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ISOLDE Solenoidal
Spectrometer

Single-nucleon transfer reactions probed in inverse kinematics with the ISOLDE Solenoidal Spectrometer – recent highlights

D. K. Sharp
The University of Manchester, UK

Nuclear Structure 2022, Berkeley

Overview

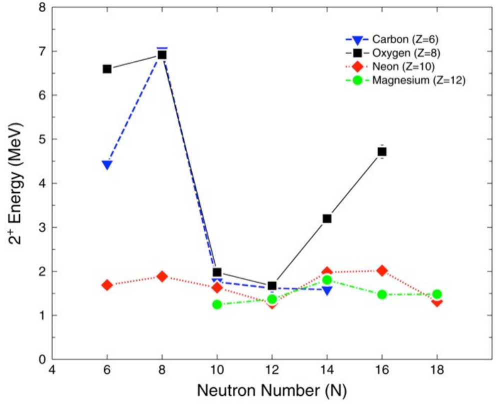
- *Changing structure in light neutron-rich nuclei*
    - *^{28}Mg(d,p)^{29}Mg – early implementation campaign*
    - *^{30}Mg(d,p)^{31}Mg – very preliminary*

- *Trends in single-particle behavior in heavier nuclei*
    - *^{212}Rn(d,p)^{213}Rn – preliminary*

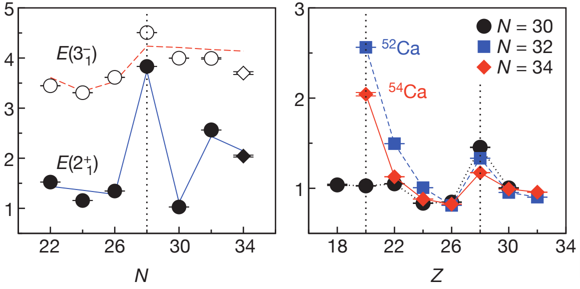
Evolution of single-particle structure

*Studies of the evolution of shell structure in light neutron-rich systems has led to discoveries of dramatic changes leading to the **weakening** and **appearance** of shell closures.*

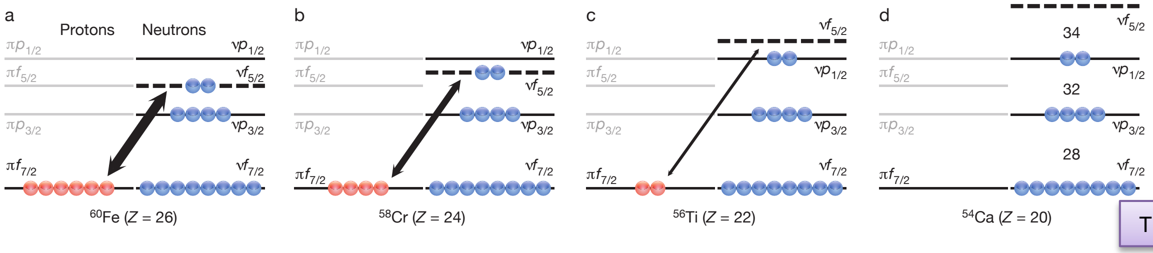
*Such changes can be interpreted as arising from effects of the **valence nucleon interactions**, where increasing occupation of a particular valence proton orbital will have a larger interaction on valence neutrons, for example.*

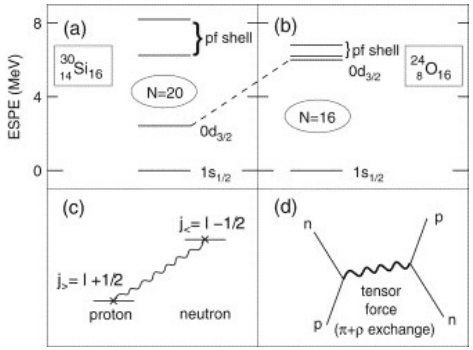


C. Hoffman *et al*, Phys. Lett. B **672** 17 (2009)



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

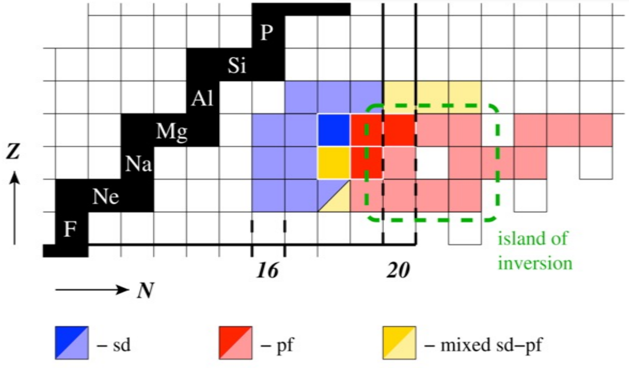




T.Otsuka and D. Abe Prog. In Particle and Nuclear Physics **59** 425 (2007)

N=20 Island of inversion

J. Phys G. 44 (2017)

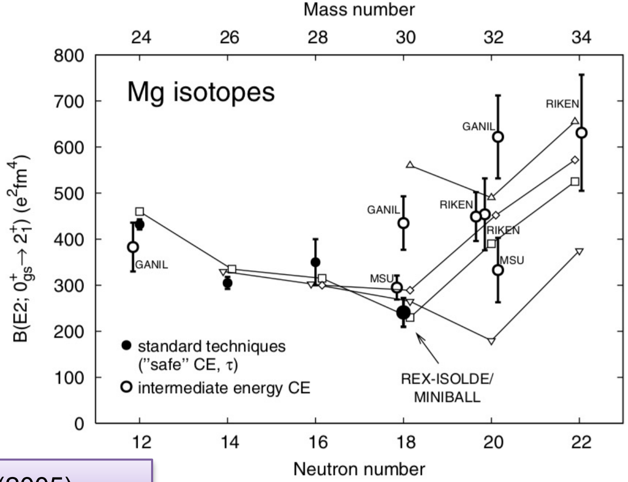


First observed in anomalous ground-state binding energies.

*Deformed configurations in low-lying and ground states due to ph excitations across N=20 – evidenced by **unnatural-parity configuration** in low-lying and ground states.*

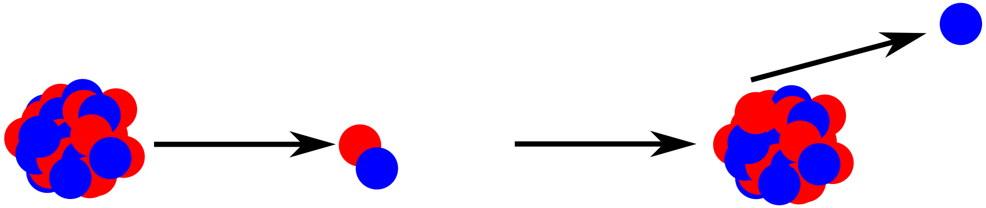
*Island of inversion has been charaterized using numerous probes (mass measurements, beta-decay, **coulex**, multi-nucleon transfer, pair-transfer, knock-out).*
Details on SP properties are perhaps lacking. (knock-out)

*Measurements of the **single-particle properties** moving in to the island of inversion provide important data on the behaviour of the relevant orbitals and shell gaps.*



PRL, **94** 172501 (2005)

Probing single-particle structure around island of inversion – transfer reactions



Single-nucleon transfer probes single-particle properties of nuclei.

