Production of ^{40}Mg Following 2p Knockout from ^{42}Si

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OUTLINE

- Introduction
  - Evolution of nuclear shell structure
  - Structure approaching the neutron dripline
  - Shape evolution along the N=28 isotones below $_{20}$Ca
- Two-proton knockout at RIBF RIKEN
  - Cross-section for 2p knockout from ^{42}Si
  - Understanding the inclusive cross-section in comparison to shell-model
  - Nature of the ^{40}Mg ground state

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Evolution of Single-Particle States

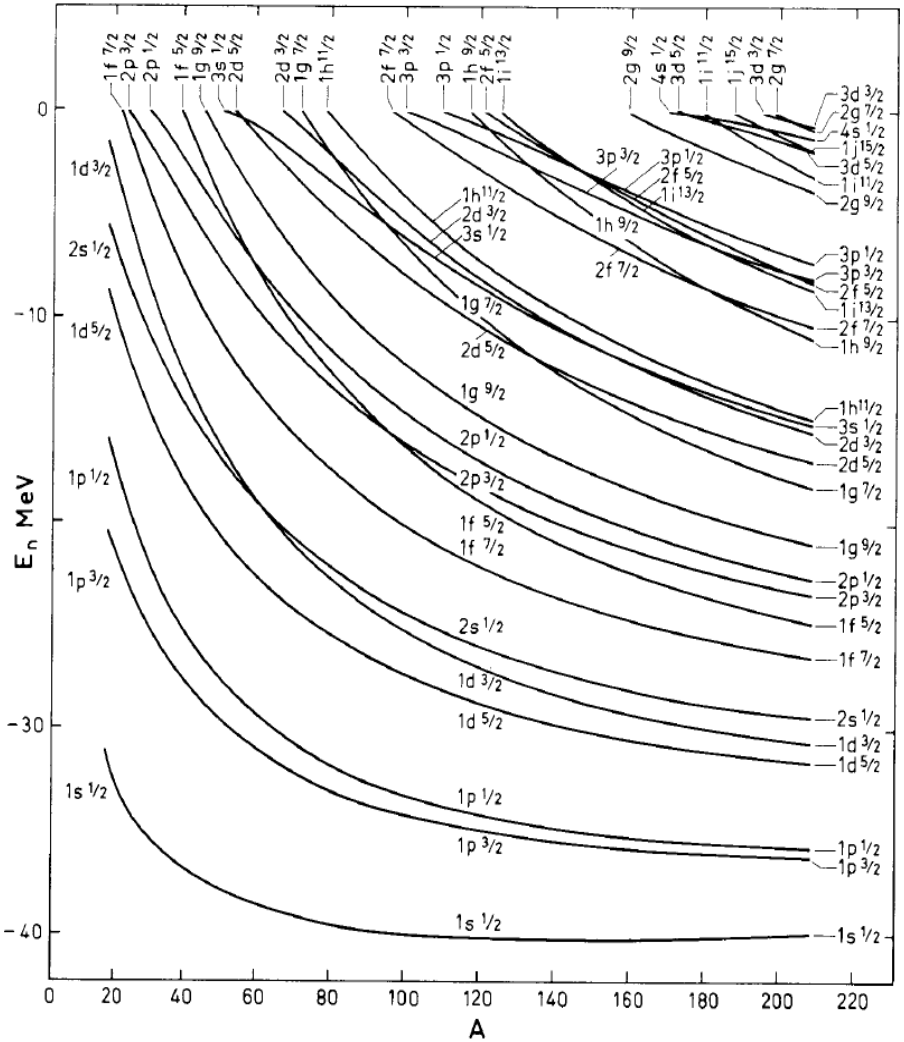
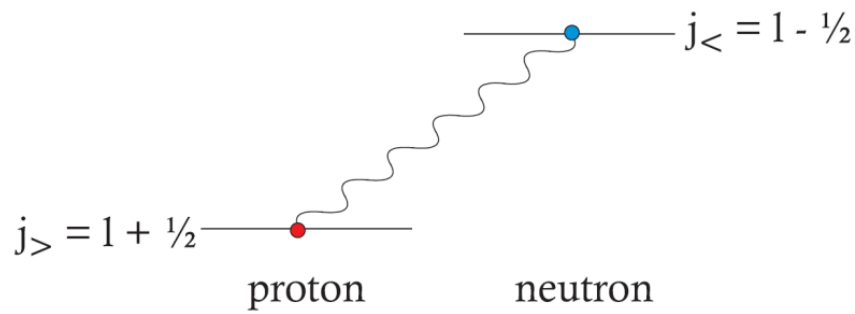
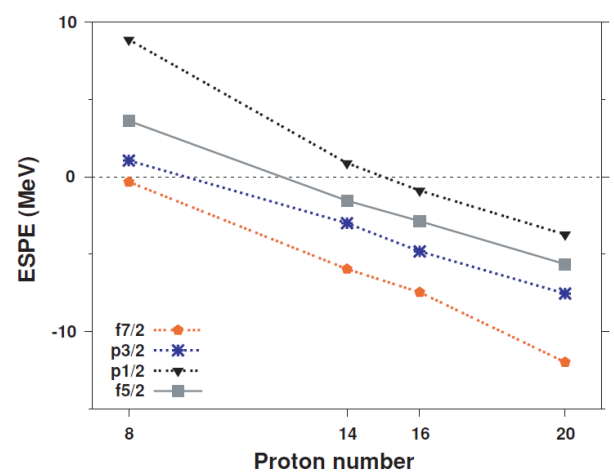


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

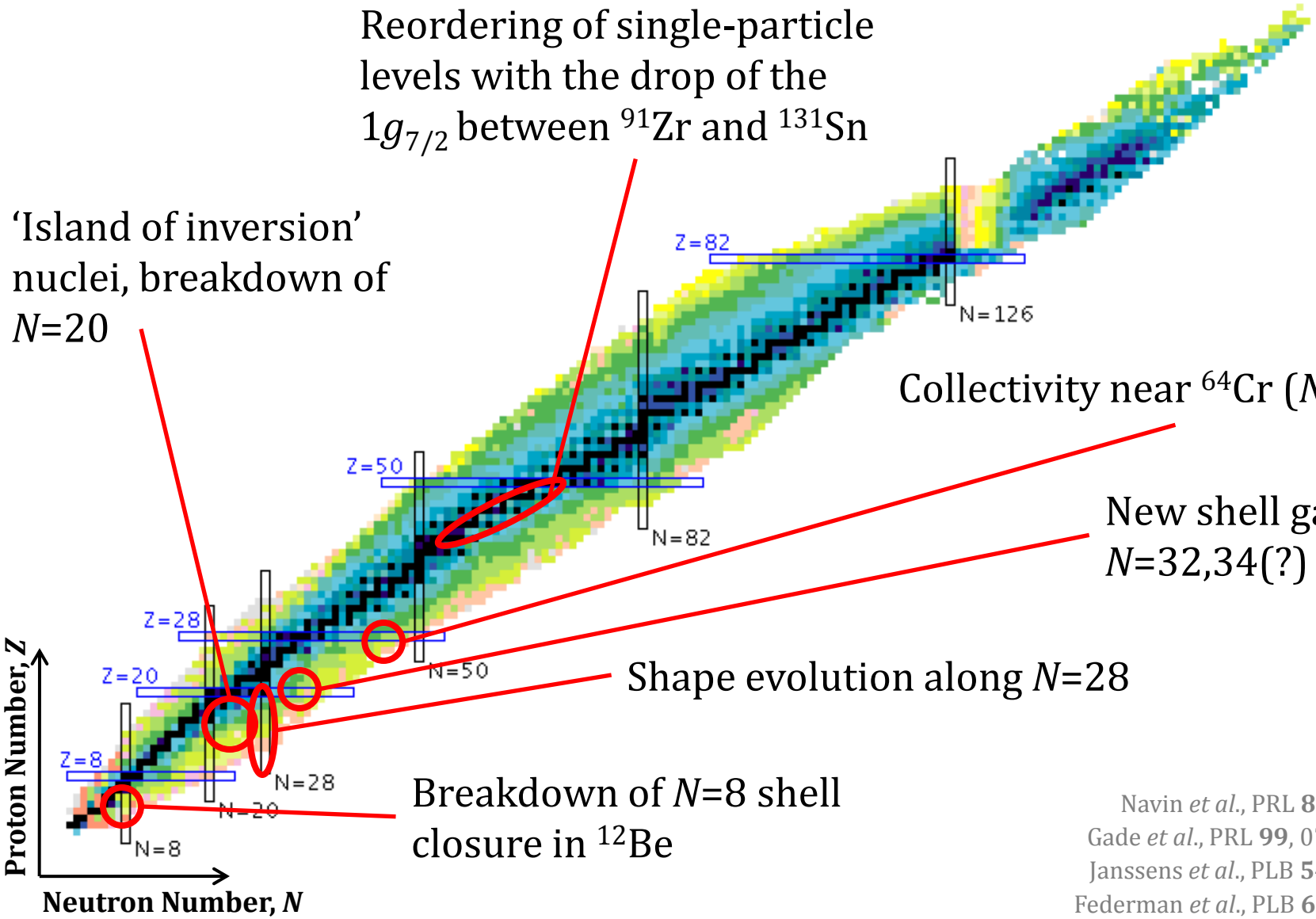
- In a well-bound nucleus:
  - Steady evolution of energy levels within a 1-body potential
  - 2-body (NN) interactions modify this evolution (i.e. tensor interaction)





A.Bohr and B.R. Mottelson, vol. 1
F. Nowacki and A. Poves, PRC **79**, 014310 (2009).

Shell Structure Across the Nuclear Landscape



Reordering of single-particle levels with the drop of the $1g_{7/2}$ between ^{91}Zr and ^{131}Sn

'Island of inversion' nuclei, breakdown of N=20

Collectivity near ^{64}Cr (N=40)

