The University of Manchester

MANCHESTER 1824

ISOLDE Solenoidal Spectrometer

Single-proton properties around the N=20 island of inversion

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Requested shifts: 27 shifts
Beams: ^{28}Mg and ^{30}Mg at 10 MeV/u
Target: Tritiated titanium
Installation: ISOLDE Solenoidal Spectrometer

INTC meeting, February 8th 2023

Changing nuclear structure in light neutron-rich nuclei

Monopole shifts

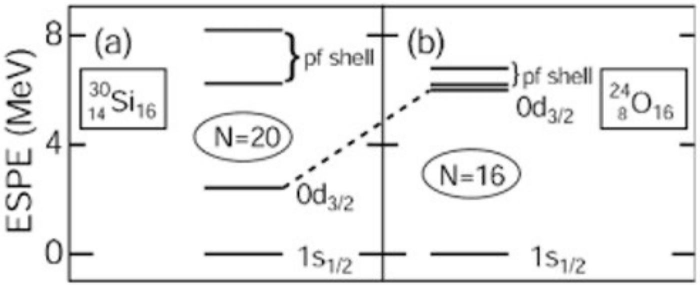
ISOLDE Solenoidal Spectrometer

In the oxygen isotopes, the N=20 shell gap has been shown to disappear with ***the emergence of an N=16*** *shell gap in ^{24}O.*

*Along N=16, **$\pi d_{5/2}$** is emptying. Different overlaps with **$\nu d_{3/2}$**, **$\nu f_{7/2}$** and **$\nu p_{3/2}$** results in* ***different monopole shifts****.*

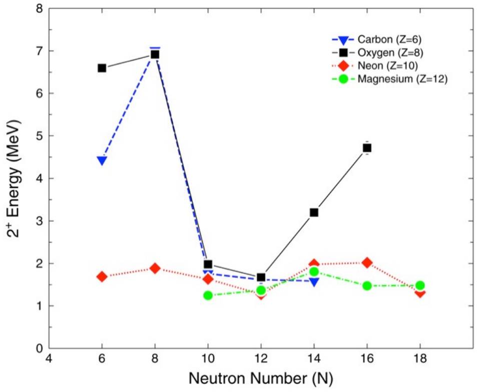
Changes in ESPE's and occupancies provide details on ***relative strengths of interactions****.*

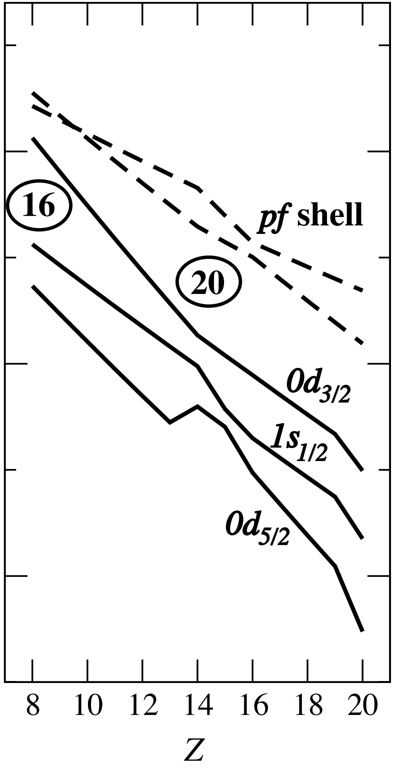
T. Otsuka *et. al.*, Eur. Phys. J. A 15, 151–155 (2002)



T. Otsuka *et. al.*, PRL 87, 082502 (2001

CR. Hoffman et al PLB **672** 17 (2009)





