Experimental Results Towards ^{40}Mg at FRIB

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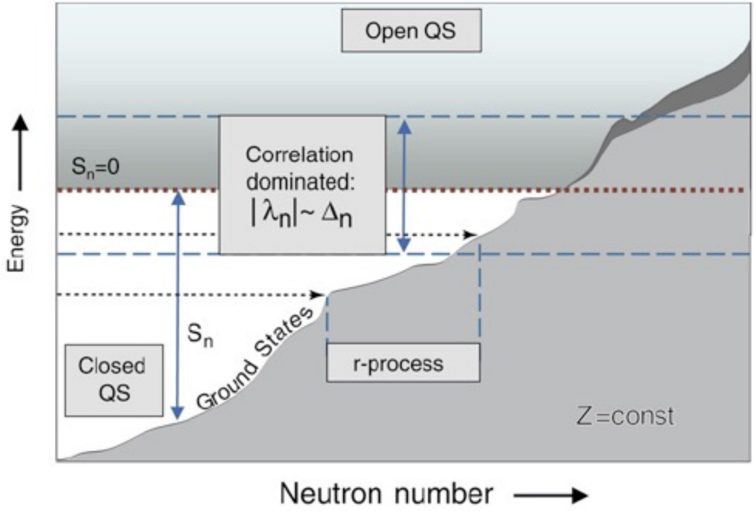
HaloWeek '24 – Nuclei at and beyond the driplines -- June 9-14, 2024 -- Chalmers University of Technology

Overview

- Weak binding in nuclei – one of our big open questions?
- Neutron-rich Mg Isotopes
  - The "Peninsula" of deformation along Z=12
  - Evolution of shape along the N=28 isotones
- Toward the dripline: ^{40}Mg
  - Current status
- Future prospects for the region of ^{40}Mg at FRIB
- First results from FRIB – β decay approaching ^{40}Mg

How is the nucleus affected by weak binding and neutron excess?

Explore properties of weakly bound nuclei and ask what happens in the transition from well-bound to weakly-bound “open” systems



Weak Binding

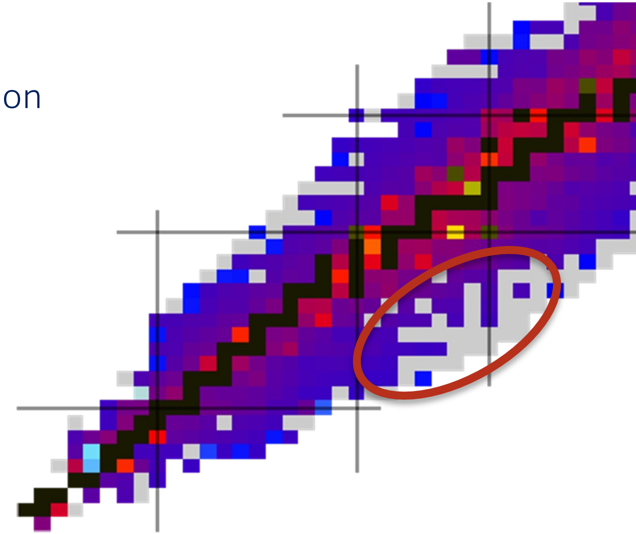
Extended wavefunctions; Neutron halo

Shell Evolution

T=0 (spin-isospin) interaction

Tensor force

T=1 pairing correlations



- Rates make studies all the way to ^{40}Mg possible – can fully explore the N=28 isotones, and to the dripline to Z~12

Energy Levels in a Woods Saxon Potential

⇒ In a well bound nucleus
- steady evolution of energy levels in a 1 body potential
- modified by 2-body NN interaction (monopole average - $\sigma.\tau$, tensor)

⇒ A second distinct effect is due to weakly bound levels
- low l levels (s, p) → extended wavefunctions (“halos”)
- valence nucleons can become decoupled from the core
- coupling to continuum states

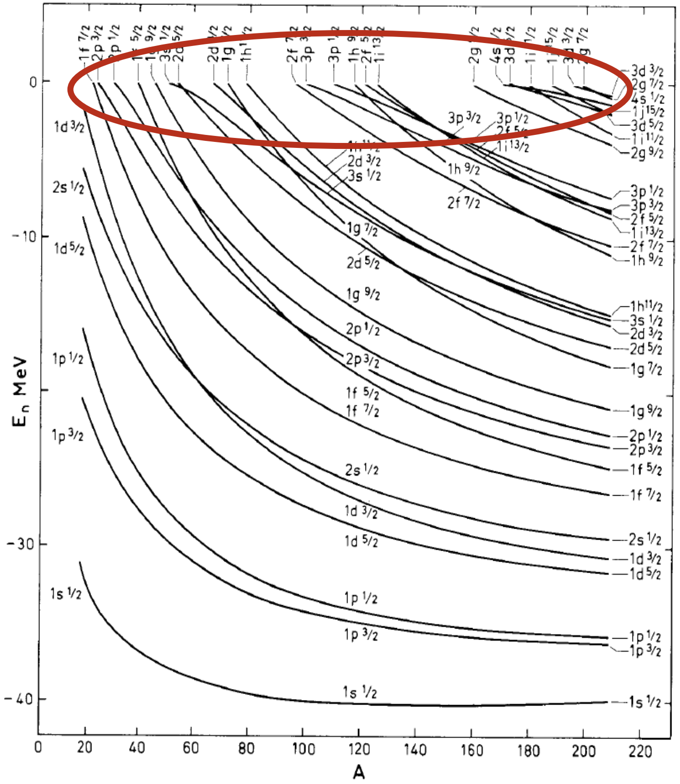
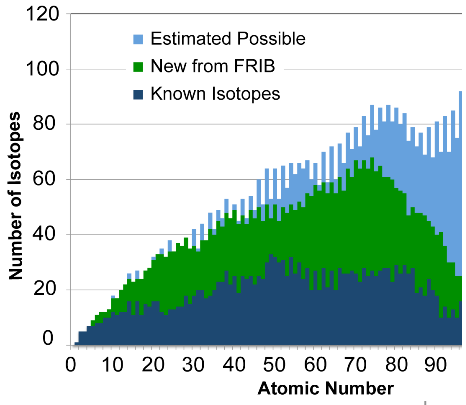
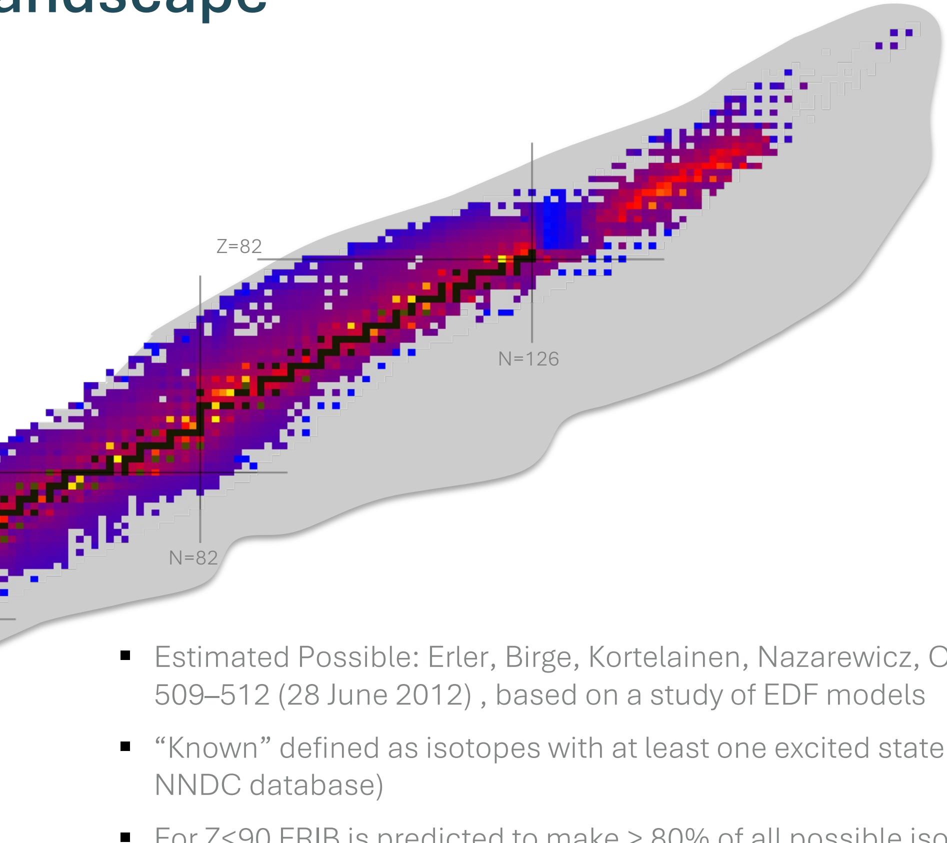


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

A.Bohr and B.R. Mottelson, vol. 1

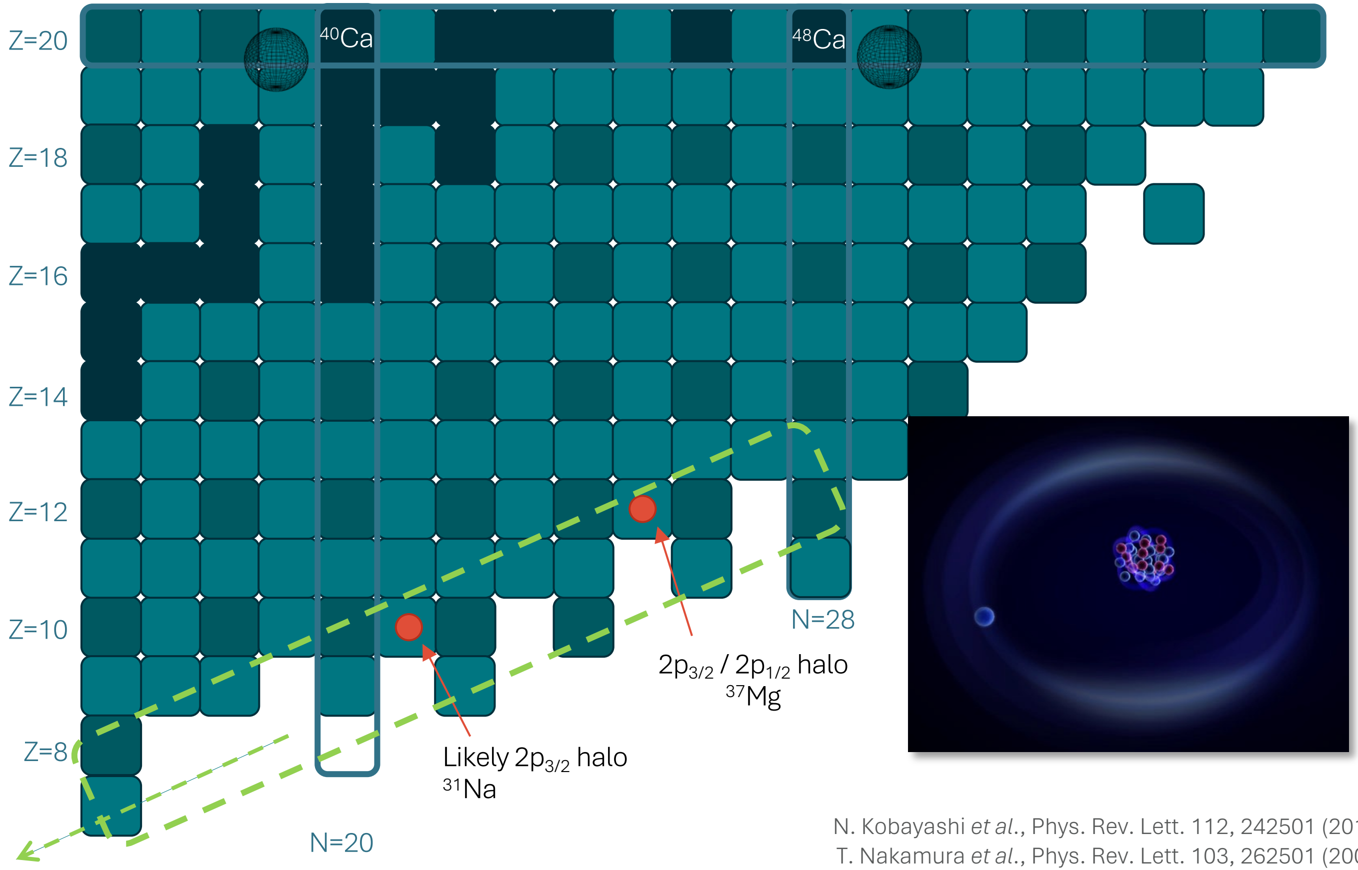
The Nuclear Landscape





- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models
- “Known” defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- For Z<90 FRIB is predicted to make > 80% of all possible isotopes
- The neutron driplines should be accessible up to *Z*=20; as far as *Z*=30-40 with FRIB400

Limits of Stability: Halo Nuclei



N. Kobayashi *et al.*, Phys. Rev. Lett. 112, 242501 (2014).
T. Nakamura *et al.*, Phys. Rev. Lett. 103, 262501 (2009).

Weak Binding Phenomena

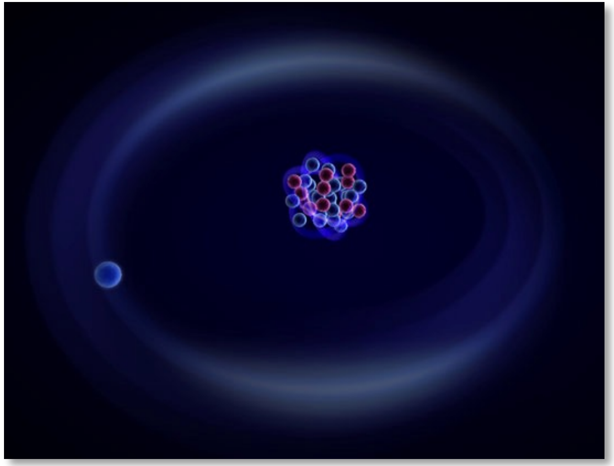
- Currently we know of examples of weak binding and delocalized wavefunctions giving rise to nuclear halos
- When we do have halo structures then what is the nature of the valence-core interaction?

Do the delocalized, weakly bound nucleons

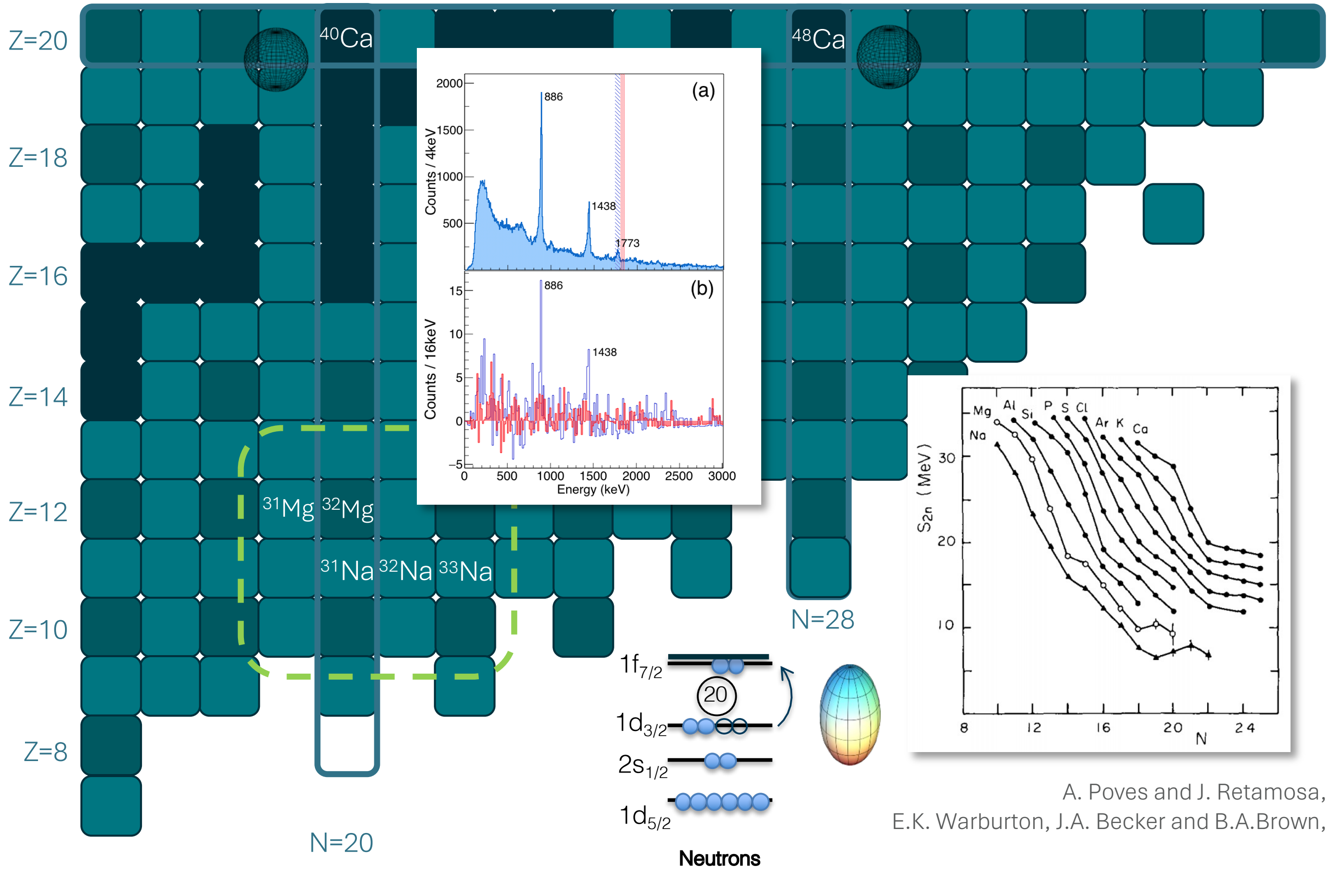
- decouple from the core and/or
- couple to the continuum?

What about spectroscopic observables?

- transition energies, rates ...