New shell gaps at N=32,34(?) in Ca

Shape evolution along N=28

Breakdown of N=8 shell closure in ^{12}Be

Navin *et al.*, PRL **85**, 266 (2000).
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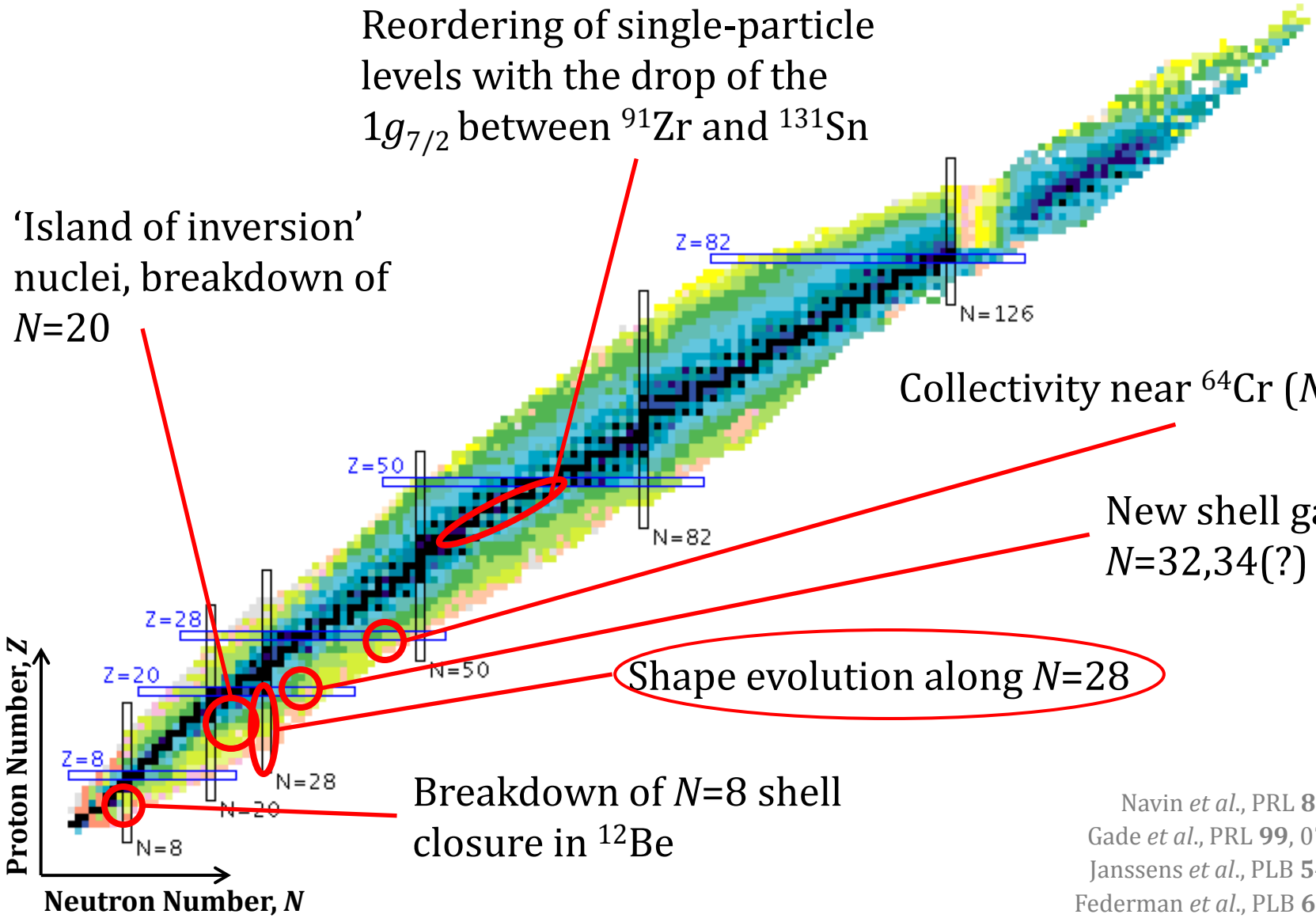

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Shell Structure Towards the Dripline

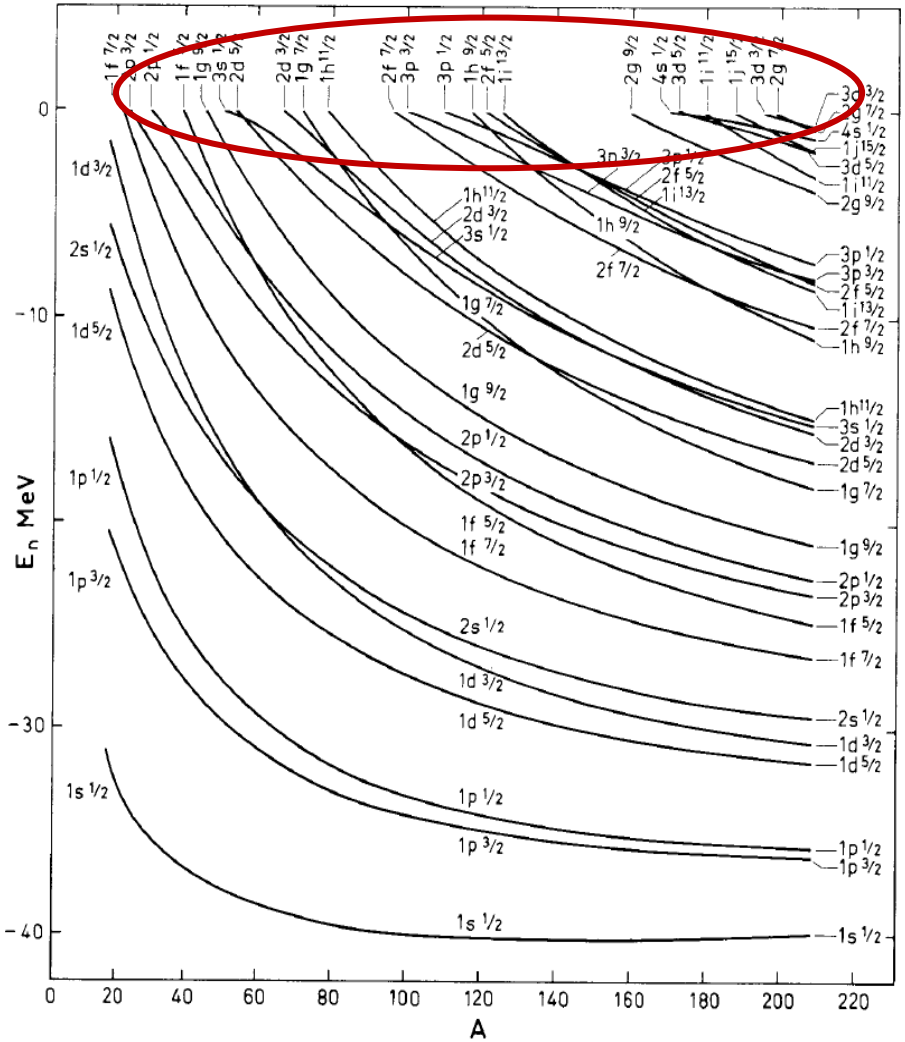
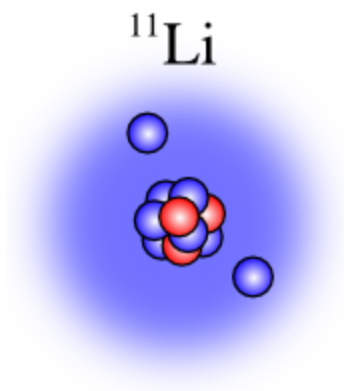


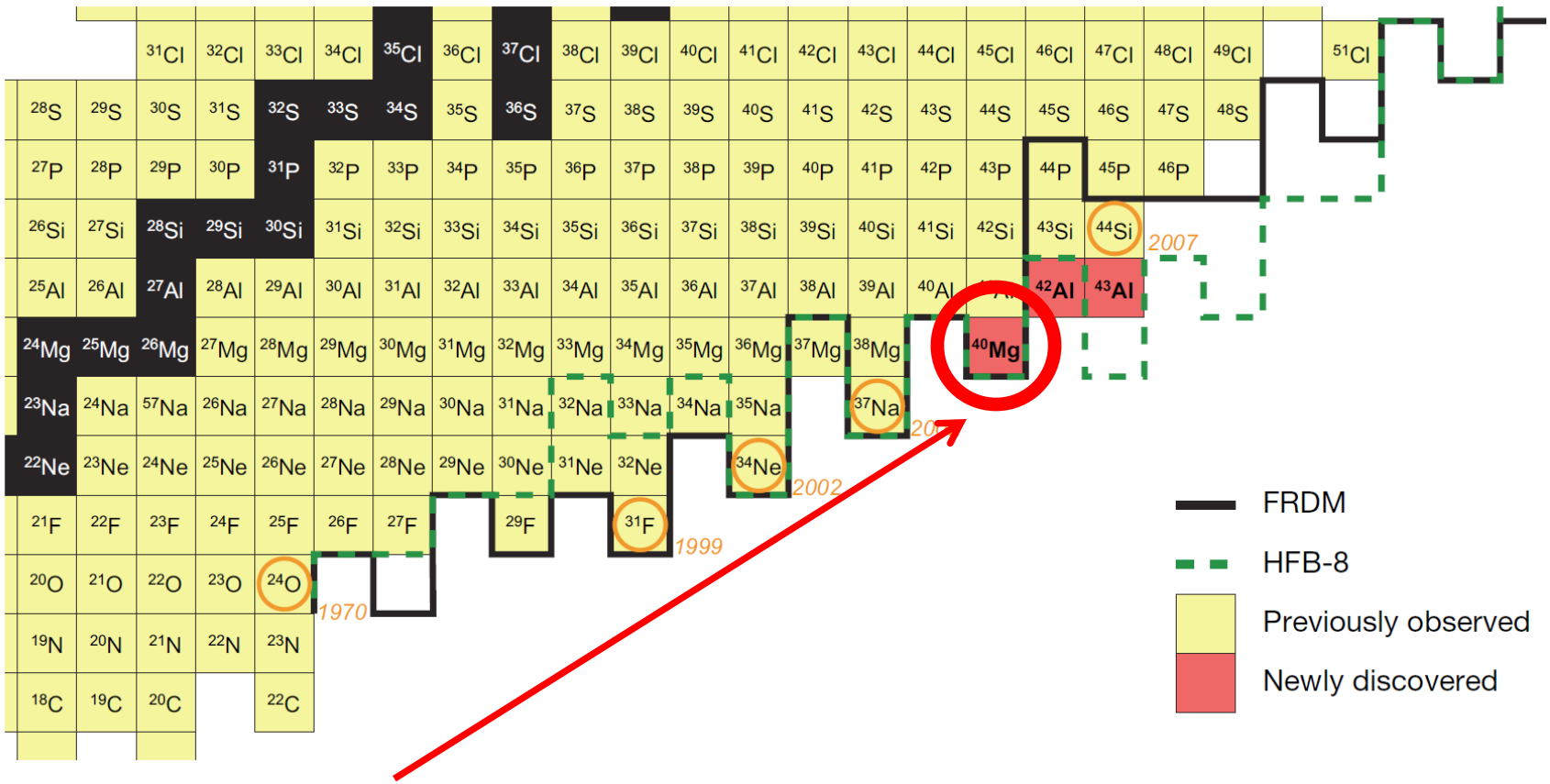
Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

- A second distinct effect is introduced due to weakly bound levels
  - Low *l* levels → extended wavefunctions ("halos")



  - Valence nucleons decouple from the core, coupling to continuum states

Mapping the Dripline in the *sd* Shell



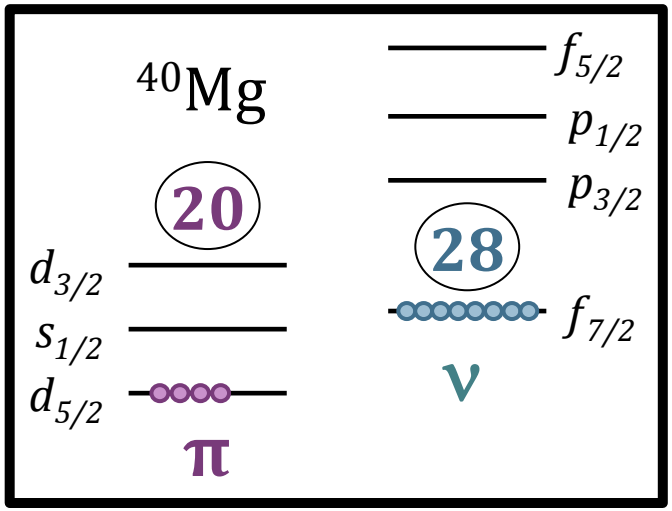
Only 5 years ago, ^{40}Mg was first observed at NSCL, and beam intensities are now approaching those required to perform spectroscopy in this nucleus.

With present-day facilities, ^{40}Mg may be one of the heaviest drip-line(?) nuclei experimentally accessible.

Baumann *et al.*, Nature **449**, 1022 (2007).