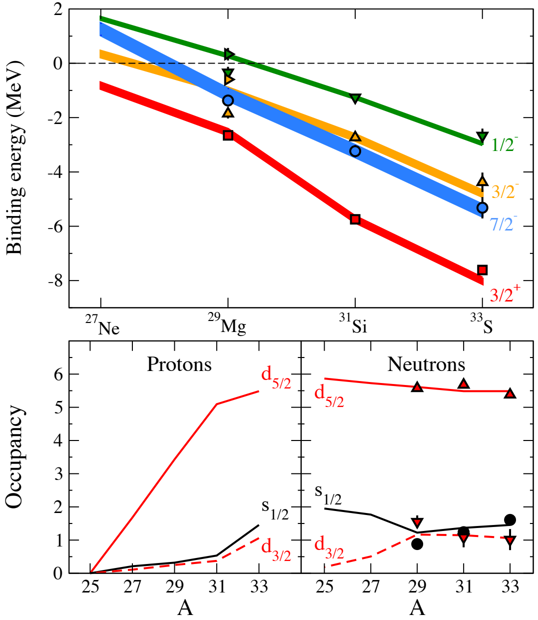
Changing nuclear structure in light neutron-rich nuclei

Monopole shifts

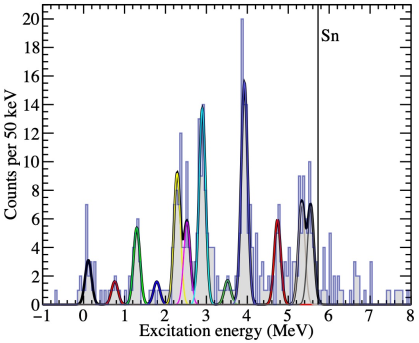
We have measured properties of neutron single-particle properties along N=17 in ^{29}Mg and ^{28}Na (ISS) and ^{30}Al (HELIOS).

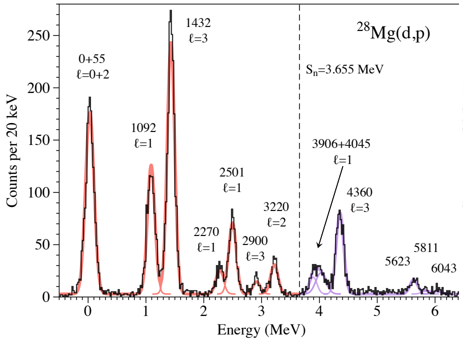
Systematic picture of neutron properties

Details on proton single-particle properties missing.

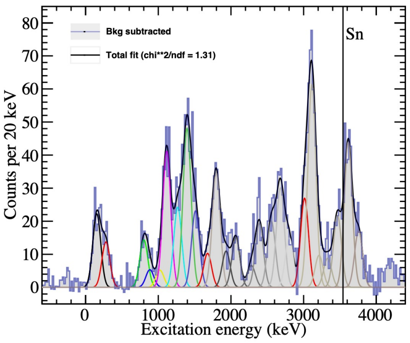


29Al(d,p)30Al





27Na(d,p)28Na



PT. MacGregor et al., PRC 104, L051301 (2021).

Changing nuclear structure in light neutron-rich nuclei

ISOLDE Solenoidal Spectrometer

Island of inversion

First observed in anomalous ground-state binding energies.

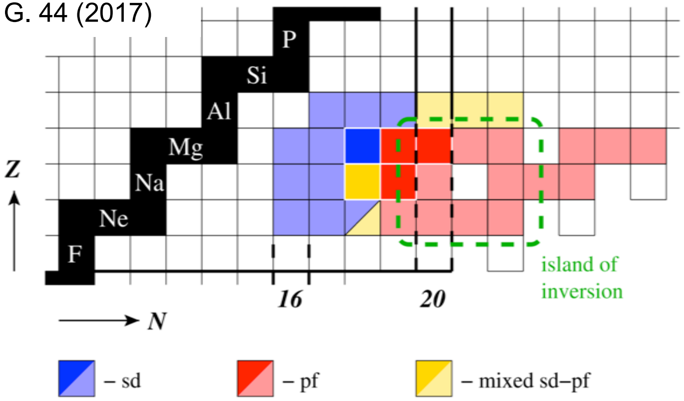
Deformed configurations in low-lying and ground states due to ph excitations – evidenced by unnatural-parity configuration in low-lying and ground states.

