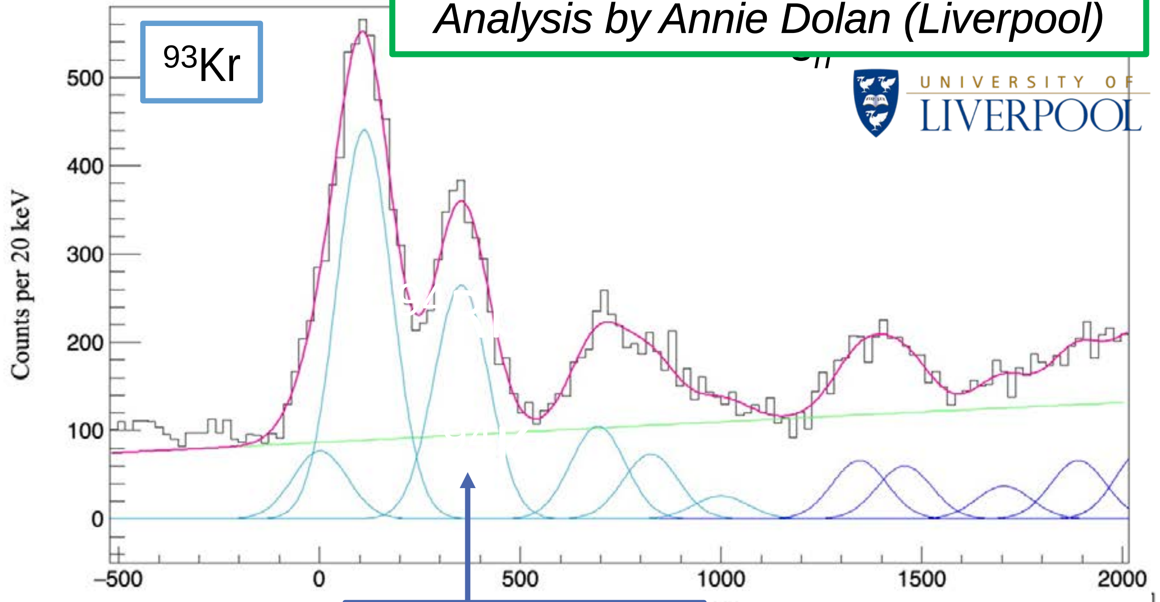
ISOLDE Solenoidal Spectrometer

UNIVERSITY OF LIVERPOOL

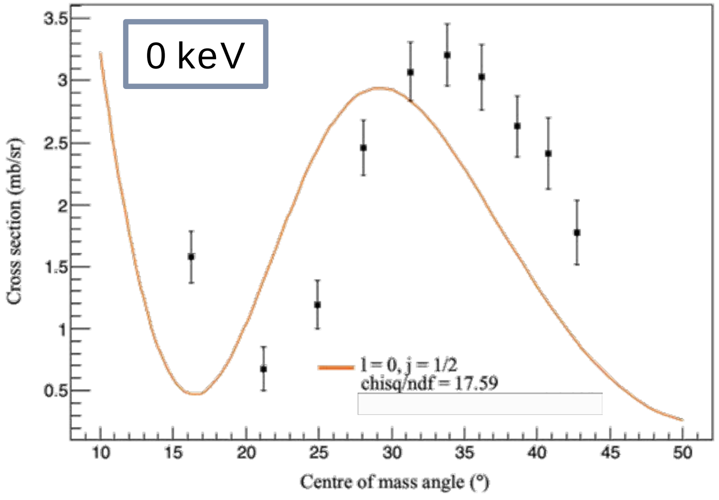
Onset of deformation at N=60 – $^{92}Kr(d,p)^{93}Kr$

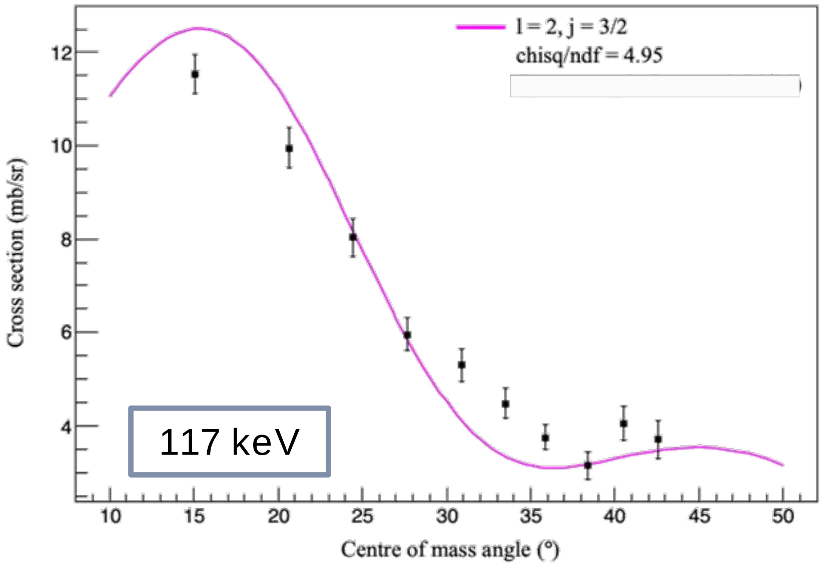
- 7 states populated up to ~1 MeV; known energy from β-decay studies.
  - 12 new states populated up to S_n.
- Angular distributions give definitive ℓ assignments.
  - DWBA analysis to extract SFs.

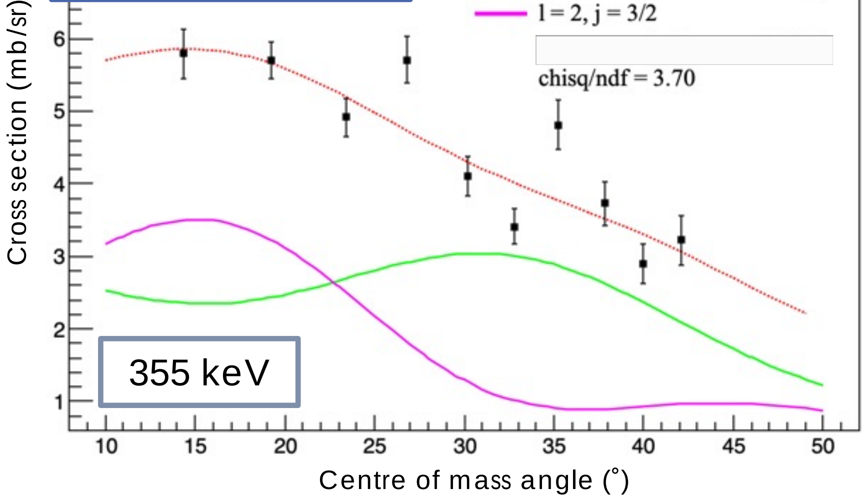
Analysis by Annie Dolan (Liverpool)



Resolved doublet
$\nu g_{7/2}$ strength found!