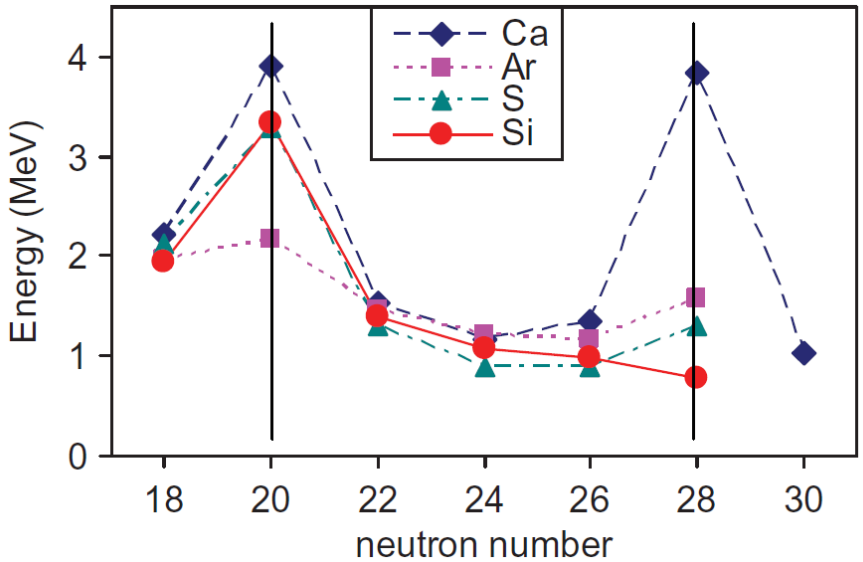
Toward the Dripline at Z=12

^{40}Mg is at the edge of the experimentally-known neutron dripline, and the last bound neutron orbital is expected to be the $1p_{3/2}$ state.



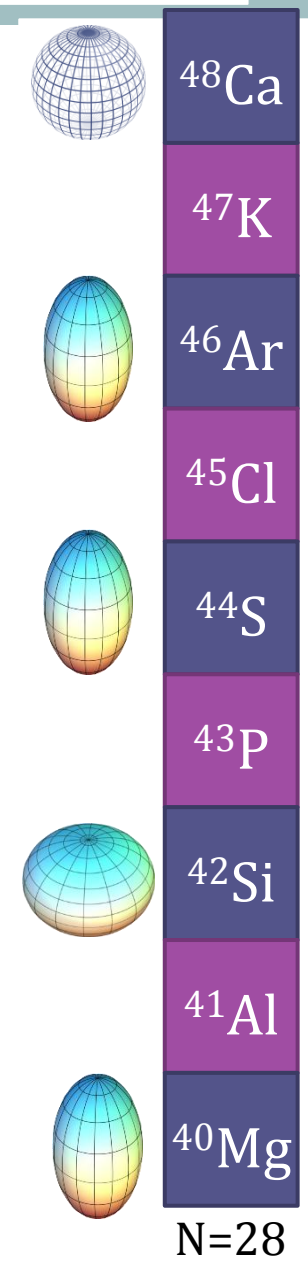
Neutron configuration with l=1 occupancy can lead to formation of neutron halo.

N=28 Isotones Below $_{20}$Ca



At Z=20, N=28 is a good shell gap, and ^{48}Ca is a spherical, doubly-magic nucleus

Below Z=20, E(2+) and B(E2) data provided first indications that N=28 was no longer magic.



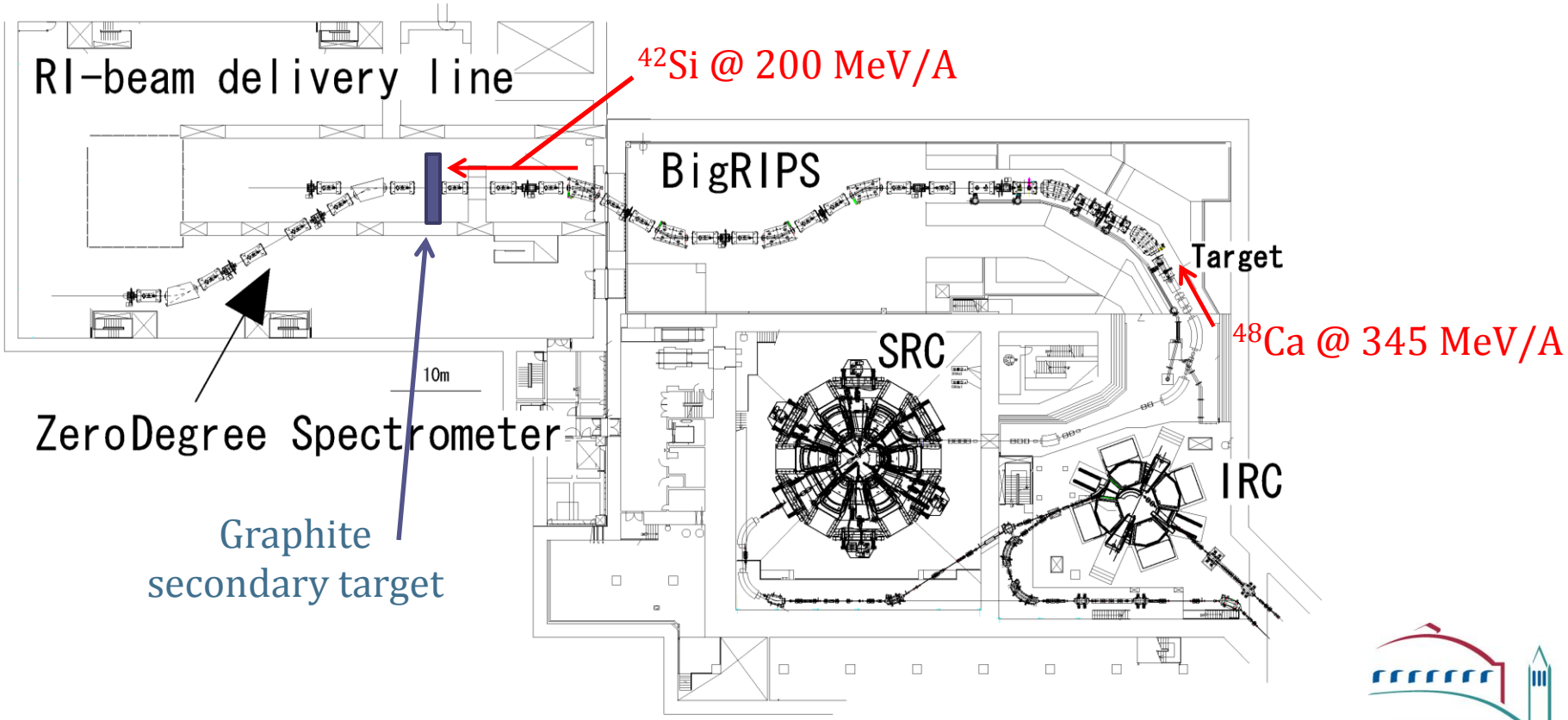
Quenching of the N=28 gap leads to deformation, predicted in both shell-model and relativistic mean-field calculations.

Rapid shape evolution and shape coexistence are also predicted in theoretical approaches.

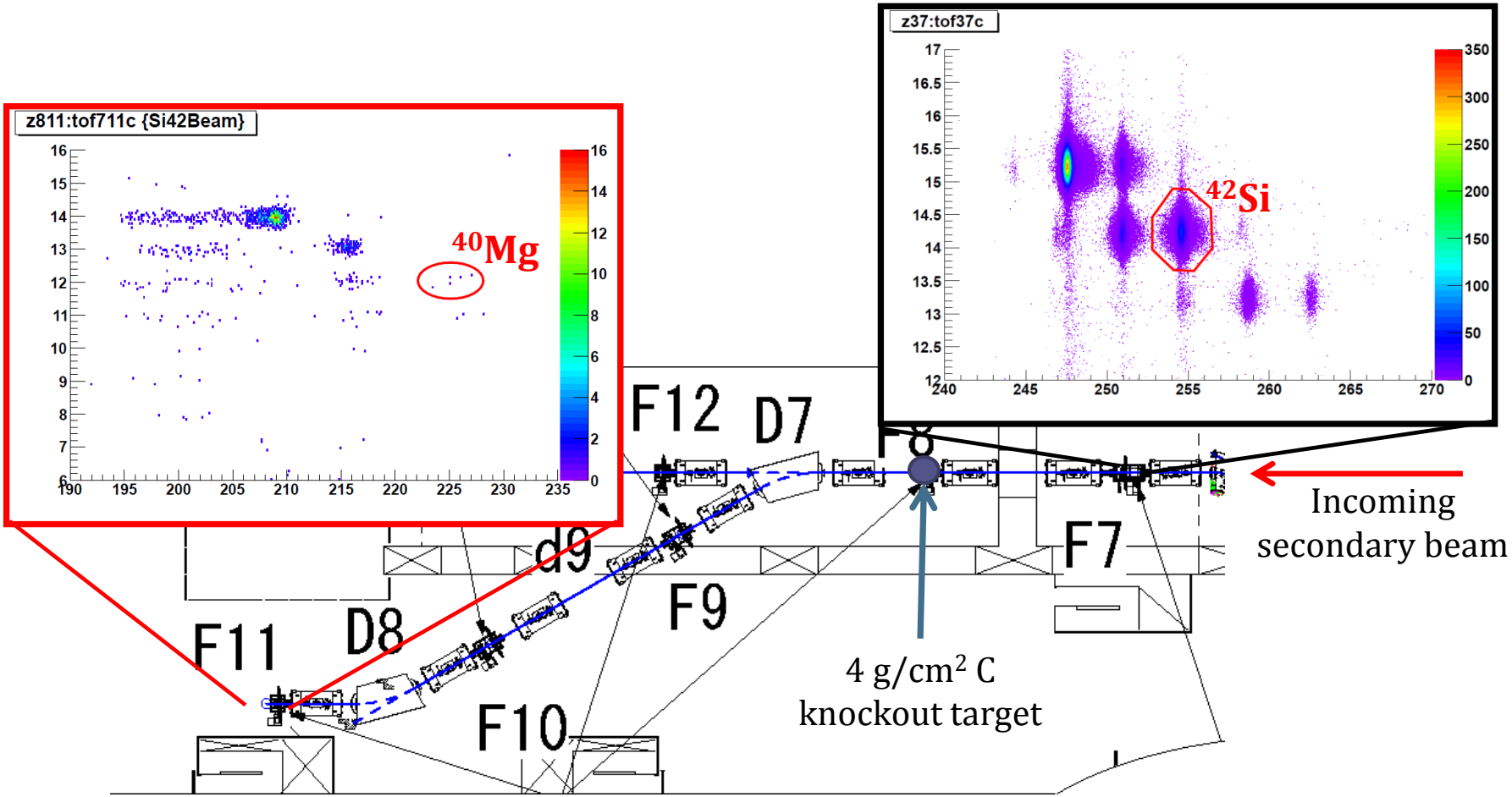
Gaudefroy and Grevy, Nucl. Phys. News **20**, 13 (2010).
Li *et al.*, PRC **84**, 054304 (2011). Nowacki and Poves, PRC **79**, 014310 (2009).