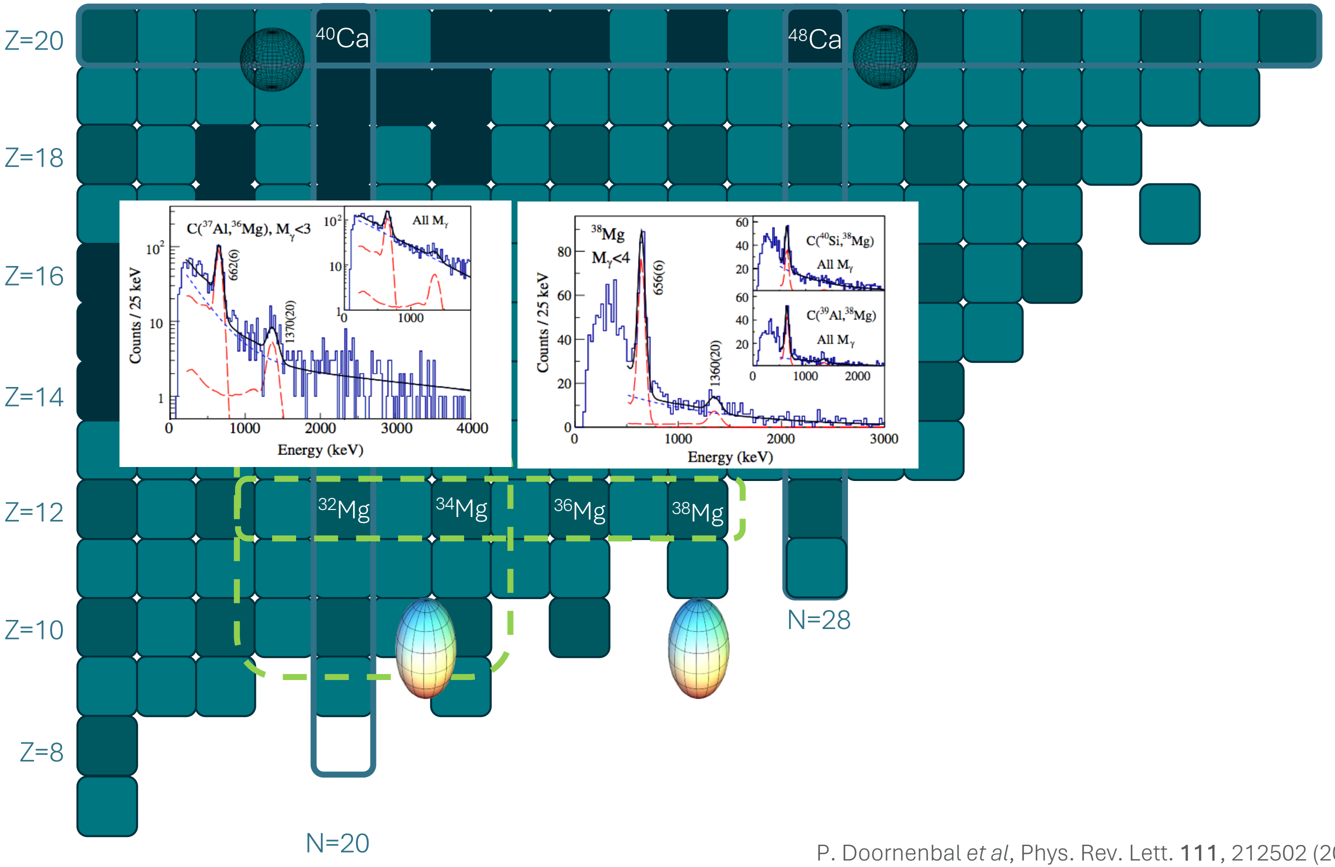


N=20 Island of Inversion



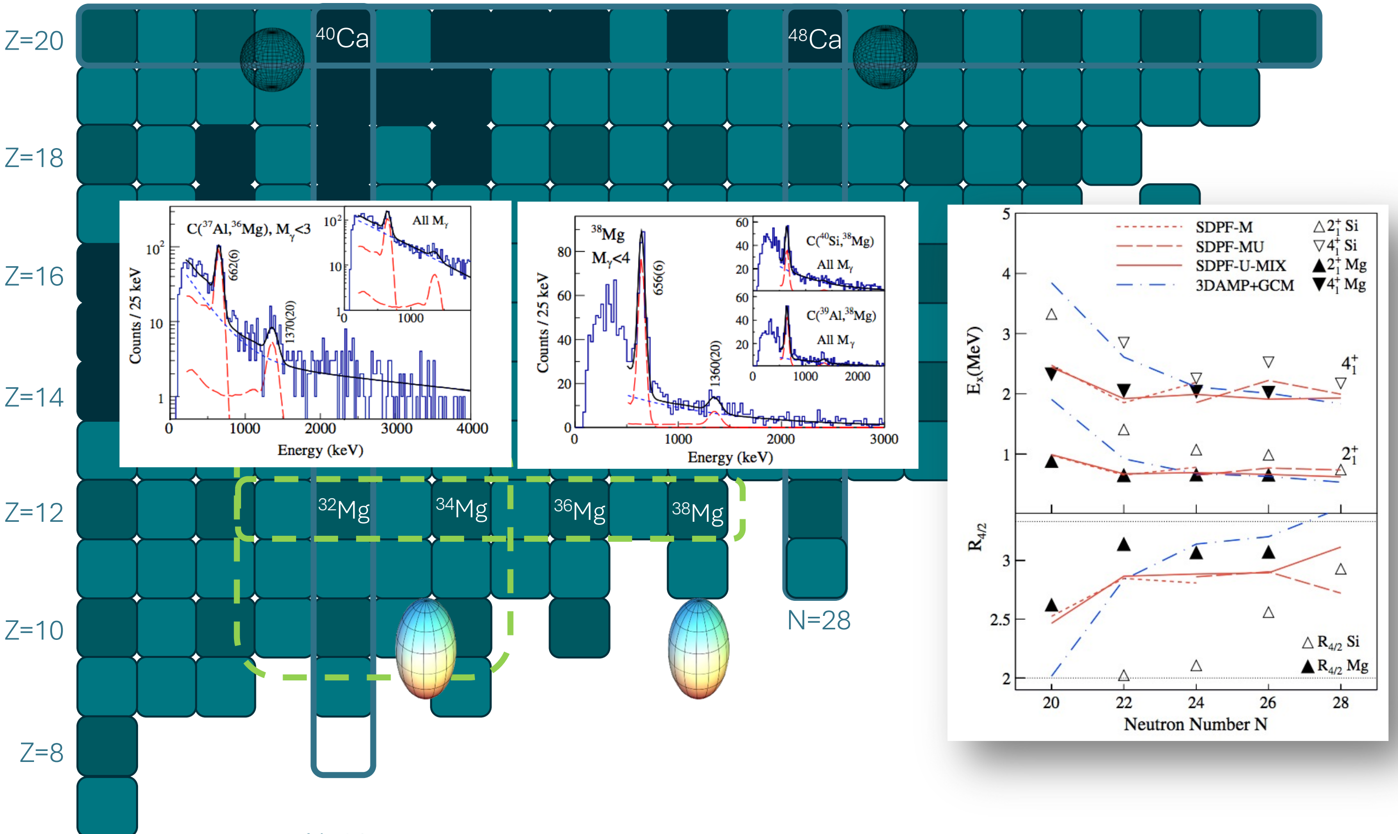
A. Poves and J. Retamosa, Phys. Lett. B 184, 311 (1987).
E.K. Warburton, J.A. Becker and B.A.Brown, Phys. Rev. C 41, 1147 (1990).

Z=12 'Peninsula' of Inversion



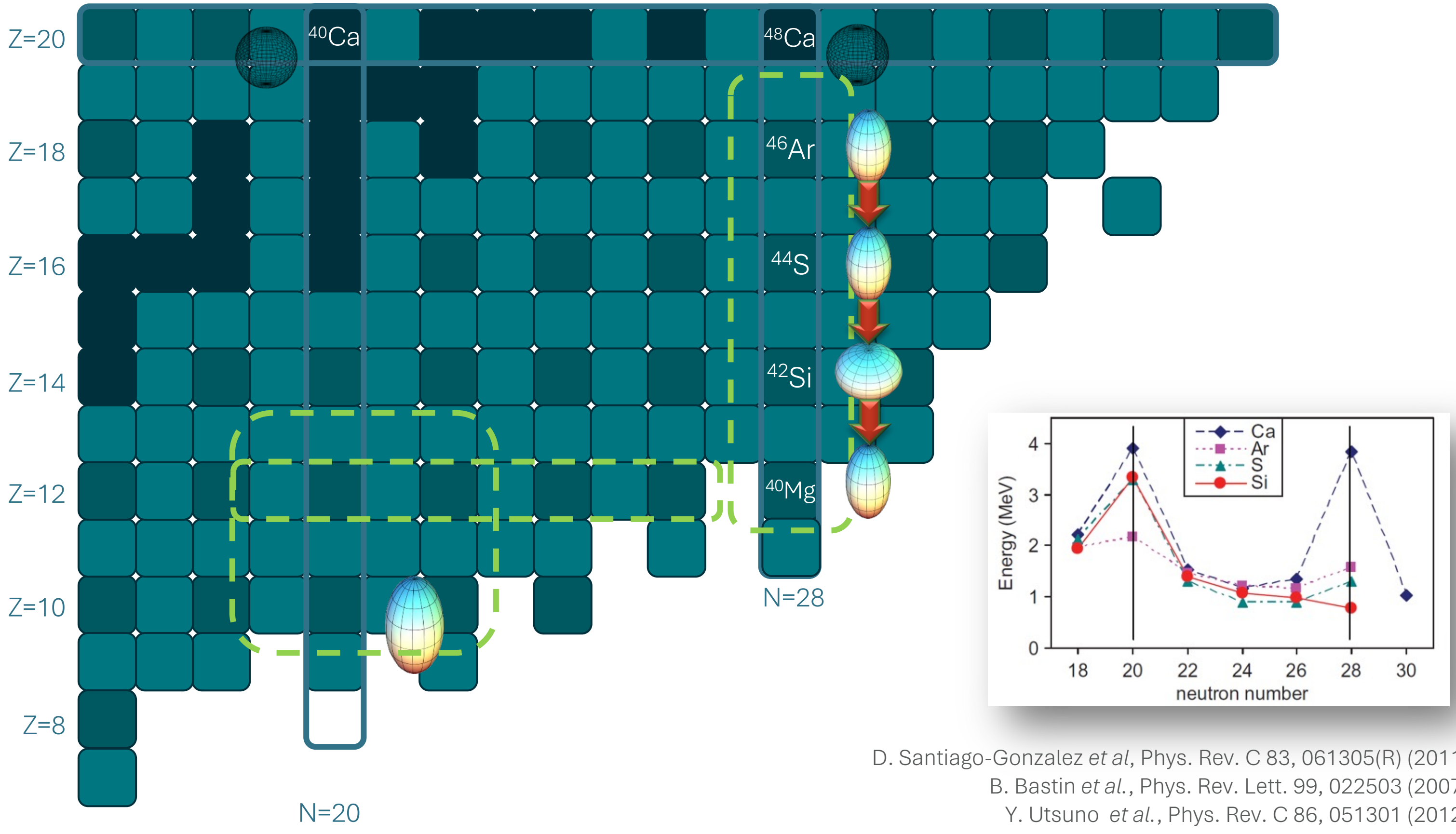
P. Doornenbal *et al*, Phys. Rev. Lett. **111**, 212502 (2013).

Z=12 ‘Peninsula’ of Inversion



P. Doornenbal *et al*, Phys. Rev. Lett. **111**, 212502 (2013).

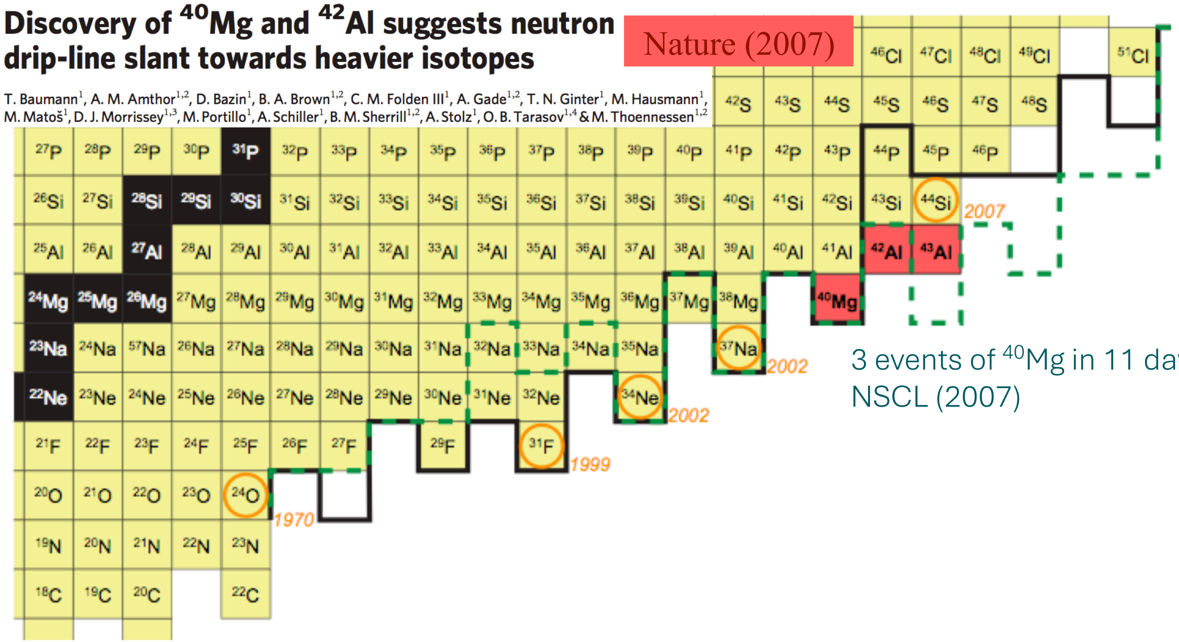
N=28 Evolution of Nuclear Shapes



D. Santiago-Gonzalez *et al*, Phys. Rev. C 83, 061305(R) (2011).
B. Bastin *et al.*, Phys. Rev. Lett. 99, 022503 (2007).
Y. Utsuno *et al.*, Phys. Rev. C 86, 051301 (2012).
HLC *et al.*, Phys. Rev. C **89**, 041303 (2014).

Mapping the dripline in the sd shell

Way back in 2007…



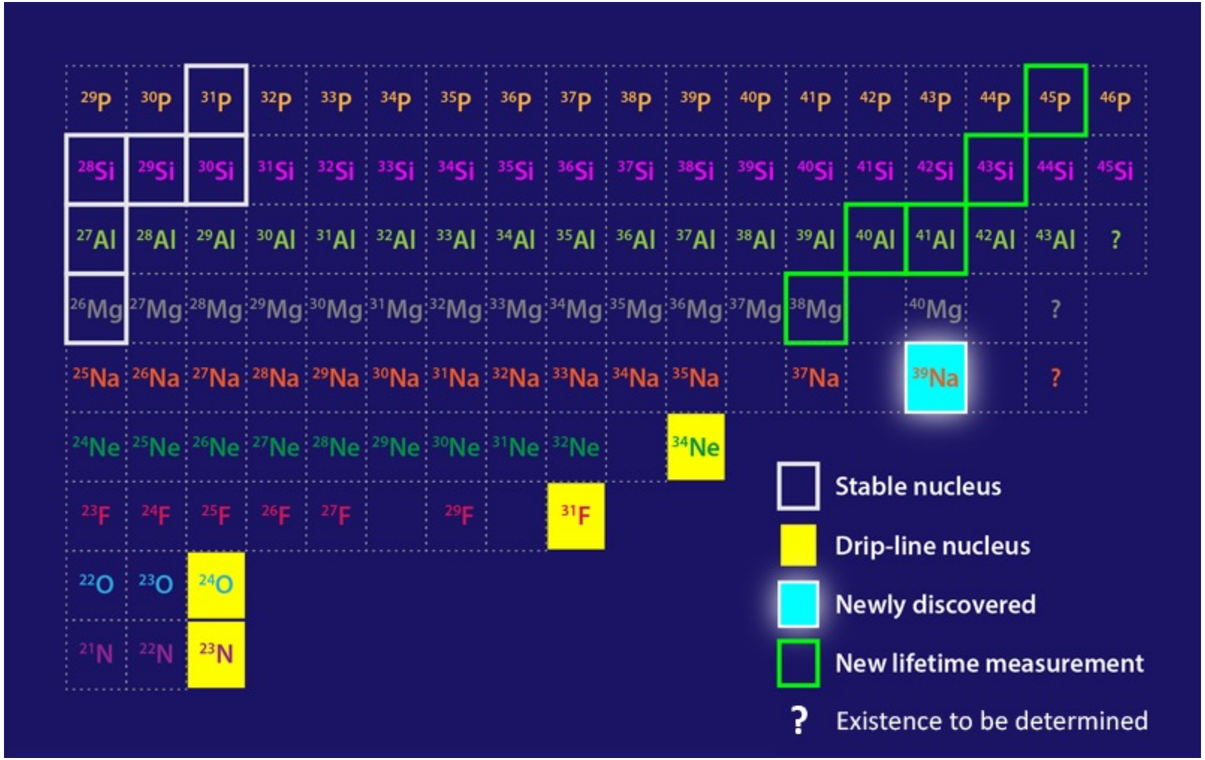
3 events of ^{40}Mg in 11 days
NSCL (2007)

Mapping the dripline in the sd shell

More recently - 2022

In 15 years, one additional neutron-rich nucleus has been added. More will come with FRIB, but…

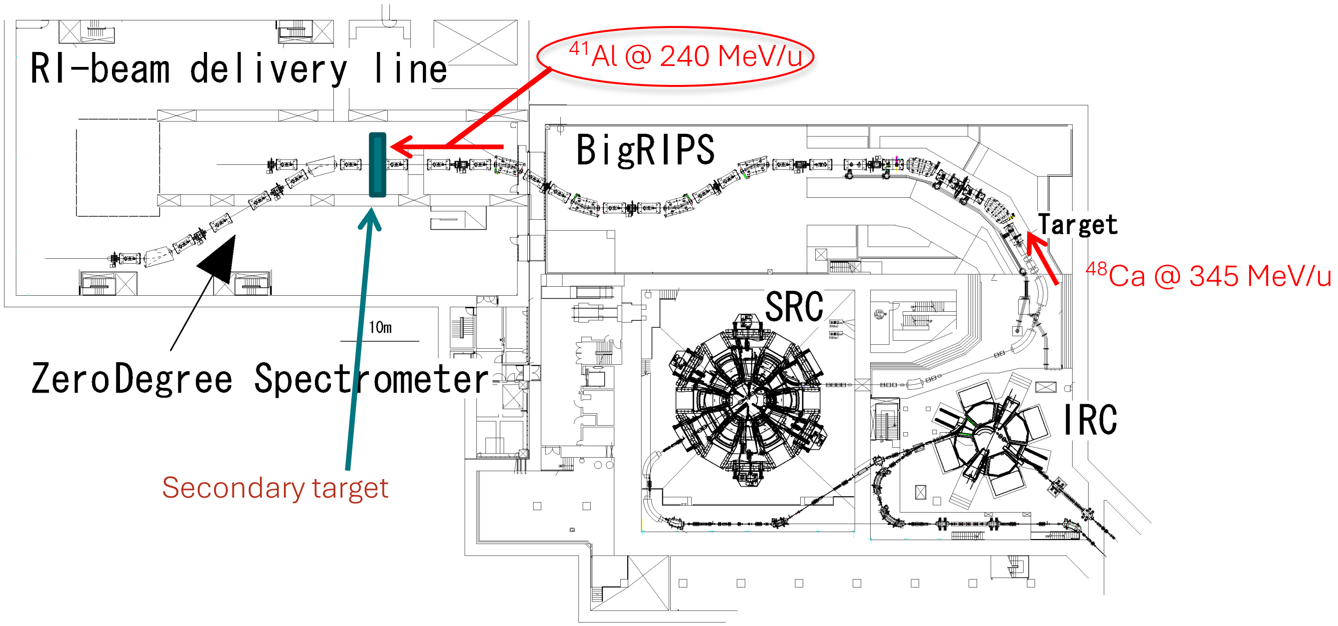
^{40}Mg may be one of the heaviest drip-line(?) nuclei experimentally accessible for detailed study, even at FRIB.