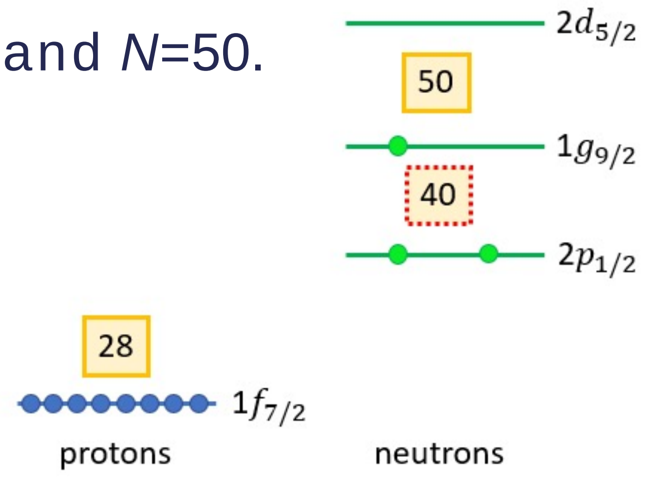


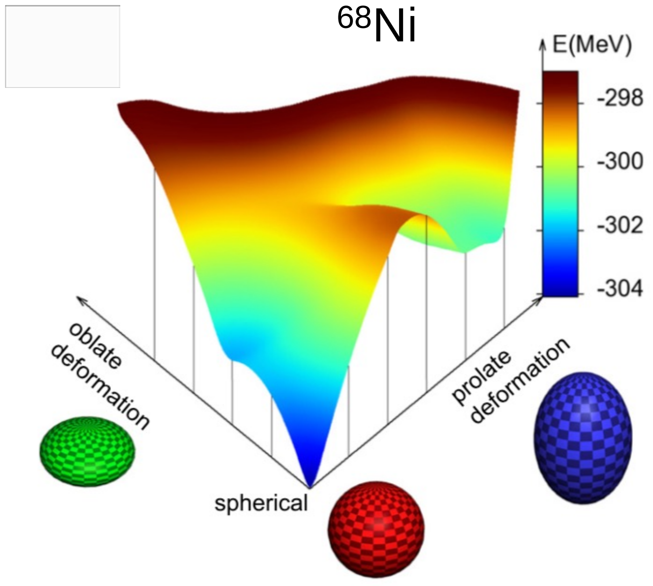


ISOLDE Solenoidal Spectrometer

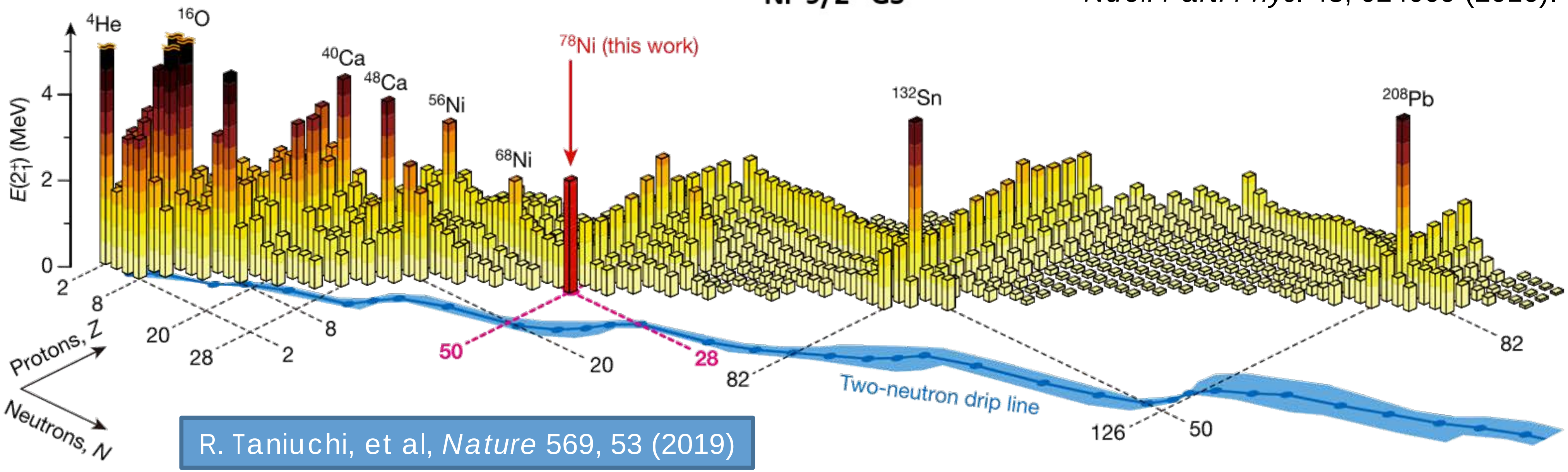
Semi-magic ^{68}Ni - ^{68}Ni(d,p)^{69}Ni

- Two doubly-magic Ni isotopes at N=28 and N=50.
- Sub-shell closure at N=40 → ^{68}Ni.
- Deformed intruder states predicted.
- Next two neutron orbitals define the N=50 shell gap: $1g_{9/2} \leftrightarrow 2d_{5/2}$