- *Ejectile energy - > Excitation of residual nucleus.*
- *Yield -> cross section.*
- *Angular distributions -> ℓ.*

***Spectroscopic factor**: Measure of the overlap between the final and initial state.*

$$SF = \left| \left\langle \Phi^{M_B}_{J_B} \middle| \mathcal{A}\left[\Phi_{J_A}\phi_j\right]^{M_B}_{J_B} \right\rangle \right|^2$$

$$SF = \frac{\sigma_{EXP}}{\sigma_{IPM}}$$

$$\varepsilon_j = \frac{\sum E_j S_j}{\sum S_j}$$

*Single-particle structure **towards IOI***
^{29}Mg outside ^{31}Mg inside.

*Single-particle structure **along N=16**.*
***^{29}Al(d,p)^{30}Al (HELIOS)**,*
^{28}Mg(d,p)^{29}Mg (ISS)
***^{27}Na(d,p)^{28}Na** – ISS later this year*

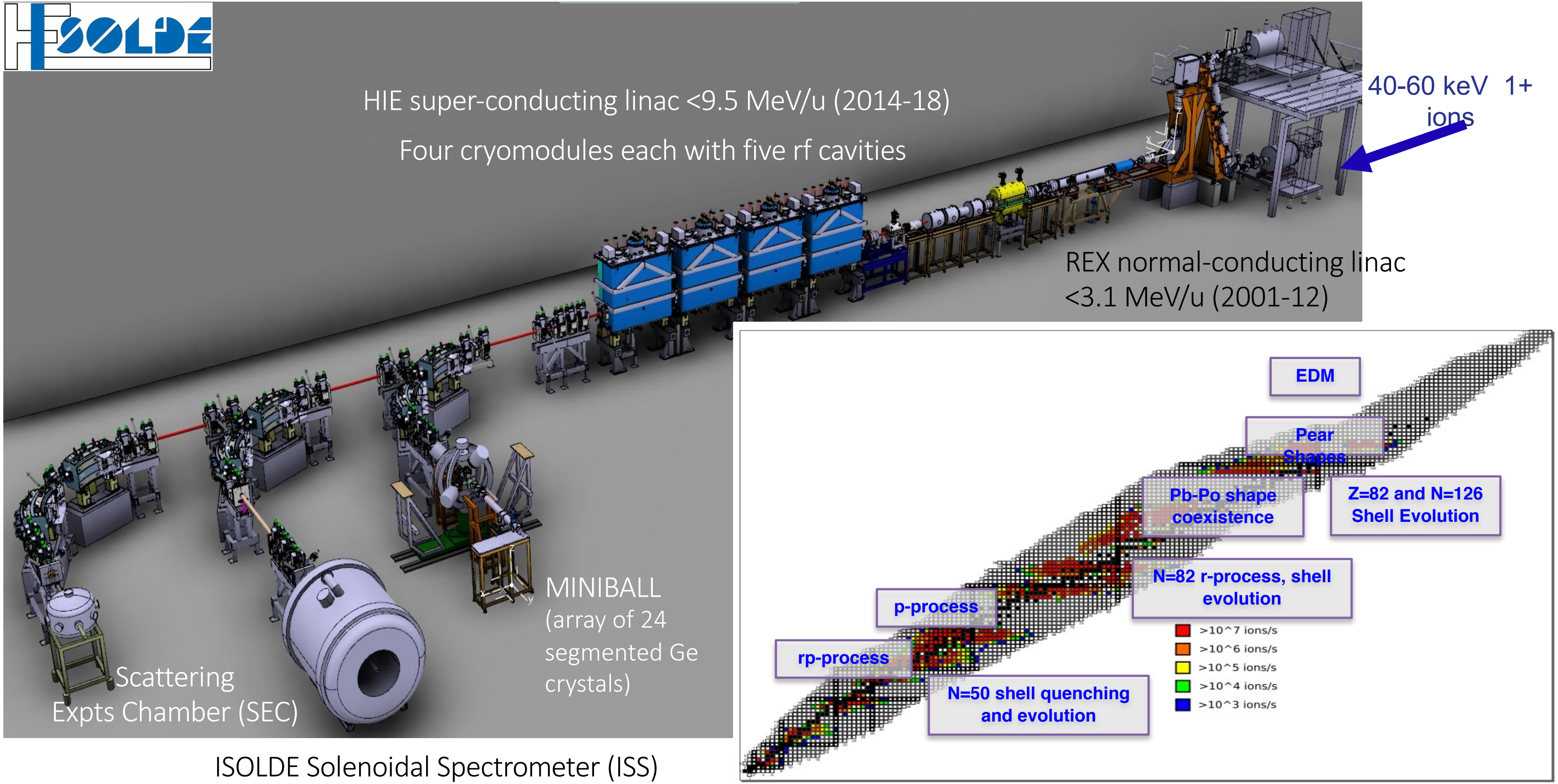
*Role of **np interactions***

*Role **of weak-binding** – possible to probe $p_{3/2}$ and $p_{1/2}$ strength.*

*Benchmark new **SM calculations**.*

Physics at HIE-ISOLDE with a solenoid

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



HIE super-conducting linac <9.5 MeV/u (2014-18)

Four cryomodules each with five rf cavities

40-60 keV 1+ ions

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

MINIBALL (array of 24 segmented Ge crystals)

Scattering Expts Chamber (SEC)

ISOLDE Solenoidal Spectrometer (ISS)

^{28}Mg(d,p)^{29}Mg with ISS

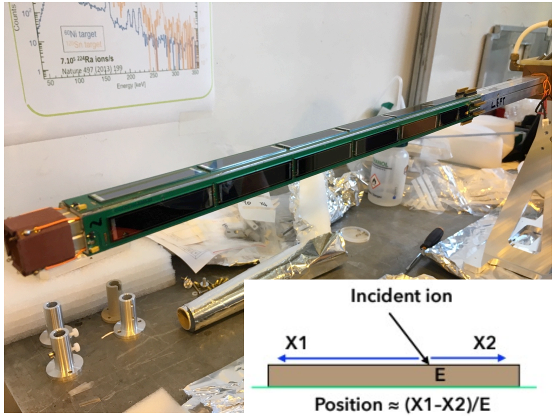
10^6 pps 9.47 MeV/u (dE/E = 0.3%) beam of ^{28}Mg – **highest HIE-ISOLDE RIB beam energy per nucleon**.