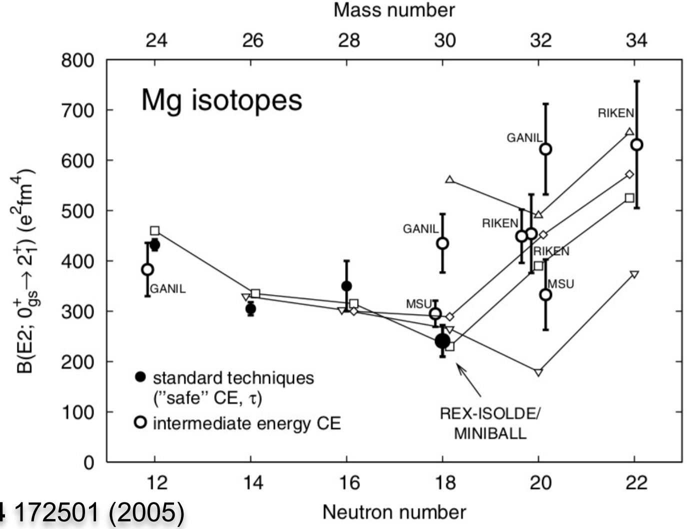
Mg isotopes exhibit rapid transition into this region. ^{30}Mg outside ^{31}Mg inside.

Island of inversion has been charaterized using numerous probes (mass measurements, beta-decay, ***coulex****, multi-nucleon transfer, pair-transfer, knock-out).*

Few probes of SP properties, and no consideration of protons.

J. Phys G. 44 (2017)





PRL, **94** 172501 (2005)

Changing nuclear structure in light neutron-rich nuclei

Island of inversion

We have recently made a measurement of the ^{30}Mg(d,p) reaction, populating neutron single-particle states inside the island of inversion.

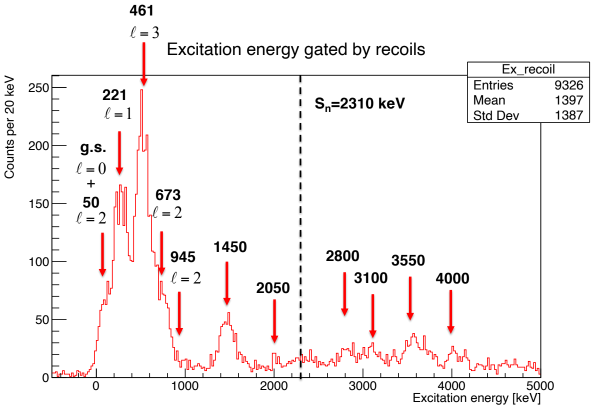
Provide us details of changes across boundary when combined with data on 28Mg(d,p).

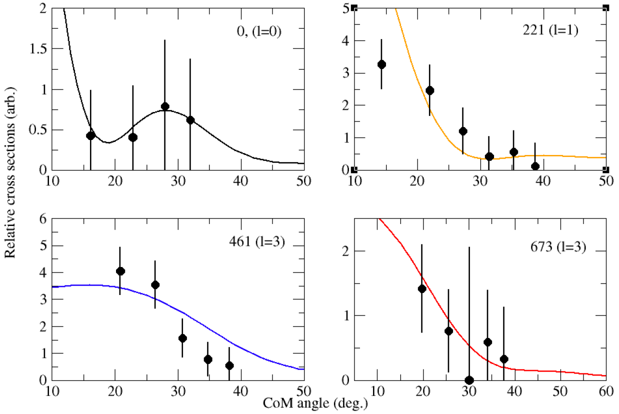
Opportunity to probe proton properties

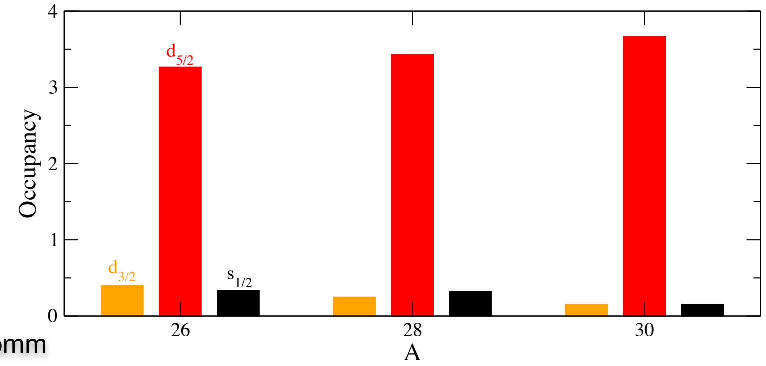
Effect of evolving deformation on protons – Type II SP evolution.