T. Otsuka and Y. Tsunoda, *J. Phys. G Nucl. Part. Phys.* 43, 024009 (2016).

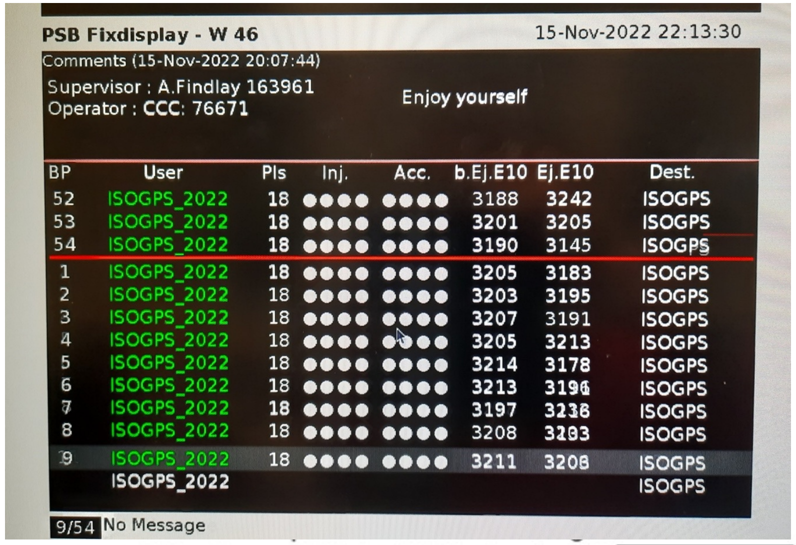


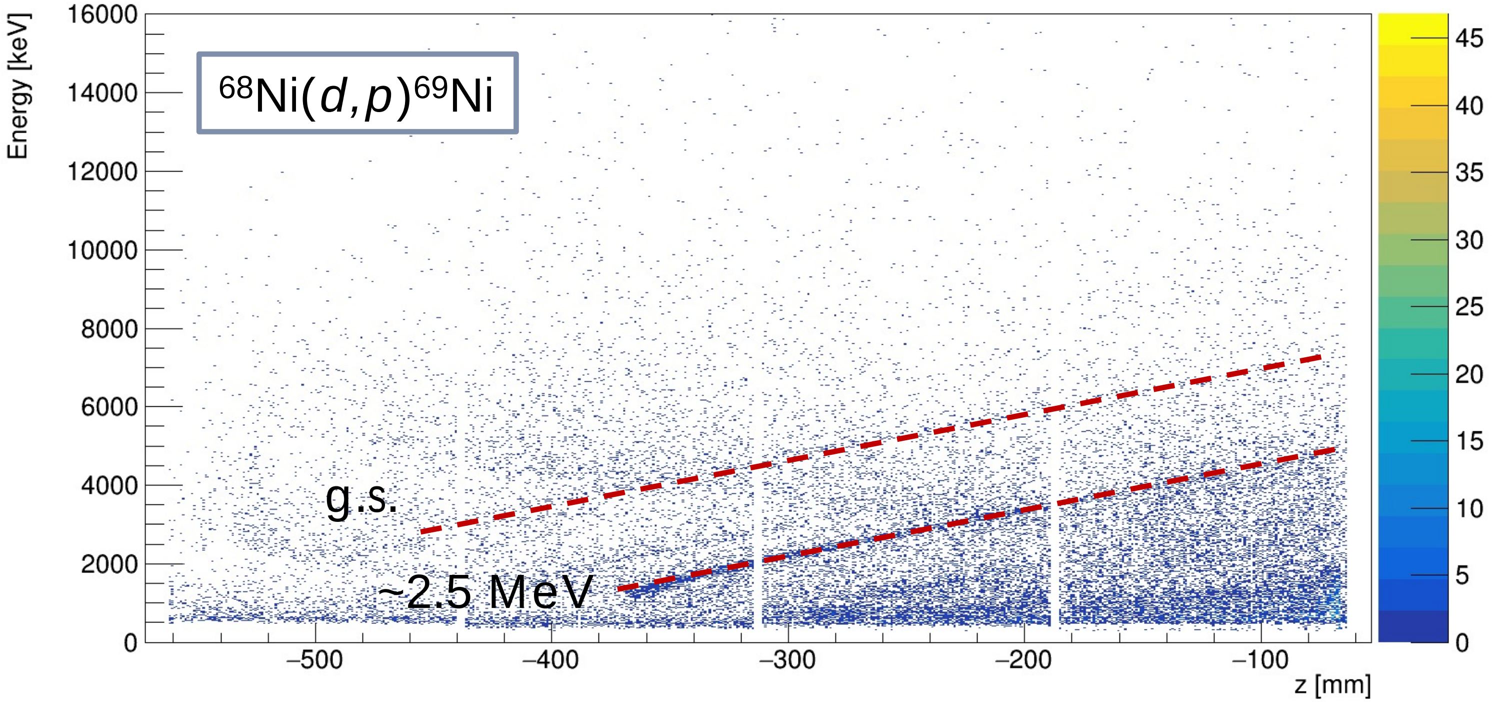
R. Taniuchi, et al, *Nature* 569, 53 (2019)

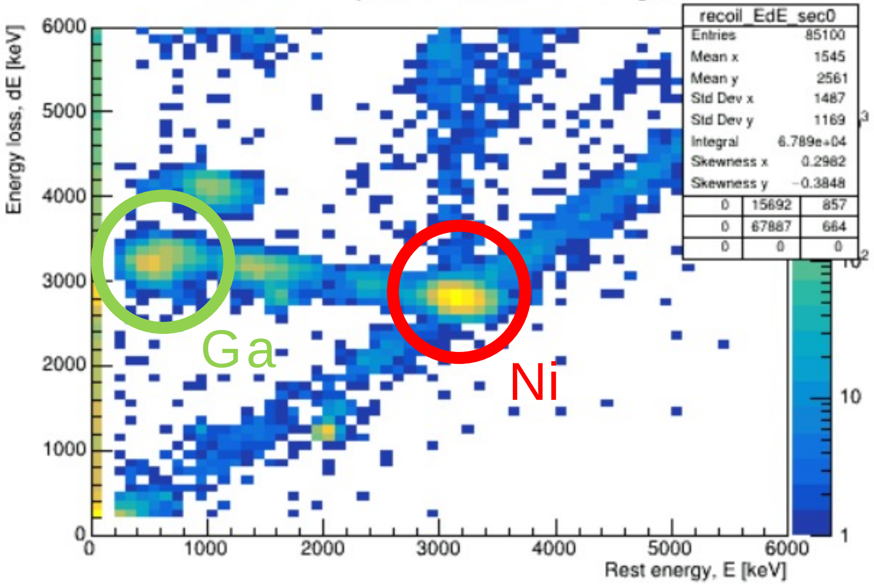
ISOLDE Solenoidal Spectrometer

Semi-magic ^{68}Ni - ^{68}Ni(d,p)^{69}Ni

- Large contamination from ^{68}Ga, suppressed with proton beam gate and *interesting* supercycle structure.
  - Subtraction possible with “laser off + beam gate off” run.