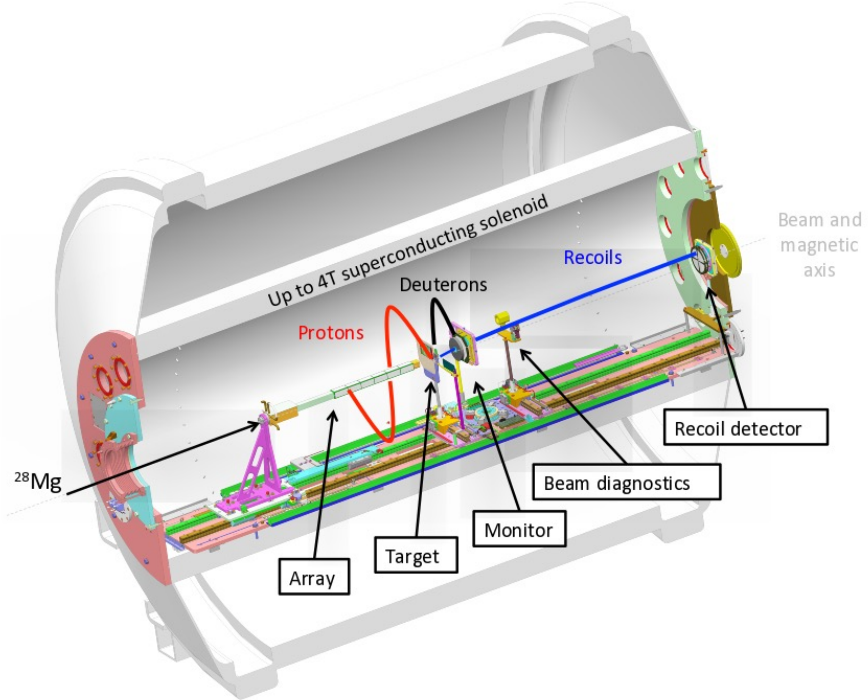
ISS set at a field of ***2.5T*** *– 2 target-array positions used to cover* $10^{o}<\theta_{cm}<40^{o}$ *for states up to ~ 4MeV.*

Quadrant silicon recoil detector at rear of magnet.

Annular silicon detector for luminosity monitor.

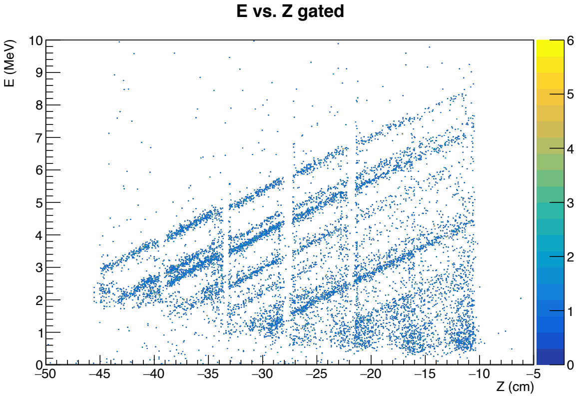
Beam diagnostics including ISOLDE FC and a zero-degree dE-E.

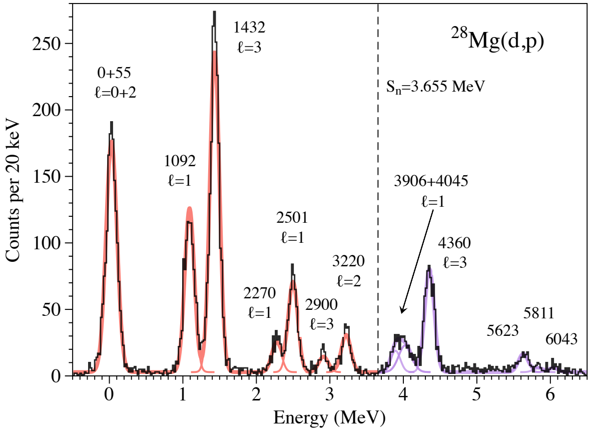


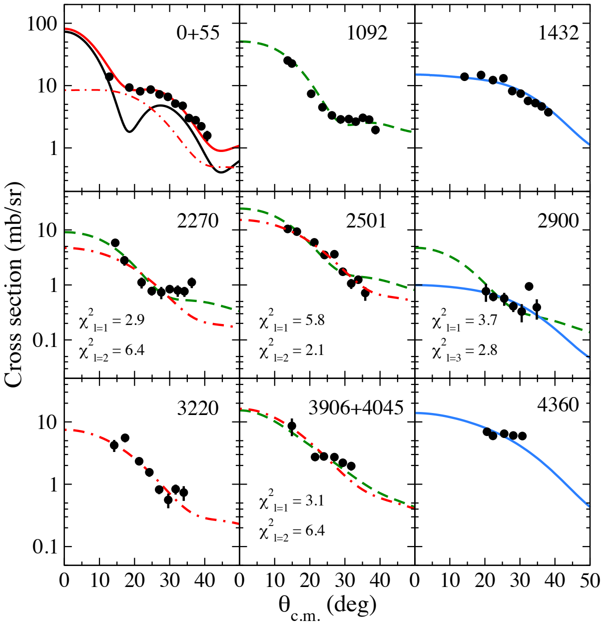


P.T.MacGregor *et. al.*, PRC **104**, L051301 (2021).

^{28}Mg(d,p)^{29}Mg - Results







Comprehensive study of states in ^{29}Mg including fragmentation.

Resolution ~140 keV.

States above S_n which contain significant fragments of SP strength.

Angular distributions extracted for 9 peaks (inc. 2 doublets) up to 4.35 MeV.

Majority of SP strength accounted for – two fragments.

FSU – R. Lubna *priv. comm.* **SDPF-MU** – Y. Utsuno *priv. comm.* ***EEdf1*** *– Taken from* A. Matta *et. al.*, PRC **99**, 044320 (2019).

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

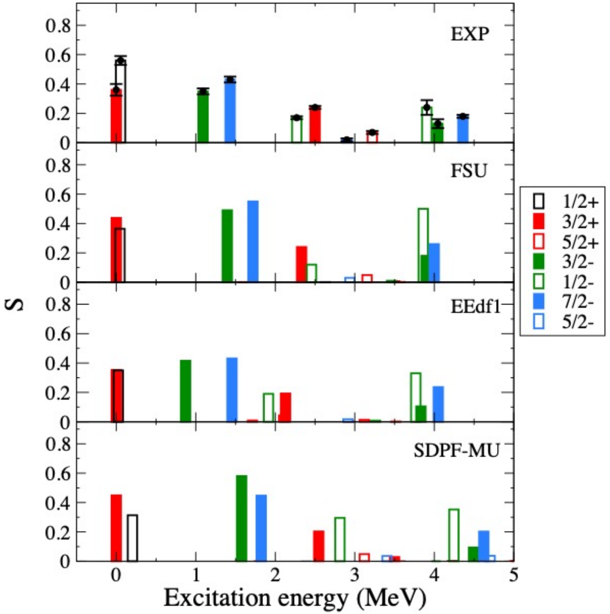
Trends in N=17 isotones

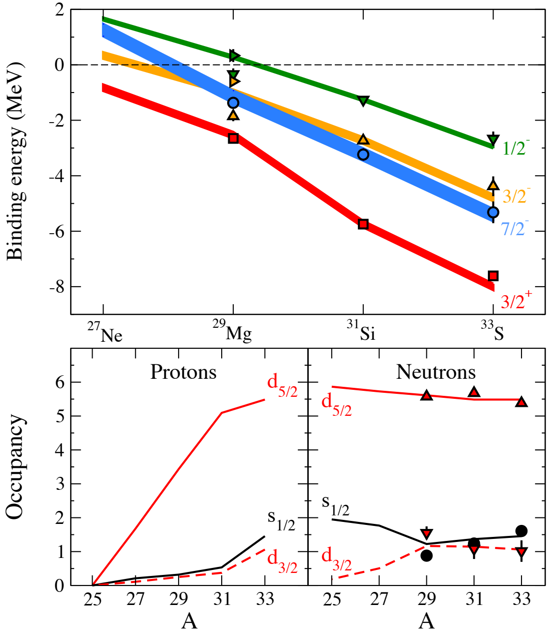
Strength distribution compares well to calculations – only 0p-0h or 1p-1h needed.