D. S. Ahn *et al.*, Phys. Rev. Lett. 129, 212502 (2022).

December 2016 at RIBF – NP1312-RIBF03R2

^{41}Al produced following fragmentation of a high-intensity ^{48}Ca primary beam at RIBF in RIKEN



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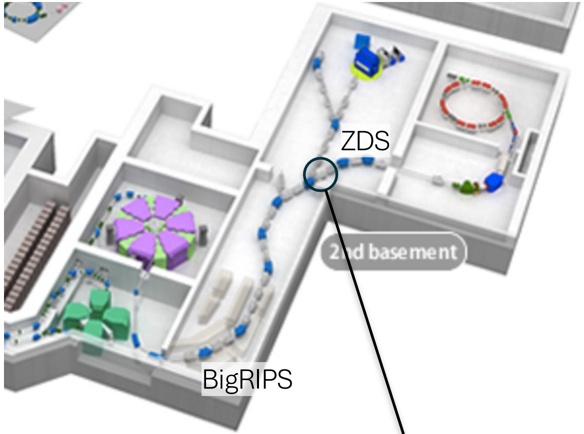
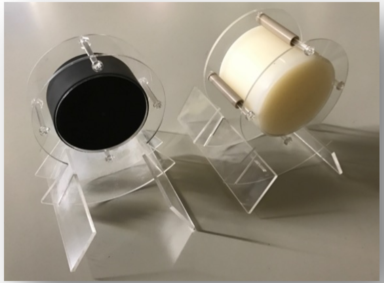
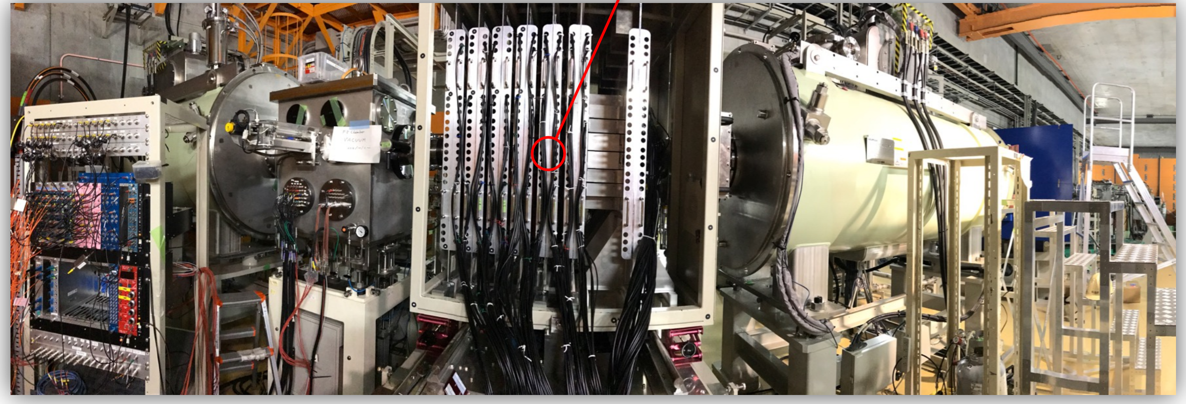
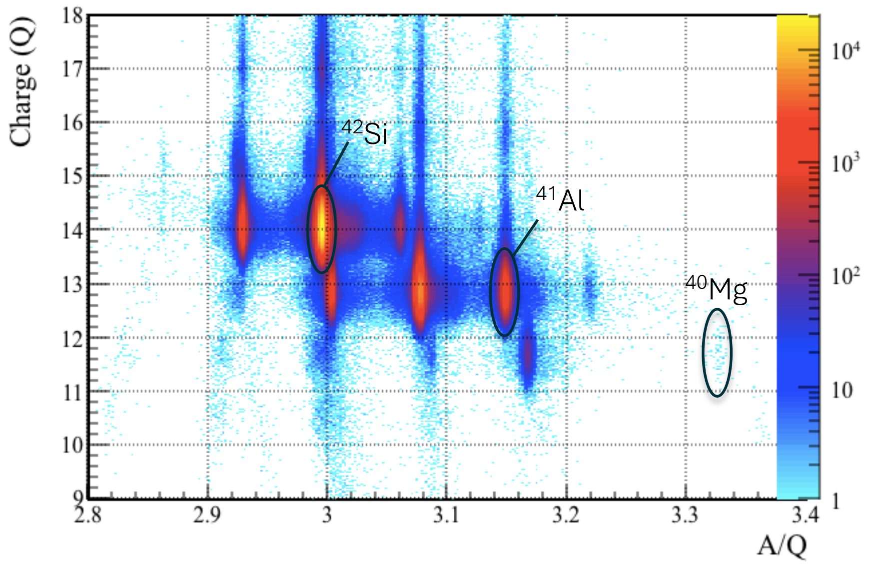


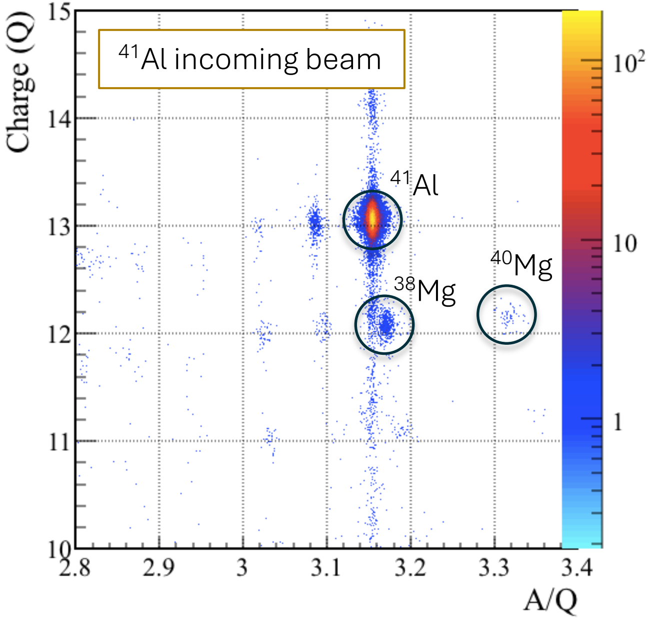


Self-supporting Carbon (graphite) and CH_2 targets
$CH_2 \Rightarrow 3.82$ g/cm^2; Carbon $\Rightarrow 3.80$ g/cm^2



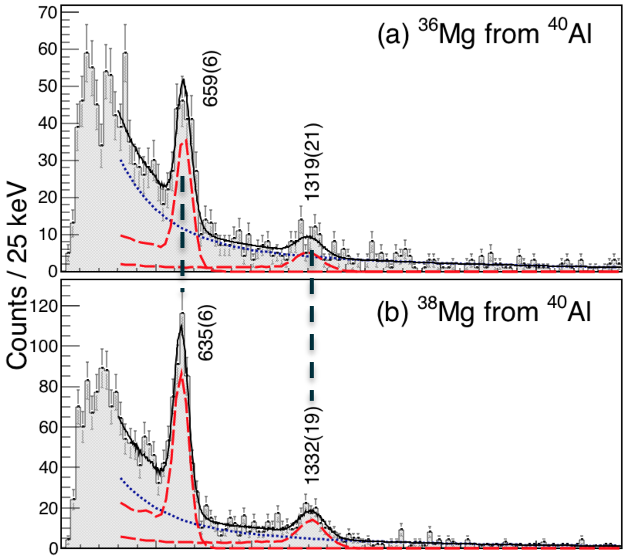
Particle Identification

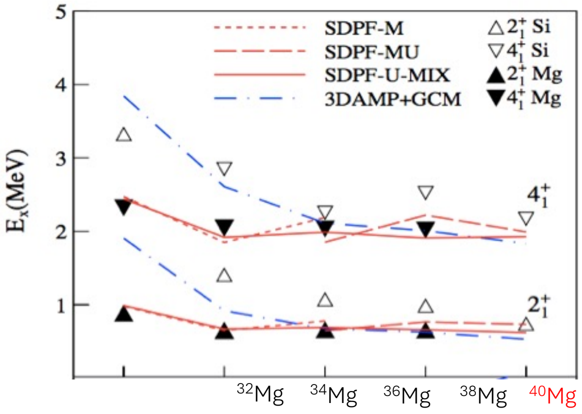




- BigRIPS fragment separator was centered on ^{41}Al; ZeroDegree was centered on ^{40}Mg
  - Average ^{48}Ca primary beam intensity of order 400 pnA (~6.5 kW)

Results: ^{36,38}Mg and ^{40}Mg Spectra





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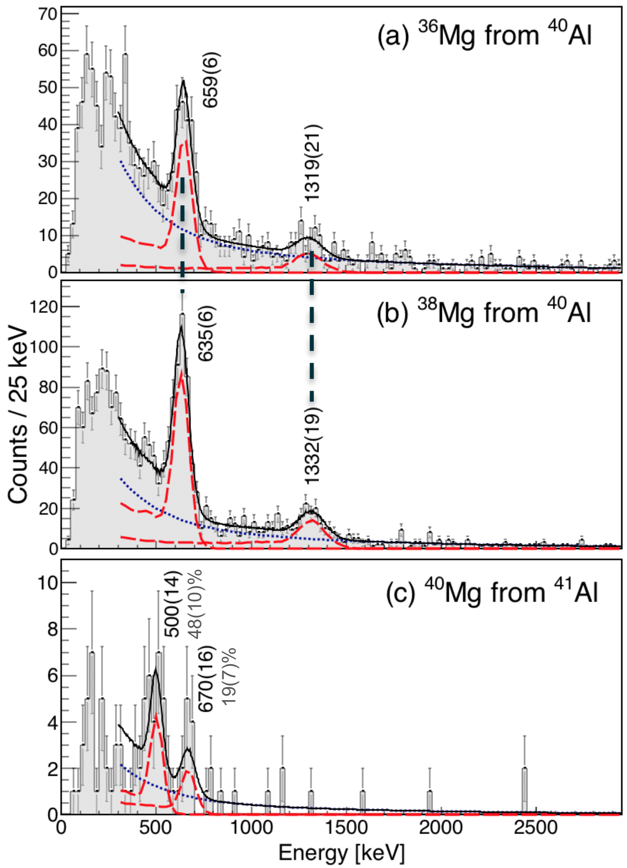

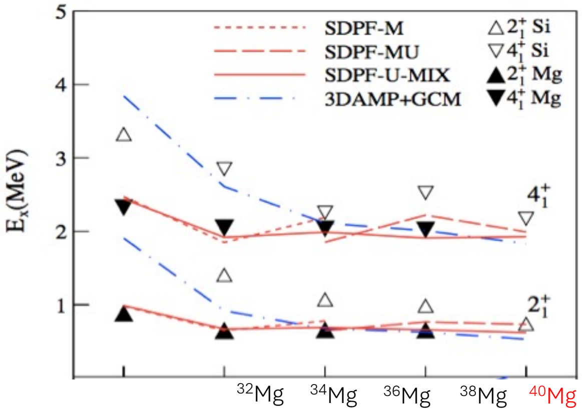

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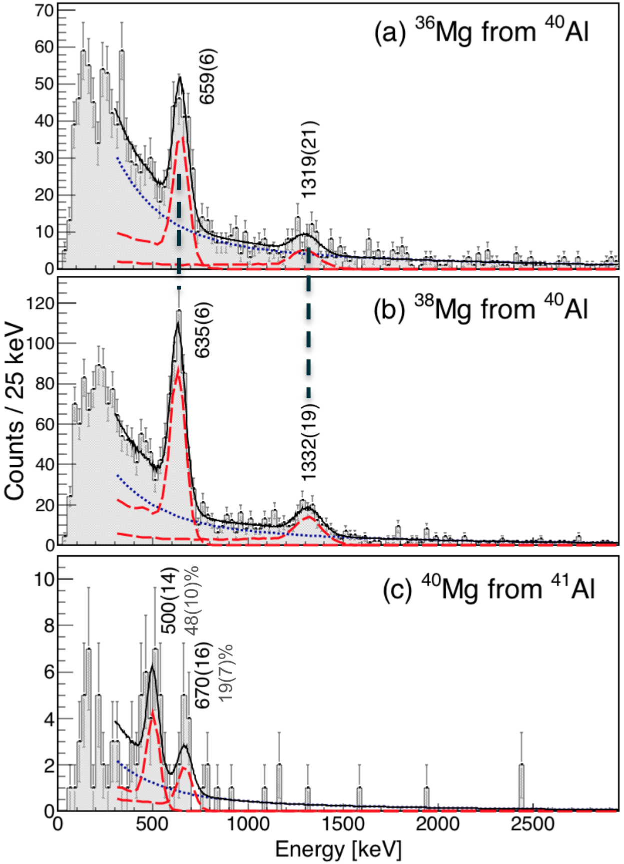
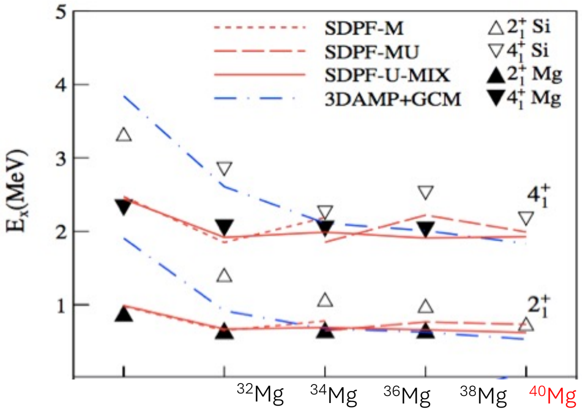


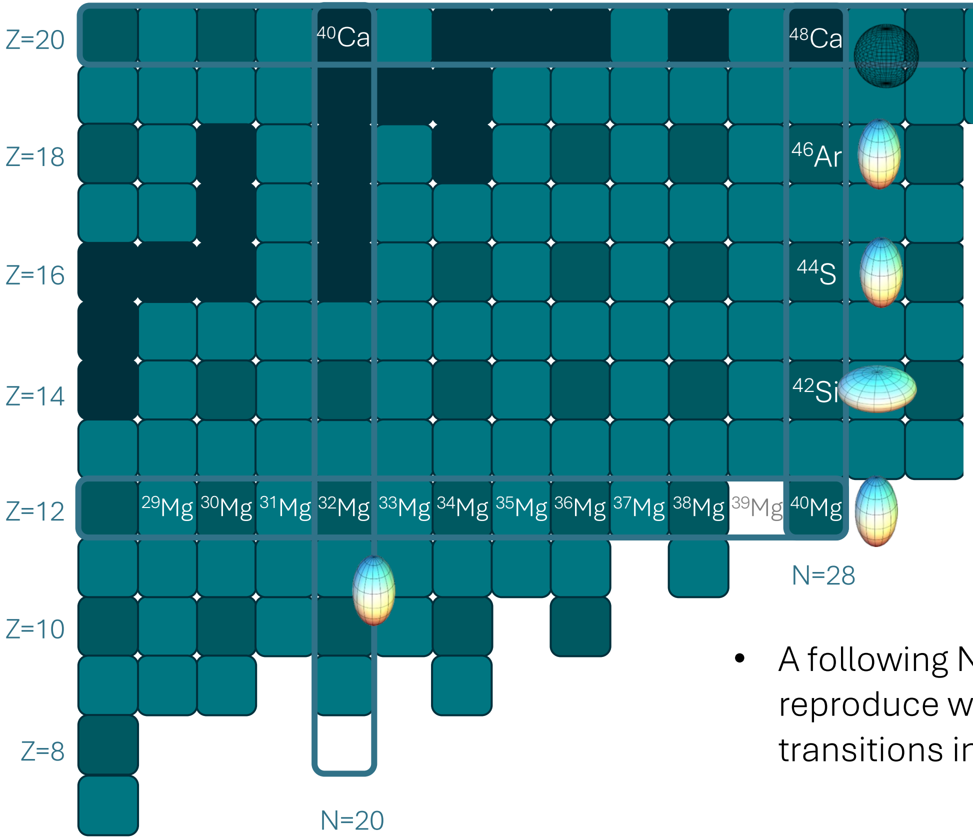


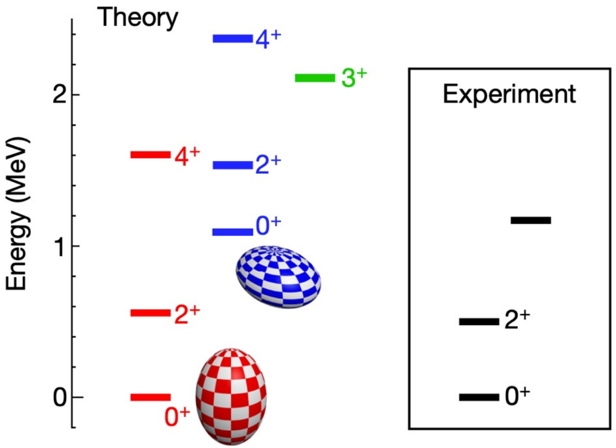
- 500 keV transition assigned to $2^+_1 \rightarrow 0^+_1$
- 650 keV transition ?