Configuration	Ratio Ni:Ga
No beam gate	1:7
With beam gate	4:1

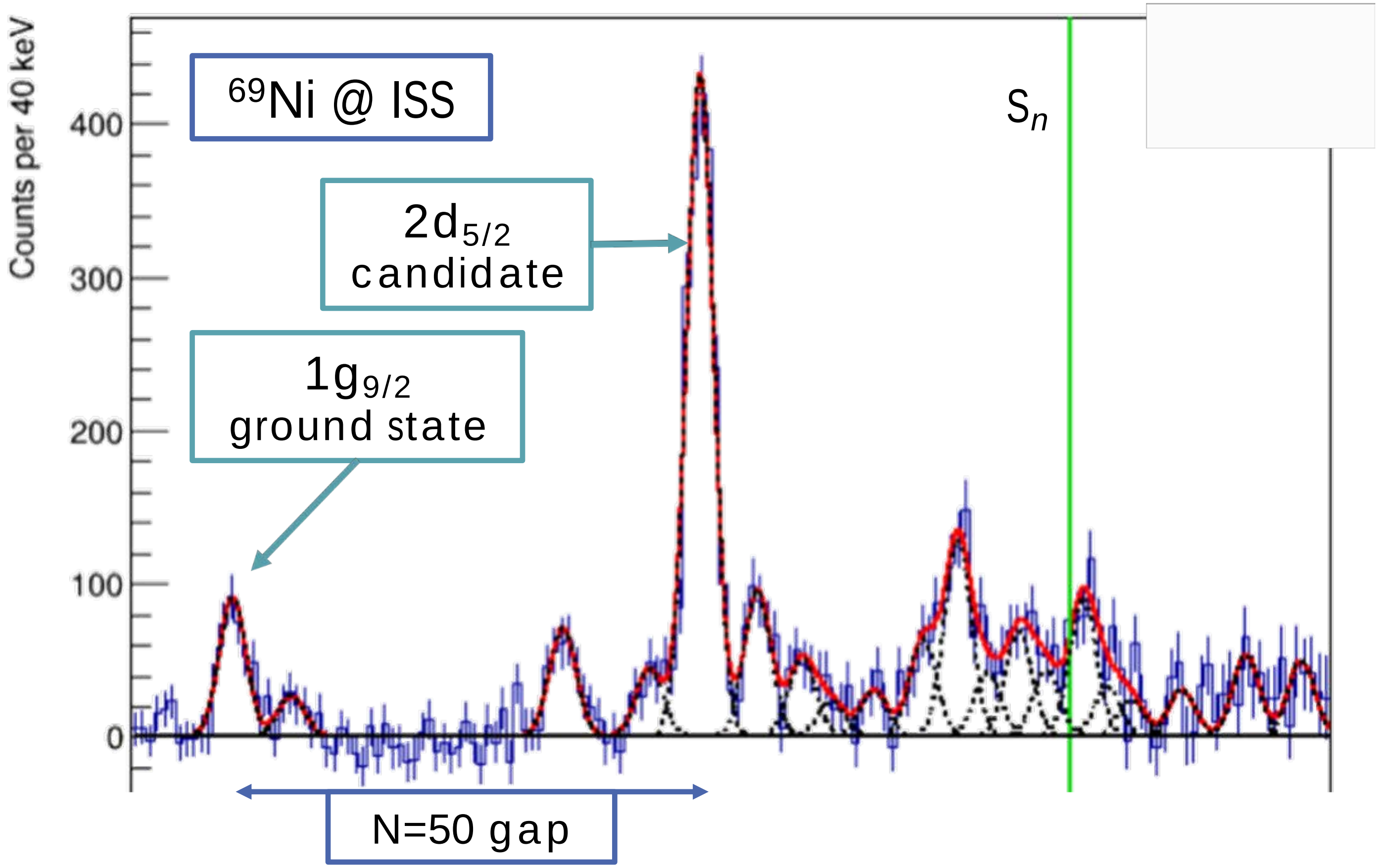
ISOLDE Solenoidal Spectrometer

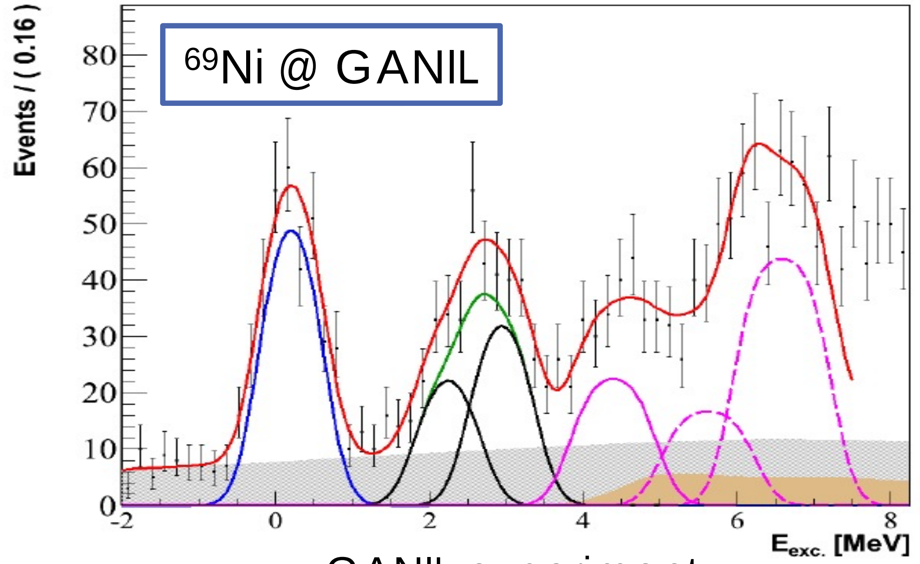
Analysis by Andreas Ceulemans (KU Leuven)