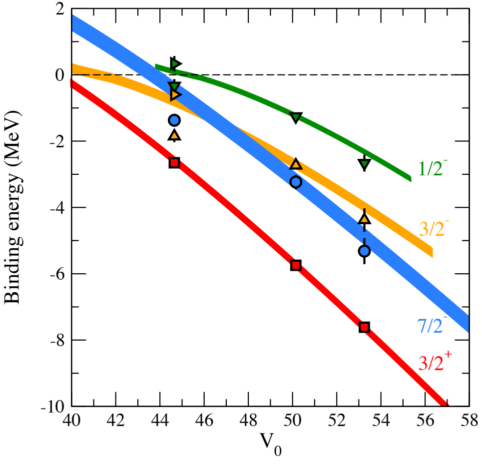
ESPE's are well reproduced by SM calculations. Qualitatively and quantitatively (calculations are only shifted by ~500 keV on to the data).

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.







^{30}Mg(d,p)^{31}Mg

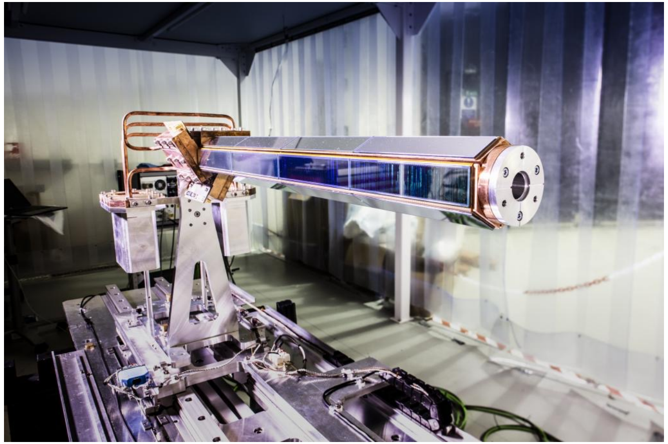
New silicon array

Six-sided array consisting of four DSSSDs with ASICs readout on each side.

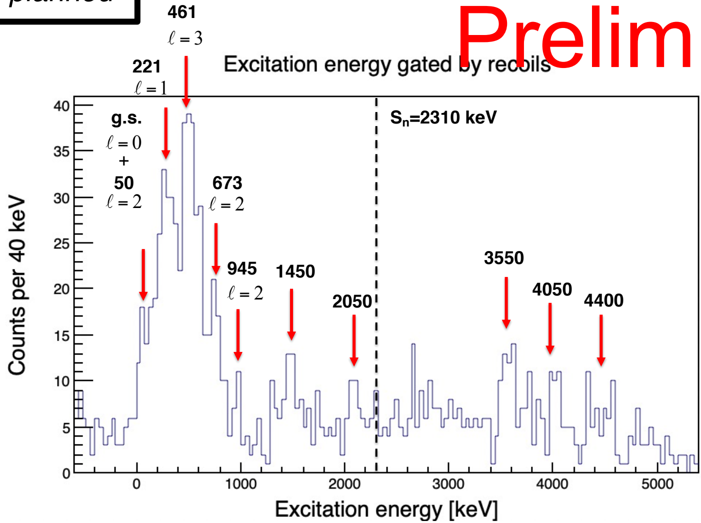
*Each detector consists of **128 x 0.95mm strips** along the length of the detector **11 x 2mm** along the width. **1668** channels of readout. Total length of silicon is 510.4mm (486.4mm active).*

10^4 pps 8.2 MeV/u ^{30}Mg

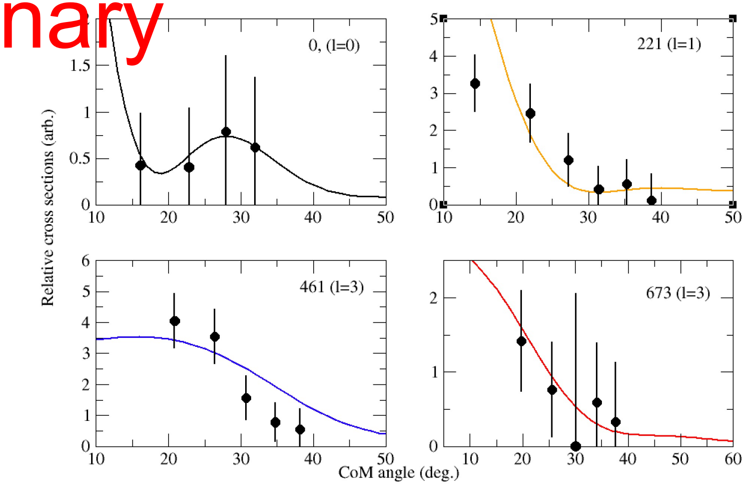
factor of 5 lower than planned



Preliminary



200ug/cm^2
CD2 target
180 keV
resolution

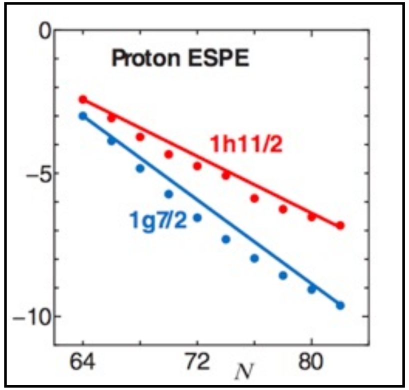


Evolution of single-particle structure outside closed shells

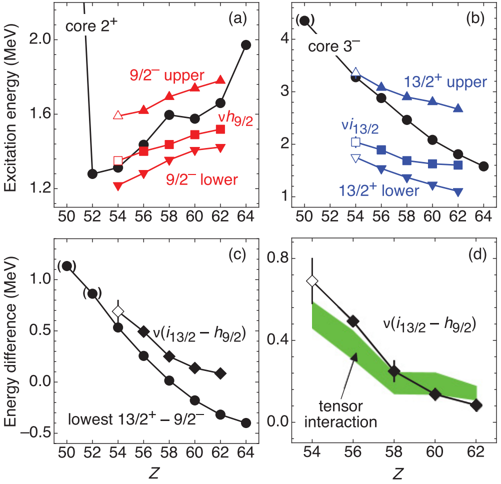
Trends observed in light nuclei have even been observed in stable heavier nuclei - Changes in high-j states as high-j orbitals are filling.

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).

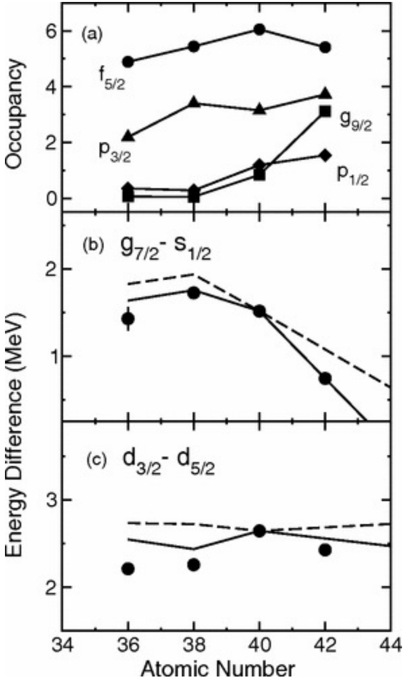
Access to RIBs at HIE-ISOLDE will allow access to measurements across large chains of isotopes/isotones probing the interactions further from stability and in new regions such as N=127.