Nucleon Knockout at RIBF

- High intensity of ^{48}Ca primary beam at RIBF in RIKEN made possible measurement of ^{42}Si 2p knockout to ^{40}Mg
- ^{42}Si produced at a rate of 25 pps/100 pnA following fragmentation of a ^{48}Ca beam



2p Knockout – ^{42}Si into ^{40}Mg



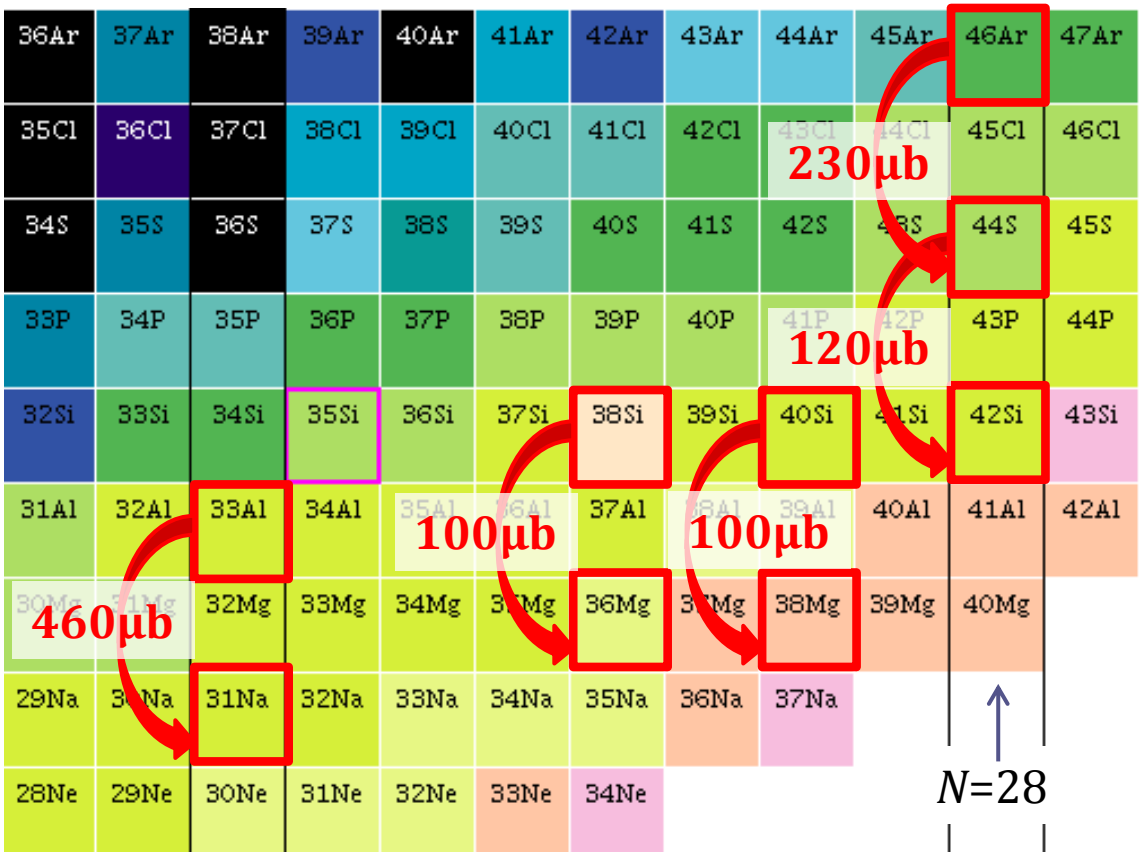
- Knockout from 200MeV/A ^{42}Si on a 4 g/cm^2 target
- Based on 5 observed ^{40}Mg, measured inclusive 2p knockout cross-section of ~40 μb.

What Do We Expect?

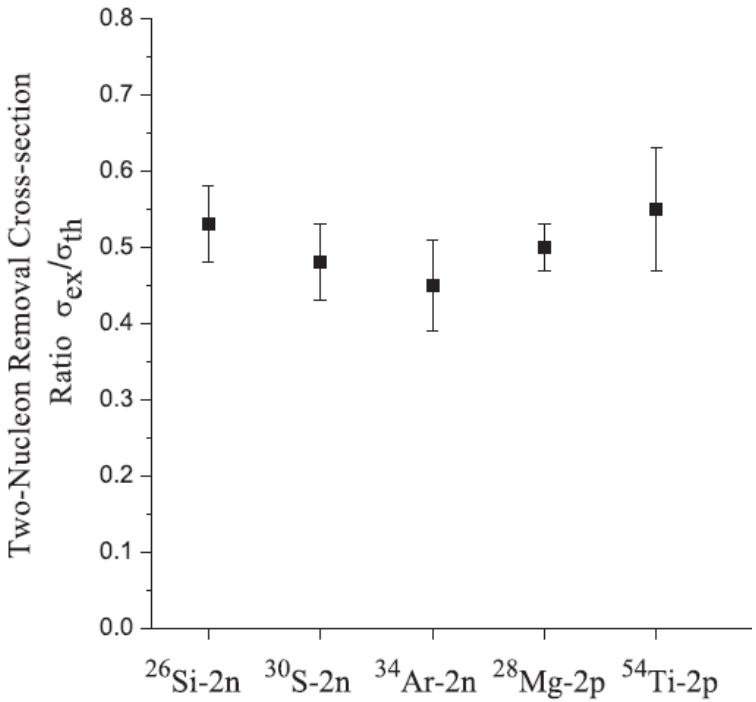
$\sigma_{-2p\ (inclusive)}\ (^{42}Si \rightarrow {}^{40}Mg) = 40\ \mu b$

In this region, 2p inclusive removal cross-sections are nominally on order of a few hundred μb

⇒ cross-section into ^{40}Mg appears to be low



2p Knockout Cross-Section Suppression?



Two nucleon knockout experiments have suggested suppression of experimentally observed inclusive cross-sections by factor of ~2 compared to theoretical values.

Fallon *et al.*, PRC **81**, 041302(R) (2010).

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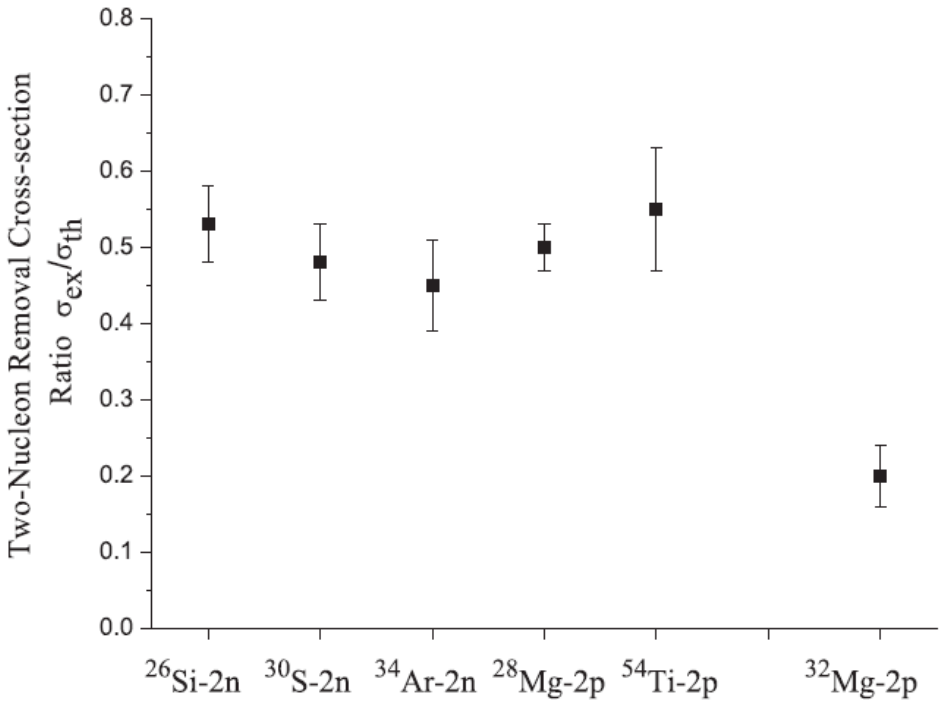

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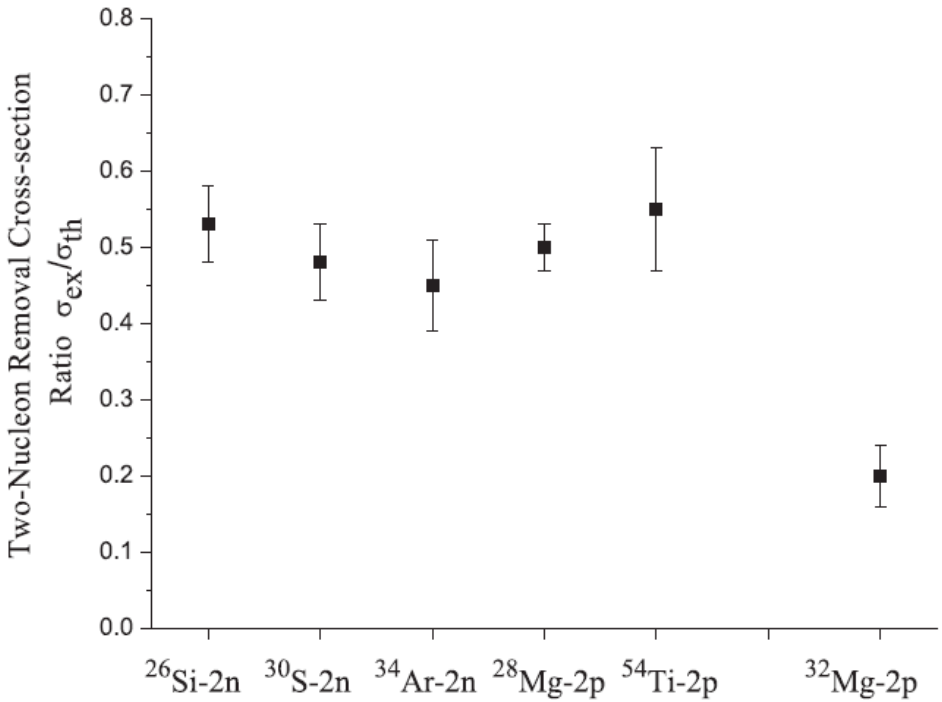

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Additional suppression has been attributed to nuclear structure effects.

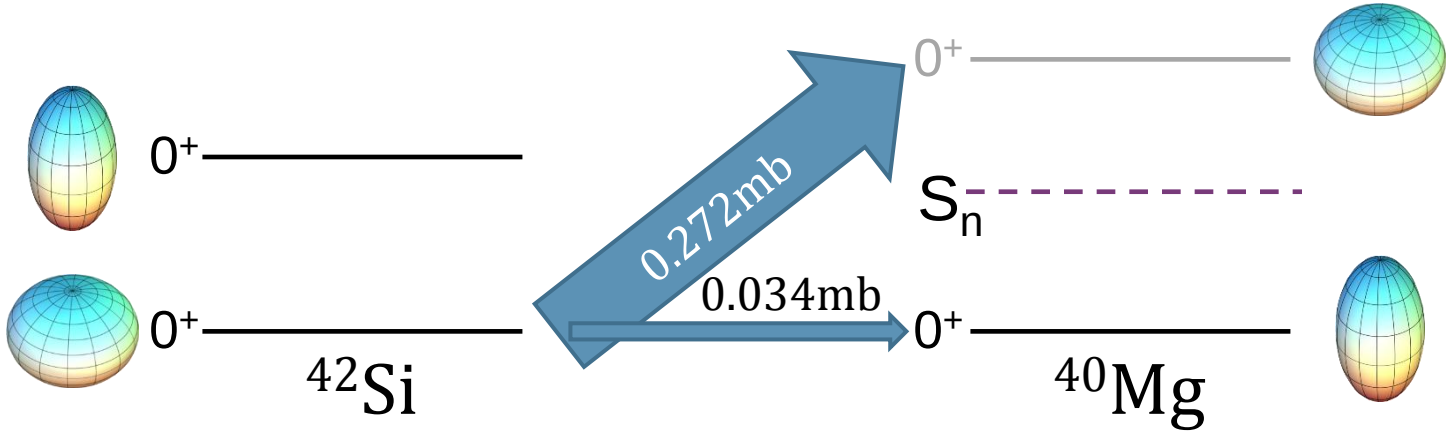
If we assume that ^{42}Si → ^{40}Mg + 2p should have a suppression of ~0.5, what can we learn from the shell-model?