Test of SM calculations that have optimized including more details on cross shell interactions.

Not tested in island of inversion – here we probe around the border with ^{29}Na a transitional nucleus.







FSU interaction – R.Lubna, priv. comm

Proton removal reactions

Transfer reactions are ideal probe of SP properties.

Access **excitation energies** of states, **angular momentum** of state, **spectroscopic factor**.

Proton-removal probes occupancy.

Centroid of SP strength – related to effective SPE's.
Relative (absolute) **occupancies/vacancies** of relevant orbitals.

Strength distributions can be compared to calculations.

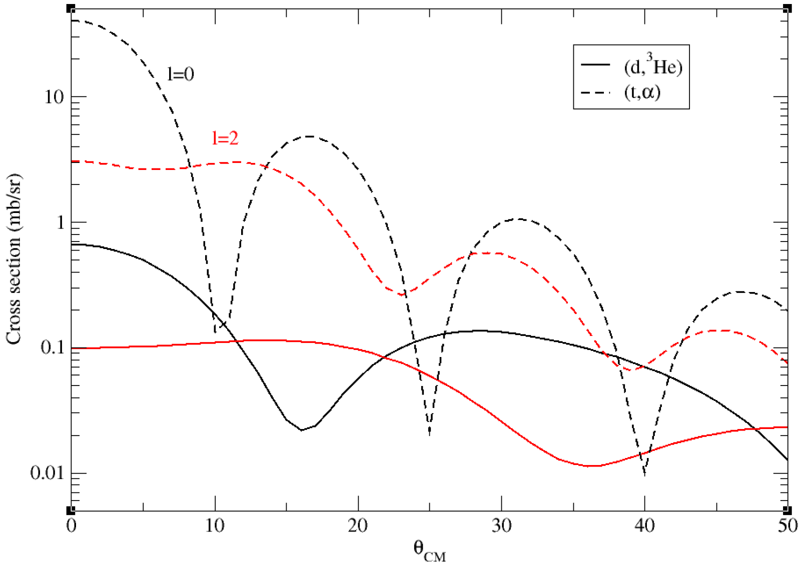
Would be preferable to measure the (d,3He) reaction
- stable target
- better resolution

However, energies to access reaction not available from HIE-ISOLDE

(t,a) reaction proceeds with cross sections that are an order of magnitude higher.

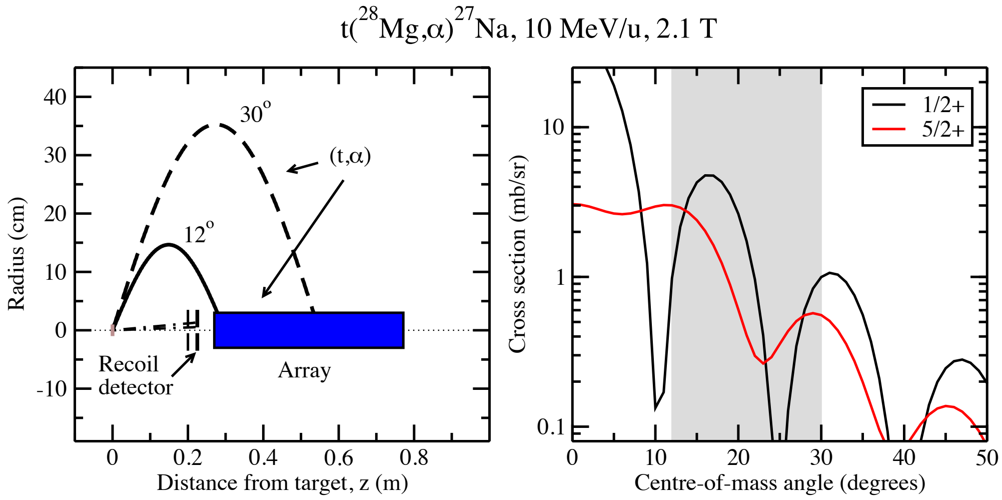
Relatively low Q value for this reaction means reaction is still well matched for low-l transfer.