  $2^+_2 \rightarrow 2^+_1$ $0^+_2 \rightarrow 2^+_1$ $4^+_1 \rightarrow 2^+_1$ + ...
- No scenario fit with existing expectations (systematics) nor predictions from calculations at the time

P. Doornenbal *et al.*, PRL 111, 212502 (2013).
HLC *et al.*, PRL 122, 052501 (2019).

MCSM Success for ^{40}Mg?

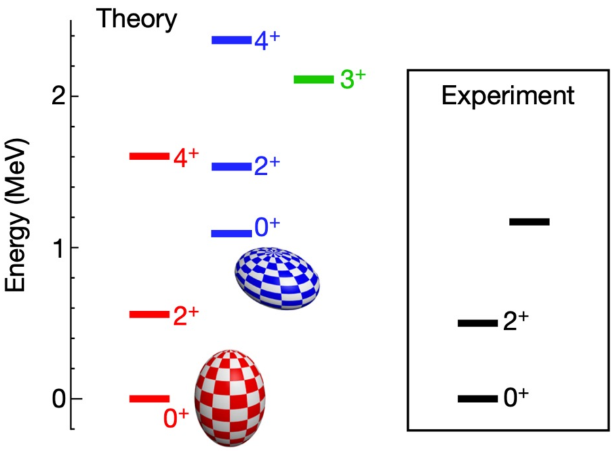


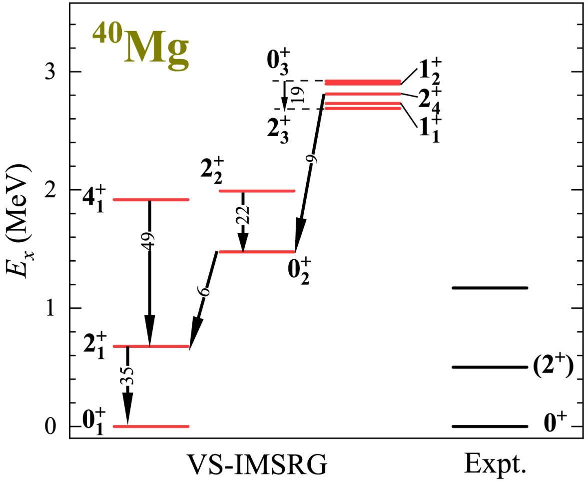


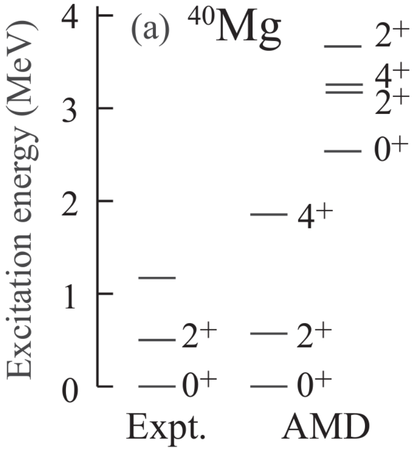
- A following Nature article showed MCSM results which reproduce well the observed energy levels, assuming transitions in cascade

N. Tsunoda, T. Otsuka *et al.*, Nature 587, 66 (2020).

Nuclear Structure Theory Description for ^{40}Mg







- Consistently, structure theories predict shape coexistence in ^{40}Mg with prolate ground state and low-lying oblate-deformed structure
- Both MCSM and VS-IMSRG suggest energies compatible with the observed second state as a second 0^+

N. Tsunoda, T. Otsuka *et al.*, Nature 587, 66 (2020).
Y. Suzuki *et al.*, Prog. Theor. Exp. Phys. **6**, 063D02 (2022).
Q. Yuan *et al.*, Phys. Lett. B **848**, 138331 (2024).

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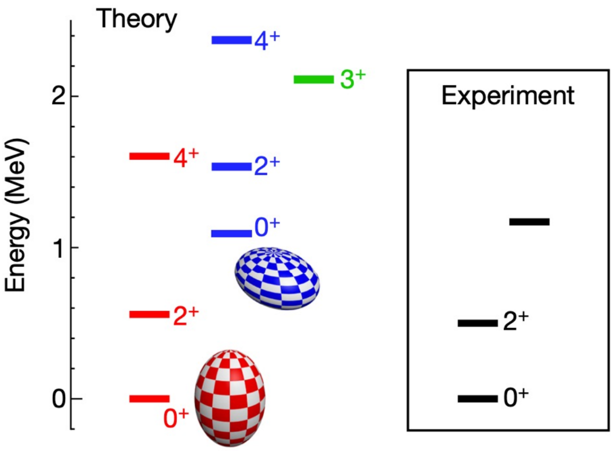
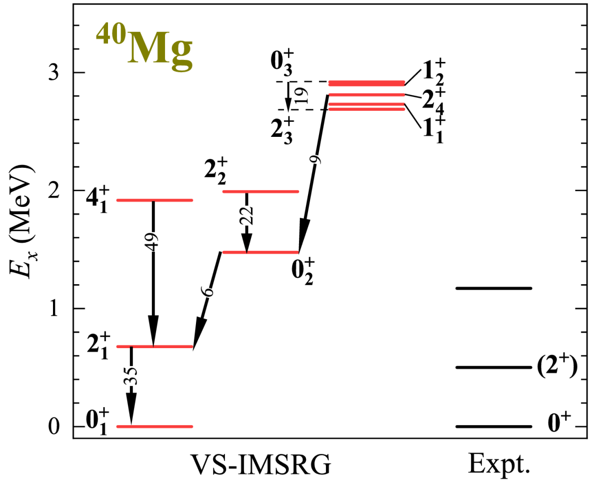
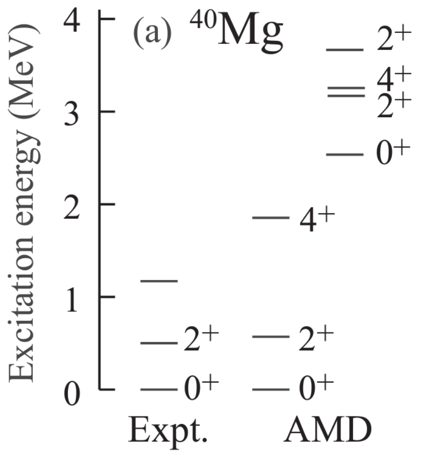


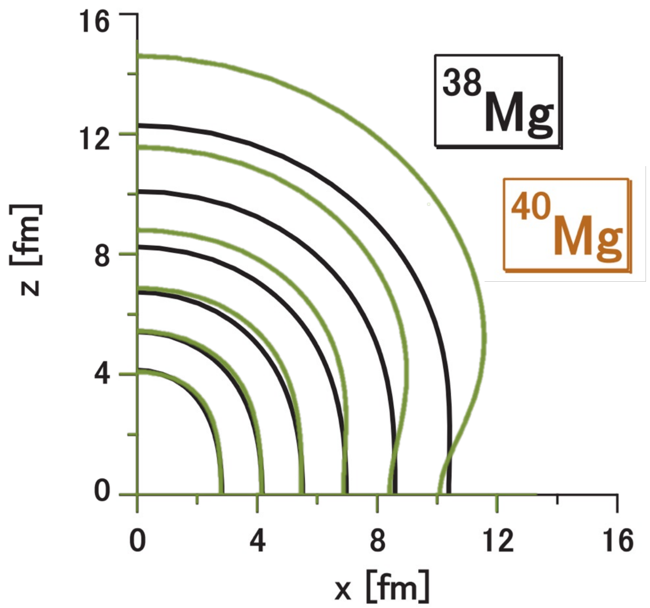




- Consistently, structure theories predict shape coexistence in ^{40}Mg with prolate ground state and low-lying oblate-deformed structure
- Both MCSM and VS-IMSRG suggest energies compatible with the observed second state as a second 0^+
- Experimentally this is dis-favoured based on cross-section arguments, both for ^{41}Al(-1p) and ^{42}Si(-2p)

N. Tsunoda, T. Otsuka *et al.*, Nature 587, 66 (2020).
Y. Suzuki *et al.*, Prog. Theor. Exp. Phys. **6**, 063D02 (2022).
Q. Yuan *et al.*, Phys. Lett. B **848**, 138331 (2024).

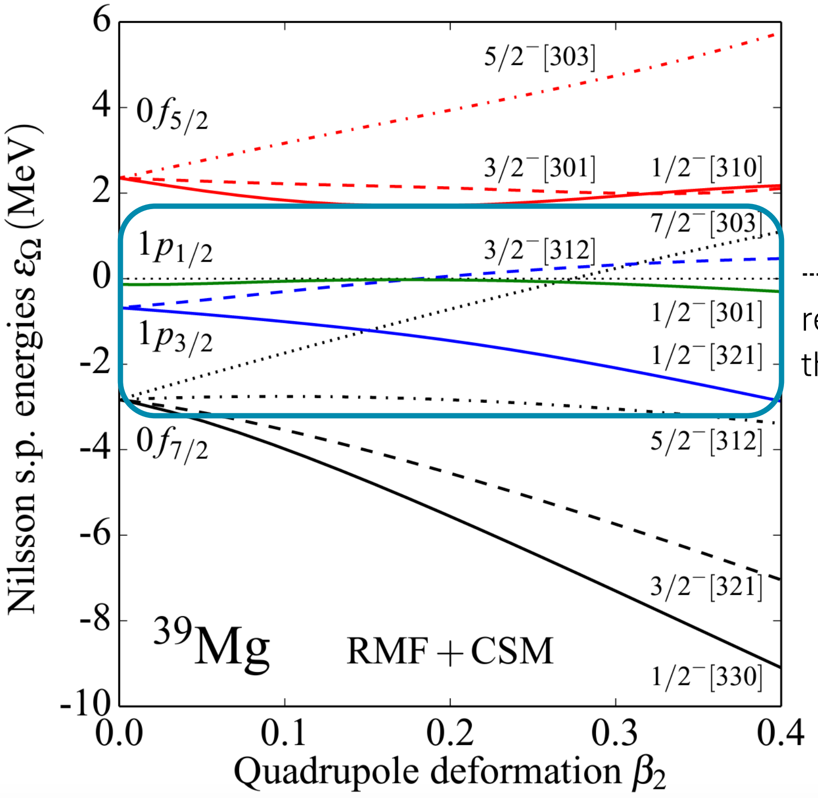
HFB Calculation of Neutron-Rich Mg Isotopes…



⇢ $p_{3/2}$ deformed halo and quenched pair correlation in ^{40}Mg

H. Nakada and K. Takayama, PRC **98**, 011301(R) (2018).
K. Yoshida, PRC **105**, 024313 (2022).

Is ^{40}Mg structure evidence of weak-binding or continuum influence?



⇢ with deformation in this region, the low l orbitals are at the Fermi surface

K. Fossez *et al.*, PRC **94**, 054302 (2016).

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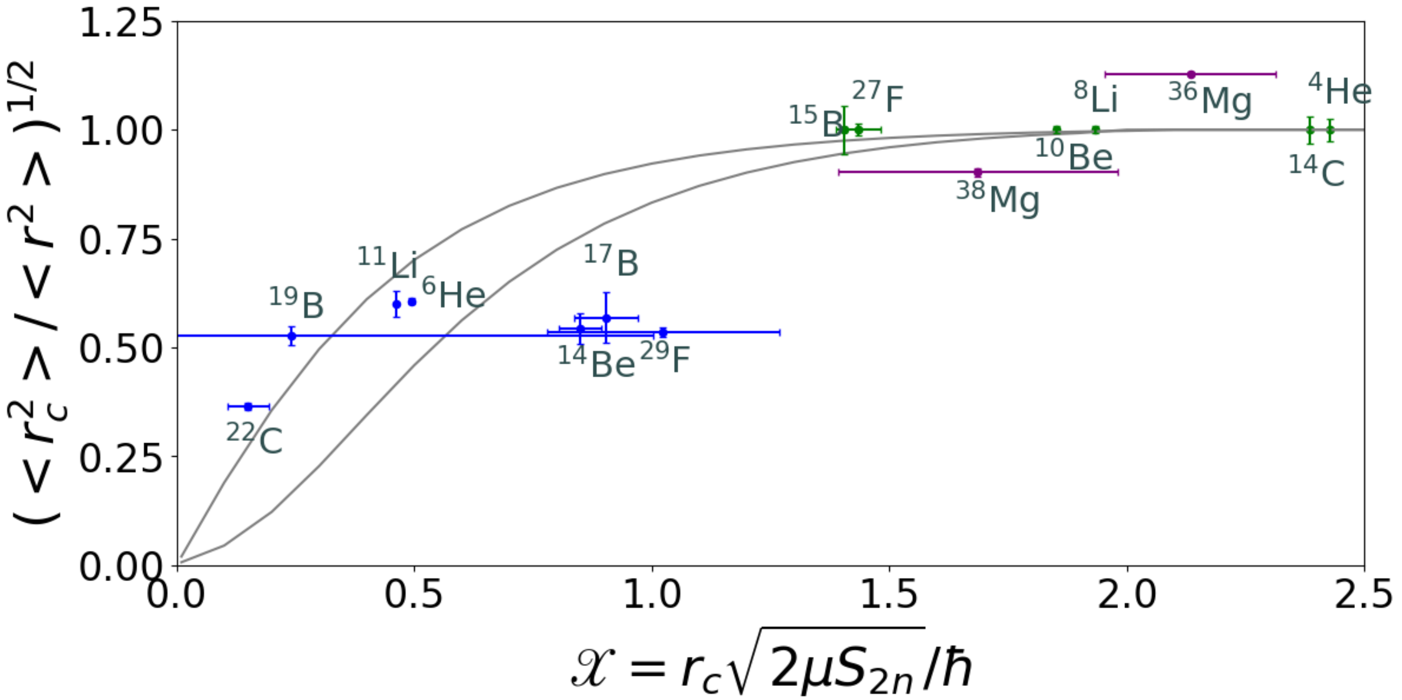

A. O. Macchiavelli, HLC *et al.*, EPJA **58**, 66 (2022).
P.G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987).

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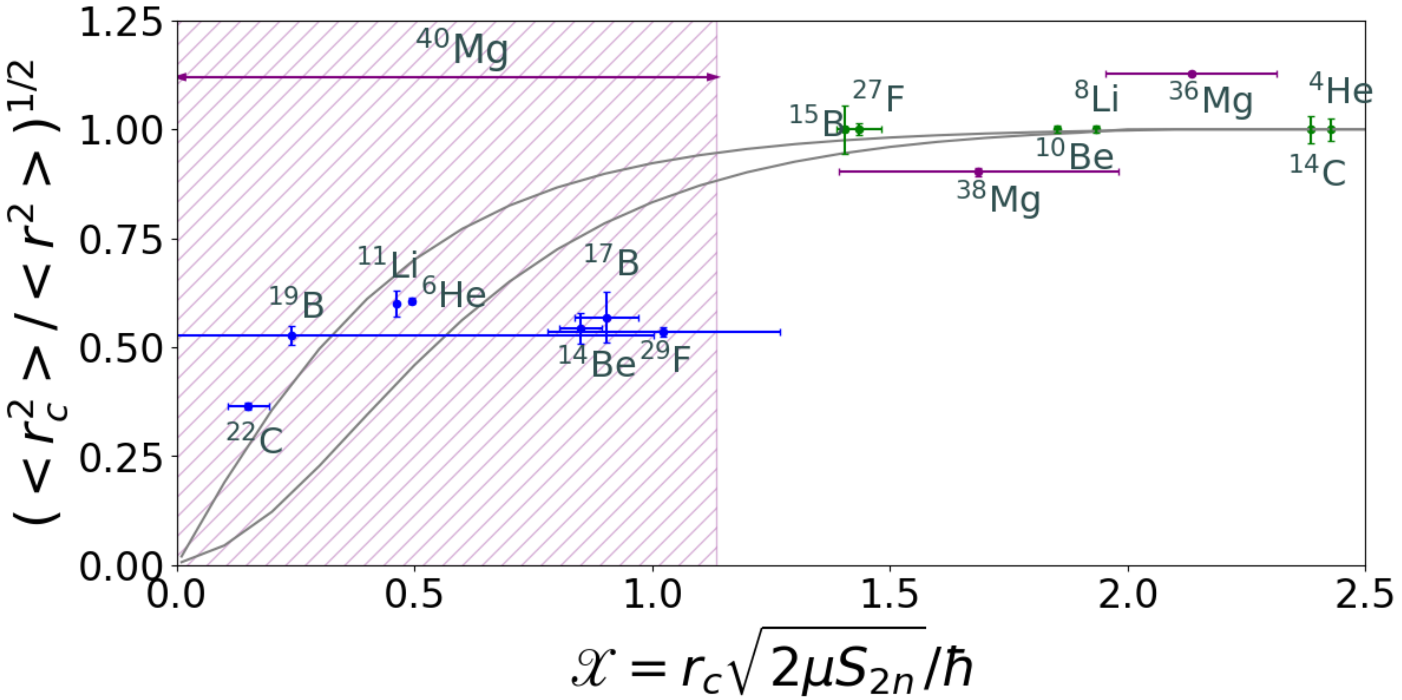
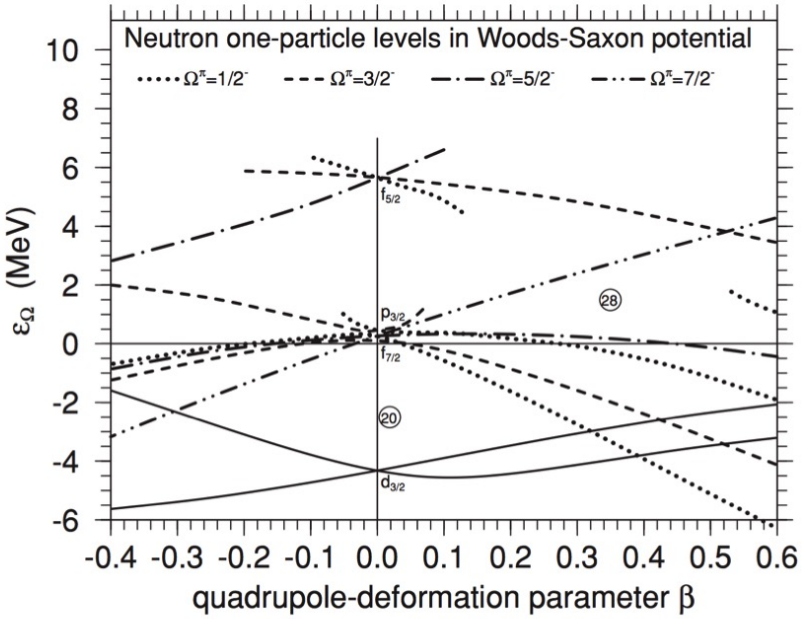
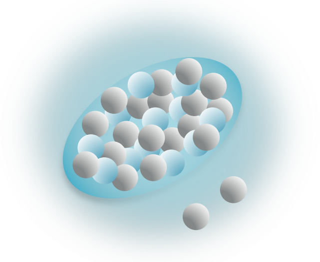