KU LEUVEN

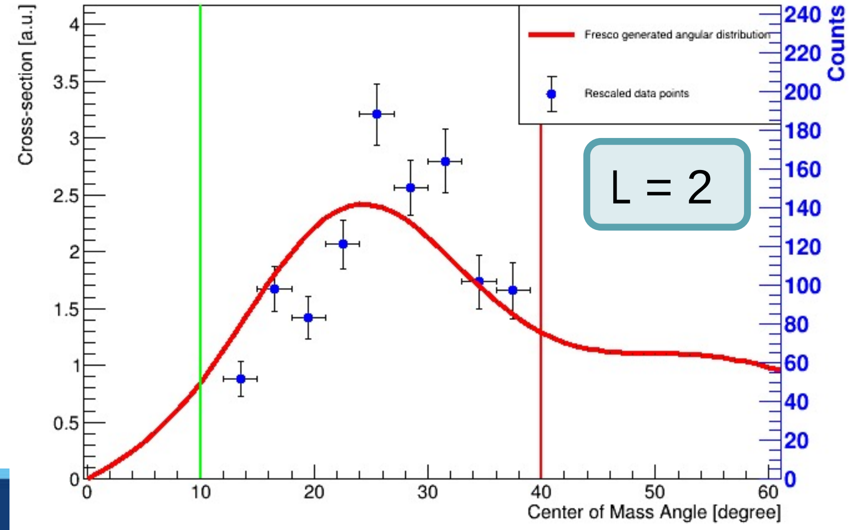
Semi-magic ^{68}Ni - ^{68}Ni(d,p)^{69}Ni

- ^{68}Ni beam ~2 x 10^4 pps @ 6.0 MeV/u (matched for ℓ=2)





GANIL experiment
(2010, unpublished, M. Moukkamad et al.)
E_{beam} = 25.14 MeV/u; CD_2 Target : 2.6 mg/cm^2

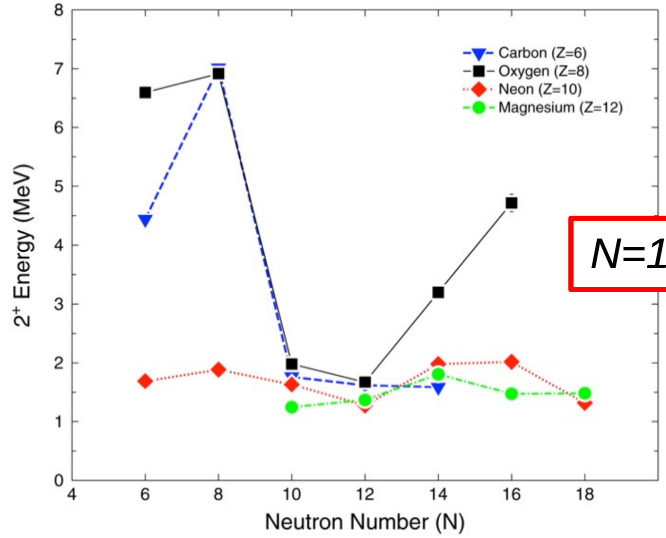


ISOLDE Solenoidal Spectrometer

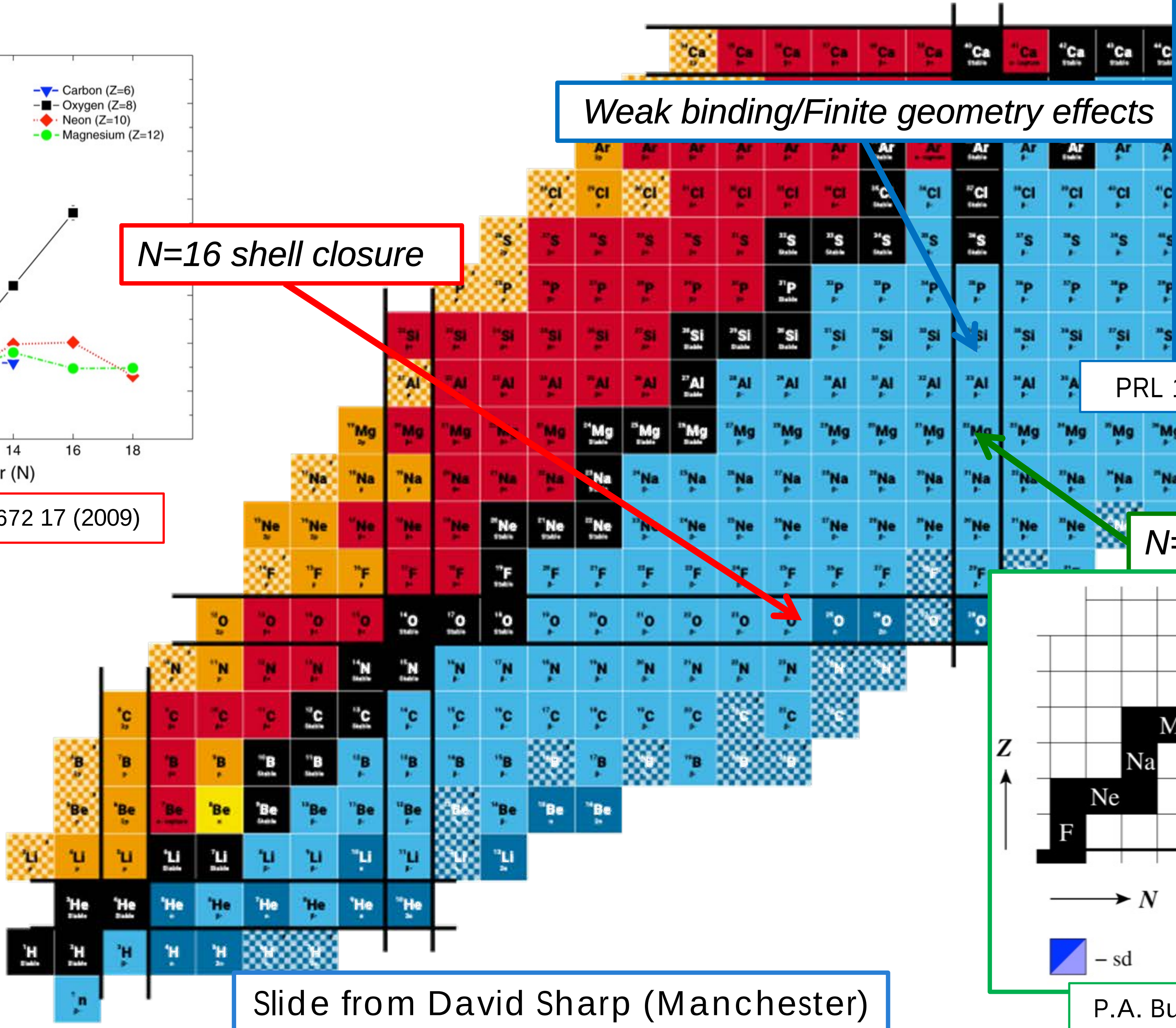
Analysis by Andreas Ceulemans (KU Leuven)