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



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



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

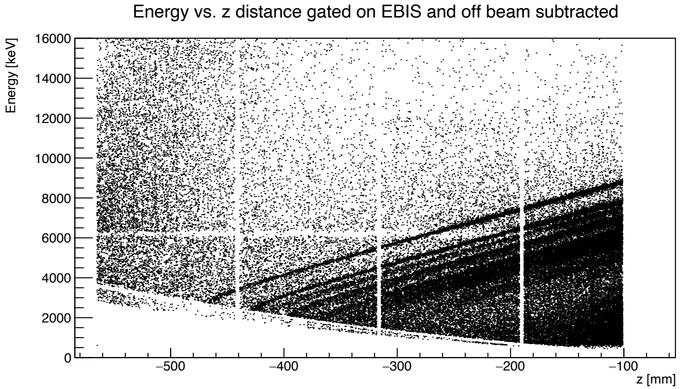
Probing single-particle structure along N=127 north of ^{208}Pb

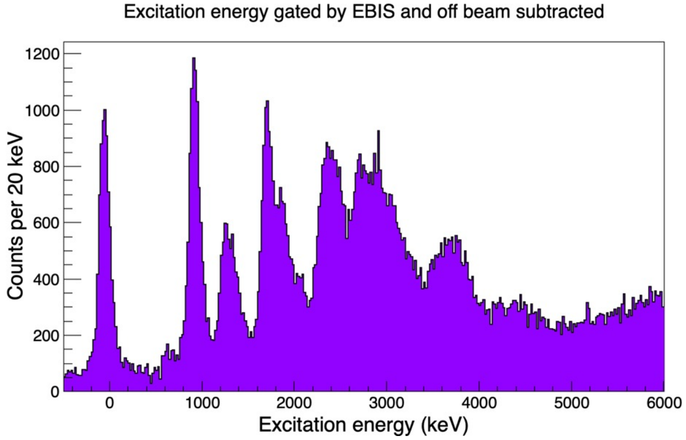
*~**5x10^6 pps** of ^{212}Rn, **7.63 MeV/u** .*

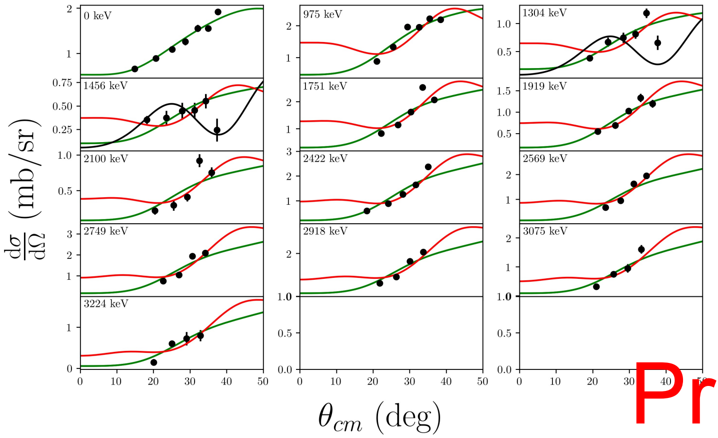
Best case resolution ~100 keV.

Background from alpha decay of beam and fusion-evaporation.

24 states identified up to 5 MeV – predominantly l=2 and 4 strength.


Energy vs. z distance gated on EBIS and off beam subtracted


Excitation energy gated by EBIS and off beam subtracted

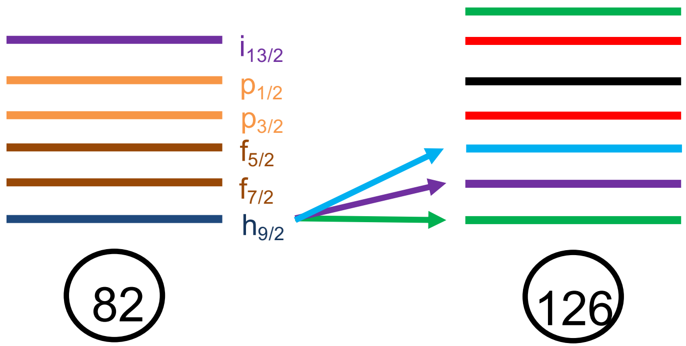


Preliminary

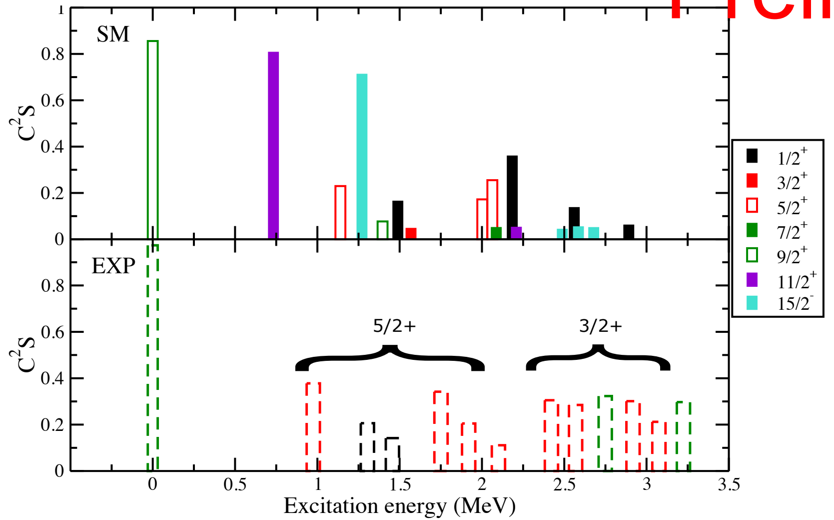
Probing single-particle structure along N=127 north of ^{208}Pb

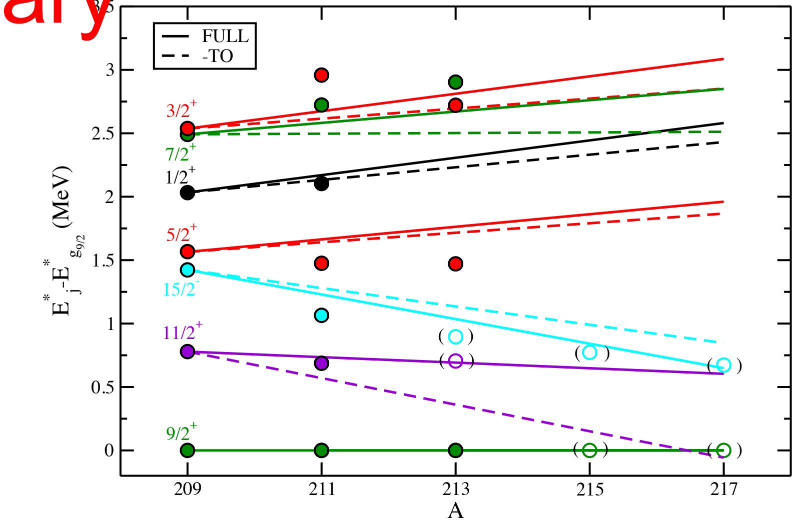
Preliminary analysis have identified majority of 3/2+, 5/2+, 7/2+, 9/2+ strength – though work on improving fitting is underway..