Weakly bound neutrons in ^{40}Mg

- 2-body NN interaction ($\sigma.\tau$, Tensor) works to modify the N=28 shell gap
- Occupation of low l levels ($p_{3/2}$) leads to extended wavefunctions ("halos")

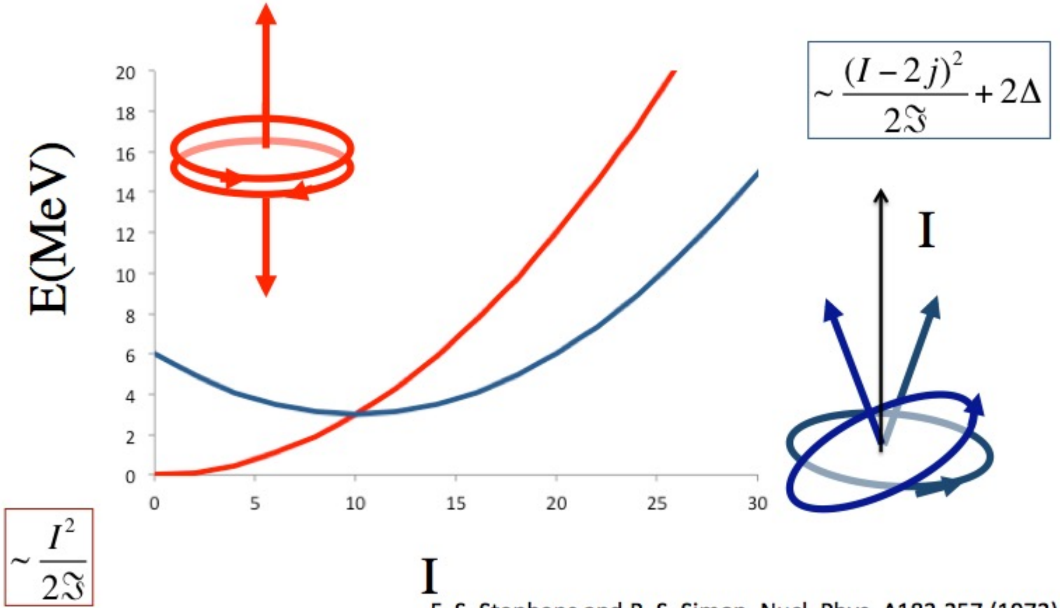




- Consider ^{40}Mg as a deformed ^{38}Mg core and a 2-neutron p-wave halo

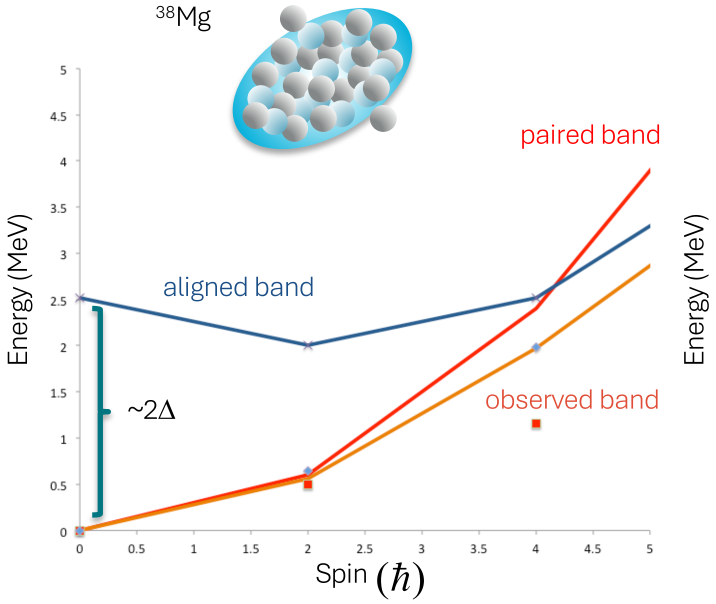
- How do the halo neutrons interact with the core in ^{40}Mg ?

Rotation and Alignment



F. S. Stephens and R. S. Simon, Nucl. Phys. A183,257 (1972).

Rotation in ^{40}Mg – “decoupled valence pair”



In ^{40}Mg, the energy to break pair is reduced (“diagonal pair” matrix element only)

A. O. Macchiavelli, HLC *et al.*, EPJA **58**, 66 (2022).

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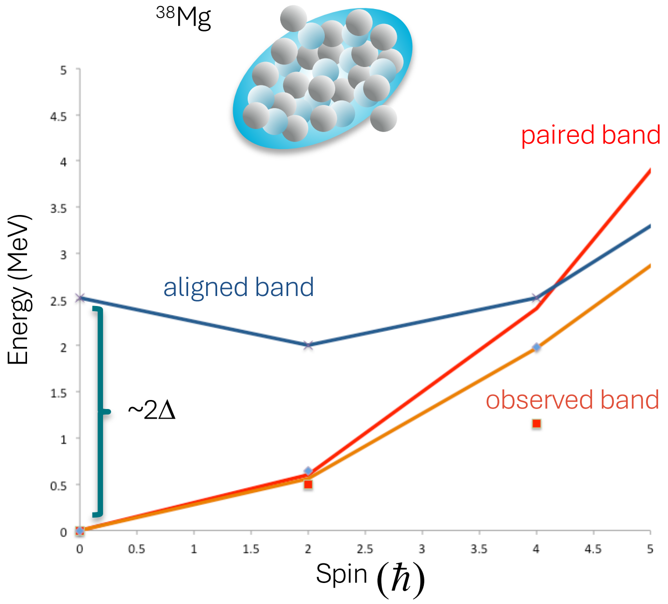

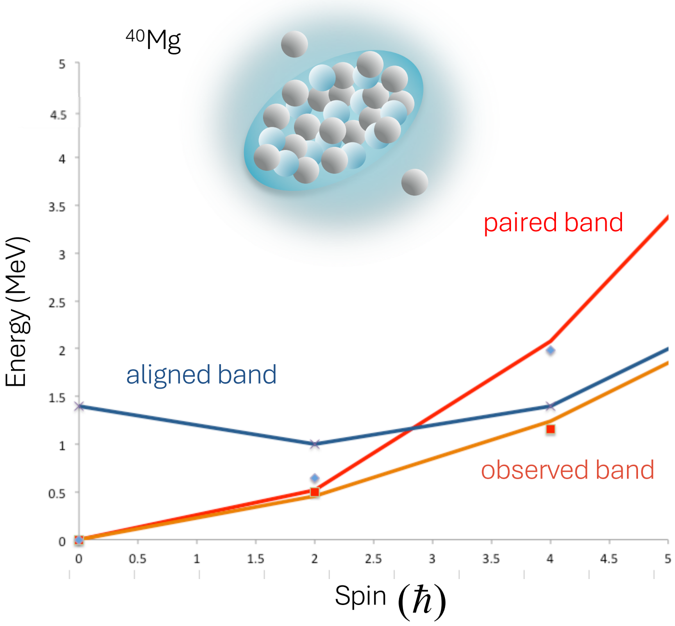

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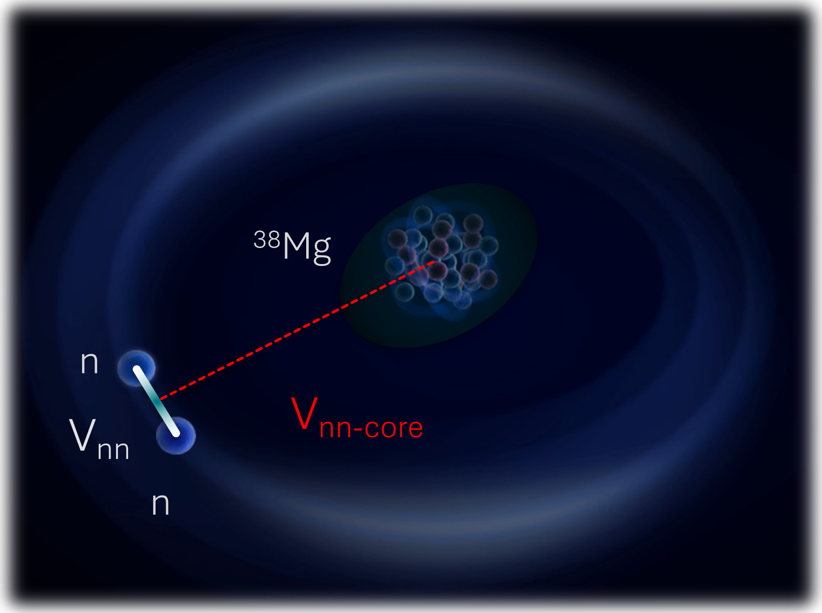
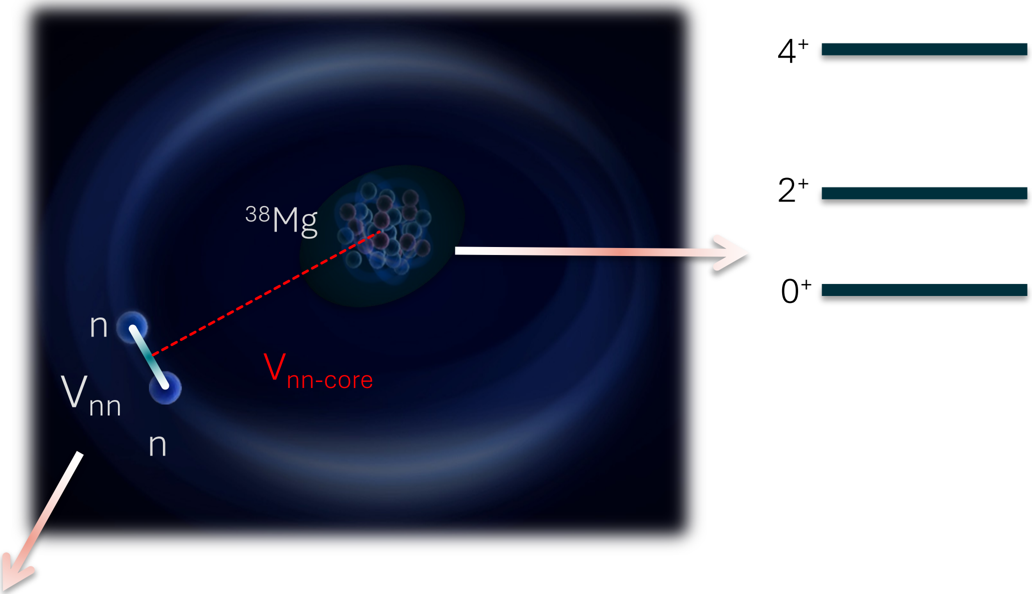
Coupling of valence (halo) neutrons to the core

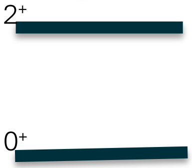
- ^{11}Li – “strong” coupling – ^{9}Li core surface is “soft” towards surface vibrations
- ^{6}He – “weak” coupling – ^{4}He core surface is “hard”



Weak coupling of valence (halo) neutrons to the core



H_{Core}

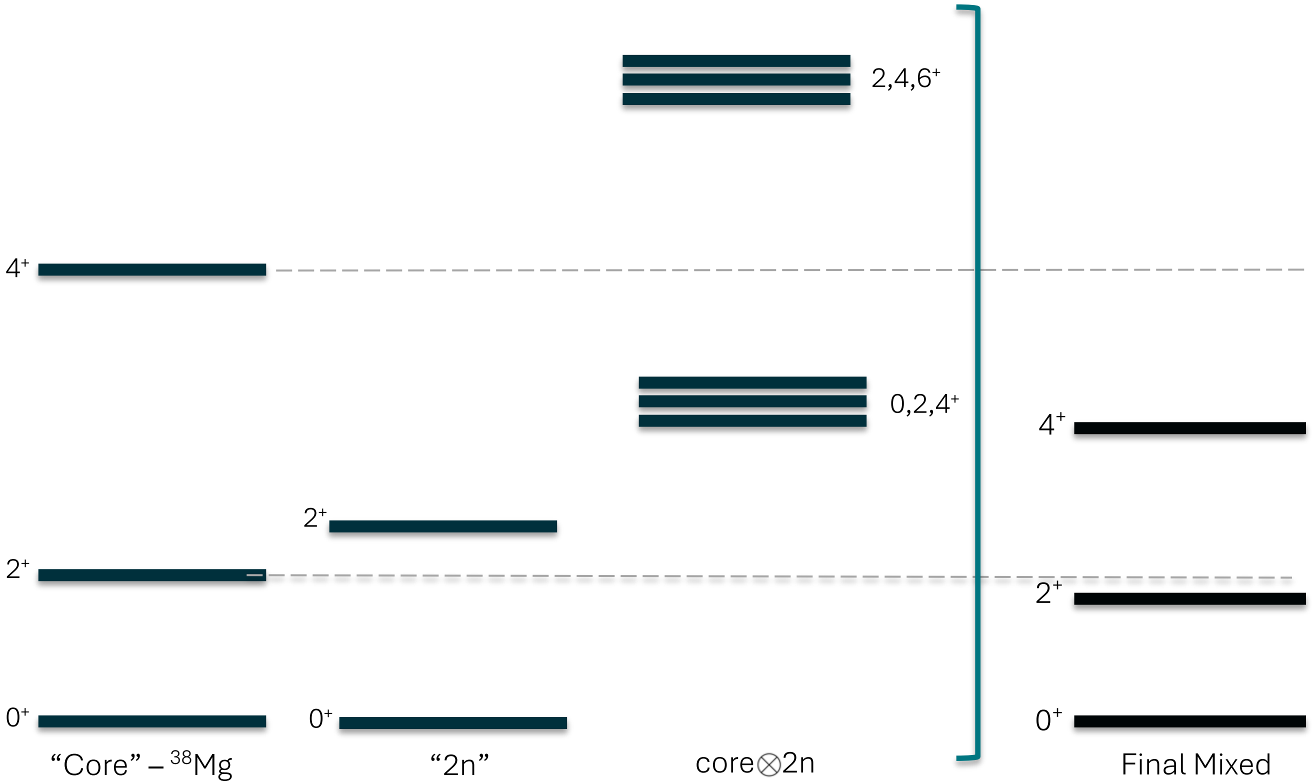


V_{nn}

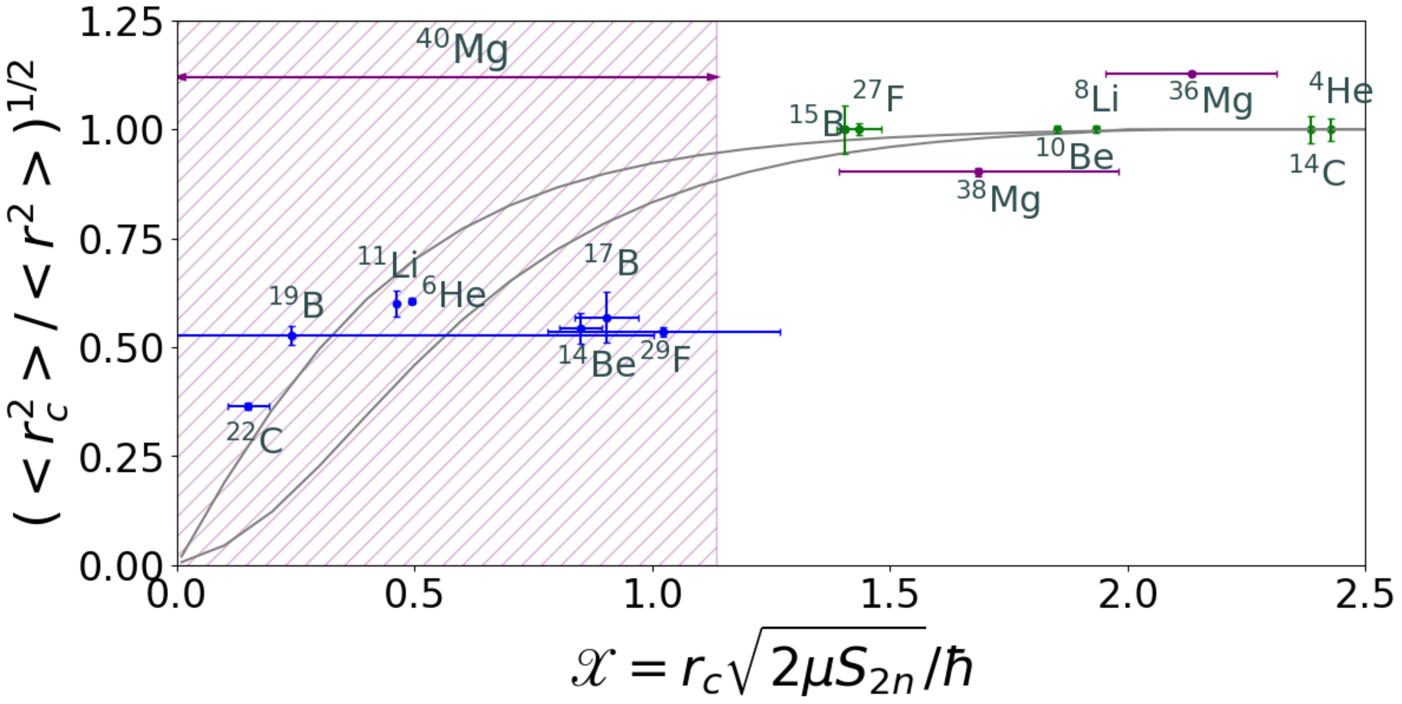
$$H_{40Mg} = \underbrace{H_{38Mg} + V_{nn}}_{\text{Core} \otimes \text{2n basis}} + \underbrace{V_{nn\text{-}core}}_{\text{Mixing}}$$

A. O. Macchiavelli, HLC *et al.*, EPJA **58**, 66 (2022).

Weak coupling of two degree of Freedom



Is ^{40}Mg structure evidence of weak-binding or continuum influence?