($d,^3He$) versus (t,a)



ISOLDE Solenoidal Spectrometer set up

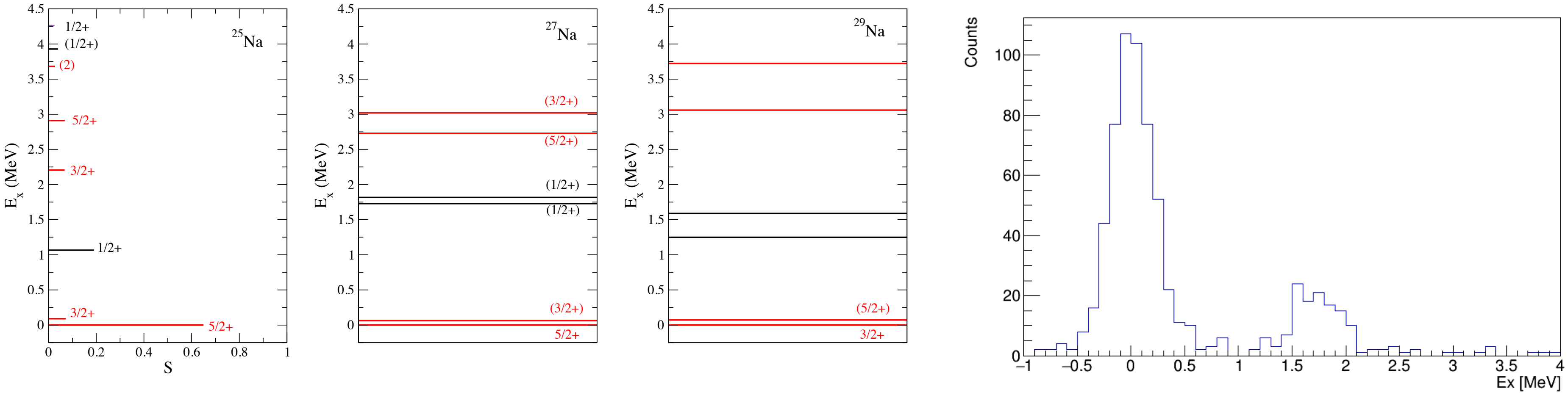
ISOLDE Solenoidal Spectrometer



- *2.1T field. Array-to-target +28cm.*
- *Silicon recoil detectors in front of array*
- *Elastic scattering incident on array for normalization*
- *Beam diagnostics – FC and zero-degree detector.*

- *Beam energy of 10 MeV/u.*
- *CoM angular coverage for protons 12-30 degrees.*
- *Expect <50% Al contamination – reaction of interest selected using recoil detectors.*
- *Instantaneous rate in recoil detectors <10kHz per sector*
- *95% ^{28}Mg if we use SiC.*

Simulations



- *^{27}Na and ^{29}Na have been studied through a combination of beta-decay, (d,n) and FE reactions.*
- *This data combined with systematics in stable Mg and SM calculations using FSU interaction has been used to simulate expected excitation energy.*
- *Majority of strength expected in a single peak.*
- *FWHM 450 keV.*

Proposed measurements

ISOLDE Solenoidal Spectrometer

Propose measurement of ^{28,30}Mg(t,a)^{27,29}Na reactions at <u>10.0 MeV/u</u> using the ISOLDE Solenoidal Spectrometer (ISS)

- *Proton-removal reactions ideal probes for accessing proton occupancies.*
- *Combined with existing data on neutron properties in these systems provides a complete picture of the behaviour of both protons and neutrons along N=16 and into the island of inversion from a SP perspective.*
- *Request a total of **9 shifts** for ^{28}Mg(t,a) and **18 shifts** for ^{30}Mg(t,a) at 10.0 MeV/u*
- *Assuming 5x10^{5}pps ^{28}Mg expect >100 counts a day in the whole array for states of interest. A rate of 1x10^{5}pps is assumed for ^{30}Mg which will give >20 counts per day. Extraction of SF with 15% statistical uncertainty.*
- *Beam rates are based on <u>measured rates</u> at ISS during IS621 (2018) of **1x10^{6}pps** ^{28}Mg and IS680 (2022) of **>2.5x10^{5}pps** ^{30}Mg with 2uA. Deduced from elastic scattering measurements.*
    - *^{28}Mg rate from SiC target (1uA). UCx preferred if we run both measurements together.*
    - *^{30}Mg also previously delivered at 1x10^{5}pps [*PHYSICAL REVIEW C **90**, 011302(R) (2014)].
    - Can except a further factor of 2 if there are concerns on reproducing these rates.