Fallon *et al.*, PRC **81**, 041302(R) (2010).

Shell Model Interpretation

Using TNAs from shell-model calculations using the SDPFU(Si) effective interaction, reaction theory predicts the following for ^{42}Si 2p knockout:

^{40}Mg State	Calculated σ (mb)
0+ (g.s.)	0.034
2+	0.008
4+ (unbound)	0.001
0_2+ (unbound)	0.272



Knockout from the ^{42}Si g.s.

Calculations from. B.A. Brown and J. Tostevin
Nowacki and Poves, PRC **79**, 014310 (2009).

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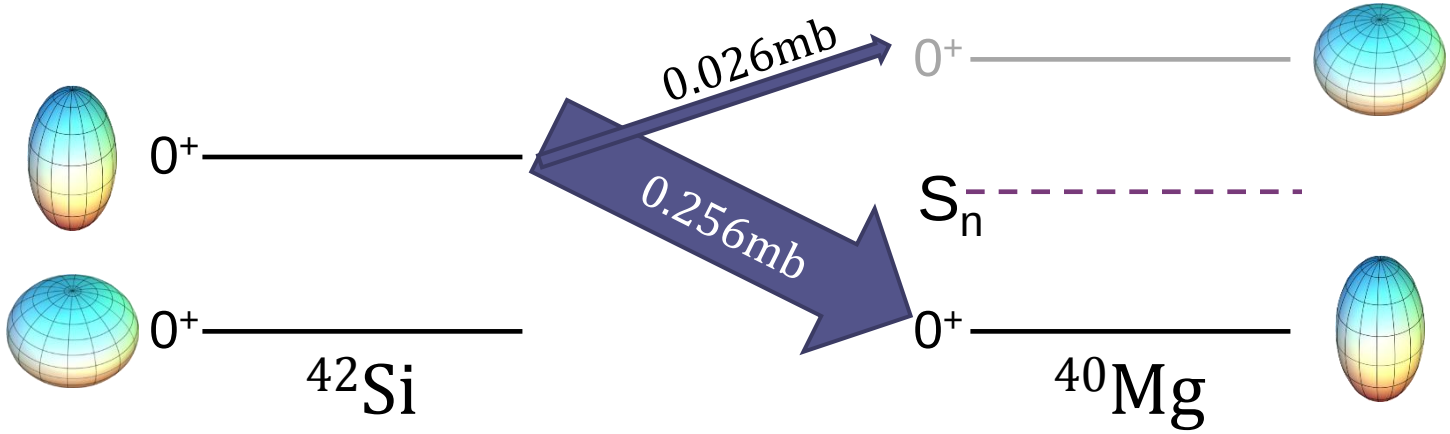


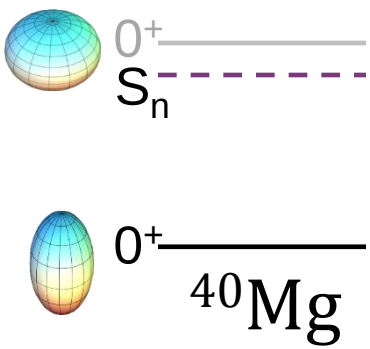
Knockout from the ^{42}Si first excited 0+ state

Calculations from. B.A. Brown and J. Tostevin
Nowacki and Poves, PRC **79**, 014310 (2009).

Accounting for Suppression in ^{40}Mg

- Based on suppression of well-described two-nucleon knockouts, expect 2p knockout to have a similar suppression of ~0.5
- Assuming a 0.5 suppression, we can consider the structural possibilities for ^{40}Mg

^{40}Mg State	Experiment (μb)	Calculated σ (μb)	Calculated σ (μb)	Calculated σ (μb)
0+ (g.s.)	--	17		
2+	--	4		
4+	--	0.5		
0_2+	--	136		
Inclusive	**40(20)**	**21**		



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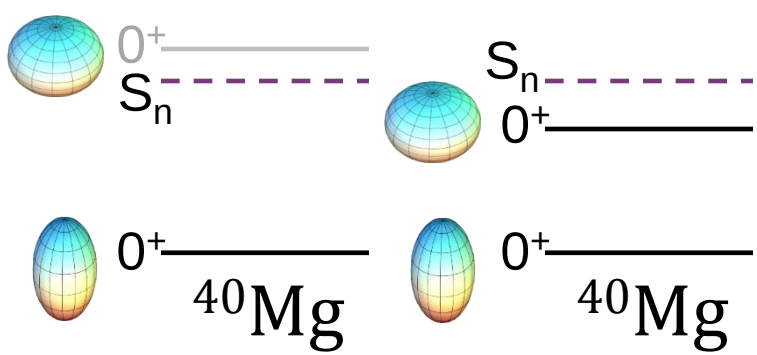

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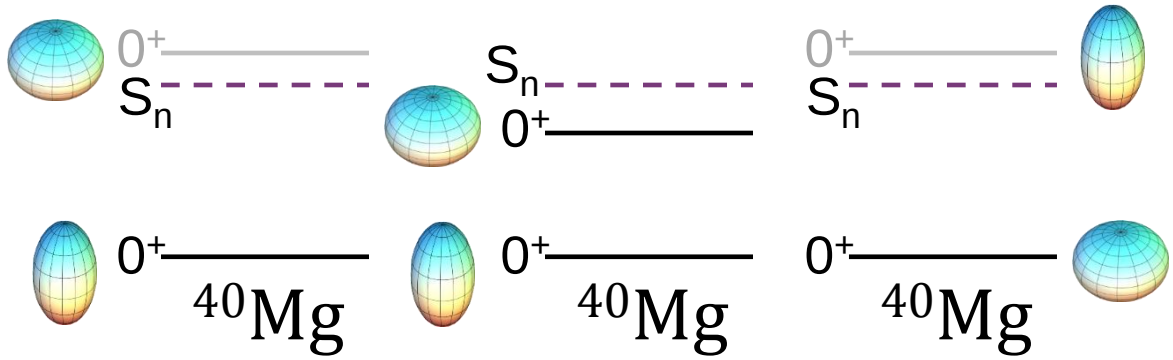

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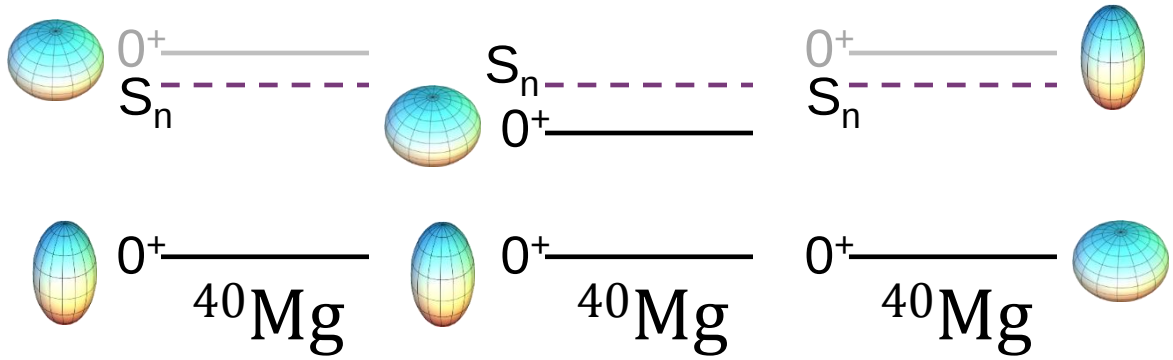
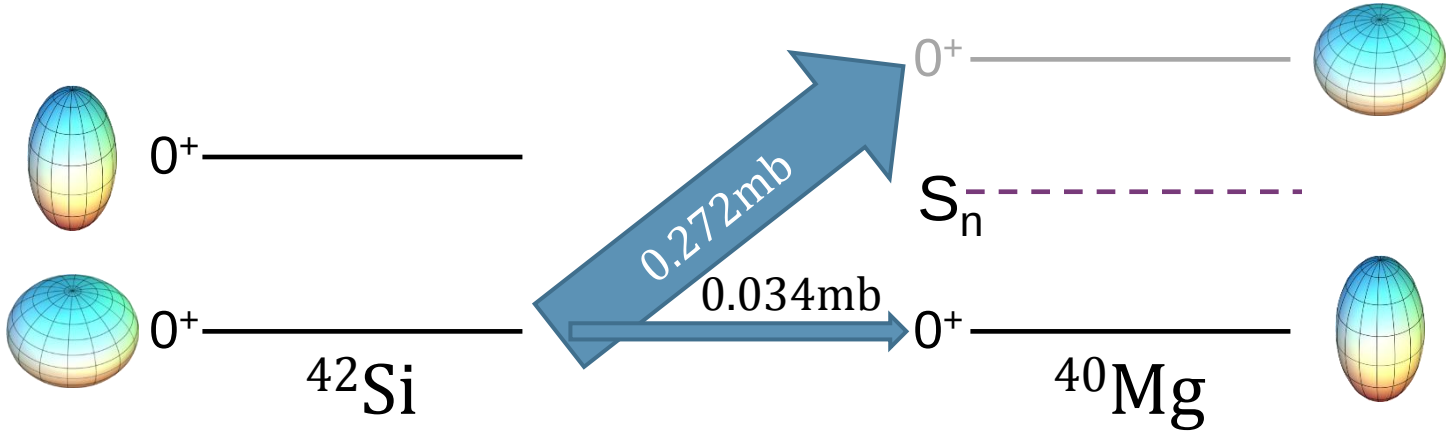


CONCLUSIONS

- Beam intensities available at RIBF have made possible first direct reaction experiments to study ^{40}Mg
- Proton knockout cross-sections from ^{42}Si have been measured at RIBF
- Under the assumption of an expected 0.5 suppression relative to shell-model + reaction theory, ^{40}Mg appears to have a ground state configuration different than ^{42}Si (i.e. prolate vs. oblate), while the second major configuration (i.e. oblate configuration) is unbound



Knockout from the ^{42}Si g.s.

Acknowledgements

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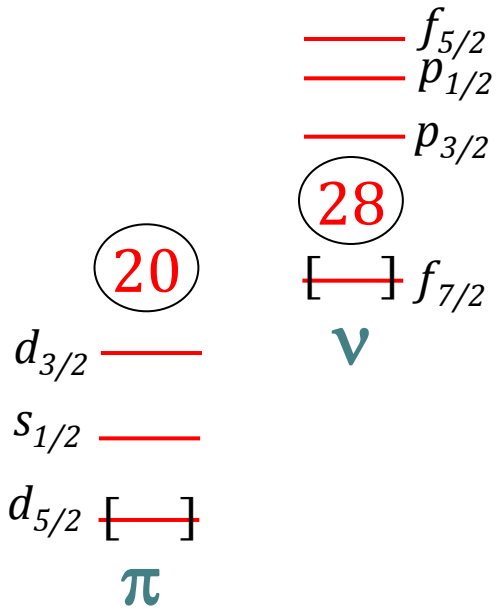
T.L. Bleis

Thank You!