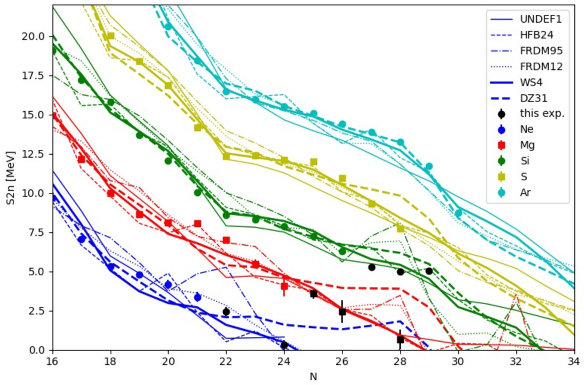


Next Steps Planned at FRIB

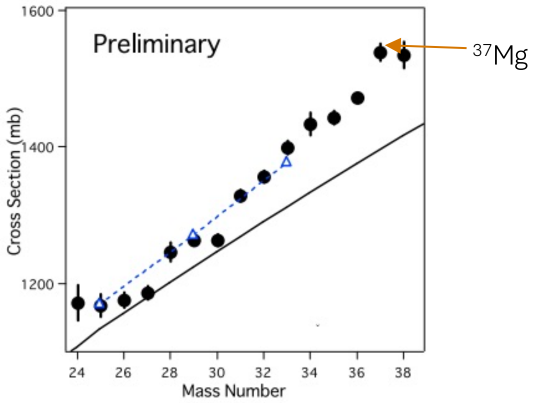
^{40}Mg reaction cross-section and mass measurement (S_{2n})

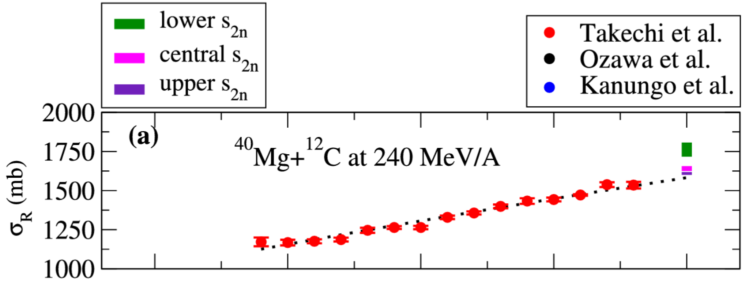
- A total reaction cross-section measurement will answer the question of whether there is an extended matter radius (Crawford, Bazin, Kanungo)
- With a TOF mass measurement, the 2n separation energy can be established – also constrains Q_β (Estrade, Crawford, Fallon, Schatz)

⇒These experiments are both approved at FRIB



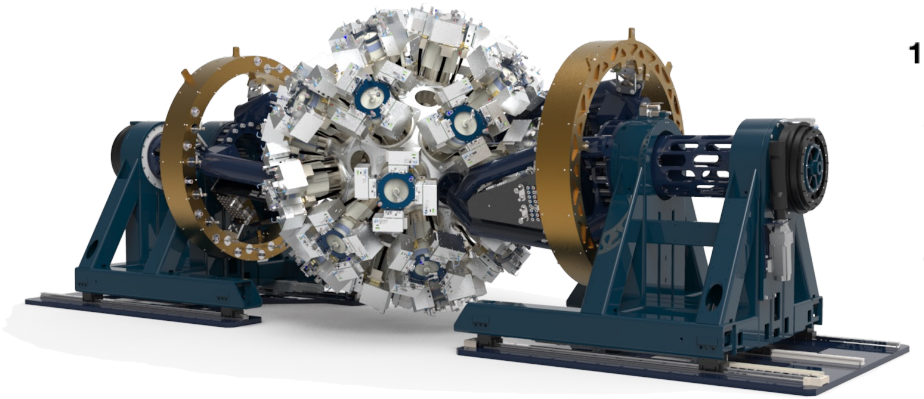
M. Takechi *et al.*, Phys. Rev. C **90**, 061305(R) (2014).

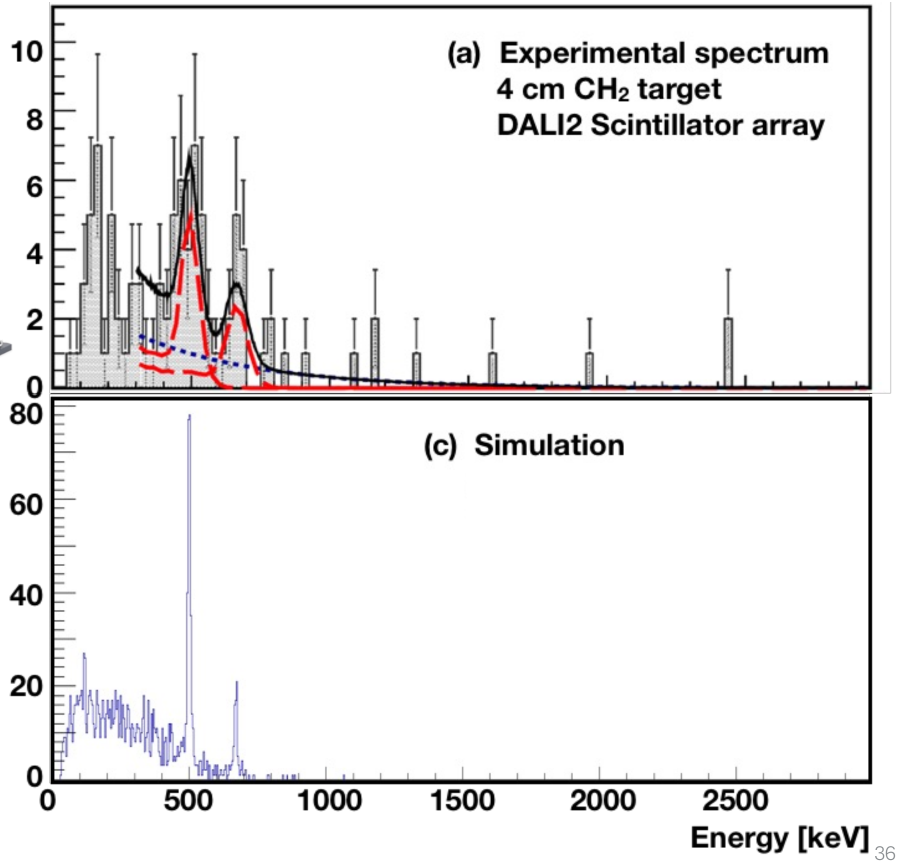




J. Singh *et al.*, Phys. Lett. B **853**, 138694 (2024).

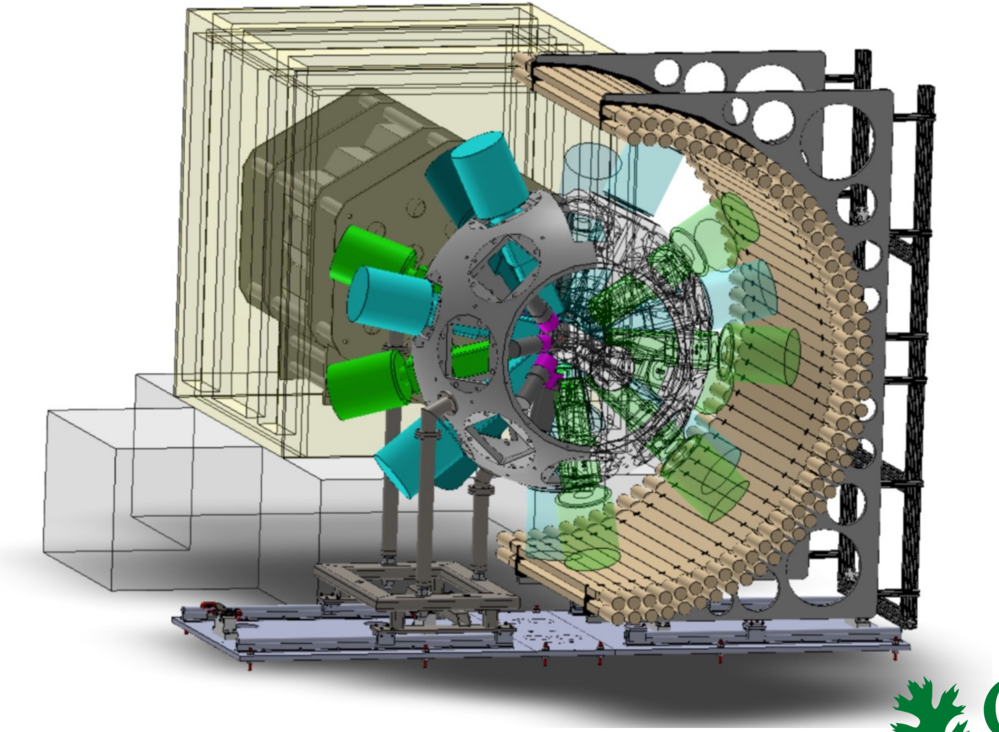
High-Resolution Spectroscopy in ^{40}Mg





- GRETA will provide an unprecedented combination of full solid angle coverage, high efficiency, excellent energy and position resolution, and good background rejection
- Unmatched resolving power will enable further push to the driplines and other spectroscopic frontiers

The FRIB Decay Station Initiator (FDSi)



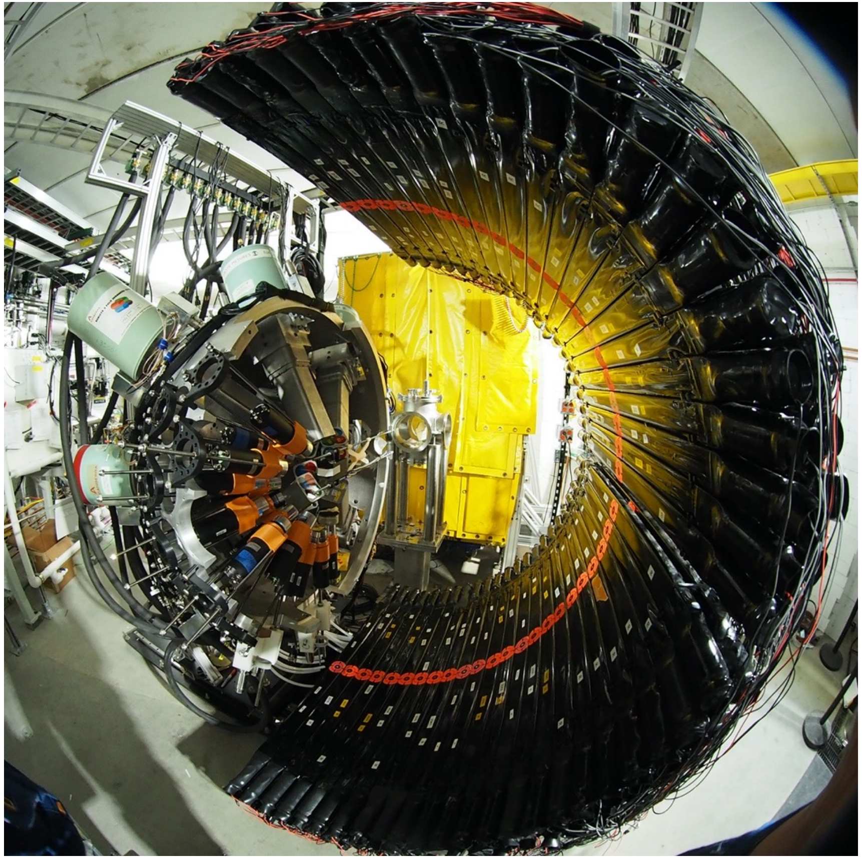
Decay studies with the FRIB Decay Station Initiator (FDSi)

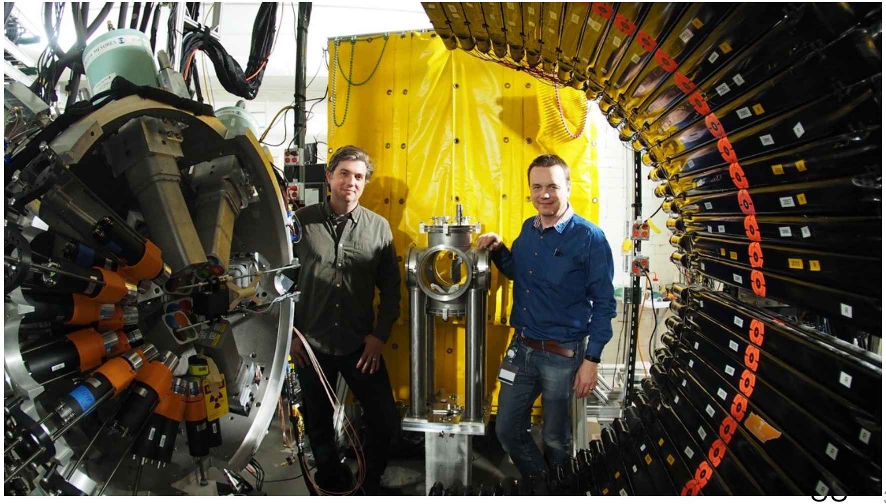
- FDSi enables total decay spectroscopy, with γ, particle and neutron spectroscopy
- Segmented YSO implantation detector with segmented SiPM readout
- HPGe clovers and $LaBr_3$ fast-timing detectors
- Neutron detection with detectors from VANDLE
- Combination with MTAS (or SuN) further extends the physics

OAK RIDGE National Laboratory

THE UNIVERSITY OF TENNESSEE KNOXVILLE

FRIB Decay Station Initiator (FDSi)

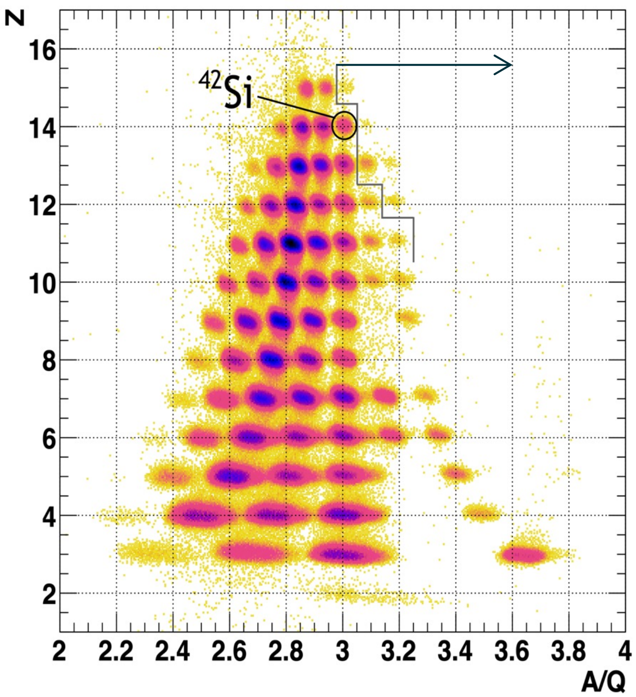


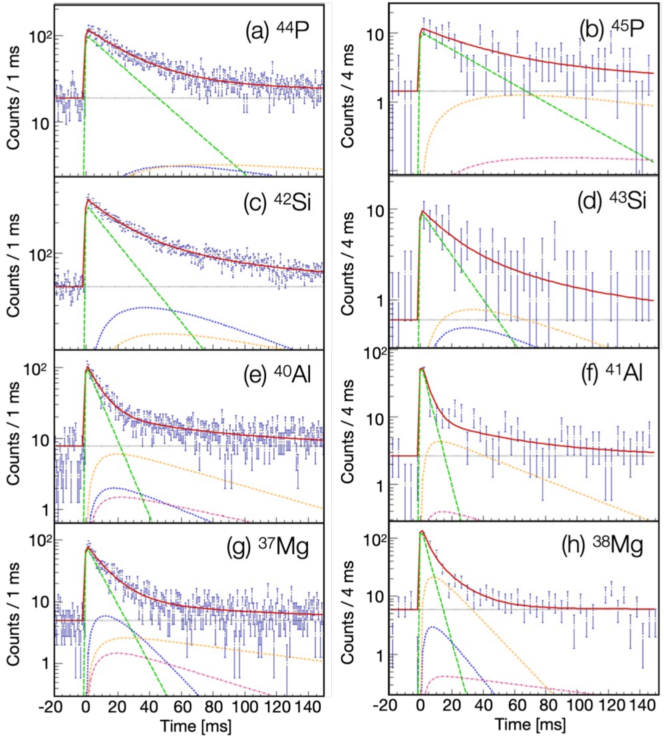


First Results from FRIB

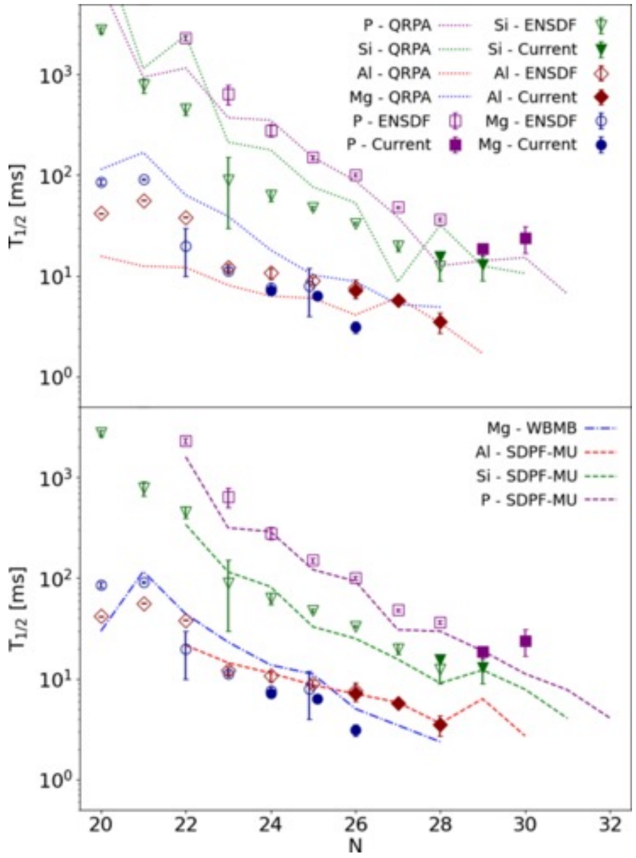
E21062: Decay Near N=28 (Allmond, Crawford, Crider, Grzywacz, Tripathi)