Total counts	s1/2 (S=0.16)	d3/2 (S=0.06)	d5/2 (S=0.57)
27Na	450	300	3750
29Na	300	120	1500

Summary

ISOLDE Solenoidal Spectrometer

First measurement of proton-removal reactions from neutron-rich Mg nuclei using (t,a) reaction.

Lots of emerging data on single-neutron behaviour.

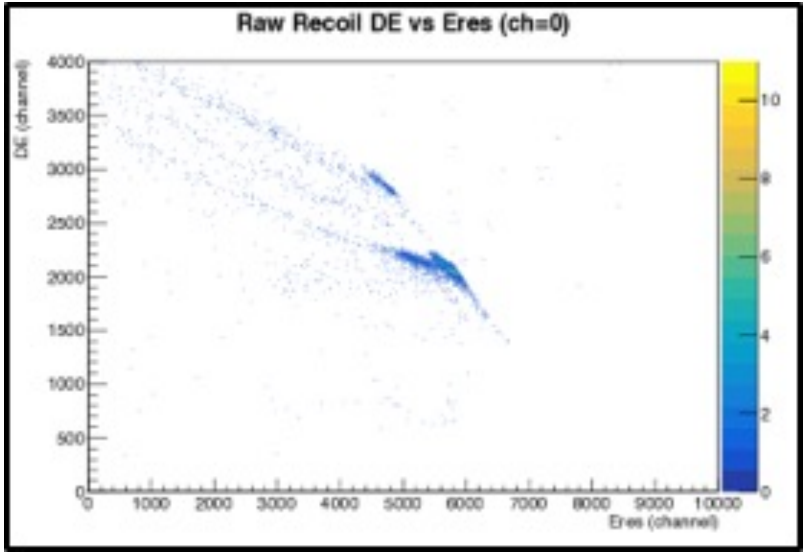
Proton removal or addition reactions are harder to access – lack of information.

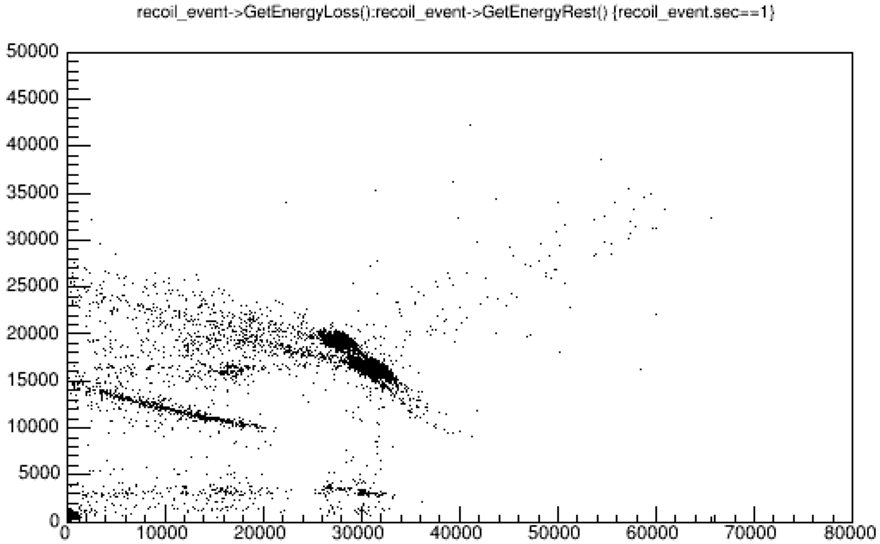
Fundamental in describing monopole shifts and testing SM calculations.

Opportunity with tritium targets to use (t,a) reaction to access this data with ISS.