N=28 Isotones Below $_{20}$Ca



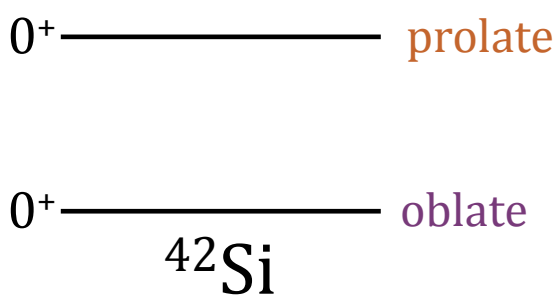
Role of the $\pi d_{5/2} - \nu f_{7/2}$ interaction

Reduction of the N=28 shell gap allows correlations to build up, and leads to well-deformed configurations.

Some data is available down to ^{42}Si, but not below – with ^{41}Al and ^{40}Mg (observed only in 2007), how does evolution proceed? Does weak-binding of these nuclei affect the structure?

What is the Nature of ^{42}Si?

	$A = 36$	$A = 38$	$A = 40$	$A = 42$	$A = 44$
$E^*(2_1^+)$ th.	1.36	0.96	0.80	0.82	0.87
$E^*(2_1^+)$ exp.	1.40	1.08	0.99	0.77	
$B(E2)(2_1^+ \rightarrow 0_1^+)$ th.	34	39	54	86	44
$B(E2)(2_1^+ \rightarrow 0_1^+)$ exp.	39(12)	38(14)			
$Q_s(2_1^+)$ th.	+3	−9	−9	+20	+4
$E^*(4_1^+)$ th.	2.74	1.83	1.99	1.79	2.53
S_{2n} th.	9.82	8.33	7.04	5.61	3.47

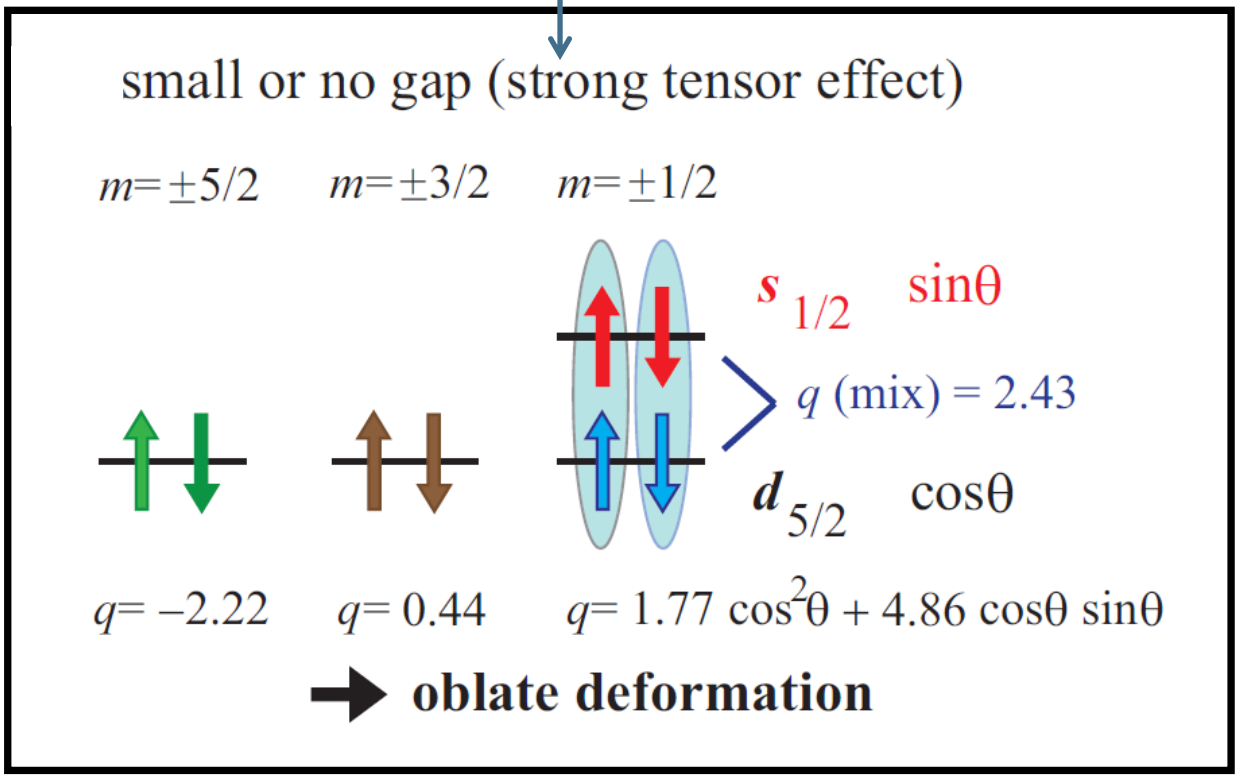


Shell-model calculations predict the g.s. in ^{42}Si to be oblate-deformed, and predict a second 0+ at 1.08 MeV with a similar absolute quadrupole moment, but opposite sign.

Nowacki and Poves, PRC **79**, 014310 (2009).

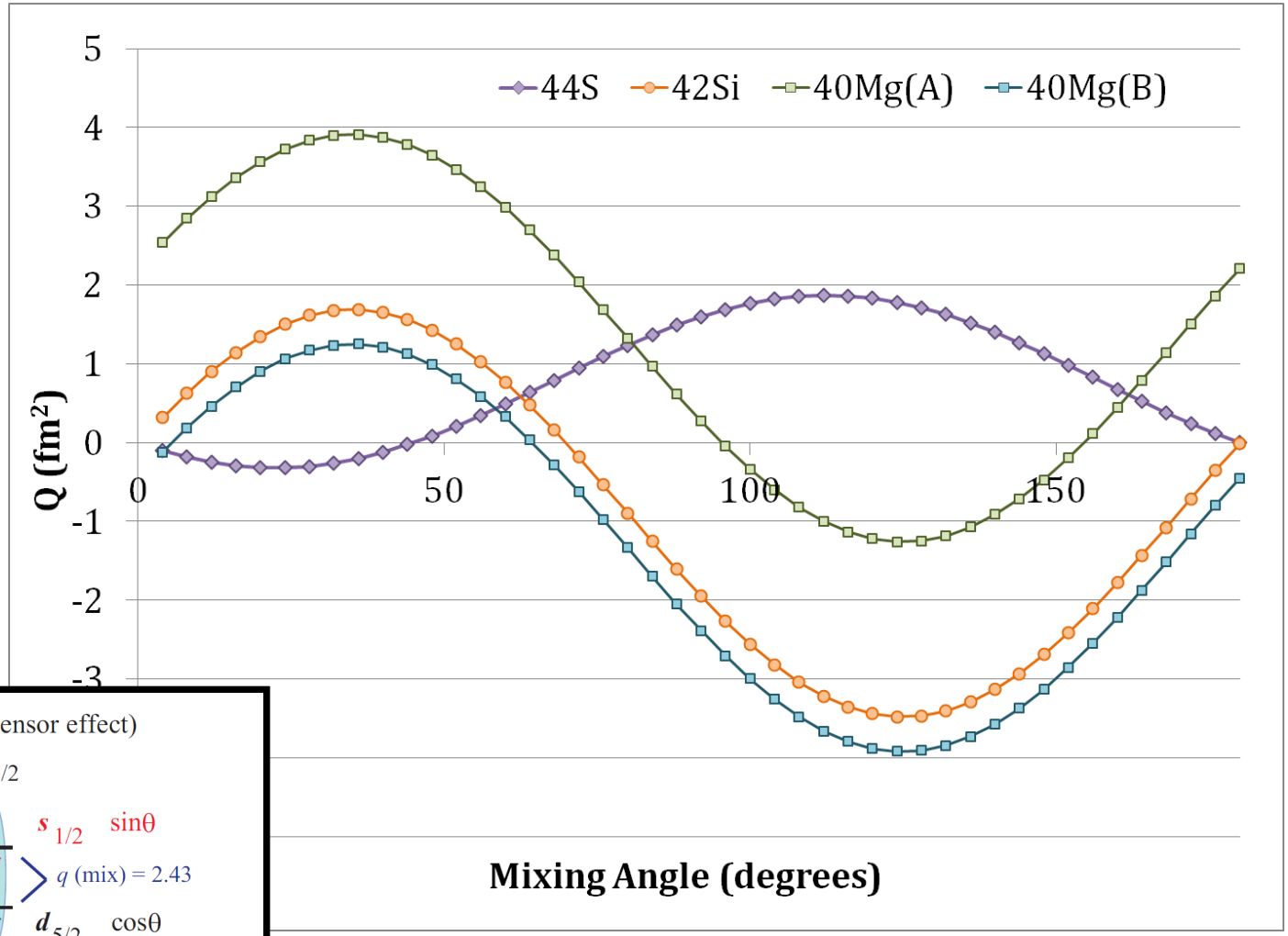
Understanding Oblate ^{42}Si

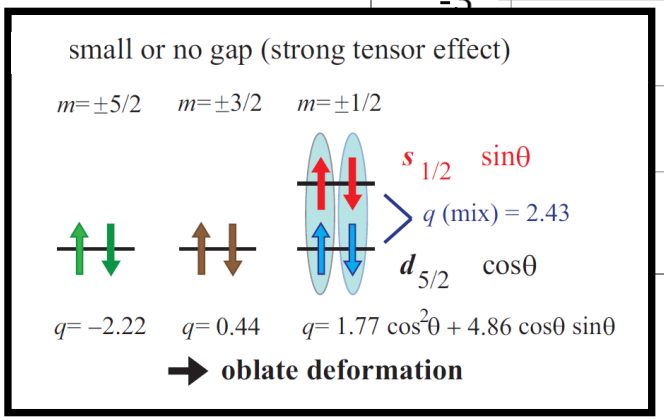
Neutrons filling the $1f_{7/2}$ orbital up to N=28 have strongly repulsive monopole interaction with $1d_{5/2}$ protons, causing a narrowing of the $d_{3/2}$-$d_{5/2}$ spin-orbit splitting, and **$1d_{5/2}$-$2s_{1/2}$ gap**