- 5 isotopes with no published half-life information were measured, with improved half-life values provided for numerous additional species

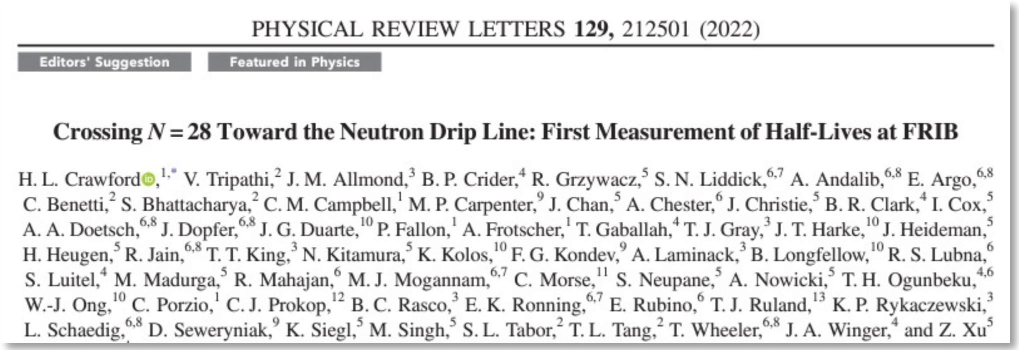




First Results from FRIB



- Half-life systematics were extended the Mg, Al, Si and P chains
- Overall agreement with available shell model calculations is consistent with a well-developed region of deformation
- Clear evidence for erosion of Z=14 subshell closure
- Intriguing reduction in the half-life for ^{38}Mg – still awaiting theoretical values

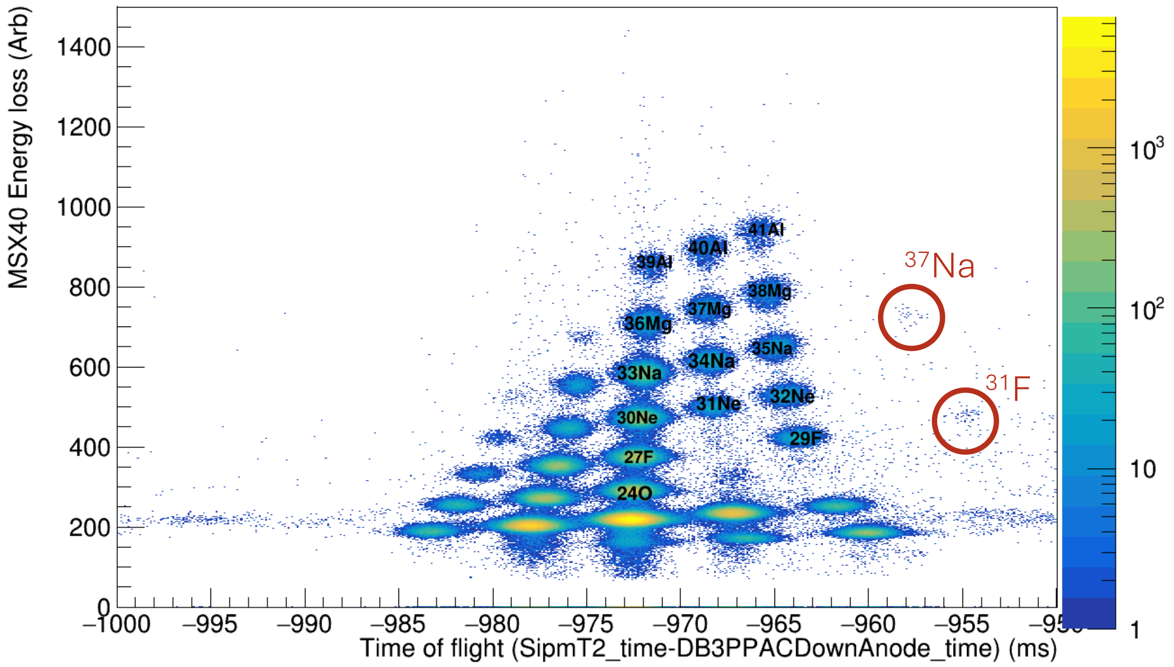

PHYSICAL REVIEW LETTERS **129,** 212501 (2022)

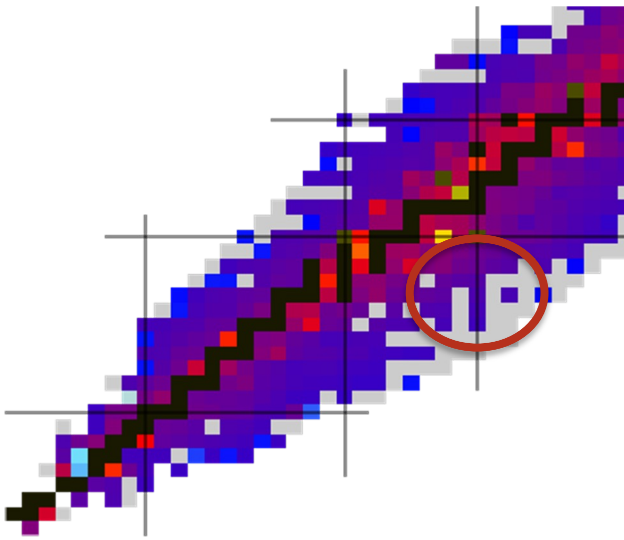
Editors' Suggestion Featured in Physics

Crossing $N = 28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

H. L. Crawford,[1,*] V. Tripathi,[2] J. M. Allmond,[3] B. P. Crider,[4] R. Grzywacz,[5] S. N. Liddick,[6,7] A. Andalib,[6,8] E. Argo,[6,8] C. Benetti,[2] S. Bhattacharya,[2] C. M. Campbell,[1] M. P. Carpenter,[9] J. Chan,[5] A. Chester,[6] J. Christie,[5] B. R. Clark,[4] I. Cox,[5] A. A. Doetsch,[6,8] J. Dopfer,[6,8] J. G. Duarte,[10] P. Fallon,[1] A. Frotscher,[1] T. Gaballah,[4] T. J. Gray,[3] J. T. Harke,[10] J. Heideman,[5] H. Heugen,[5] R. Jain,[6,8] T. T. King,[3] N. Kitamura,[5] K. Kolos,[10] F. G. Kondev,[9] A. Laminack,[3] B. Longfellow,[10] R. S. Lubna,[6] S. Luitel,[4] M. Madurga,[5] R. Mahajan,[6] M. J. Mogannam,[6,7] C. Morse,[11] S. Neupane,[5] A. Nowicki,[5] T. H. Ogunbeku,[4,6] W.-J. Ong,[10] C. Porzio,[1] C. J. Prokop,[12] B. C. Rasco,[3] E. K. Ronning,[6,7] E. Rubino,[6] T. J. Ruland,[13] K. P. Rykaczewski,[3] L. Schaedig,[6,8] D. Seweryniak,[9] K. Siegl,[5] M. Singh,[5] S. L. Tabor,[2] T. L. Tang,[2] T. Wheeler,[6,8] J. A. Winger,[4] and Z. Xu[5]

Decay Spectroscopy Near N=28
The Second Beam Time of E21062





^{31}F Q_β = 25.7 MeV decay into ^{31}Ne
^{37}Na Q_β = 24.9 MeV; decay into ^{37}Mg

Summary

- The structure of ^{40}Mg may be expected to manifest multiple influences
- Observed excitation energy spectrum in ^{40}Mg is outside expectations from systematics and theoretical predictions – possible evidence of weak-binding effects?
  - Weak binding / reduced pairing interaction may push the observed excitation energies in the right direction
  - Future planned experiments will (hopefully!) provide some clarity, or at least more data
- Future approved experiments will continue to probe ^{40}Mg as a halo candidate

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contracts No. DE-AC02-05CH11231 (LBNL).

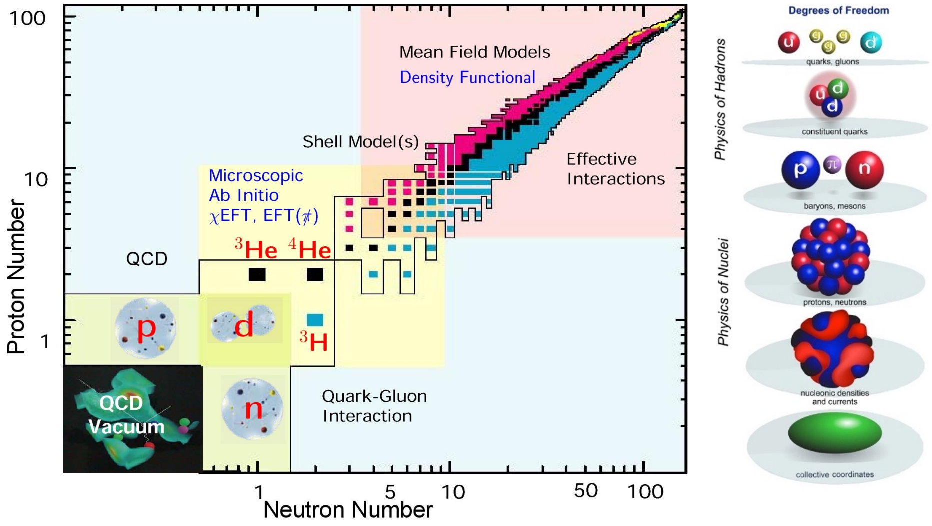
Thank you!

The Key Role of Theory

There has been and continues to be active development in theory toward the goal to “develop a predictive understanding of nuclei and their interactions grounded in fundamental QCD and electroweak theory”.

“New measurements drive new theoretical and computational efforts which, in turn, uncover new puzzles that trigger new experiments.”

“A strong interplay between theoretical research, experiment, and advanced computing is essential for realizing the full potential of … discoveries.”



Progress relies on understanding which measurements can best inform a given theory or approach – close collaboration through analysis and publication will maximize science output and impacts in nuclear structure.

Energy Levels in a Woods Saxon Potential

⇒ In a well bound nucleus
- steady evolution of energy levels in a 1 body potential
- modified by 2-body NN interaction (monopole average - $\sigma.\tau$, tensor)

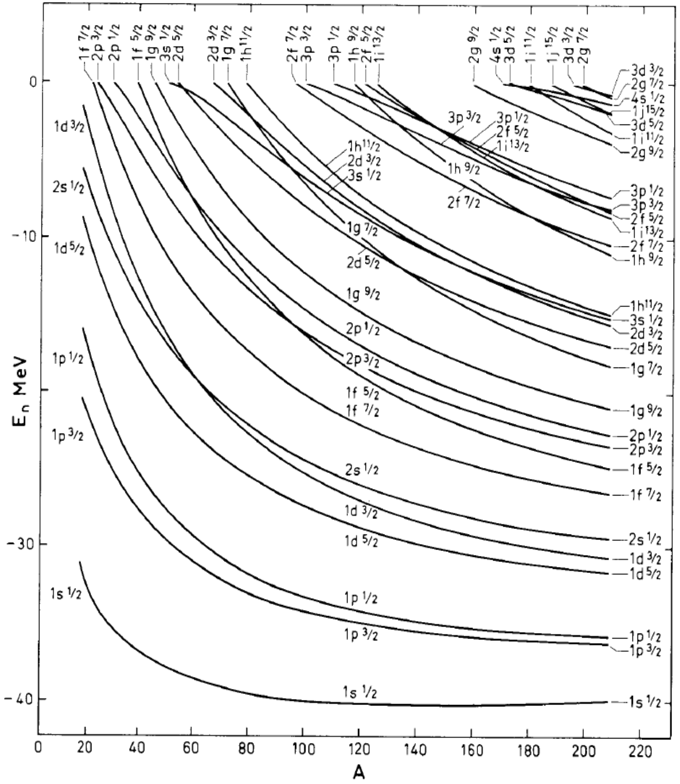


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

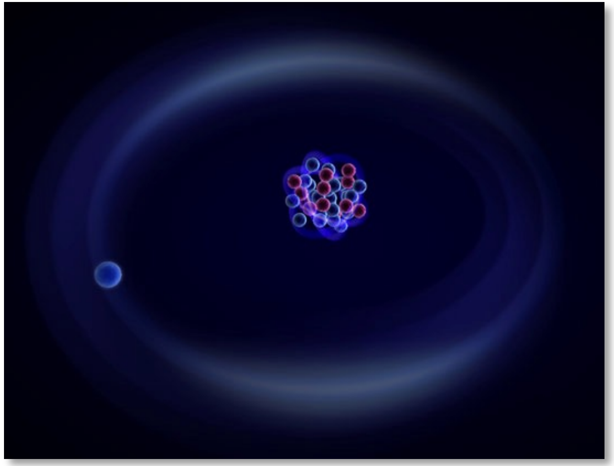
A.Bohr and B.R. Mottelson, vol. 1

Weak Binding Phenomena

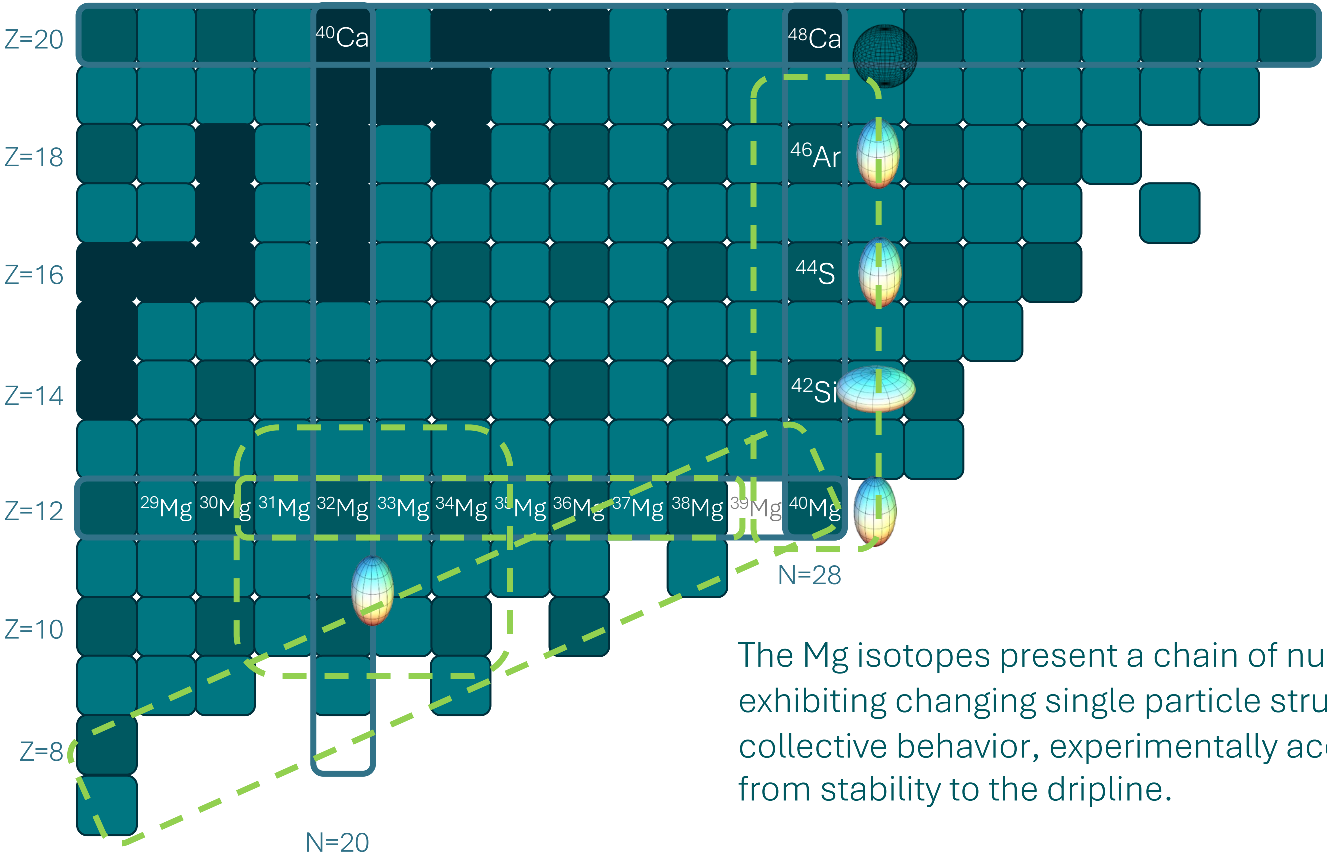
- Currently we know of examples of weak binding and delocalized wavefunctions giving rise to nuclear halos
- When we do have halo structures then what is the nature of the valence-core interaction?