KU LEUVEN

Towards the (1^{st}) Island of Inversion

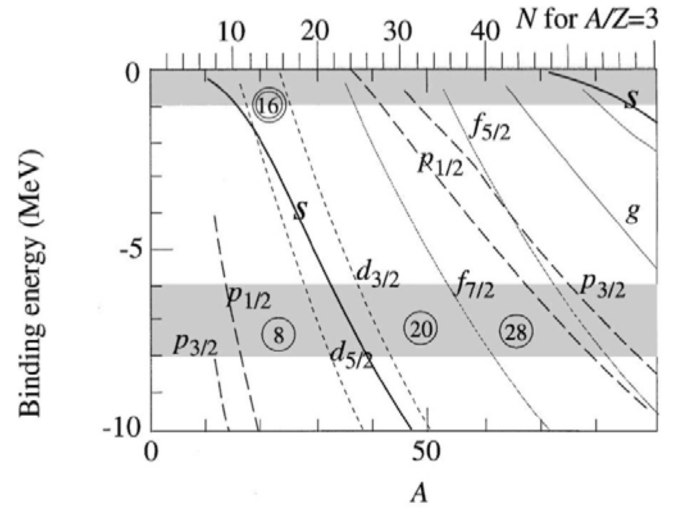


C.R. Hoffman, et al., PLB 672 17 (2009)



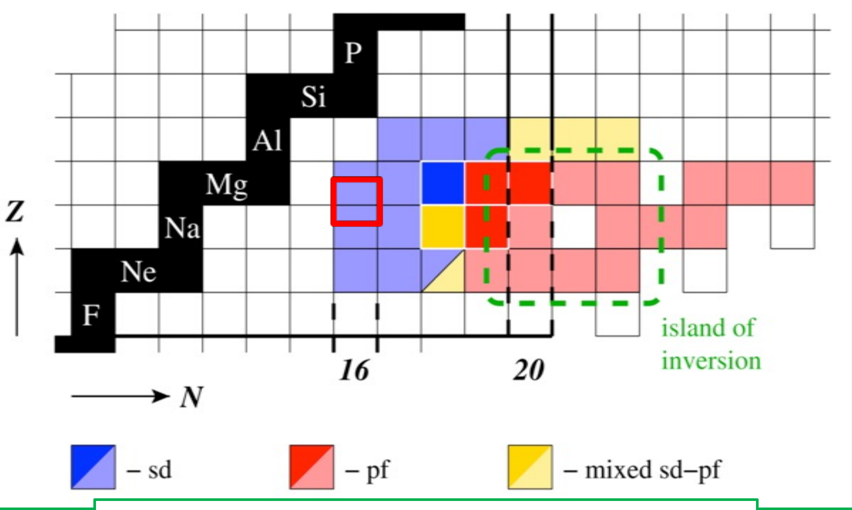
N=16 shell closure

Weak binding/Finite geometry effects



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

N=20 Island of Inversion



P.A. Butler, et al., JPG 44, 044012 (2017)

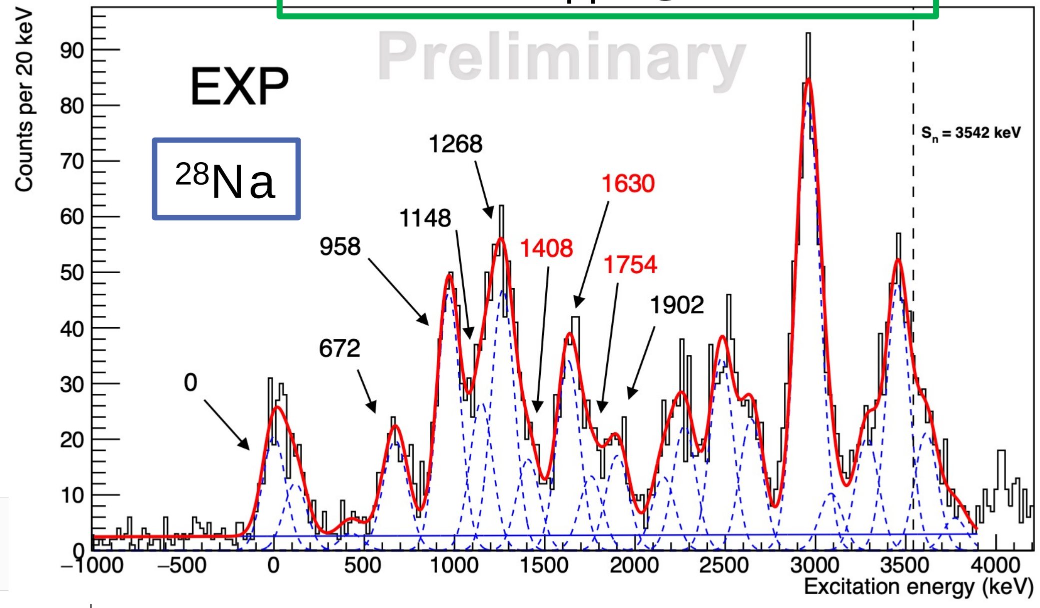
Slide from David Sharp (Manchester)