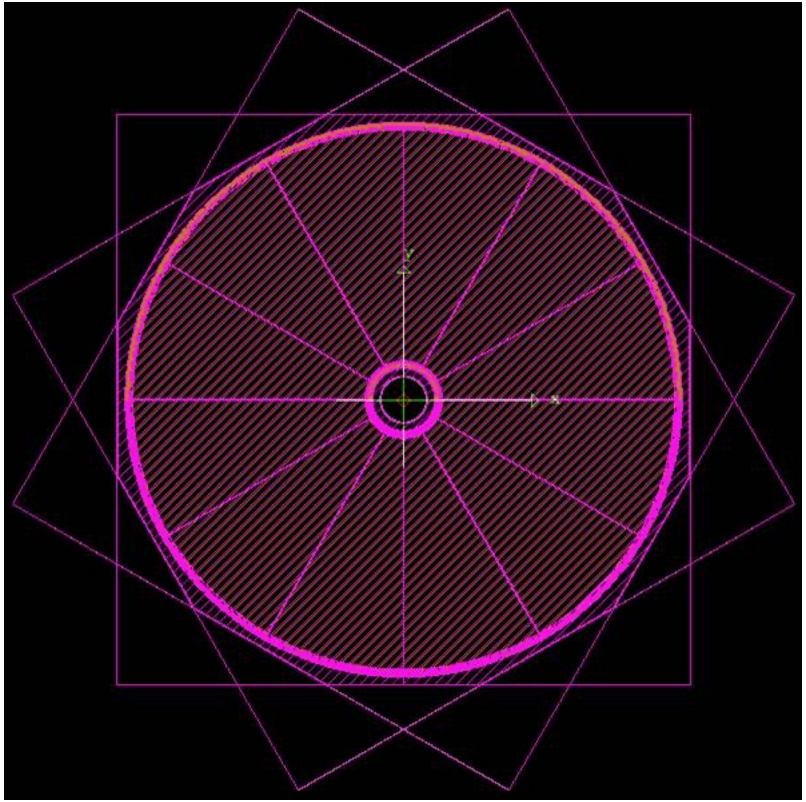
Probe changes in protons occupancy along N=16 and into the island of inversion.

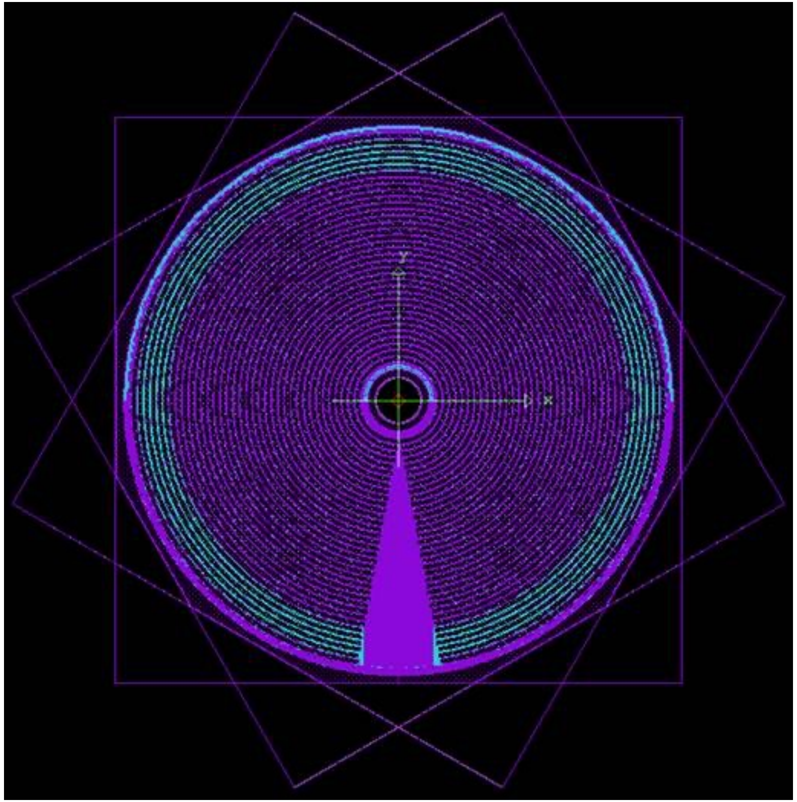
Recoils


Raw Recoil DE vs Eres (ch=0)
DE (channel)
Eres (channel)


recoil_event->GetEnergyLoss():recoil_event->GetEnergyRest() {recoil_event.sec==1}