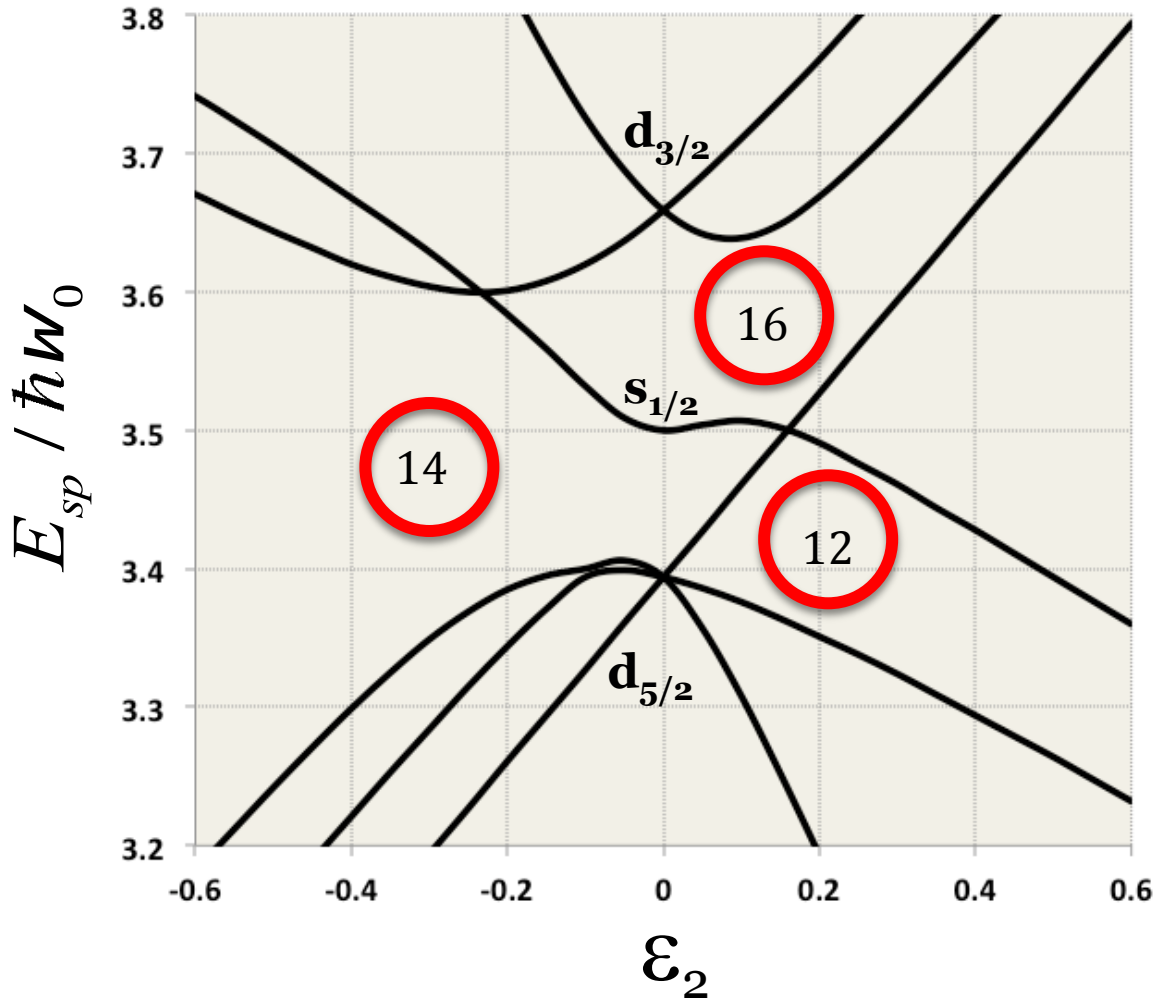
Utsuno *et al.*, arXiv:1201.4077v1 (2012).

Shapes Along the N=28 Isotones

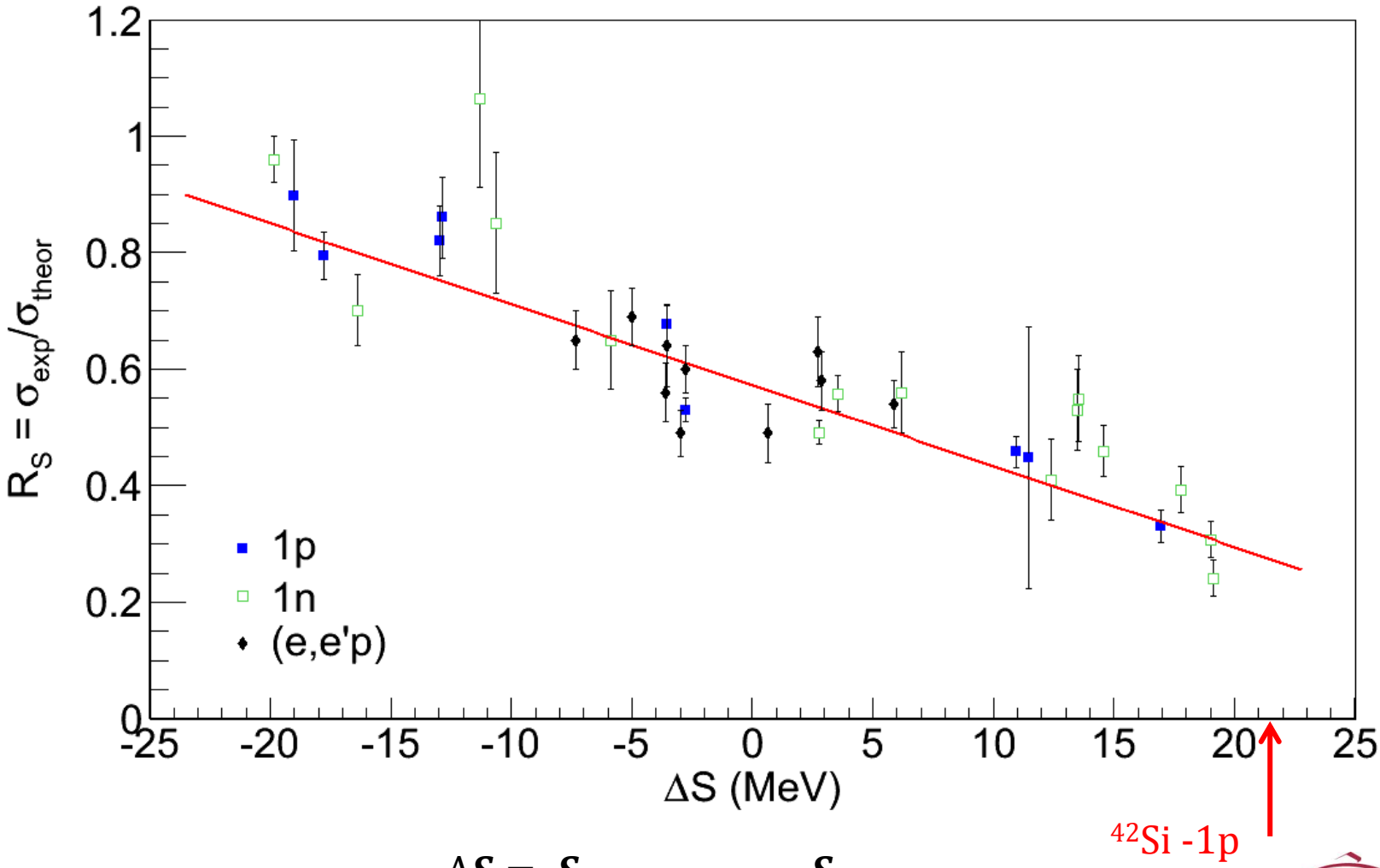




What About in a Nilsson Picture?



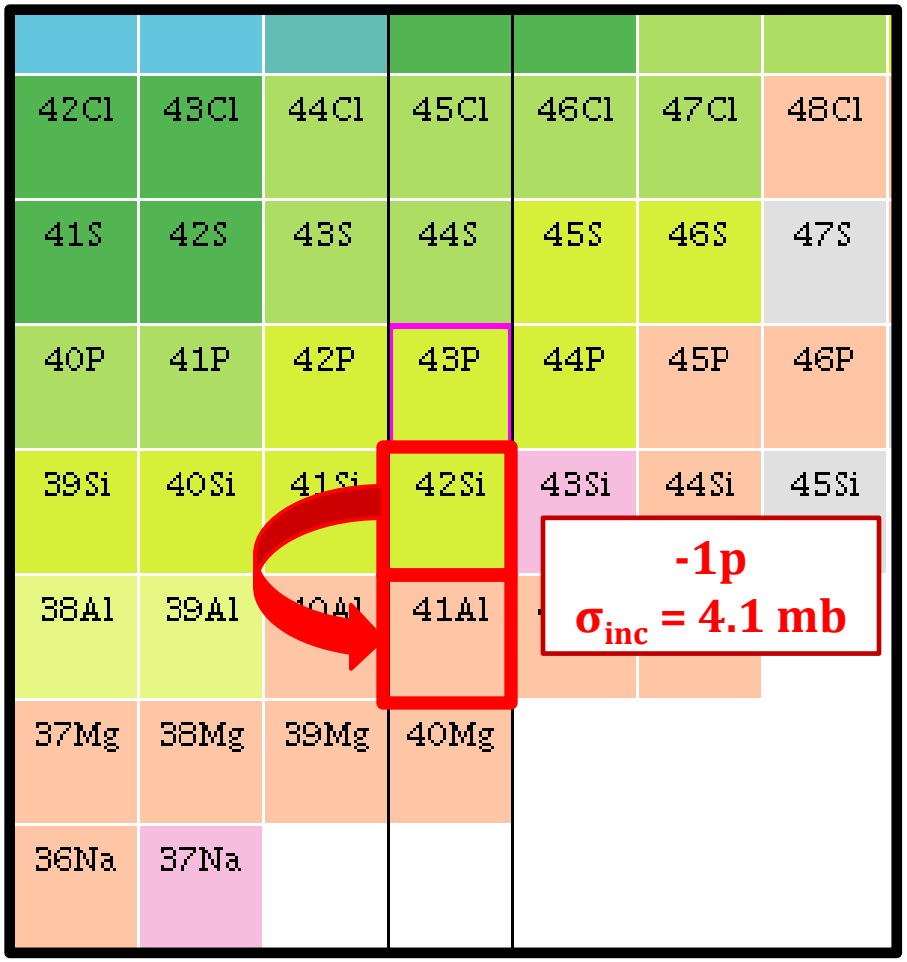
Systematics of One Nucleon Knockout



$$\Delta S = S_{knocked\ out} - S_{spectator}$$

Gade *et al.*, PRC **77**, 044306 (2008), and references therein.