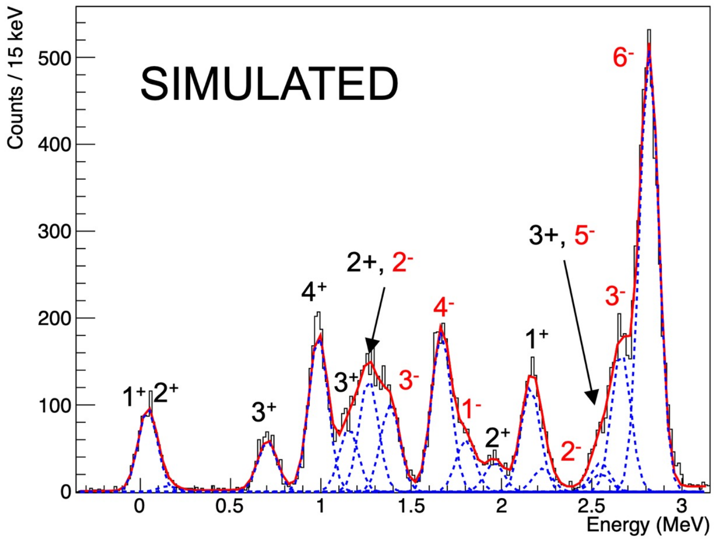
ISOLDE Solenoidal Spectrometer

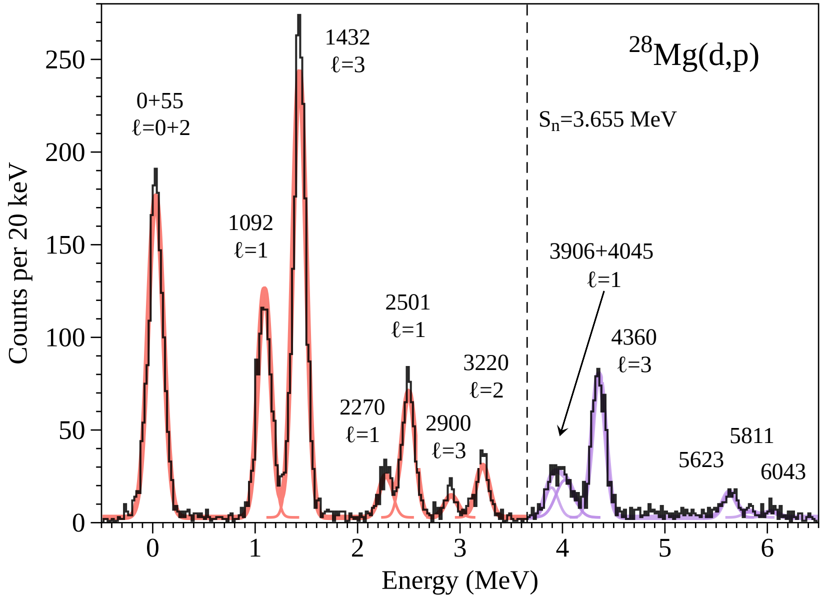
Towards the (1st) Island of Inversion

- Range of probes already used to study IoI.
- Single-particle evolution towards IoI important for tracking orbitals and occupancies…
- ISOLDE provides excellent beams in this region, programme at ISS focussing on N=17 and along the Mg chain

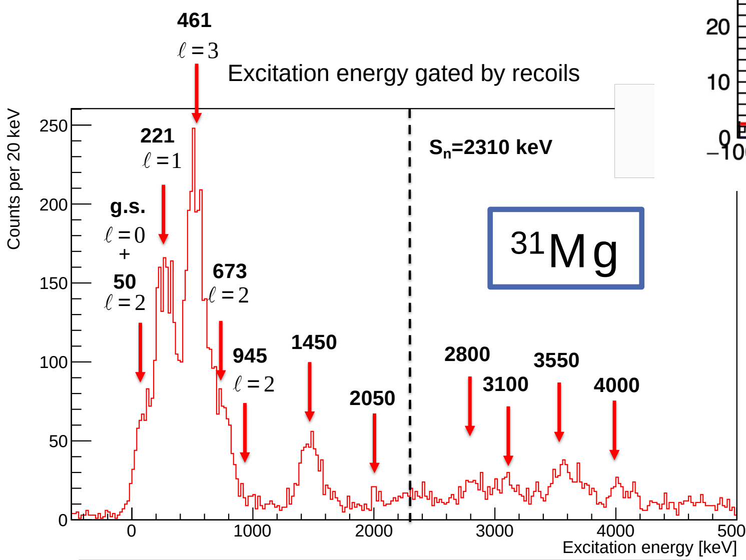
^{27}Na - 8x10^{5} pps @ 9.7 MeV/*u*







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



^{30}Mg - 1x10^{5} pps @ 8.2 MeV/*u*

Analysis by Sam Reeve (Manchester)