Can compare to monopole shift calculation (HKT interaction) – requirement for tensor interaction. Some deviations in agreement but preliminary



Preliminary





Conclusions – Part II

Resolving power of ISS, and excellent beam provided by HIE-ISOLDE, provided a comprehensive study of single-particle states in ^{29}Mg (just outside island of inversion).

New effective interactions describe the data well with no evidence of higher-order p-h excitations, as expected for a system outside the island of inversion.

Comparison of data to simple models highlights the potential role of weak-binding in influencing the evolution of structure in this region.

New data of SP states in island of inversion would provide more stringent tests on SM interactions, and further data on odd-Z nuclei will provide a systematic picture of SP structure along N=17.

Single-particle states probed for the first time in exotic N=127 nuclei, north of 208Pb.

Data north of 208Pb, combined with existing data, starts to provide a systematic picture of single-neutron states outside N=126.

Benchmark SM calculations – large model space.

Monopole shifts – np interaction, protons are filling $h_{9/2}$.

ISS collaboration

MANCHESTER 1824
The University of Manchester

Argonne
NATIONAL LABORATORY

ISS
ISOLDE Solenoidal Spectrometer

UNIVERSITY OF LIVERPOOL

ISOLDE

KU LEUVEN

UNIVERSITY OF SURREY

UNIVERSITY OF THE WEST of SCOTLAND
UWS

UNIVERSITY OF CONNECTICUT 1881

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Universidad de Huelva

THE UNIVERSITY of EDINBURGH

LSU
LOUISIANA STATE UNIVERSITY

TECHNISCHE UNIVERSITÄT DARMSTADT

lpc caen

IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

UNIVERSITÀ DEGLI STUDI DI PADOVA

UNIVERSITY of York

Science & Technology Facilities Council

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

UiO : University of Oslo

Current/future upgrades to ISS

KU LEUVEN

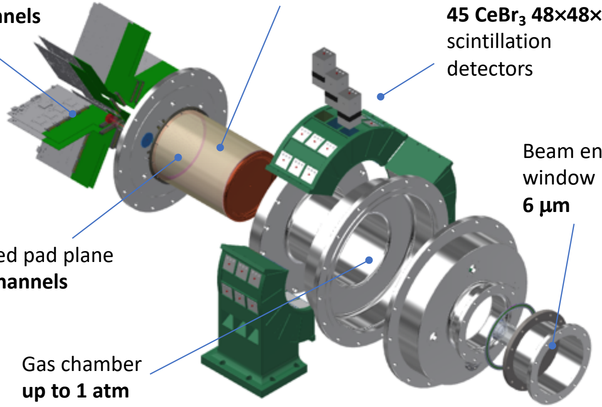
SpecMat – R. Raabe

Time-projection chamber with gamma-ray detection.

Helium or hydrogen species as gas.

CeBr$_3$ detectors have been characterized.

Commissioning at ISS 2020.