Do the delocalized, weakly bound nucleons

- decouple from the core and/or
- couple to the continuum ?



^{40}Mg: The Intersection Point

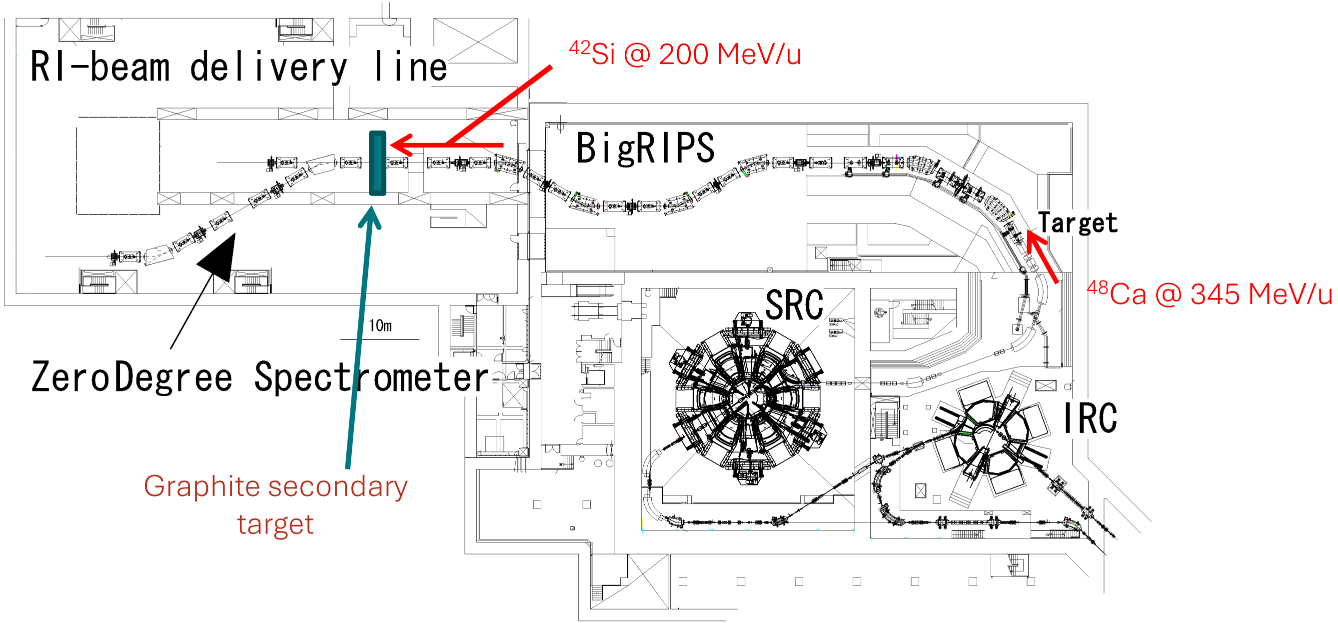


The Mg isotopes present a chain of nuclei exhibiting changing single particle structure and collective behavior, experimentally accessible from stability to the dripline.

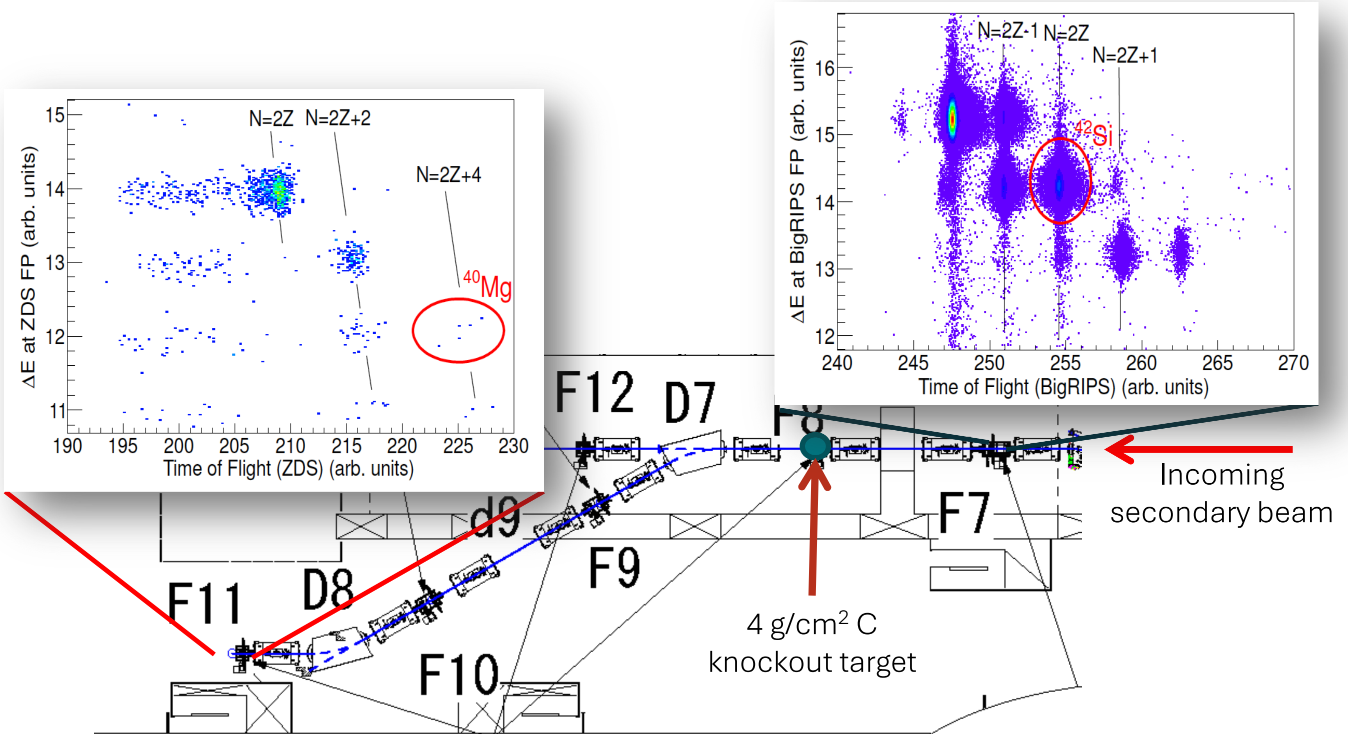
2010: Nucleon knockout at RIBF

December 2010 – Sunday Campaign (NP1312-RIBF03)

^{42}Si produced following fragmentation of a high-intensity ^{48}Ca primary beam at RIBF in RIKEN



2p knockout: ^{42}Si into ^{40}Mg



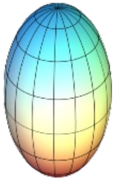
- Approximately 10 hours of beam-on-target
- 5 events of ^{40}Mg observed -- measured inclusive $\sigma_{(-2p)}$ of 40(18) μb

^{40}Mg: Where we left it in 2014

Based on the inclusive cross-section from ^{42}Si(-2p):

- ^{40}Mg likely only has one bound 0^+ state (the ground state)
- The ground state deformation is likely opposite in sign to that of ^{42}Si

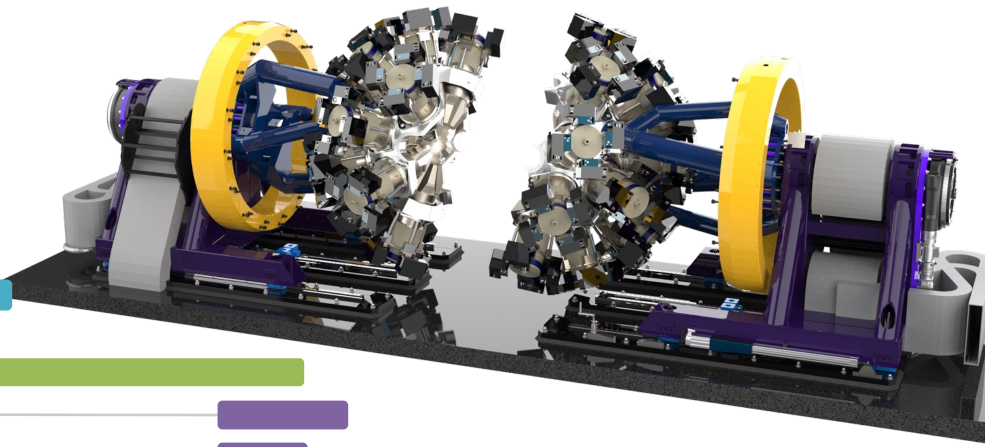
^{40}Mg

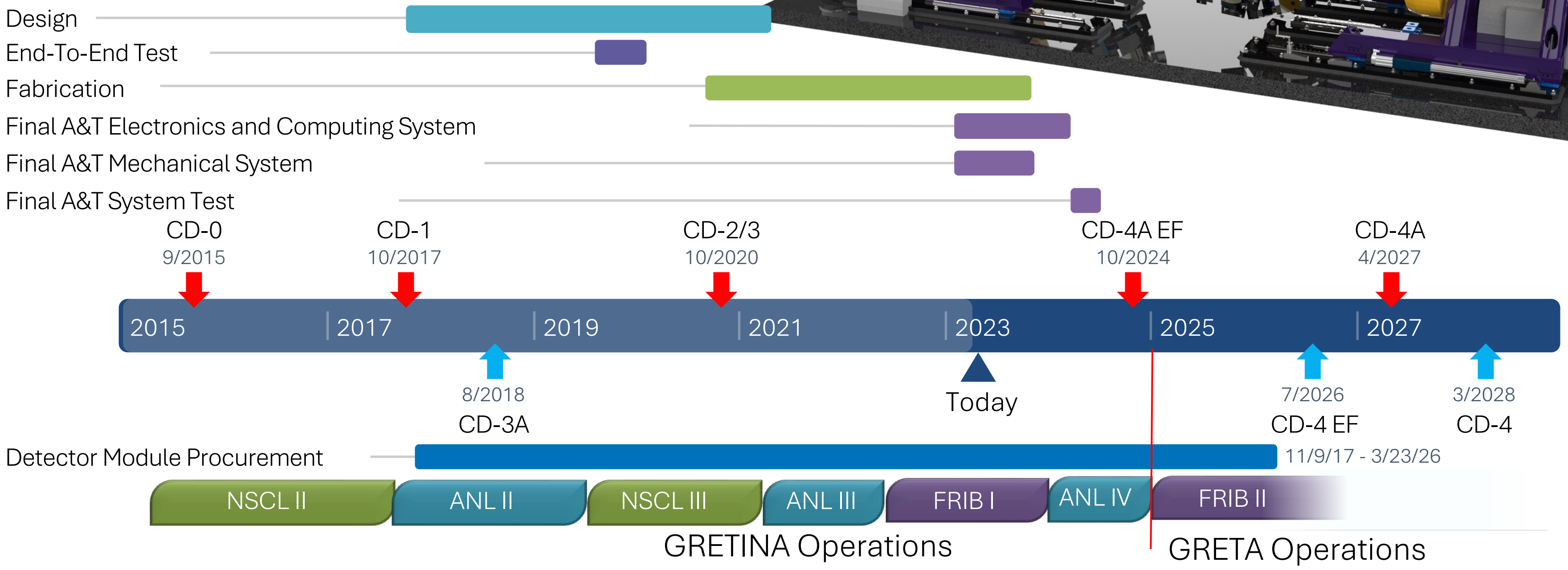


Open questions:

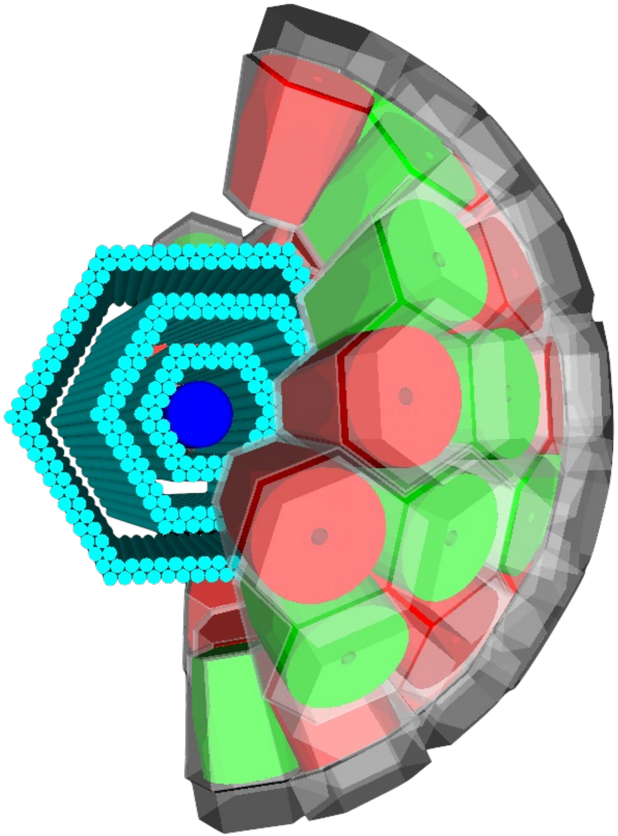
- Are there any bound excited states? (S_n = 1.300(700) MeV)
- Is E(2^+) in line with expectations from shell-model?
- Is the ground state consistent with prolate deformation?
- Is there evidence for weak-binding effects in the spectrum of ^{40}Mg?

GRETA

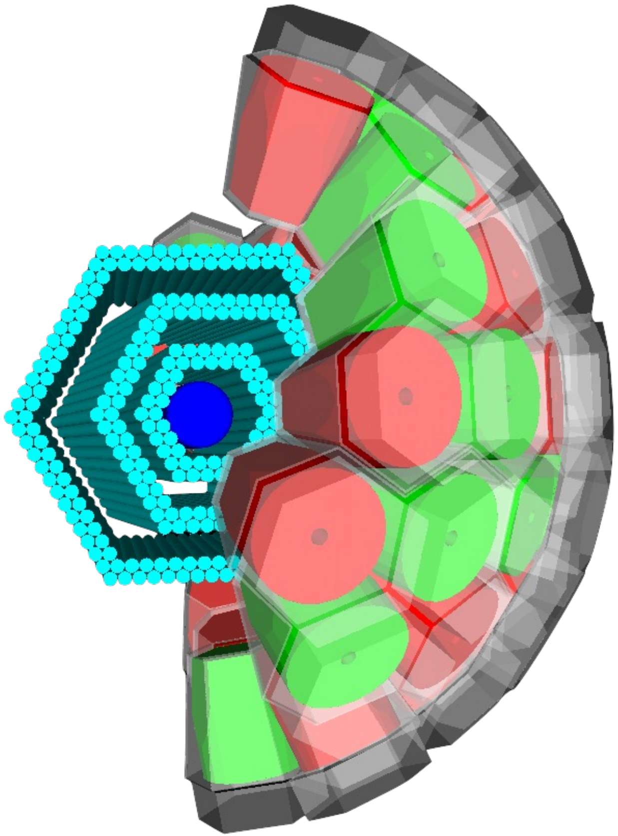



Design
End-To-End Test
Fabrication
Final A&T Electronics and Computing System
Final A&T Mechanical System
Final A&T System Test
CD-0
9/2015
CD-1
10/2017
CD-2/3
10/2020
CD-4A EF
10/2024
CD-4A
4/2027
2015
2017
2019
2021
2023
2025
2027
8/2018
CD-3A
Today
7/2026
CD-4 EF
3/2028
CD-4
Detector Module Procurement
11/9/17 - 3/23/26
NSCL II
ANL II
NSCL III
ANL III
FRIB I
ANL IV
FRIB II
GRETINA Operations
GRETA Operations

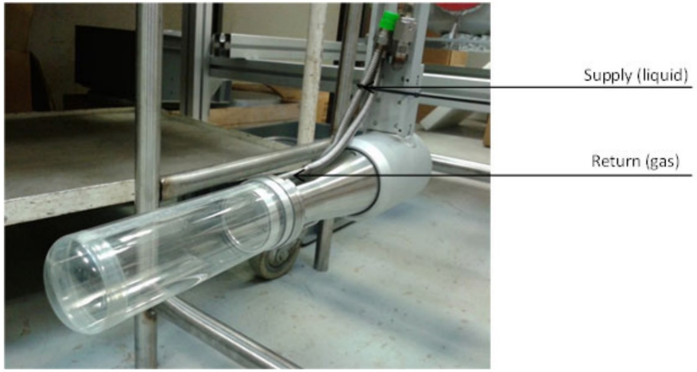
Extended Proton Tracking Target to Maximize Luminosity

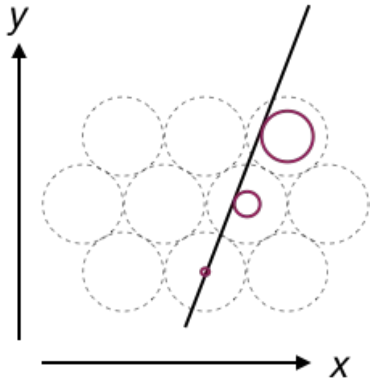


Extended Proton Tracking (ExPrT) Target to Maximize Luminosity



- Take the MINOS LH_2 target (developed by A. Obertelli et al.) as inspiration
- An extended (5-15 cm) LH_2 cell will be surrounded by a compact configuration of straw-tube (small diameter gas counters) detectors for proton detection and vertex reconstruction





Extended Proton Tracking Target to Maximize Luminosity