Recoil detector





Changing nuclear structure in light neutron-rich nuclei

Weak binding/finite geometry

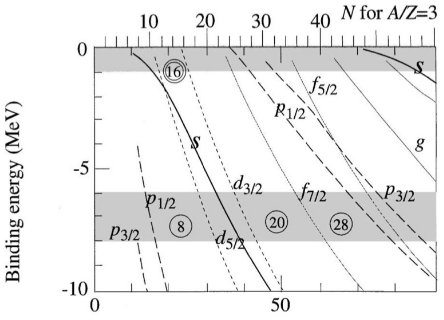
Near threshold low-ℓ orbits experience a smaller (or no) centrifugal barrier – more extended wavefunction – lowers energy.

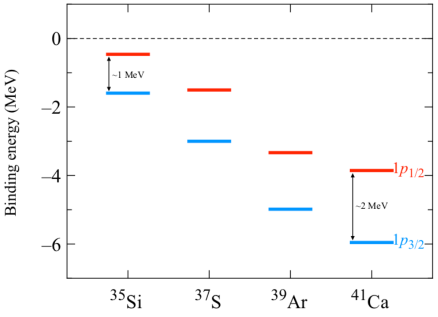
S-states linger – halo-formation

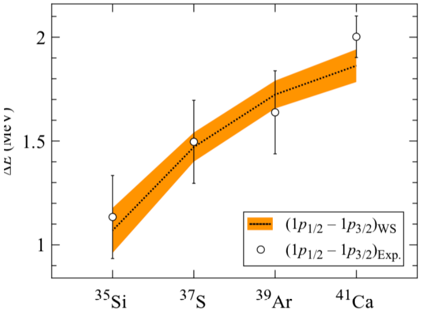
Also apparent in p-states - as $p_{1/2}$ approaches threshold before $p_{3/2}$ then reduction in splitting.

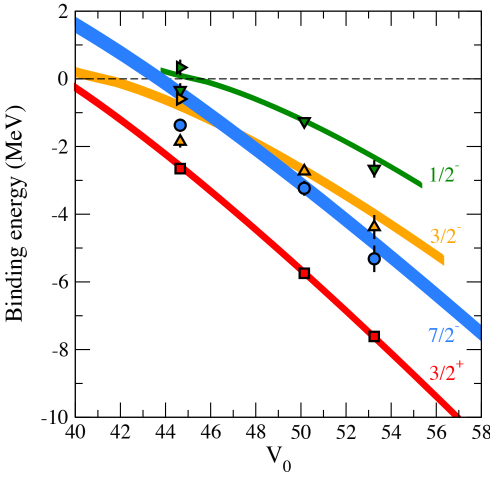
Another explanation for observed behaviour along N=17.

Details of changes in proton occupancy will help disentangle monopole shifts in SM calculations from weak-binding effect.









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

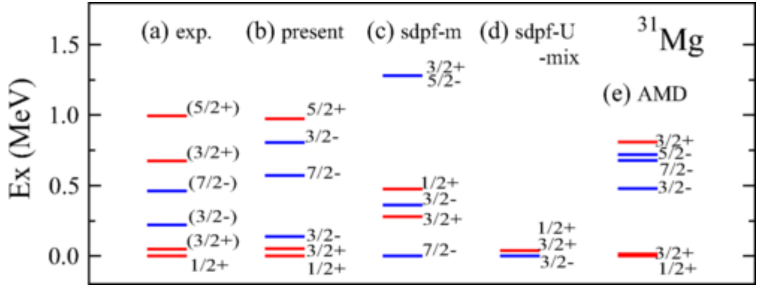
New shell-model interactions

Generally shell-model calculations have difficulties reproducing nature of negative-parity states inside the Island of Inversion (or even approaching it) – without ad-hoc changes.

Has stimulated the development of new interactions.

FSU-interaction – Fitting method including more TBMEs for pf shell.

EEfd1 – New interaction derived using Chiral-EFT and EKK method. Multiple ph excitations.



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