Readout electronics
100MS/s 12bit
3072 channels

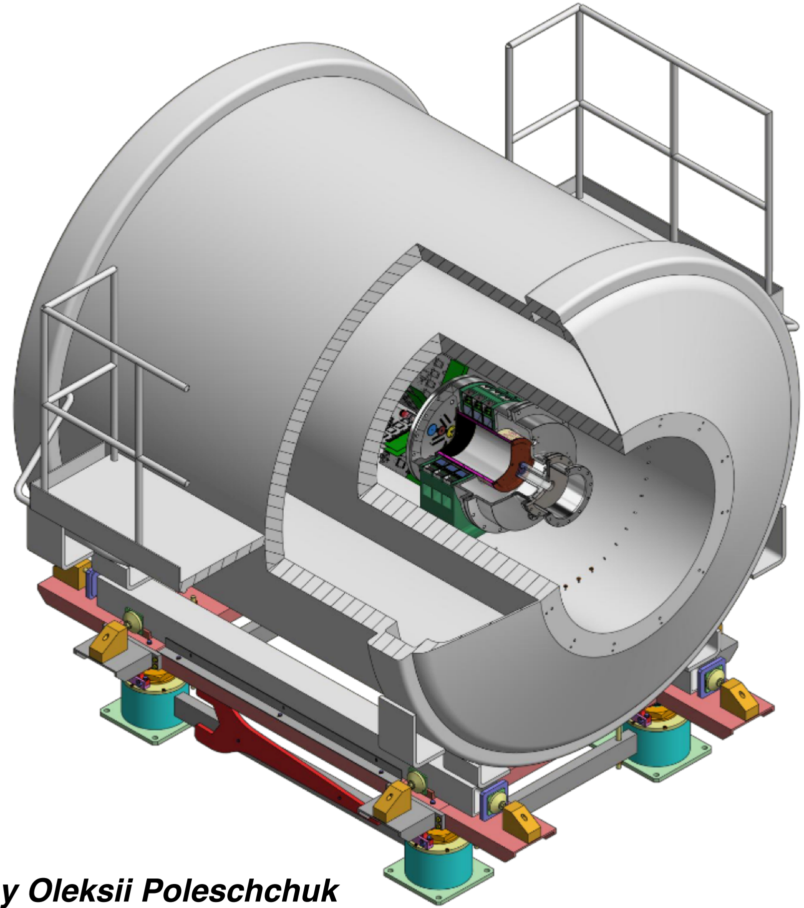
Field cage
up to 30kV

45 CeBr$_3$ 48×48×48mm
scintillation
detectors

Beam entrance
window
6 µm

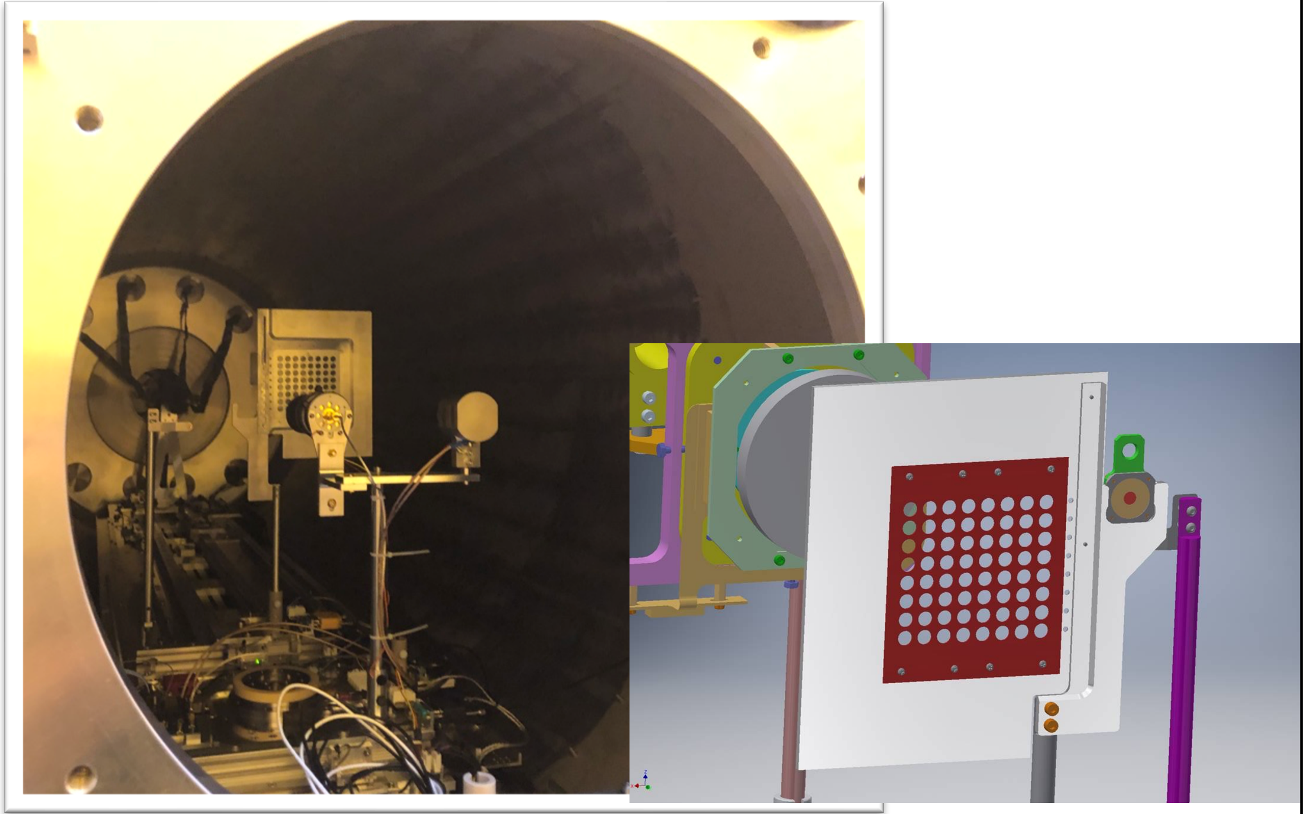
Pixelated pad plane
3072 channels

Gas chamber
up to 1 atm



Figures made by Oleksii Poleschchuk

^{212}Rn(d,p)^{213}Rn – SP structure outside N=126

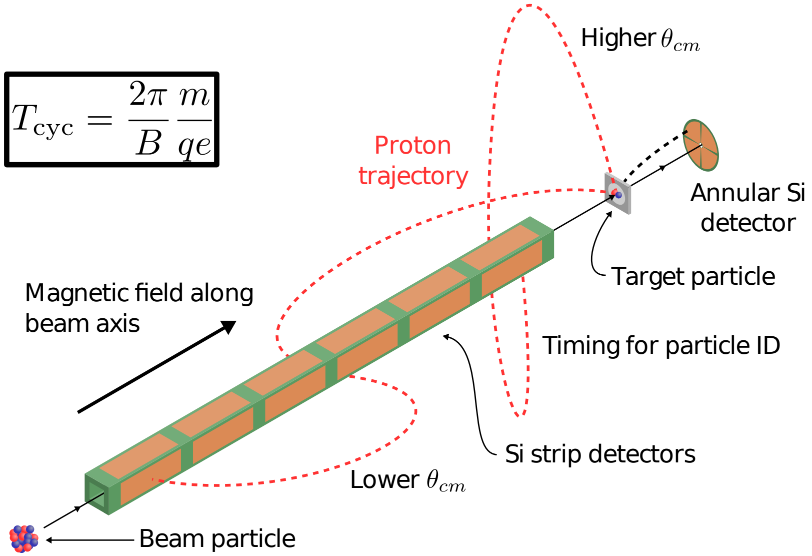


Experimental info:

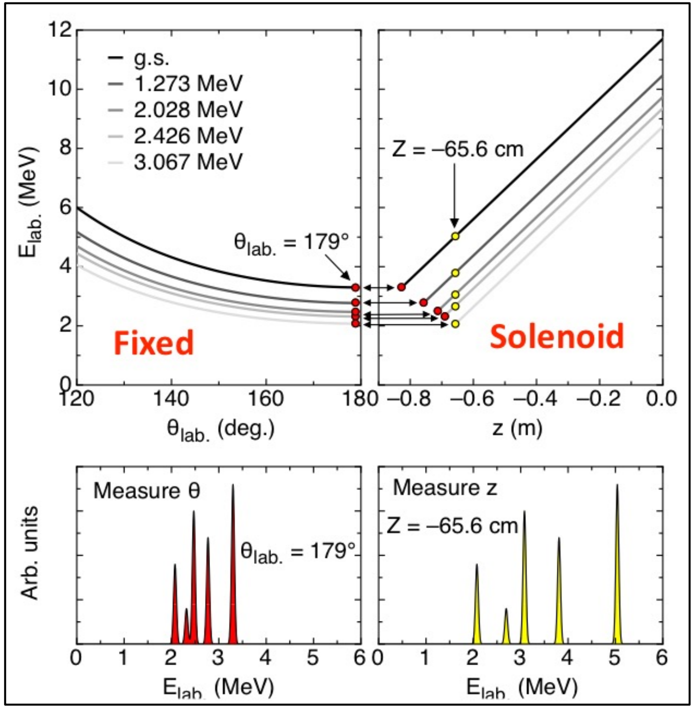
- *~**5x10^{6} pps** of ^{212}Rn.*
- *Produced using cold transfer line from the target – contaminants condense out of beam*
- *A **7.63 MeV/u – highest total HIE-ISOLDE beam >1.6 GeV***
- *Measured in singles mode*
- *Beam purity **>99%**.*
- *Using **>20 deuterated polyethylene targets** of ~125μg/cm2*
- *ISS set to B-field of 2.5 T*

Direct reactions with a solenoid

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



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



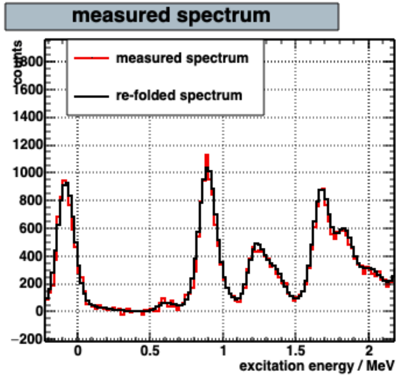
MEASURED QUANTITIES: position z, cyclotron period T_{cyc} and lab particle energy E_{p}.

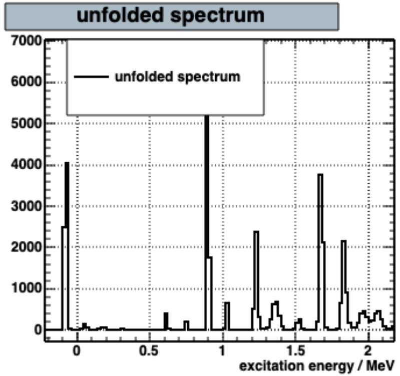
Suffers no kinematic compression of the Q-value spectrum.