1p Knockout into ^{41}Al



$$R_S = {}^{\sigma_{exp}}/_{\sigma_{theor}} = \frac{4.1}{27.83} = 0.15$$

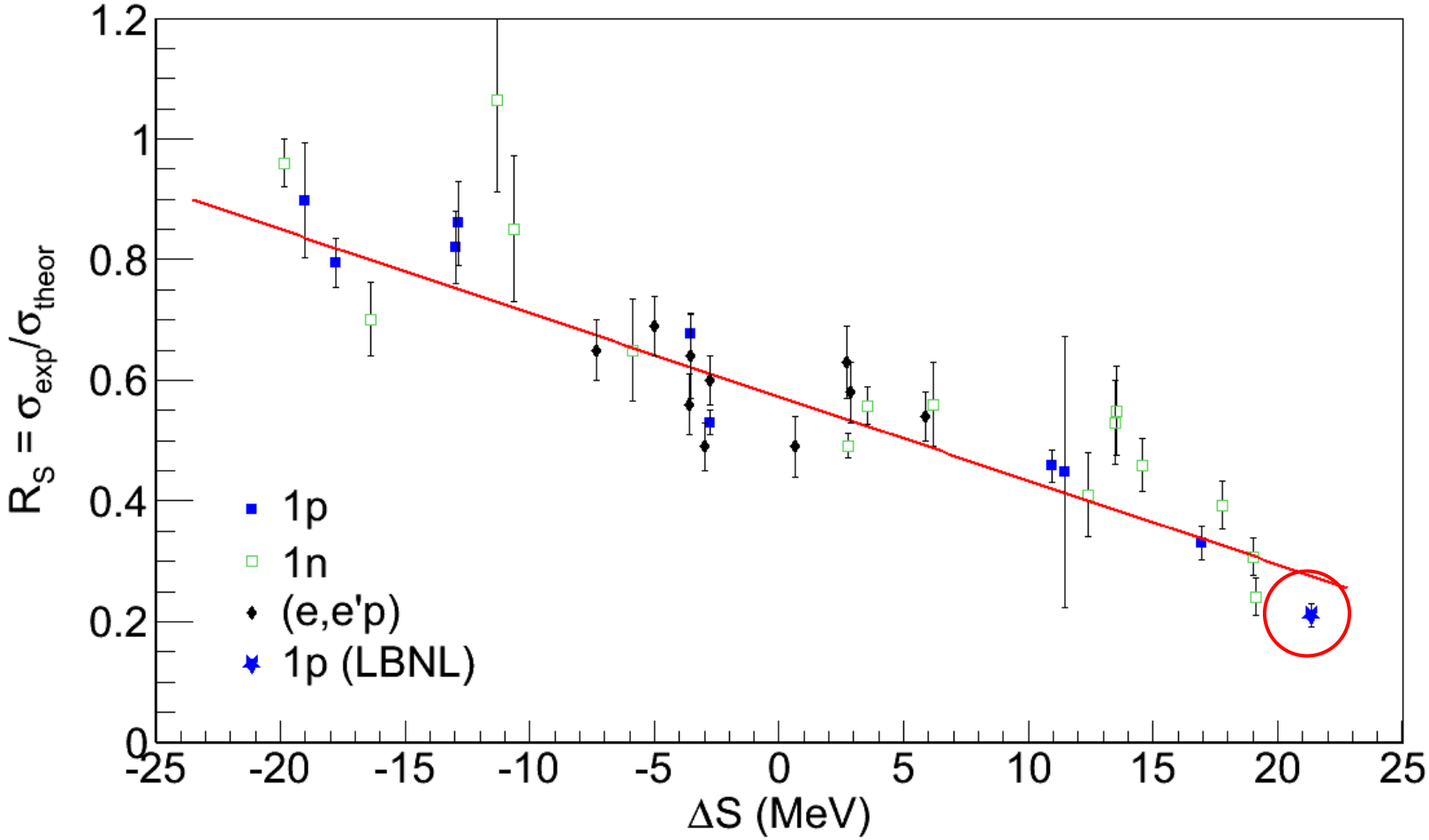
1p knockout from ^{42}Si was in a dedicated run centered on ^{41}Al

60 counts of ^{41}Al were observed, corresponding to an inclusive knockout cross-section of 4.1mb

^{41}Al State	Calculated σ (mb)
5/2+ (g.s.)	5.03
5/2+ (0.723 MeV)	6.91
5/2+ (0.747 MeV)	10.23
3/2+ (0.959 MeV)	1.25
1/2+ (1.098 MeV)	2.83
5/2+ (1.762 MeV)	0.62
3/2+ (1.854 MeV)	0.96
Inclusive	27.83

Calculations from. B.A. Brown and J. Tostevin

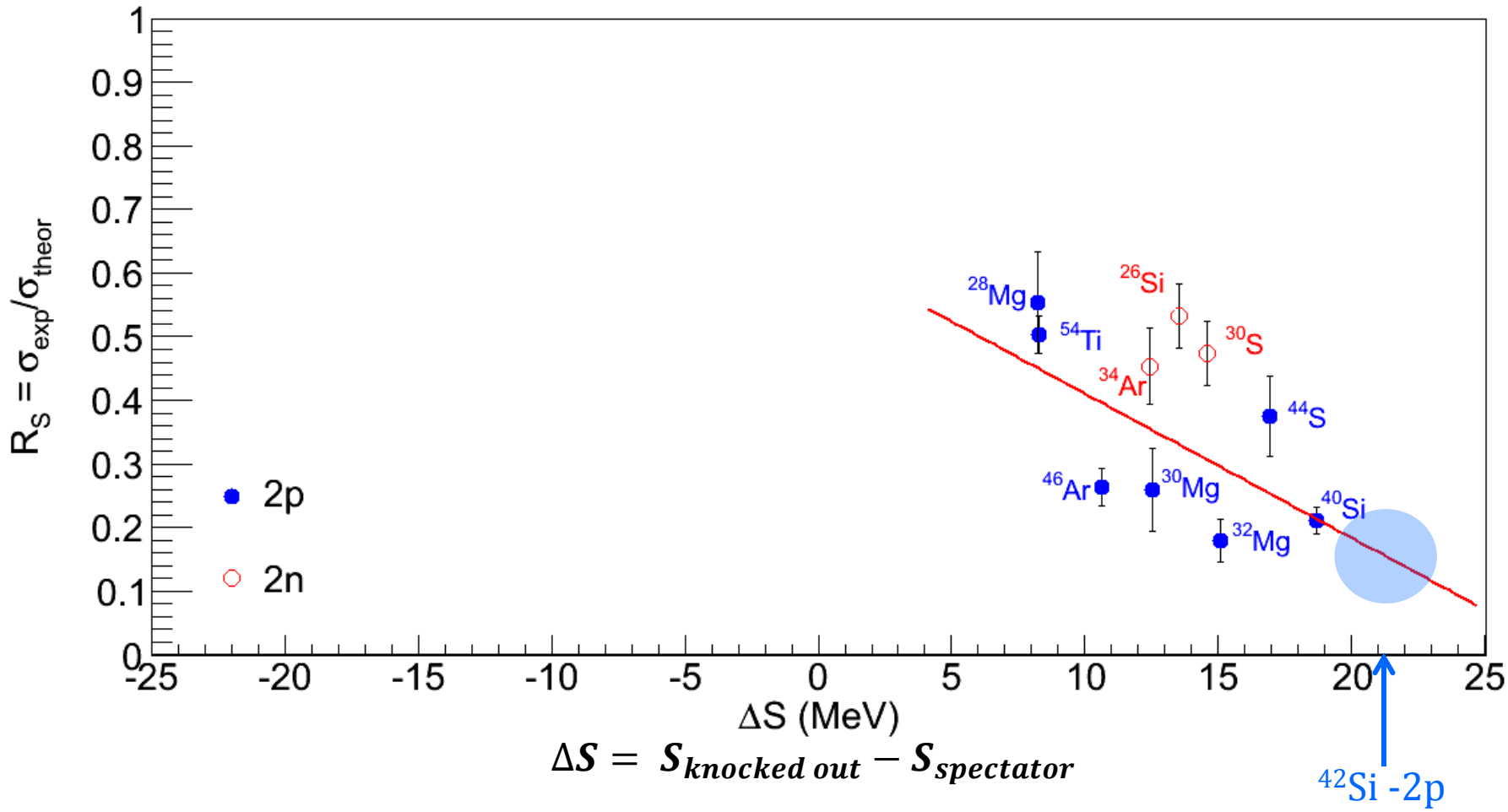
Systematics of One Nucleon Knockout



$$\Delta S = S_{knocked\ out} - S_{spectator}$$

Gade *et al.*, PRC **77**, 044306 (2008), and references therein.

Two Nucleon Knockout Suppression

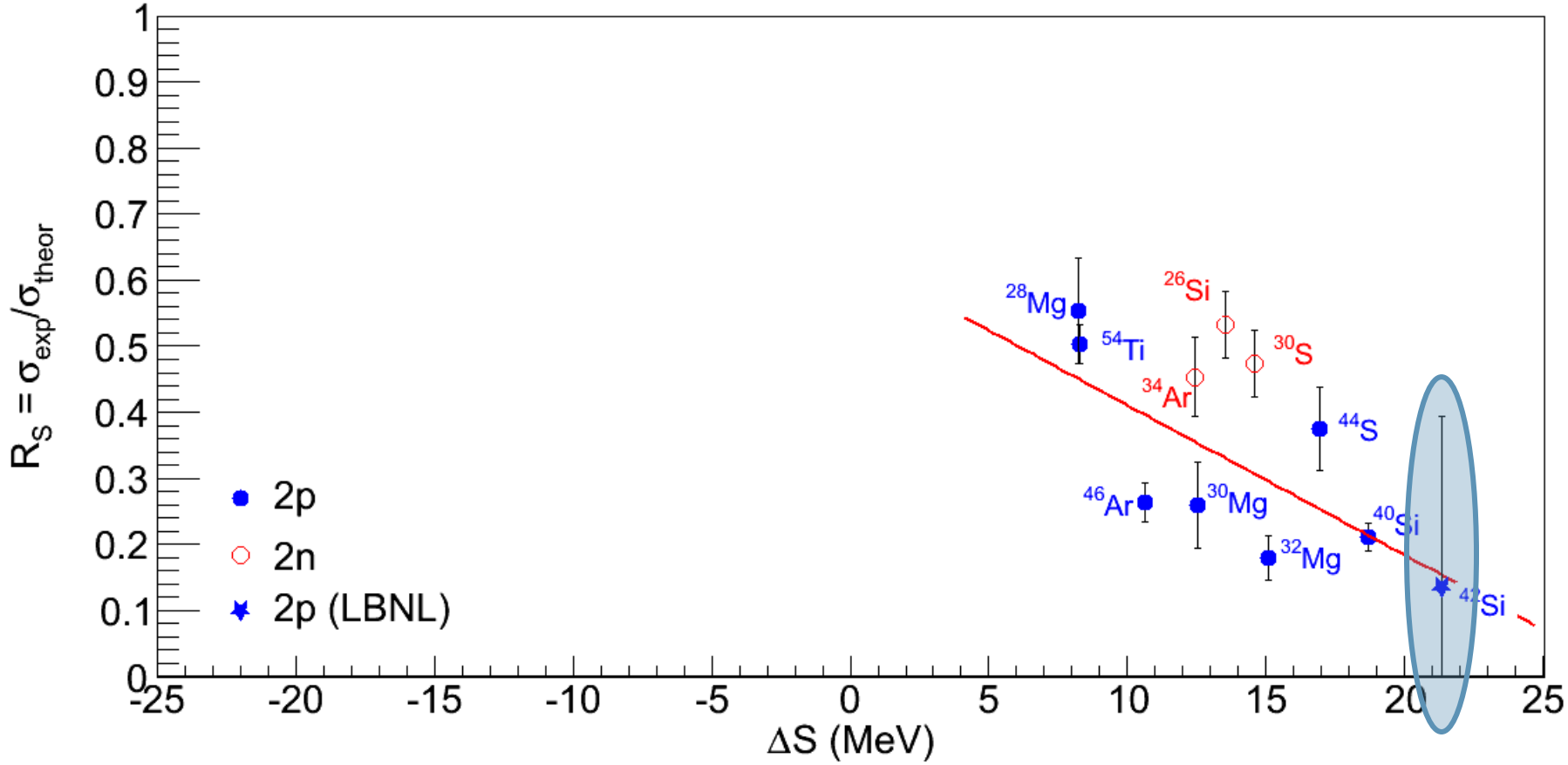


$$\Delta S = S_{knocked\ out} - S_{spectator}$$

While limited, systematics of two-nucleon knockout appears to show trend of increasing suppression for more deeply bound nucleon knockout, similar to one-nucleon knockout.

Gade *et al.*, PRC **77**, 044306 (2008), and references therein.

How Does ^{42}Si -2p Fit In?



$$\Delta S = S_{knocked\ out} - S_{spectator}$$

Gade *et al.*, PRC **77**, 044306 (2008).

What's Next Near ^{40}Mg?

Region of *N*=28 below $_{20}$Ca:

- We are working with in-beam gamma-spectroscopy group at RIKEN to assist with analysis of data already collected

Towards spectroscopy of ^{40}Mg:

- We still have beam time remaining at RIBF, and will request one day to measure the 1p knockout cross section from ^{41}Al to ^{40}Mg
- From there, can determine best route to ^{40}Mg, and first spectroscopy

Something else to think about…find the second 0+ in ^{42}Si. Feasible at RIBF, if we are clever about detecting the conversion electrons...