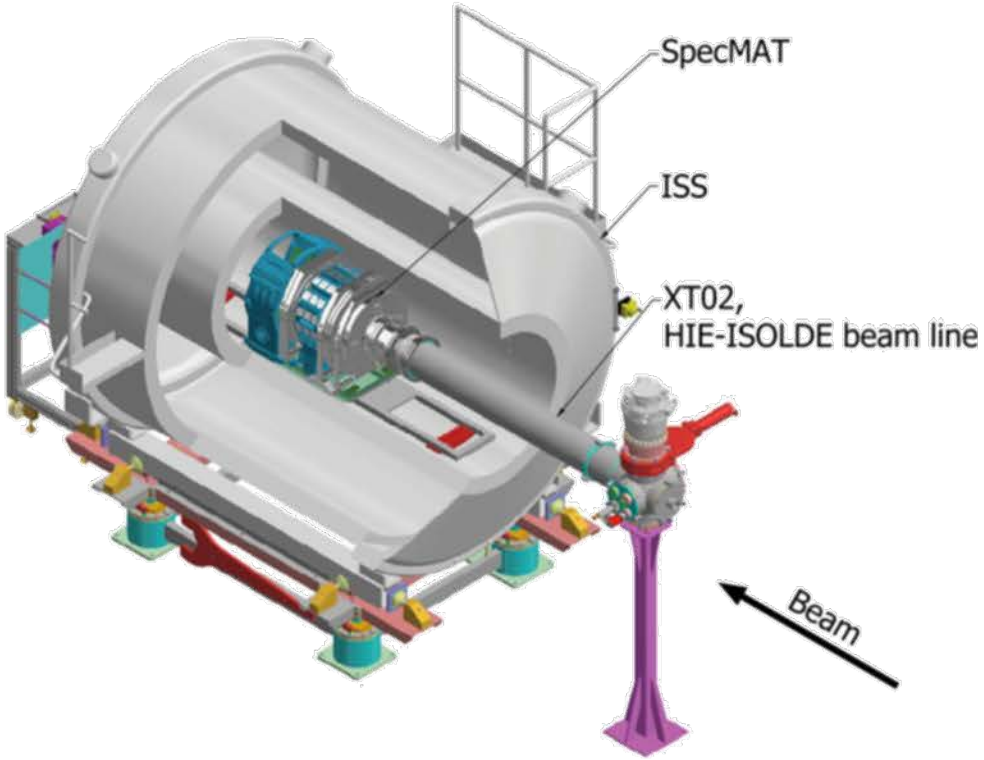
ISOLDE Solenoidal Spectrometer

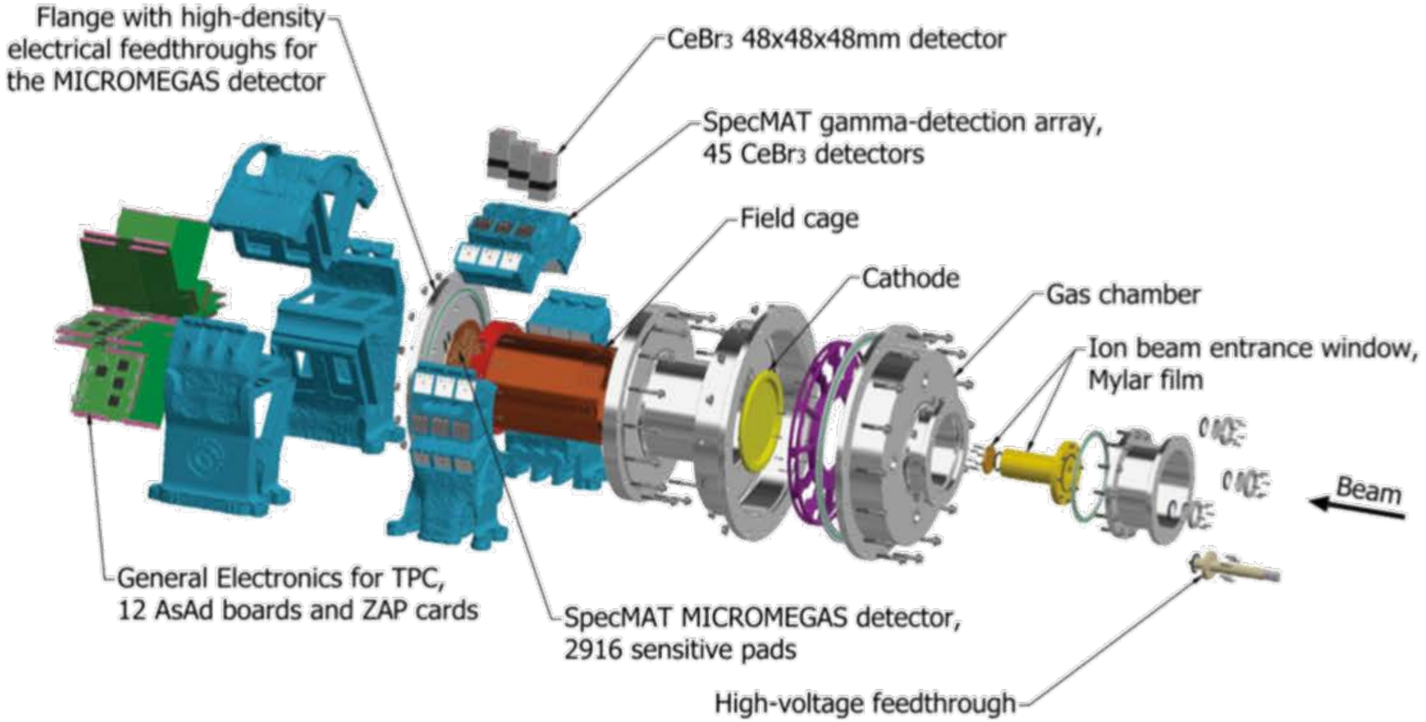
MANCHESTER 1824
The University of Manchester

SpecMAT active target – first beam

KU LEUVEN

SpecMAT

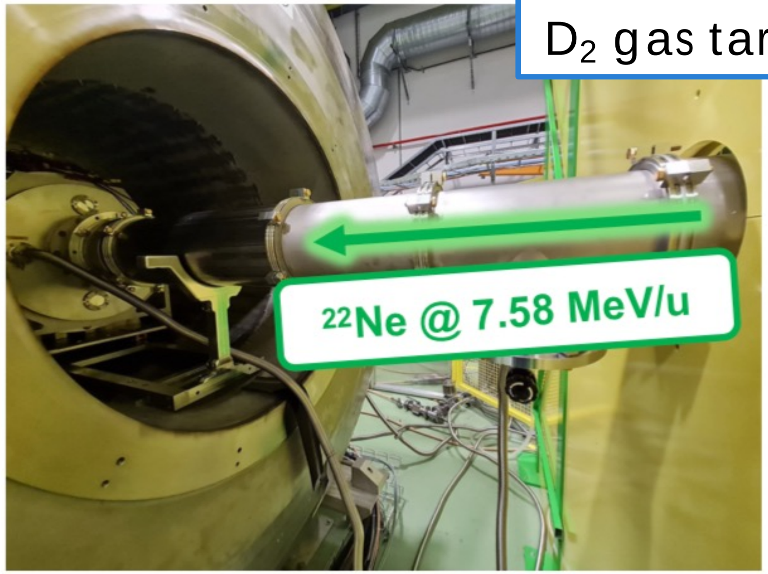




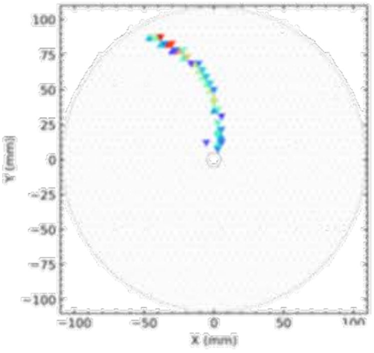
Active target within ISS combined with a time-projection chamber and CeBr detectors. Led by team from KU Leuven

SpecMAT active target – first beam

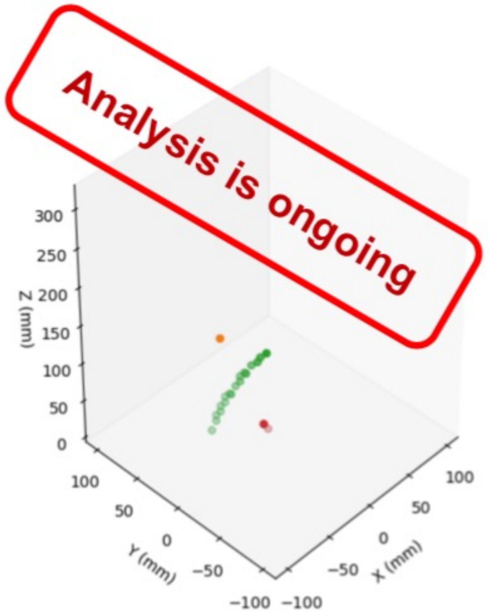
June 2023
D_2 gas target



SpecMAT installed in the ISS solenoid at ISOLDE



α-particle track measured in B=2.5T (offline)



ISOLDE Solenoidal Spectrometer

Thanks to Oleksii Poleshchuk (KU Leuven)

Thanks to collaboration and funders