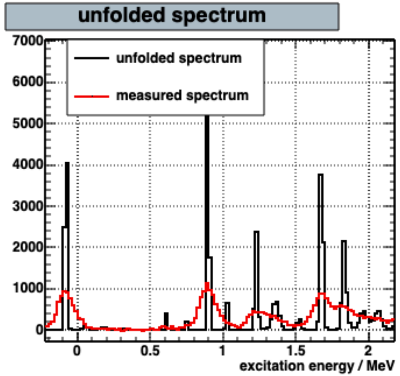
Linear relationship between E_{cm} and E_{lab}.

Identifying states

iterative deconvolution







re-convolution with response matches measured spectrum (verifies solution is correct, assuming the response matrix is correct)

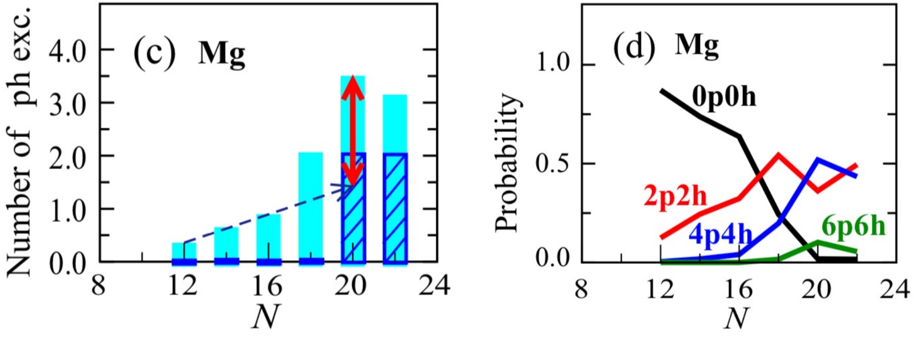
New shell-model interactions

Shell-model calculations can have 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)

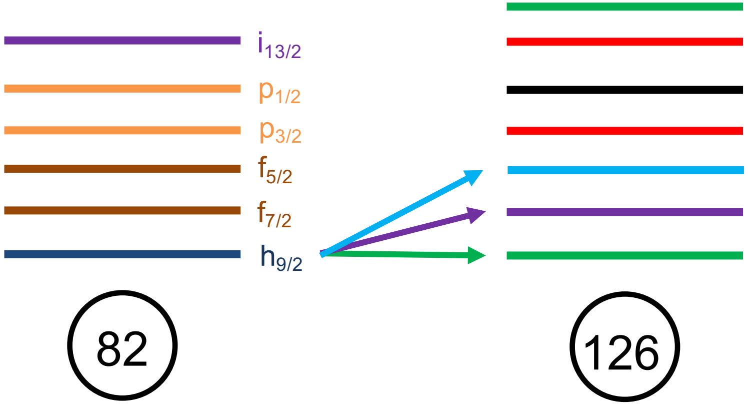
Single-particle evolution along N=126

ISOLDE Solenoidal Spectrometer

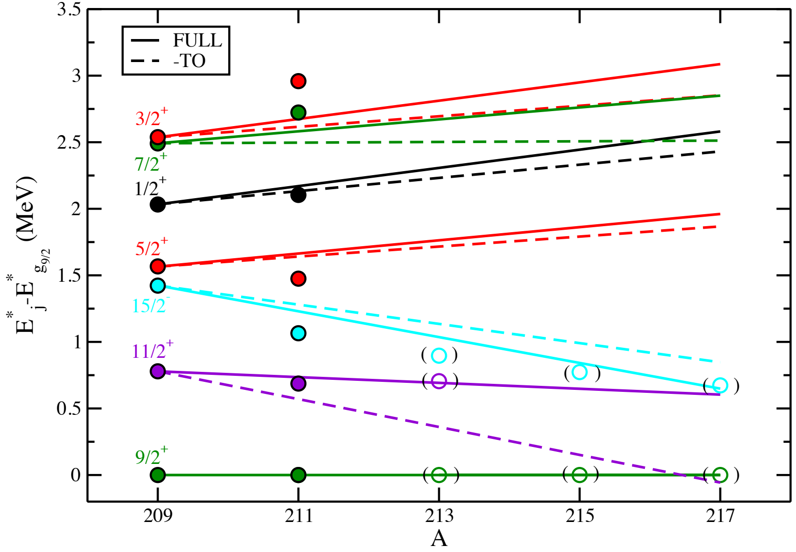
Data on SP strength distribution and centroids from ^{212}Rn(d,p)^{213}Rn reaction allows evolution of these (related to ESPE's) to be mapped out along N=127.

Protons are filling $h_{9/2}$ (from Pb to U). Changes in SP centroids related to NN interaction between protons and single neutron – monopole shifts.

Reveal details on strength of interactions and importance of different components.



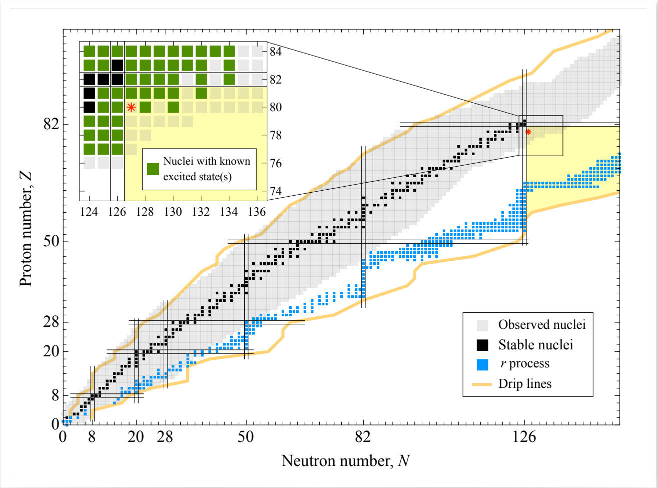
Shifts calculated using TBME's computed using HKT interaction.

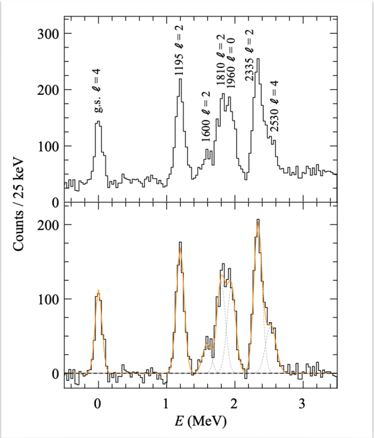


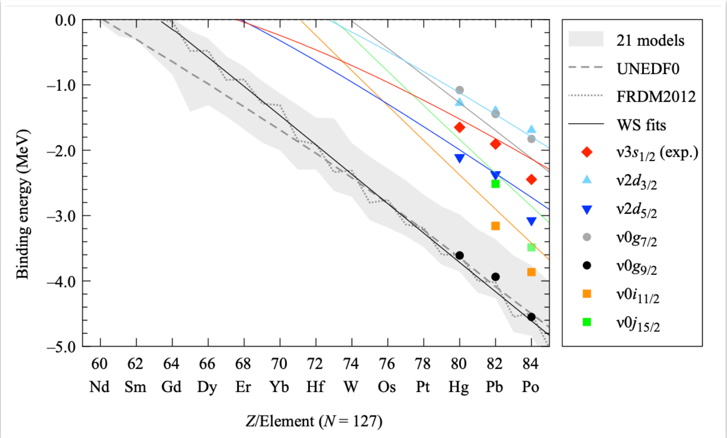
Slide courtesy of B Kay

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).